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Physiological impact of powered back-support exoskeletons in construction: Analyzing muscle fatigue, metabolic cost, ergonomic risks, and stability

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ABSTRACT

Powered back-support exoskeletons (BSEs) are emerging as ergonomic interventions in construction to reduce musculoskeletal injuries by actively enhancing user strength. However, their adoption remains slow due to limited understanding of potential physiological impacts, including muscle fatigue, metabolic cost, joint hyperextension, and fall risk. This paper empirically investigates the potential physiological risk associated with the powered BSEs during construction tasks. A user-centered experiment assessed the impact of powered BSEs on muscle fatigue, metabolic cost, ergonomic posture, and stability during common construction activities. The results indicated that the powered BSEs significantly decreased muscle activity for back and abdominal muscle groups by an average of 60 %, reduced metabolic costs by 17 %, and lowered ergonomic risks by 50 % without impacting stability. This study contributes to the understanding of the physiological impacts of powered BSEs in construction, providing empirical evidence of their effectiveness in reducing muscle fatigue, metabolic costs, and enhancing ergonomic safety.

1. Introduction

Construction work is often inherently complex, involving physically strenuous and repetitive tasks often executed in unconventional postures for a prolonged period. Given such hazardous nature of construction tasks, workers are often exposed to an increased risk of biomechanical strain on their musculoskeletal system [1,2], resulting in work-related musculoskeletal disorders (WMSDs). Exoskeletons are gaining traction in the construction industry as a significant means to reduce the incidence of WMSDs by offering lift assistance, distributing weight more evenly, and correcting posture. [3,4]. Exoskeletons fall into two categories: active (powered) or passive [5]. A powered exoskeleton is equipped with actuators like electric motors, pneumatics, or hydraulics, delivering direct mechanical power aid to the user [6]. This active augmentation of human strength and endurance allows workers to perform tasks that involve heavy lifting or repetitive movements with reduced effort and lower risk of injury. On the other hand, passive exoskeletons operate without external power sources. Instead, they rely on materials, springs, or dampers to capture and store energy from the user's movements, which is then used to power the device as needed [6,7]. In this vein, passive exoskeleton offers support and reduces strain by assisting with weight distribution and posture correction during tasks. Although passive exoskeletons are often more affordable and simpler to deploy, the construction industry tends to favor powered exoskeletons for their ability to actively assist workers in managing the physical demands of construction tasks [8].

The active augmentation of human strength and endurance makes powered exoskeleton particularly suitable for construction tasks involving heavy lifting or dynamic construction tasks, such as material handling, rebar tying, etc. The mechanical assistance provided by the powered systems reduces the physical effort required, minimizing the risks of overexertion and associated injuries. By actively assisting with movements, powered exoskeleton reduces the physical effort required from workers, thereby increasing their endurance and ability to work longer hours without fatigue. This benefit is particularly valuable in construction environments where tasks are often physically demanding and prolonged. While passive exoskeletons do offer advantages such as lower cost, simpler maintenance, lighter weight, and assistance for prolonged static postures, these benefits are outweighed by the limitations in providing optimal force assistance and versatility for

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construction tasks involving labor-intensive or dynamic construction tasks [9,10]. Researchers have suggested that the effectiveness of passive exoskeletons varies significantly with different tasks and postures [9]. This variability necessitates the development of multiple task-specific devices, which can be costly and complex. On the other hand, powered exoskeletons, equipped with powered actuators, are better suited for dynamic and labor-intensive construction tasks. By providing augmented strength and reducing the physical burden on workers, powered exoskeletons help prevent injuries and enhance productivity in labor-intensive or dynamic construction activities. The more robust support provided by powered exoskeletons is particularly crucial in preventing musculoskeletal disorders and reducing injury risks associated with heavy lifting and repetitive motions common in construction work.

Research indicates that back-related WMSDs are among the most common types of musculoskeletal issues in the construction industry [11,12]. Specifically, in 2020, back pain accounted for approximately 40 % of all WMSD cases within the construction field, leading to an average of seven days of lost work per incident [13]. The significant effects of workers' back pain on safety and consequently, the productivity and quality of work underscore the importance of adopting powered exoskeletons to mitigate back-related WMSDs. According to recent research, 23 % of construction contractors plan to adopt exoskeletons in the next three years, given the potential of exoskeletons to improve productivity and safety on construction sites [8]. Similarly, three out of four contractors believe that wearable technology will enhance safety conditions on construction sites [8]. These insights suggest the impending widespread implementation of powered back-support exoskeletons (BSEs) in the construction sector.

As powered BSEs start being integrated into construction sites, there will inevitably be new challenges stemming from the shift from a primarily human-centric work environment to one that emphasizes collaboration between humans and technology [14]. The augmentation of workers' ability enabled by the powered BSEs could introduce potential physiological risks factors, including local muscular fatigue [7], fall risks [15], joint hyperextension [16], and metabolic risks [17], for the users. Therefore, to ensure the safe integration of powered BSEs into work environments, it is crucial to comprehend how the use of powered BSEs impacts muscle fatigue, ergonomic posture, stability, and energy expenditure. Several researchers have attempted to understand the changes in muscle activation [18–23], ergonomic posture [24], stability [25,26], and metabolic cost [19,27] with use of passive exoskeletons. The power assistive nature of powered exoskeletons introduces unique challenges and opportunities that differ from the passive exoskeletons. Powered systems can significantly alter the way tasks are performed, impacting muscle activation patterns, stability, metabolic cost, and ergonomic posture in ways that are not fully understood through the assessment of unpowered exoskeletons. While few researchers demonstrated the efficacy of powered BSEs [28–30], it is important to recognize that this research has largely been conducted in the manufacturing sector, where tasks tend to be static, mostly involving the forward-bending postures. This differs significantly from the construction industry in which the workers perform physically demanding tasks, such as frequent lifting, carrying, bending, kneeling, stooping, etc. for extended periods in awkward postures on unstructured and dynamic job sites. The existing research does not yet provide a comprehensive understanding of the potential physiological risks that come with implementing active BSEs in construction environments. With the construction industry increasingly embracing powered exoskeletons, it becomes vital to examine their physiological impact on users. Towards that end, this study aims to empirically investigate the potential physiological risk associated with the powered BSEs during construction tasks. For this purpose, a user centered experiment was conducted to evaluate how the active BSEs impacts muscle fatigue, ergonomic posture, and metabolic efficiency in users while performing common construction tasks. The finding of the study offers insights into the potential physiological effects of implementing powered BSEs on job sites. Based on this understanding, standard regulations and guidelines can be formulated for the safe and effective use of powered exoskeletons. Further, the study can be crucial for safety managers, ergonomic specialists, and regulatory bodies in understanding the relation between enhanced physical support and the potential physiological impacts of powered exoskeleton.

2. Research background

2.1. Prevalence of work-related musculoskeletal disorders (WMSDs) in construction industry

Workers in construction environments face a multitude of occupational safety hazards, including falls, electrocutions, stuck-by, and caught-in or -between. Yet, the most frequent injuries they suffer from are soft tissue sprains and strains, which are collectively known as WMSDs [31,32]. WMSDs refers to painful disorders of soft tissues that affect the muscle, joints, nerves, tendons, cartilage, and spinal discs, occurring due to working in sustained positions, and awkward postures, forceful exertion, heavy manual material handling, and repetitive motions [31,32]. WMSDs are a major source of functional limitations, productivity declines, and in extreme situations, perennial disability [33–37]. WMSDs are prevalent due to the physically demanding nature of construction work, which include forceful hand exertions, heavy manual material handling, repetitive motions, and awkward body postures [2]. For instance, back pain resulting from prolonged periods of bending or twisting. The continuous stress on the lower back, without adequate support or rest, can lead to chronic pain or even herniated discs, as the spine is subjected to forces beyond its normal capacity for endurance and support. Likewise, cumulative trauma disorders on soft tissues can also result from performing a task repetitively in awkward postures for a prolonged period. For instance, repetitive strain injuries may develop from performing the same motion over and over, such as using hand tools or operating machinery without proper breaks. This repetitive action can lead to stress on specific body parts, surpassing the body's ability to recover, resulting in conditions like tendonitis or carpal tunnel syndrome. The U.S. Bureau of Labor and Statistics reports that WMSDs constitute approximately 37 % of all non-fatal injuries and illnesses among construction workers [13]. WMSDs impact not just the physical well-being of individuals, potentially leading to disability, but also carry substantial economic repercussions [38]. The US construction industry is estimated to face over $400 million in workers' compensation costs annually, in terms of sick leave and medical expenses [38]. Moreover, WMSDs diminish the work capacity of construction workers, often resulting in their premature retirement. Additionally, the repercussions of injuries on the physical health aspect, such as delayed healing and lost workdays, have a significant impact on the mental health of workers. Individuals dealing with persistent pain often experience heightened stress, anxiety, and depression, affecting their overall quality of life. Additionally, the discomfort and pain imposed by WMSDs can disrupt sleep patterns, contributing to fatigue and decreased overall well-being. In this vein, it is critical to explore proactive measures to mitigate the risk of WMSDs on construction workers.

Numerous federal agencies, including the Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH), have advocated for optimal ergonomic measures to reduce the likelihood of construction workers developing WMSDs [39–41]. These practices include a range of interventions, like promoting the use of ergonomically designed tools and equipment, advocating for proper lifting techniques, encouraging regular breaks to reduce fatigue, and providing training on identifying and managing ergonomic hazards. Despite such efforts to prevent WMSDs, the implementation of ergonomic intervention in the construction sector faces limitations. The dynamic and unstructured nature of the construction site makes it difficult to apply a one-size-fits-all solution.

Furthermore, there is a lack of awareness and commitment to ergonomics at all levels of management. Despite the efforts, many physically demanding tasks in construction workplaces continue to be carried out by workers repetitively in awkward positions.

2.2. Passive exoskeletons for alleviating WMSDs in construction

Exoskeletons are becoming increasingly popular in the construction industry as an ergonomic solution to reduce WMSDs by offering lifting assistance, distributing weight more evenly, and correcting posture [3,4]. Among the categories of exoskeletons, passive exoskeletons are preferred for their affordability and easy deployment. Passive exoskeletons, which rely on mechanical support rather than motors, are ideal for tasks requiring static postures or repetitive tasks [19–22,24,42,43]. For instance, Wei et al. [19] examined the effect of passive exoskeleton on muscle activity and metabolic cost on workers during static forward bending task and found the reduction of muscle activity by 35–61 % and metabolic cost by 22 % when wearing the exoskeleton. Likewise, Huysamen et al. [20] evaluate the effect of a passive upper body exoskeleton and found the reduction in muscle activity for the Biceps Brachi by 49 % and the Media Deltoid by 62 %. Similarly, Antwi-Afari et al. [22] examined the effects of a passive exoskeleton system on spinal biomechanics during manual repetitive handling tasks and found that the passive exoskeleton significantly reduced muscle activity by 11–33 %. Further, Madinei et al. [43] assessed the efficacy of two different passive exoskeleton and found the reduction in trunk muscle activity by 24–42 % during precision assembly tasks. While these studies have demonstrated the potential benefits of passive exoskeletons in reducing muscle activity and increasing endurance time during construction tasks, passive exoskeletons are more ideal for tasks requiring prolonged static postures rather than the dynamic construction tasks.

Researchers have attempted to assess the performance of passive exoskeleton during dynamic construction tasks. Golbachi et al. [42] evaluated the impact of using exoskeletons when adopting different postures during dynamic manual material handling tasks and found that the exoskeleton reduced the load on the lower back of the users. Likewise, Alemi et al. [44] explored the efficacy of two different passive exoskeletons during dynamic repetitive lifting tasks in different postures and found that both exoskeletons reduced peak back muscle activity and energy expenditure. Furthermore, Koopman et al. [10] investigated the effect of the passive exoskeleton and found reduction of peak muscle activity by 22 %. However, researchers have highlighted that the effectiveness of passive exoskeletons varies significantly with different tasks and postures [44]. This variability necessitates the development of multiple task-specific passive exoskeletons for optimal mitigation of WMSDs, which can be costly and complex. Powered exoskeletons, on the other hand, use actuators to provide adaptive assistance, making them more suitable for tasks involving significant lifting, carrying, or dynamic construction tasks, such as heavy material handling, drilling, or demolition. By providing augmented strength and reducing the physical burden on workers, powered exoskeletons can complement passive exoskeletons to prevent injuries and enhance productivity in labor-intensive activities.

2.3. Powered exoskeletons: a potential solution to mitigate WMSDs in construction industry and the implementation challenges

Powered exoskeletons, with their active augmentation of body joints, provide a more versatile solution for dynamic construction tasks. The limitations of passive exoskeletons in optimally supporting dynamic movements, and task-specific effectiveness suggest that the powered exoskeletons can provide a more effective solution for task involving significant lifting, carrying, or dynamic construction tasks, such as heavy material handling, drilling, or demolition. By using motors or actuators, powered exoskeletons deliver additional support to the muscles and joints of workers, diminishing the likelihood of fatigue and injuries [45]. Particularly, powered exoskeletons actively enhance the physical capabilities of workers, resulting in improved safety and increased productivity. The implementation of powered BSEs could also address labor shortages by allowing workers to perform tasks longer and with less strain, enabling older workers to remain employed longer, and attract a broader range of workforce to the construction sites. Powered exoskeletons are quickly becoming available as commercial products, offering promising prospects for preventing work-related injuries [45]. Powered exoskeletons are designed to assist various body parts, including the back, legs, arms, shoulders, and hands, or even the entire body. Given the high incidence rate of back-pain [11,12], powered BSEs have the potential to alleviate the risks of back-related WMSDs in the construction sector.

While the potential benefits of powered BSEs are promising, they also bring forth unintended safety and usability challenges [46]. Depending on the nature of the load and movement strategy, the additional support supplied by the exoskeleton in the form of force or torque may unintentionally lead to localized muscular fatigue, increasing the risk of discomfort and strain. Exoskeletons assisting the user in performing a task can lead to the muscles being used differently than without the device [47]. For instance, if an exoskeleton provides lift support, the user's muscles may not have to work much harder to lift the load, but the muscles may still be contracting to control the movement of the exoskeleton. Concurrently, the exoskeleton may amplify resistance to the user's movements, which increases muscle activity, causing the muscles to become fatigued more quickly than they would without the exoskeleton. Also, during lifting tasks, the use of an exoskeleton can increase the activation of the specific muscle groups due to the need to push against the device to initiate the support mechanism. This increased muscle activity can lead to localized fatigue in the muscles. Another key physiological challenge is the potential increase in metabolic cost. For instance, powered BSEs may result in increased metabolic costs due to the possible changes in lifting techniques (e.g., from a stoop lift to a semi-squat lift) that require muscle groups that are not assisted by the device to work harder. Researchers have suggested that squat lifting is more metabolically costly than stoop lifting, as it involves greater muscular activity to facilitate movement through a wider range of motion [17,48]. This heightened metabolic cost might negate the potential benefits provided by the exoskeleton. Additionally, the inherent weight of the exoskeleton, even if it's relatively light, may add to the user's energy burden [49]. This becomes particularly noticeable during tasks involving extensive movement or when the exoskeleton must be worn for long periods. Further, if the exoskeleton restricts any natural movement, it can lead to less efficient movement patterns that require more mechanical energy from the body [50], thereby increasing the metabolic cost. Likewise, powered exoskeletons may induce changes in postural strategies adopted by users, which could counterproductively increase the risks of joint hyperextension [51–53]. For instance, powered BSEs might lead users to push their body joints beyond their normal range of motion. This adjustment, intended to maximize the support from the exoskeleton, could inadvertently heighten the risk of joint hyperextension. Furthermore, powered exoskeletons also can shift the users' center of gravity, which diminishes the effectiveness of the human body's recovery strategy to loss of balance, thereby increasing fall risks [3,54–56]. For instance, the additional weight of the exoskeleton could result in an uneven distribution of load on users during material handling tasks. Such disruption in body kinematics is bound to affect stability and balance. This is particularly crucial in the construction sector, where workers must perform their daily tasks on unstructured, clustered, and dynamic job sites. In this regard, it is crucial to assess the potential physiological risks factors of local muscular fatigue, metabolic risks, joint hyperextension and fall risks associated with the powered BSEs for construction workers during ongoing tasks.

Previous research has attempted to assess the varying physiological risks associated with powered exoskeletons [29,57–62]. For instance, Walter et al. [57] examined how powered BSEs affect workers during material handling tasks, finding that such devices lowered the muscle activity in the lumbar erector spinae by 25 % during lifting. Similarly, Toxiri et al. [58] found a 30 % reduction in muscle activity in the lumbar spine from using powered BSEs for material handling tasks. Kim et al. [59] showed that custom-made powered BSEs decreased muscle activity in the lumbar erector spinae by 16 % and 11 %, without significantly affecting the upper trapezius muscle activity. Blanco et al. [30] observed a more than 24 % decrease in oxygen consumption with upper-limb exoskeleton during repetitive tasks. Nuessien et al. [60] found approximately 10 % decrease in metabolic cost with knee exoskeleton. Gonzalez et al. [29] reported that the powered ankle exoskeleton didn't affect the overall balance of the users. Despite these findings, the integration of powered BSEs in the construction industry encounters significant challenges. Most of the existing research for assessing the impact of powered BSEs has been carried out in industrial settings, focusing on static tasks and forward-bending postures. Such findings might not translate to the dynamic and physically demanding nature of construction work, which often involves dynamic lifting, carrying, and extended periods of stooping. Furthermore, the current body of literature largely overlooks the impact of powered BSEs on metabolic cost, stability, and joint hyperextension during the common construction activities. Although few research has addressed the impact on metabolic cost of energy using exoskeletons, these studies predominantly focus on powered exoskeletons designed to assist various body parts [30,60], excluding the back. Additionally, the studies for investigating the impact of powered BSEs on stability and joint hyperextension have mostly been limited to passive systems in industrial settings [63–65]. In this vein, there is a critical need for an in-depth investigation on the comprehensive physiological impact of powered BSEs on construction workers.

3. Research methodology

This research aims to explore the physiological impacts of powered BSEs on construction workers while performing common construction activities. The developed research methodology is mainly orchestrated through two major key steps: User-Centered Experiment and Physiological Risk Assessment. In Step 1, a user-centered experiment was conducted to seamlessly examine different interactions with powered BSEs for safe and feasible evaluation of pertinent physical risks. Specifically, eighteen subjects were recruited to perform common construction tasks: material handling and rebar tying under two conditions (with and without active BSEs). During the tasks, the muscular activity of the workers was collected through electromyography (EMG) sensors, breath-by-breath respiration data through portable indirect calorimetry, and subjects' bodily movements across the three axes of acceleration from Inertial Measurement Unit (IMU) sensors. In Step 2, the impact of exoskeletons on workers' physiological parameters, which includes muscular fatigue, metabolic cost, ergonomic risks of awkward postures, and stability were evaluated. Notably, the EMG signals from different back muscle groups were extracted and statistically analyzed to assess the impact of active BSEs on local muscular fatigue. Likewise, energy expenditure and maximum oxygen uptake (VO_2) were extracted from the breath-by-breath respiratory data to examine the impact of active BSEs on metabolic of construction workers. Similarly, the 3D postures of subjects were extracted from the IMU sensors. Based on the estimated posture, the joint angles between body joints were calculated and Rapid Entire Body Assessment (REBA) score was generated to assess the risk of joint hyperextension. Additionally, several posture metrics, which includes velocity of center of body pressure (COPv) as well as gait stability parameters were also extracted from the IMU sensors attached to waist and ankle to assess the fall risks associated with the use of active BSEs. Lastly, the extracted metrics for all the physiological parameters under two conditions were statistically analyzed to understand the impact of powered BSEs. Fig. 1 provides an overview of the research methodology. Detailed explanation of the various steps within the research methodology are elaborated in the following sections.

3.1. Step 1: user-centered experiment

3.1.1. Subjects

Eighteen healthy construction workers (twelve male and six female) were recruited to participate in this study. The means of age, height, body mass, and body mass index were 25.2 ± 4 years, 179 ± 5.5 cm, 74 ± 6.5 kg, and 23.1 ± 2.5 kg/m^2, respectively. Each participant had experience in conducting common construction activities. Before the experiments, none of the subjects reported any history of mechanical pain or injury of the lower back extremities. Moreover, the activity level of the participants was moderate to vigorous. All the subjects were

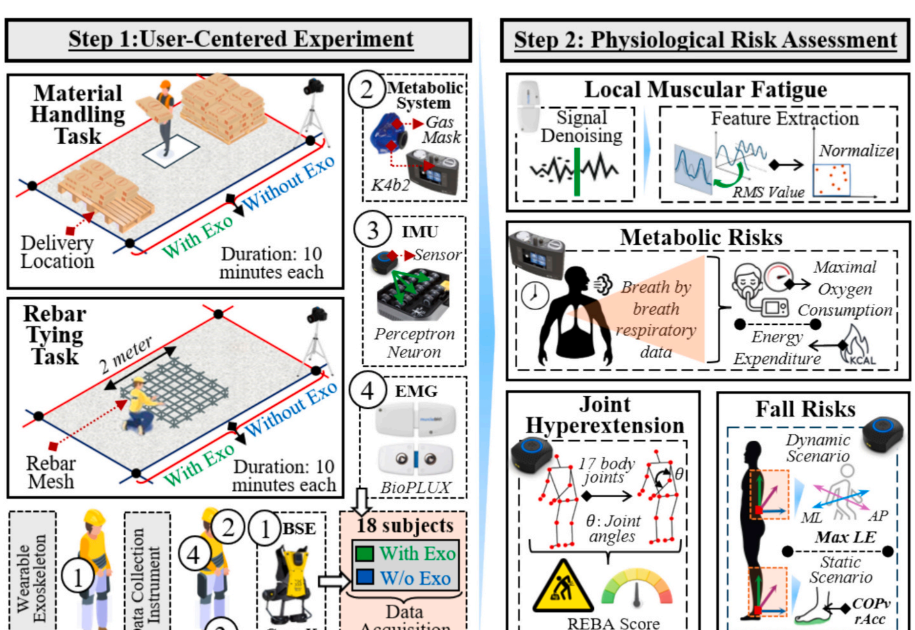

Fig. 1. Research methodology.

provided with informed consent forms explaining the purpose of this study, an extensive explanation of the experiment, and confidentiality of the data. Informed written consent was obtained from all the subjects following the procedure approved by the Institution Review Board (IRB) at University of Illinois Urbana Champaign.

3.1.2. Data collection instruments

After the informed consent forms were obtained, subjects were equipped with a portable EMG biosensor, portable indirect calorimeter, and IMU sensors (as seen in Fig. 2), detailed in following:

- EMG Sensors: In this study, the activity of the lumbar erector spinae (LES), thoracic erector spinae (TES), rectus abdominis (RA), external oblique (EO), and rectus femoris (RF) muscle groups of the subjects were measured through portable EMG sensors (BioSignal PLUX). These muscle groups were selected to analyze back and abdominal muscle activation and their roles in generating mechanical energy during physically intensive tasks or tasks performed in awkward postures for prolonged periods as well as their relevance in previous research assessing the impact of back support exoskeletons [18–23,66]. The LES and TES muscles are crucial for spinal support during lifting tasks, making their study essential for understanding back muscle activation [67]. Likewise, the RA and EO muscles play significant roles in stabilizing the core, distributing loads evenly, and controlling lateral movements during bending and twisting activities, often performed in construction sector [68]. Furthermore, the RF muscles contribute to tasks involving squatting, lifting, and other leg movements, ensuring proper load distribution and stability [69]. For assessing muscle activity, two sets of Ag/AgCl surface electrodes were attached to either side of the targeted muscle group. The detailed placement of EMG sensors can be seen in Fig. 2-A. Before attaching the sensor, the authors followed a standardized procedure for preparing the skin, ensuring that the skin impedance was reduced to below 10 kΩ. The EMG signal was sampled at a sampling rate of 1 kHz [70]. After attaching the sensor, the calibration was performed. The calibration included setting the baseline muscle activity levels for LES, TES, RA, EO, and RF muscle groups. With the electrodes in place, participants assumed a relaxed position. Then, the EMG sensors record the electrical activity of the muscle in this state. This helps to establish what constitutes the resting state for each muscle group, which sets a reference point for the minimal electrical activity in the muscle, essential for identifying any deviations from this relaxed state during experiments.
- Portable Indirect Calorimetry: In this study, participants were also fitted with a portable calorimeter (K4b2, Cosmed, Rome) and a face mask to gather the breath-by-breath respiratory data, as seen in Fig. 2-B. The breath-by breath respiratory data was collected to breath-by-breath oxygen consumption (O_2), carbon dioxide production (CO_2), and maximal oxygen consumption (VO_2 max). For this purpose, calibration of the device was carried out prior to the measurement of each participant. Specifically, the O_2 and CO_2 sensors of K4b2 were calibrated according to the instruction of the manufacturer using gases of known concentrations. This involved introducing reference gases with specific concentrations of oxygen and carbon dioxide to the sensors and adjusting the readings to match the known values. Further, room air and delay calibrations were also performed. Room air calibration involved calibrating the sensors to the ambient air conditions. The device was exposed to room air, and the readings were adjusted to reflect the baseline levels of oxygen and carbon dioxide typically found in the environment. Likewise, delay calibration was performed to account for the time delay between the gas exchange at the mouth and the sensor reading. This ensured that the timing of the gas measurements aligned correctly with the subject's breathing patterns. After the calibration, participants were asked to wear a face mask connected to the portable K4b2 unit.
- IMU Sensors: Motion capture system (Perception Neuron) with 17 IMU sensors were also attached to the subjects' body for capturing the ground truth 3D posture of the subjects, including, right ankle and waist for collecting subjects' bodily movement data across the three axes of acceleration. The sensors were placed based on the manufacturer guidelines as follows: one on the back of the head, two on the left and right side of the upper portion of the scapula, two on the upper arms just above the lateral elbow, two on the forearms just above the lateral side of the wrist, two on the back of the hands, one on the sternum (center of the chest), one on the lower back (lumbar

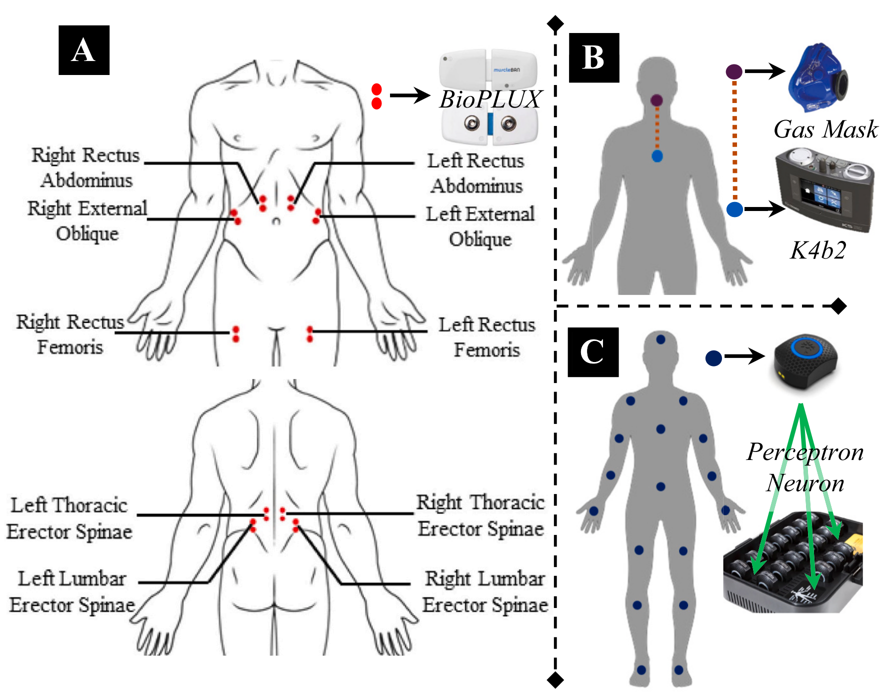

Fig. 2. Data collection instruments and their placements: A) EMG sensors; B) indirect portable calorimetry; and C) IMU sensors.

region), two on the front of the thighs just above the knee, two on the shins just below the knee, and two on top of the feet. The detailed placement of 17 IMU sensors can be seen in Fig. 2-C. For each experimental setting, the height of IMU sensor was measured using a flat tape measure. This measurement is crucial for normalizing the kinematic data collected by the IMU sensors, adjusting for individual differences in body size and sensor placement. The acceleration data was collected at a sampling rate of 60 Hz, with the acceleration being measured along the X-, Y-, and *Z*-axes. These axes corresponded to the anterior-posterior (AP), mediolateral (ML), and vertical (VT) directions of the subjects' bodies, respectively. To ensure each axis correctly aligned with the anatomical axes, the sensors were meticulously oriented according to the manufacturer's guidelines: the X-axis aligned with the AP direction, the Y-axis with the ML direction, and the Z-axis with the VT direction. Prior to data collection, a four-step calibration process was performed to ensure accurate and reliable measurements. This process included a steady pose calibration with the participant seated and motionless, an A-pose calibration with palms down on thighs and feet parallel, a T-pose calibration with shoulders abducted 90° and palms facing the floor, and a S-Pose calibration with knees bent 45° and arms forward parallel to the ground. This comprehensive calibration sequence established essential reference points across various body orientations and joint configurations, enabling precise collection of motion data by accounting for individual biomechanical variations.

3.1.3. Data collection procedure

To assess the physiological impact of powered BSEs on construction workers, an experiment setup was developed for the subjects to perform two common construction activities: material handling tasks and rebar tying tasks. The study used a randomized crossover design where each participant performed the material handling and rebar tying tasks under two conditions-with and without exoskeleton. Material handling, a prevalent and physically demanding activity in construction, is known to contribute to WMSDs among workers. Similarly, the study simulated rebar tying tasks, owing to the risks associated with the prolonged and awkward postures workers must maintain, which also elevate the risk of WMSDs.

The material handling tasks involved twenty rounds of material handling activities, where subjects were required to pick, carry, and store a 30 lb. cement bag from material staging area to the delivery location. The material handling task involved three subtasks – lifting, carrying, and lowering 30 lbs. of cement bag, as shown in Fig. 3-A. The total duration of each session lasted approximately 10 min. Likewise, the rebar tying tasks involved subjects performing rebar tying tasks for 10 min in squatting postures, as seen in Fig. 3-B. During the rebar tying tasks, participants were not in a continuous squatting position for the entire task duration. Participants were allowed to adjust their posture as needed but were instructed to perform the rebar tying tasks primarily from a squatting position. The rebar tying task was performed on a mesh consisting of eight-by-eight steel rods, each 2 m in length, with a center-to-center spacing of 25 cm between them. Participants were asked to repeatedly secure the rebars with tie-wires on the arranged mesh until the allocated time had elapsed.

The authors adopted a crossover study design in which subjects were randomly assigned into two groups (i.e., 9 subjects in each group). Subjects in the first group initiated the experiment by performing the construction tasks without the use of the powered exoskeleton. Then, the subject's crossover to the other arm of the study to perform the same tasks using the powered exoskeleton (Cray X; German Bionic Systems GmbH, Germany). Similarly, the second group of subjects will start with performing the tasks using the powered exoskeleton, followed by executing the tasks without active BSE. A period of one month between trials of each group was considered to ensure data integrity. In the study, a powered exoskeleton, Cray-X was used, as presented in Fig. 3-C. Cray X is a powered BSE manufactured by German Bionic weighing about 8 kg. The device consists of two protruded sides, a chest strap, pelvic belt, leg strap, and a motor powered by a 40-V battery. The exoskeleton is designed to be worn similarly to a backpack, with the weight of the device supported by a pelvic belt. The Cray X model is equipped with adjustable connections for fitting onto the user, including a chest strap and two leg connections. It features a display interface, allowing for control over three primary assistive modes designed to aid in lifting, bending, and walking. Two electromotors supply the power, creating extension torque at the hip level within the sagittal plane. This torque is then transferred to the wearer's body via adjustable connections.

Before initiating the case study, the researchers tailored the exoskeleton's fit to ensure each participant could wear it with ease. This process was followed by a brief, 10-min training session to familiarize participants with the exoskeleton. During this adaptation phase, the subjects identified the preferred level of assistance from the exoskeleton that felt most comfortable for them. Once this training was completed, each participant was fitted with EMG sensors, portable indirect portable calorimetry, and IMU sensors. All the devices were calibrated for each

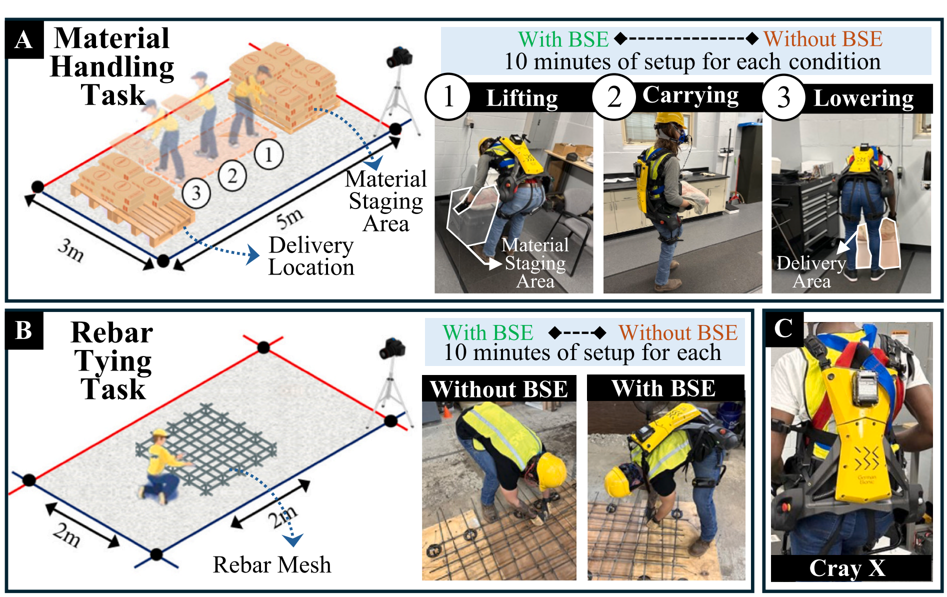

Fig. 3. Experimental Setup: A) Material Handling Task; B) Rebar Tying Task; and C) Powered Back-Support Exoskeleton (Cray-X).

participant, following the manufacturer's guidelines. During the experiments, a time -stamp camera leveraged to record the experiments and document the start and end of material handling and rebar tying tasks. Consequently, the subjects were asked to carry out the designated tasks and the physiological measures were continuously recorded for each activity. During the tasks, participants were instructed to maintain their body posture as consistently as possible, with only minor adjustments allowed to facilitate task completion. These posture adjustments were carefully reviewed in the video recordings to ensure they remained minor. Any significant deviations were documented and excluded from the analysis. The same protocol was strictly followed for both conditions (with and without the exoskeleton) to ensure comparable postures across different experimental setups. This rigorous monitoring ensured the reliability of the posture data and an accurate assessment of the effects of BSEs on workers.

3.2. Step 2: physiological risk assessment

3.2.1. Local muscular fatigue

To assess the effect of active BSE on worker local muscular fatigue during construction work, the authors collected raw EMG signals from each side of LES, TES, RA, EO, and RF muscle groups. A time -stamp camera leveraged to record the experiments, was also used to document the start and end of material handling and rebar tying tasks. Notably, as the material handling tasks involved three sub-tasks, lifting, carrying, and lowering; the recording from the camera was used to sort the EMG data accordingly. In the processing of the EMG signals, the signal recordings from the initial and final 3 s of the tasks were omitted. Such omission was performed to eliminate any induced variance that could stem from the initial positioning or abrupt ending of the task. Then, the collected signal from each session from all subjects was filtered, rectified, normalized, and averaged. To reduce the signal noises and reveal the correct fluxes in physiology, the authors implemented several noise-removal techniques based on previous investigations [70–75]. Firstly, EMG signals were band-pass filtered between 0.5 Hz and 250 Hz to reduce external signal artifacts. To remove ambient noise, a notch filter with a cutoff frequency of 60 Hz was applied. After filtering, EMG signals were rectified and, consequently, normalized [76]. Since the intensity of the signal was different for each subject, the EMG signal needs to be normalized. In this regard, maximum voluntary contraction (MVC) for each subject was conducted before the experiments. To that end, the task proposed by [77] was adopted for the MVC trials. For LES and TES muscle groups, participants lay on their stomachs and attempted to raise their upper bodies as much as they could. During this, the authors secured their legs to the floor and manually applied resistance against their upper back [78]. Likewise, for RA, EO, and RF muscle groups, the participants laid on their backs and tried to lift their trunks as far as possible. In this case, the author held their legs in place on the floor and exerted resistance against their chests [78]. The participants performed MVC trials three times, in which the duration for the contraction was 5 s, with 1 min rest in between. Using an averaging window of 100 ms, the processed EMG signals were used to generate the root mean square (RMS) value. The sampled RMS EMG data were normalized to the maximum RMS amplitude recorded across three trials of MVC and expressed as % MVC. The RMS value of MVC value was also obtained by computing the root mean square of EMG signals using a 100 ms moving window. In this vein, %MVC was computed for every subject and every muscle group. Researchers have shown that %MVC is sensitive to momentary variation in body loading and is a valuable source of information for assessing muscle activation [79]. In such regard, %MVC was used as a performance metric to assess the impact of BSEs on local muscular fatigue. To determine the appropriate inferential statistical analysis method to analyze the differences, Shapiro-Wilk method was leveraged to examine the normality of the extracted metric. As the data satisfied the normal distribution ($p > 0.05$), a paired t-test was then adopted to evaluate the statistical difference on local muscular fatigue during common construction activities under two conditions (with and without using powered BSE). The results of the analysis will be reported in section 4.1.

3.2.2. Metabolic risks

While the EMG leveraged by the authors effectively captures muscle activation of key back muscle groups, not all the relevant muscle groups can be monitored for understanding the whole-body fatigue. In this vein, metabolic demand can be assessed to understand the level of muscle recruitment and, concurrently, the risk of whole-body fatigue. To assess the metabolic risks associated with the use of powered BSE, breath-by-breath respiratory data was acquired using a portable indirect. Prior to data collection, the device was calibrated according to the manufacturer's guidelines, ensuring the accuracy and consistency of the acquired respiratory data, as mentioned in Section 3.1.2. For each trial, outcome measures included O_2, VCO_2, and $VO_2\,max$. Similarly, the energy expenditure were estimated using the Brockway equation Brockway Eq. [80], as shown below:

$$E = \frac{16.58 \times \mathrm{O_2} + 0.51 \times \mathrm{VCO_2}}{\mathrm{m}} \quad (1)$$

where, E is the energy expenditure during the given instance, O_2 is the volume rate of oxygen consumption in mL/s, and VCO_2 is the volume rate of CO_2 production in mL/s and m is the mass of the subject in kg. The energy expenditure was calculated in Joule/s/kg. The mass term was adjusted with the corresponding mass of the exoskeleton.

To eliminate the impact of the individual differences, the energy expenditure was normalized with the body weight. To analyze the impact of the active exoskeletons system on the metabolic cost of construction workers while performing common construction activities, the difference between the extracted metrics from the calorimetry device, maximal oxygen consumption and energy expenditure, were statistically analyzed. Firstly, the normality of the data was checked through Shapiro-Wilk test. The test conferred a p value of 0.8907 (greater than 0.05), which indicates that the data didn't significantly deviate from a normal distribution. As the data satisfied the normal distribution, a paired t-test was adopted to evaluate the statistical difference between metabolic costs of workers during common construction activities under two different scenarios (with and without using a powered BSE). The results of the analysis will be reported in Section 4.2.

3.2.3. Joint hyperextension

To assess the risks of joint hyperextension for the use of BSEs during construction tasks, a motion capture system (Perception Neuron Studio) with 17 body attached IMU sensors was used to collect the 3D coordinates of human poses. As previously mentioned, recording for the time -stamp camera was used to document the start and end of material handling and rebar tying tasks. Further, as the material handling tasks involved three sub-tasks, lifting, carrying, and lowering, the recording from the camera was also used to sort the IMU data accordingly. Based on the collected posture information, the joint angles between body joints were calculated and REBA score was generated to assess the risk of joint hyperextension. Previously, the authors have developed a vision-based technique [81] to extract 2D posture from 2D images and calculated the joint angles from the extracted 2D postures. However, a major limitation with 2D posture extraction from 2D images is occlusion, which leads to incomplete posture data, hindering accurate analysis of body mechanics and joint angles. Furthermore, the effectiveness of such a vision-based system can be compromised by occlusion or situations involving non-frontal views. To that end, this study leverages motion capture system equipped with 17 body attached IMU sensors to acquire reference joint coordinates. The IMU-based motion capture system with high immunity against occlusion has a relatively comparable accuracy for accurately estimating the 3D coordinates of the human poses. Based on the estimated posture, the joint angles between body joints were calculated and REBA score was generated to assess the risk of joint hyperextension. Based on the generated 3D worker posture, the authors calculated the joint angles related to the position of the worker's neck, trunk, upper limbs, and lower limbs. This is achieved by creating vectors between pairs of joints and applying the cosine law in vector form to compute the angles. Specifically, the angle between two vectors, originating from the set of trained 3D vectors, is determined using the following equation:

$$\theta = cos^{-1}\left[\frac{a_{ij}.b_{kl}}{|a_{ij}|\ |b_{kl}|}\right] \tag{2}$$

where, in 3D space, each body joint is represented as a point with three coordinates (x, y, z). The vector between two joints i and j in 3D space, denoted as a_{ij} is calculated from the difference in their respective coordinates. Similarly, b_{kl} represents another vector between joints k and l. Likewise, $a_{ij}.b_{kl}$ represents the dot product of vectors a_{ij} and b_{kl}, calculated as $a_xb_x + a_yb_y + a_zb_z$. Also, $|a_{ij}|$ and $|b_{kl}|$ are the magnitudes (or norms) of the vectors a_{ij} and b_{kl}, respectively. After calculating the required joint angles from the estimated 3D posture, the authors used the joint angles to assess workers' ergonomic risk (with and without wearing BSE) based on the REBA approach [82]. In this regard, the authors employed measured joint angles to compute an ergonomic risk score based on the Rapid Entire Body Assessment (REBA) method. REBA provides scores for various body movements such as trunk, neck, and knee flexion, as well as upper and lower arm movements. For instance, trunk flexion within 0–20 degrees adds two points to the score, 20–60 degree adds three points, and angle beyond 60 degrees adds 4 points. After scoring each body segment, the individual scores are aggregated to derive an overall body posture score using three specific tables from the REBA worksheet. The tables from the worksheet guide users to an initial score reflecting the ergonomic risk associated with a worker's posture. The initial score is added with the activity score from the worksheet to yield a final REBA score. A score of 1 indicates negligible risk, 2–3 is considered low risk, 4–7 medium risk, 8–10 high risk, and a score above 11 signifies a very high risk. Detailed information on using the REBA method to assess the ergonomic risks can be found in [82]. The final REBA score for the subjects in both conditions (with and without using a powered BSE) for the material handling task and rebar tying tasks will be reported in section 4.3.

3.2.4. Fall risks

This study leverages IMU sensors to assess the potential fall risks associated with BSEs during stationary and dynamic tasks. The recording from the camera was used to sort the IMU data for stationary tasks and dynamic tasks accordingly. For the assessment of the fall risks during stationary tasks, the recording for rebar tying task, as well as lifting and lowering subtasks of material handling tasks were used to sort the IMU data. Likewise, the recording for the carrying subtask for material handling task was used to sort the IMU data for assessing fall risks in dynamic conditions.

For stationary condition, the IMU data from the subjects' waistline (lower back) was collected. After obtaining the subjects' bodily movement data across the three axes of acceleration, COPv and rAcc were calculated, based on the authors previous study [83]. The previous study [83] showed that the measurements of COPv and rAcc could be regarded as a viable indicator of fall risk for stationary tasks. rAcc was determined by calculating the square root of the sum of the squares of the different accelerometer components across the entire dataset using $\sum\left(\sqrt{a_{xi}^2 + a_{yi}^2 + a_{zi}^2}\right)$, where a_x, a_y, and a_z are the acceleration measurements from the obtained IMU data in each of three axes. Likewise, the calculation of COPv involves several steps. Firstly, the magnitude of the resultant acceleration for each data point was calculated using equation: $A = \sqrt{a_{xi}^2 + a_{yi}^2 + a_{zi}^2}$. Then the directional cosine for each point was obtained using: $cos\alpha = \frac{a_{zi}}{A}$; $cos\beta = \frac{a_{xi}}{A}$; $cos\gamma = \frac{a_{yi}}{A}$. Here $cos\alpha$, $cos\beta$, $cos\gamma$ represent the directional cosines and α, β, γ a are the angles between the components of the acceleration (a_{zi}, a_{xi}, a_{yi}) and resultant vector A.These cosines are crucial for understanding the orientation of movement. With the directional cosines and the distance of the sensor from the ground plane d_z (calculated for every subject) known, the displacement magnitude D and the projected location d_x and d_y for each point was calculated using $D^*cos\beta$, $d_{yi} = D^*cos\gamma$, $d_z = D^*cos\alpha$. Then, the COPv was determined by adding the distances between consecutive center of pressure points and dividing by the total data collection time T, using $\frac{\sum\sqrt{(x_{i+1}-x_i)^2+(y_{i+1}-y_i)^2}}{T}$; where generated d_x and d_y were used as inputs.

For dynamic conditions, fall risks were assessed by using gait stability metrics. In this study, the authors extracted spatiotemporal gait data from the IMU attached to the users' right feet to calculate the gait cycles by identifying the local minimums and maximums of gait-stride displacements along the vertical axis. This process allowed for determining the stride length and height during each gait cycle. Additionally, the gait-stride time (gait speed) was calculated as an additional metric for evaluating gait stability. Further, Maximum Lyapunov Exponents (MLE) in the AP and ML direction obtained from the subjects' right ankle IMU data across the tasks was calculated by leveraging the Rosenstein Algorithm as mentioned in [84]. MLE is a validated gait stability metric for fall risk assessment, as demonstrated by the previous studies [85,86]. More details about the Max LE calculation can be found in [85].

To assess the impact of active BSEs on construction workers' fall risk, the authors conducted statistical analysis comparing the extracted metrics from stationary and dynamic condition for subjects wearing active BSE and those performing the tasks without BSEs. Initially, the normality of the data was checked through Shapiro-Wilk test. The test resulted in a p value greater than 0.05, indicating that the data did not significantly deviate from a normal distribution. With the data confirmed to follow a normal distribution, the authors applied a paired t-test to evaluate the statistical differences in fall risks between workers with and without powered BSE. Section 4.4 will report the results of the analysis.

4. Results -physiological impact of powered BSEs to construction workers

4.1. Impact of powered BSEs on local muscular fatigue

Fig. 4 represents the calculated %MVC for the all the muscle groups (i.e. LES, TES, RA, EO, and RF) while subjects performed the material handling task and rebar tying task under two conditions (with and without using an exoskeleton). For the lifting subtask of material handling task (as seen in Fig. 4-A), the result showed statistically significant reduction in muscle activity for the LES, TES, and EO on both sides, and for the RA on the left side. In particular, the %MVC for left LES muscle decreased by 66.67 % ($p = 5.92\text{e-}04$), left TES muscle by 53.65 % ($p = 0.0065$), left RA muscle by 50.98 % ($p = 0.00012$), and left EO muscle by −58.33 % ($p = 0.0096$). Likewise, %MVC for right LES muscle decreased by 58.82 % ($p = 5.35\text{e-}04$), right TES muscle by −62.85 % ($p = 1.33\text{e-}04$), and right EO muscle by −74.15 % ($p = 0.0057$). The significant decrease in LES, TES, and EO muscle groups on both sides suggests that the powered BSE effectively supports the trunk and may contribute to a more ergonomic lifting posture, reducing the demand on these core stabilizing muscles. By supporting the lower back, the BSE may encourage better posture during lifting, which can more evenly distribute the load across the spine and reduce the need for excessive contraction of the back and abdominal muscles.

Likewise, Fig. 4-B presents %MVC for the all the muscle groups engaged in a carrying task within a material handling scenario. The findings indicate a significant decrease in muscle activity in LES and TES

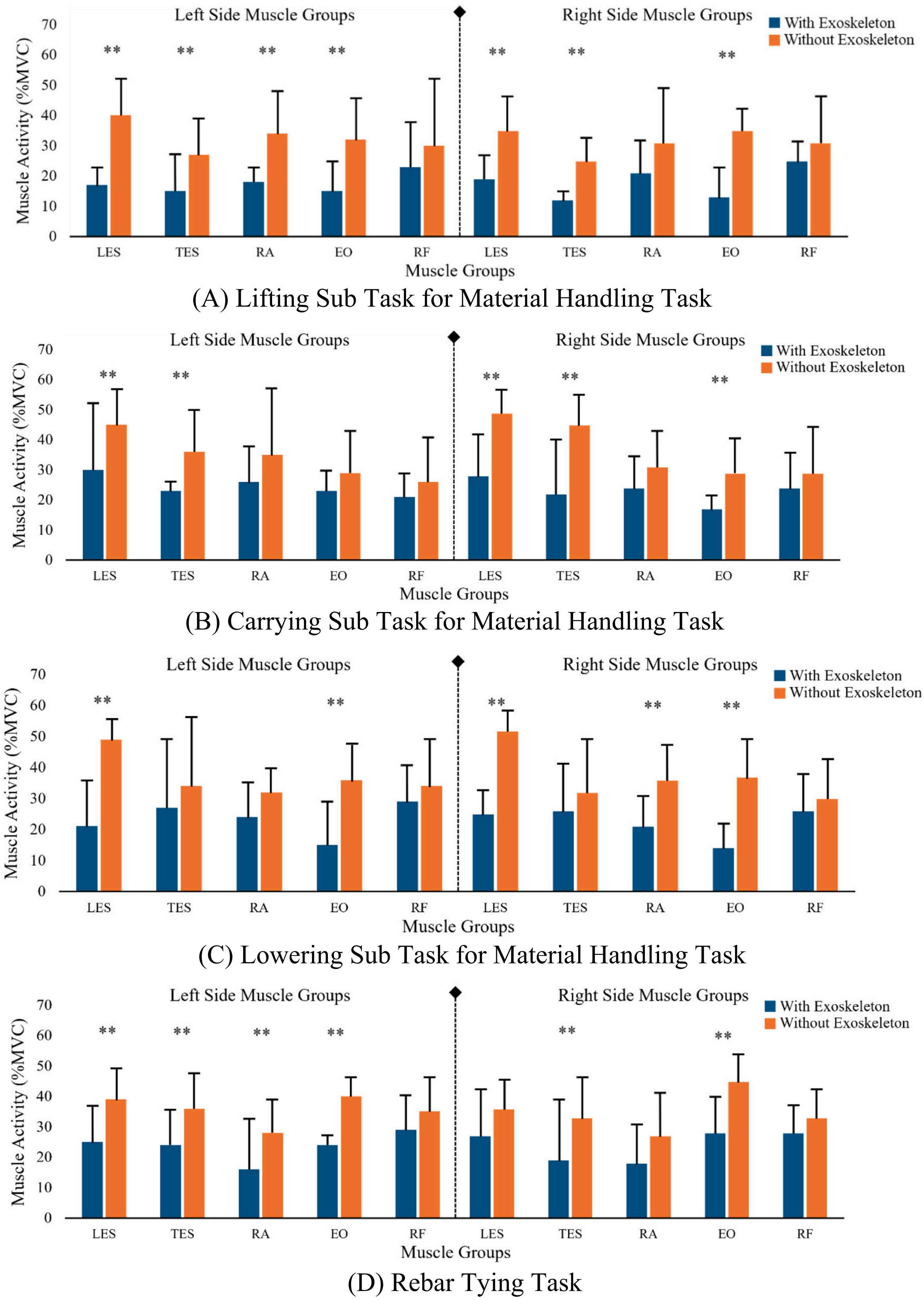

Fig. 4. Impact of powered BSEs for each muscle group during: (A) lifting subtask for material handling task; (B) carrying subtask for material handling task; (C) lowering subtask for material handling task; and (D) rebar tying task. **Note:** Error bar indicates standard deviation; ** indicates a significant difference ($p < 0.05$).

on both sides, as well as EO on the right side with the use of powered BSE. In particular, the muscle activation level for left LES muscle decreased by 38.89 % ($p = 0.021$) and left TES muscle decreased by 41.37 % ($p = 0.0057$). On the right-side muscle groups, the %MVC for right LES muscle decreased by 47.36 % ($p = 2.12\text{e-}04$), right TES muscle by −56.25 % ($p = 0.0047$), and right EO muscle by 45.45 % ($p = 3.13\text{e-}04$). The significant decrease in LES and TES muscle activity on both sides suggests that the powered BSE is effective in offloading stress and strain from these primary muscles involved in the carrying task. The LES and TES are critical for maintaining trunk stability and erect posture, especially under load. By supporting the trunk and potentially promoting a better lifting posture, the active BSE helps to reduce the activation level of these muscles, which could decrease the risk of muscle fatigue.

Similarly, Fig. 4-C shows the %MVC for the all the muscle groups during the lowering subtasks in material handling. The results show significant decreases in muscle activation for LES and EO on both sides, and for RA on the right side with the use of powered BSE. Specifically, the %MVC for left LES muscle decreased by 74.62 % ($p = 3.22\text{e-}04$) and left EO muscle by 69.23 % ($p = 4.97\text{e-}04$). Likewise, the %MVC for right LES muscle decreased by 75.67 % ($p = 1.26\text{e-}06$), right EO muscle by 69.38 % ($p = 3.21\text{e-}04$), and right RA muscle by 45.61 % ($p = 0.0065$). For the LES muscle groups, the significant muscle activity reduction during lowering tasks implies the powered BSE plays a key role in supporting the lower back, crucial for the controlled descent of loads. The decrease in EO muscle activation highlights the BSE's effectiveness in assisting with the trunk's rotational and lateral adjustments during lowering tasks, essential for maintaining balance and stability. Lastly, the reduction in RA muscle activity on the right side emphasizes the BSE's contribution to anterior trunk support, vital for preventing forward leaning and promoting a neutral spine posture during the precise and often asymmetric demands of lowering materials.

Furthermore, Fig. 4-D demonstrates the calculated %MVC for the all the muscle groups while subjects performed the rebar tying task. The result showed reductions in muscle activity for the TES and EO on both side of muscle groups, and for the LES and RA on the right side are statistically significant. Specifically, %MVC for left LES muscle decreased by 47.61 % ($p = 0.00035$), left TES muscle by 50.84 % ($p = 0.0046$), left RA muscle by 43.47 % ($p = 0.0129$), and left EO muscle by 39.84 % ($p = 0.0075$). Likewise, the %MVC for right TES muscle decreased by 48.6 % ($p = 0.0015$) and right EO muscle decreased by 42.28 % ($p = 0.0062$).

The considerable decrease in muscle activity for the TES and EO on both sides during the rebar tying task underscores the role of powered BSE in significantly reducing the workload on muscles critical for maintaining upper trunk stability and rotational movements. This reduction is particularly relevant to the rebar tying task, which involves repetitive bending and twisting motions, suggesting that the BSE effectively minimizes the physical demand of such actions on the worker's body. Additionally, the decrease in LES and RA activity on the left side further underscores the role of powered in supporting the anterior and lower trunk stability, crucial for the precise and controlled movements required in rebar tying. Further details about the difference in %MVC for subjects with and without exoskeletons for all the muscle groups across all the tasks can be found in Table 1.

4.2. *Metabolic risks of powered BSEs*

Fig. 5 shows the energy expenditure for a representative subject (Subject #2) across two scenarios (with and without using an active BSE) under material handling and rebar tying task.

Fig. 5 illustrates that, as time progresses, the energy expenditure for both scenarios rise, which may reflect the accumulation of fatigue. However, the red line, representing the condition without exoskeleton, is consistently higher than the blue line, which denotes the condition with exoskeleton. This consistent gap between the two lines throughout the graph indicates that the subject exhausts more energy during the material handling tasks and rebar tying tasks when not assisted by the powered BSE. Notably, the separation between the energy expenditure in rebar tying tasks is more noticeable as compared to the material handling task. For both tasks, the energy expenditure goes up as both tasks progress, which is a common physiological response as muscles tire and more effort is required to maintain the same level of performance. Table 2 shows the results of VO_2 max and energy expenditure measured during the ten minutes material handling task.

Result indicated that the average VO_2 max recorded with an exoskeleton was 12.72 ± 1.54, suggesting a lower demand on cardiovascular effort as compared to the average VO_2 max without powered BSE, which was 14.62 ± 2.16. The results highlight that the maximal oxygen consumption decreased by approximately 15 % with the use of the exoskeleton. Furthermore, the energy expenditure also followed a similar trend, with a mean ± SD of 5.72 ± 0.78 when the exoskeleton was used, as opposed to the slightly higher 6.24 ± 0.92 without it. The percentage difference demonstrates the reduction of energy expenditure by approximately 17 % with the use of a powered BSE. Likewise, Table 3 shows the results of VO_2 max and energy expenditure measured during the ten minutes rebar tying task. For rebar tying tasks, indicated that the VO_2 max observed when using the active BSE was 14.73 ± 2.54, reflecting a lower cardiovascular demand than the VO_2 max without the exoskeleton, which was 16.02 ± 1.85. The results denote a reduction in maximal oxygen consumption by approximately 16 % with the assistance of the active BSEs in rebar tying tasks Similarly, energy expenditure was 6.42 ± 1.88 when the powered BSE was worn, compared to a slightly higher 7.74 ± 1.62 without the exoskeleton, indicating a decrease in energy expenditure by about 20.5 % with the use of a powered BSE.

To evaluate the statistical significance of the performance differences between the two conditions, a paired *t*-test was utilized. The *p*-values obtained for both the VO2 max and energy expenditure metrics during material handling and rebar tying tasks were below 0.01 (level of threshold =0.01), as detailed in Table 2 and Table 3. These p-values indicate that the observed differences are statistically significant, suggesting that the use of powered BSEs leads to reduced metabolic costs during the material handling and rebar tying in the construction sector. The observed 15 % decrease in maximal oxygen consumption and a 17

Table 1
Difference in %MVC for subjects with and without exoskeleton for all the muscle groups across all the tasks.

Tasks	Muscle Groups									
	Left Side Muscle Groups					Right Side Muscle Groups				
	LES	TES	RA	EO	RF	LES	TES	RA	EO	RF
Lifting	−66.67*	−53.65*	−50.98*	−58.33*	−22.22	−58.82*	−62.85*	−34.45	−74.15*	−10.9
Carrying	−38.89*	−41.37*	−22.9	−23.07	−28.57	−47.36*	−56.25*	−24.18	−45.45*	−18.86
Lowering	−74.62*	−13.33	−29.62	−69.23*	−6.45	−75.67*	−14.28	−45.61*	−69.38*	−10.91
Rebar Tying	−47.61*	−50.84*	−43.47*	−39.84*	−9.83	−17.58	−48.6*	−33.6	−42.28*	−12.9

* Statistically significant with $p < 0.05$.

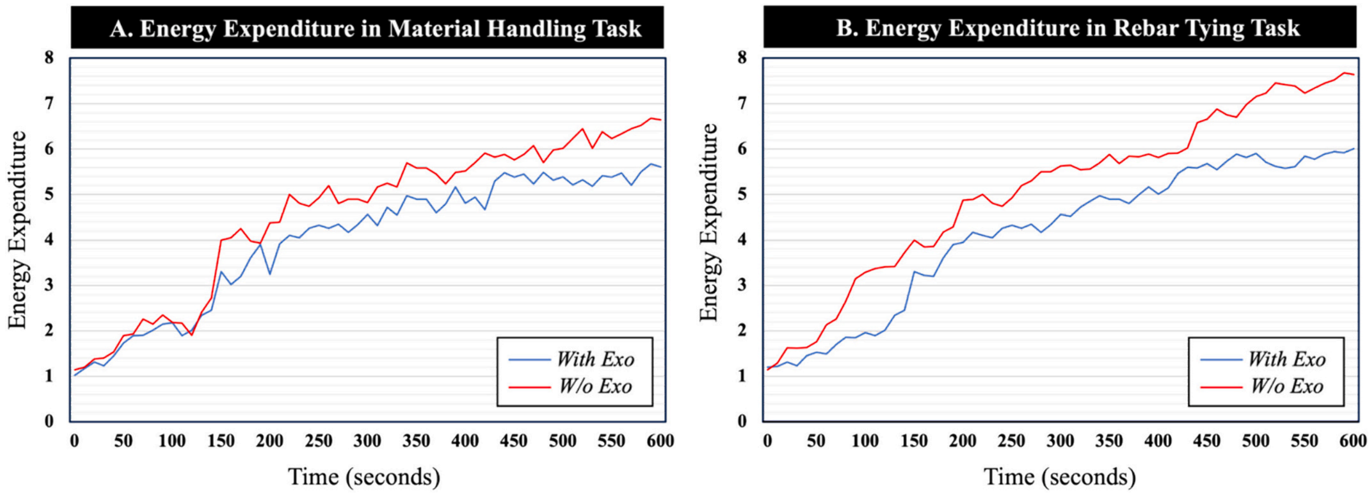

Fig. 5. Energy Expenditure for Subject 2 under two experimental conditions (with exoskeleton and without exoskeleton): A) Material Handling Task; and B) Rebar Tying Task.

Table 2
Results of VO_2 and energy expenditure measured during material handling task.

Extracted Measures	With Exoskeleton	Without Exoskeleton	% Difference	p-value[1]
Maximal Oxygen Consumption (VO_2 max)	12.72 ± 1.54	14.62 ± 2.16	−14.96	0.00036
Energy Expenditure (Joule/s/kg)	5.72 ± 0.78	6.24 ± 0.92	−17.3	0.0064

[1] Level of significance = 0.01.

Table 3
Results of VO_2 and energy expenditure measured during rebar tying task.

Extracted Measures	With Exoskeleton	Without Exoskeleton	% Difference	p-value[1]
Maximal Oxygen Consumption (VO_2 max)	14.73 ± 2.54	17.14 ± 1.85	−16.38	0.00012
Energy Expenditure (Joule/s/kg)	6.42 ± 1.88	7.74 ± 1.62	−20.56	0.0071

[1] Level of significance = 0.01.

% reduction in energy expenditure during material handling tasks, as well as 16 % decrease in maximal oxygen consumption and a 20 % reduction in energy expenditure during rebar tying tasks are particularly noteworthy, as they imply that workers could sustain longer periods of activity with less exertion when aided by an exoskeleton. Result suggest that the support offered by exoskeletons in maintaining proper ergonomic postures prevents overexertion that would otherwise elevate oxygen consumption and energy usage. Such improved endurance resulting from less fatigue, because of the support from exoskeleton means that the body muscle can operate more efficiently over long period, requiring less oxygen and producing less lactic acid, which is a byproduct of anerobic respiration in fatigued muscles. The more noticeable separation in the rebar tying task suggests that rebar tying task may benefit more from the exoskeleton in terms of energy savings. This could be due to the specific demands of rebar tying, which might involve sustained postures that the exoskeleton effectively assists with. The result of this study is consistent with similar studies which suggest that the powered back-support exoskeleton reduces the energy expenditure of the user [30,60].

4.3. Ergonomic risks of powered BSEs

Fig. 6 shows the REBA scores across all subjects with and without the powered BSE on all the lifting, carrying, and lowering subtasks of material handling, as well as rebar tying task. The score for each subject was the average score of all the REBA scores assessed for the subject during the tasks. For the lifting subtask of material handling tasks, REBA scores varied across the subjects but showed a general decrease (Fig. 6-A) when the active BSE was used. By comparing the REBA Score assessed from these two conditions, the result showed that, on average, the exoskeleton reduced the workers' ergonomic risk by 47.6 % during the lifting task. Similarly, for the carrying subtask in material handling, the use of exoskeleton demonstrated a trend towards reduced REBA scores, indicating a decrease in ergonomic risk (Fig. 6-B) by 41.5 % on average. The lowering subtask (Fig. 6-C) also saw a notable decrease in REBA scores by 45.3 % with exoskeleton use. This indicates that the exoskeleton effectively aids in maintaining safer postures, thereby reducing the risk during the lowering of materials. On the other hand, the use of powered BSE demonstrated the most significant risk reduction with a 57.5 % decrease in REBA scores during the rebar tying task (Fig. 6-D). Rebar tying is a task that inherently involves awkward postures, including stooping, bending, and repetitive hand movements. These postures significantly elevate the ergonomic risk, as indicated by higher REBA scores without exoskeleton use. The substantial reduction in REBA scores for the rebar tying task can be attributed to the active BSE's ability to mitigate the ergonomic risks associated with these awkward postures. By providing support to the lower back and potentially aiding in maintaining an upright posture, the powered exoskeleton reduces the physical strain during bending and stooping. Further, the reduction of ergonomic risk during lifting, bending, and carrying subtasks also indicates that powered BSE could correct subjects' awkward postures in the trunk and knee during the material handling task. Notably, the data showed individual differences in REBA scores both with and without the exoskeleton, which highlights the influence of personal factors such as individual anthropometry, task execution style, and possibly the degree of exoskeleton fit. While the consistent reduction in REBA scores for most subjects suggests that exoskeletons may serve as a beneficial ergonomic intervention., the persistent variability in scores among subjects indicates that additional measures such as tailored training, or ergonomic task modification might be necessary to fully leverage the potential ergonomic benefits offered by exoskeleton usage.

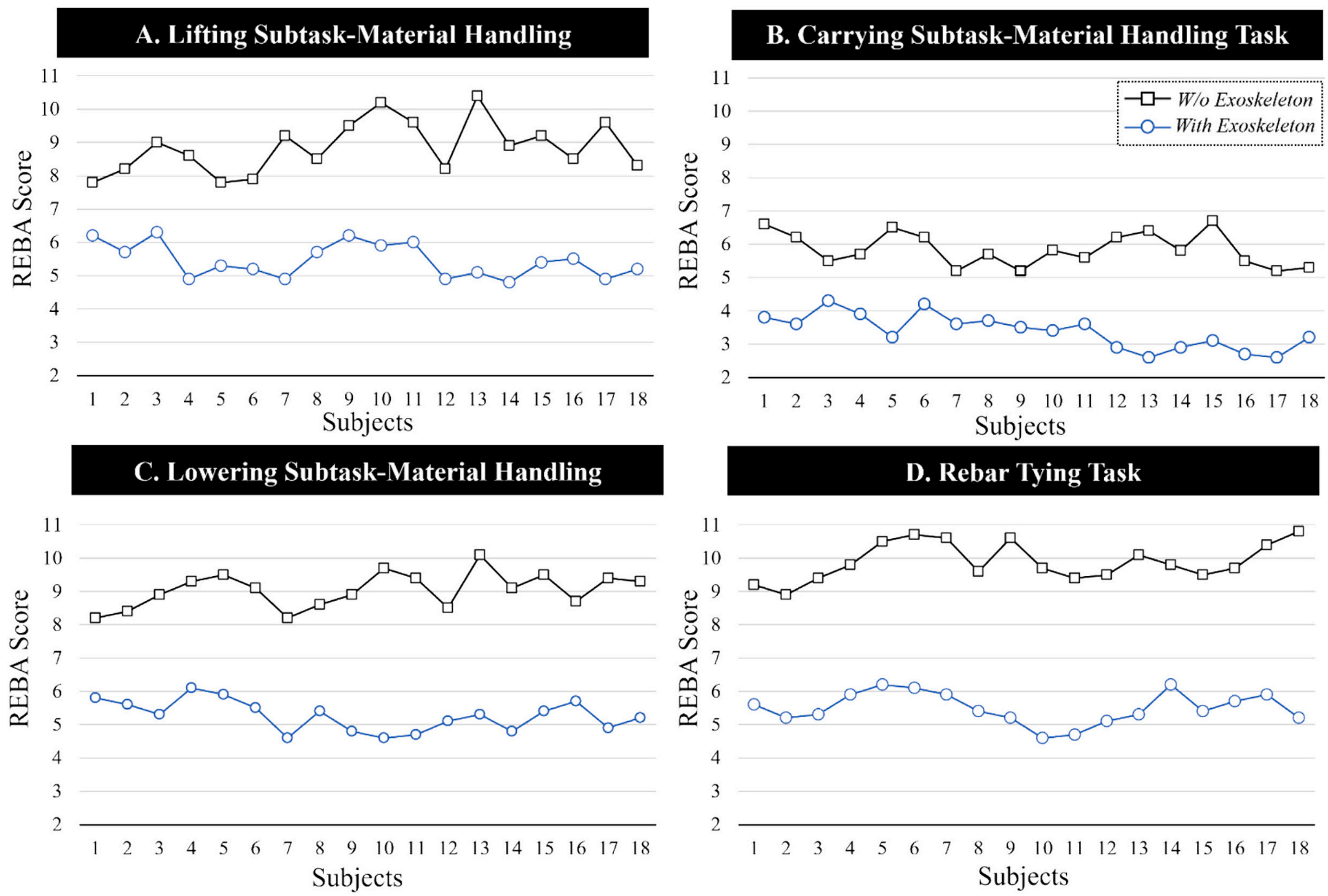

Fig. 6. REBA score for all the subjects under two experimental conditions (with exoskeleton and without exoskeleton): A) Lifting Subtask; B) Carrying Subtasks; C) Lowering Subtask; and D) Rebar Tying Task.

4.4. Impact of powered BSEs on stability

Fig. 7 shows the mean and SD of COPv and rAcc for all subjects with and without the powered BSE on stationary conditions. In lifting subtasks for material handling, the COPv and rAcc value was higher for the subjects with exoskeleton compared to the subjects without exoskeleton. On the other hand, the COPv and rAcc value for subjects with exoskeleton was lower for subjects wearing exoskeleton for lowering subtask and rebar tying task in comparison with the subjects working without exoskeleton. In particular, the COPv for subjects with exoskeleton was 38.21 ± 12.72 and subjects without exoskeleton was 32.37 ± 10.56 for lifting subtask. Likewise, rAcc for subjects with exoskeleton was 3.46 ± 1.35 and subjects performing the tasks without exoskeleton was 2.83 ± 1.17 for lifting subtask. The increased COPv and rAcc in subjects using the exoskeleton during lifting might indicate that the BSE is enabling subjects to lift with more dynamic movement, possibly due to added

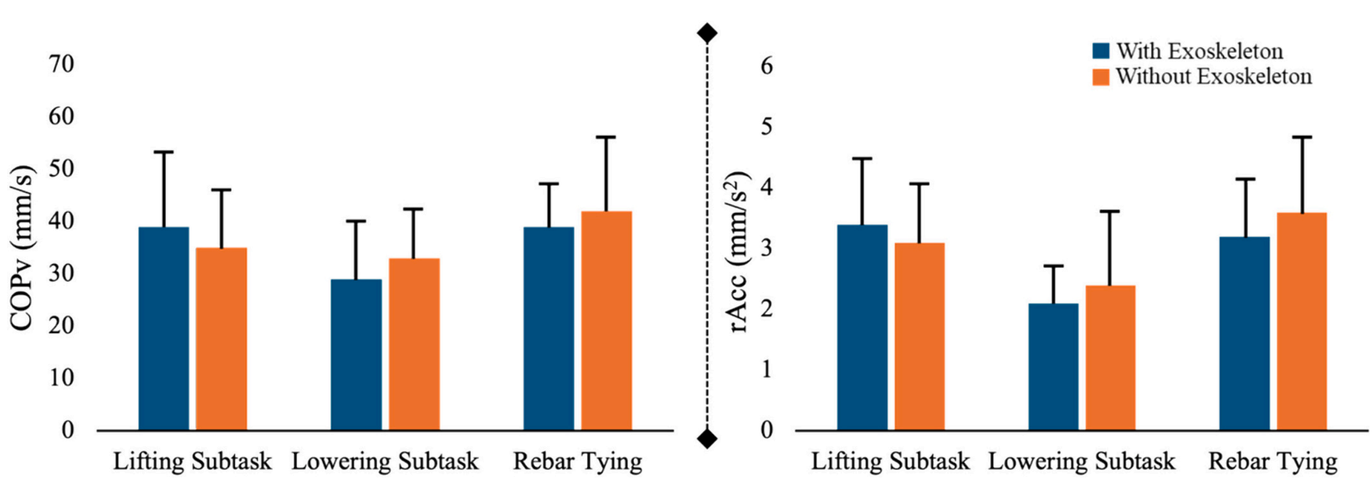

Fig. 7. COPv and rAcc values for all the subjects in stationary condition under two experimental settings (with exoskeleton and without exoskeleton) **Note:** Error bar indicates standard deviation.

support in movement. Similarly, the COPv for subjects with exoskeleton was 29.44 ± 9.84 and subjects without exoskeleton was 31.86 ± 10.52 for lowering subtask. Likewise, rAcc for subjects with exoskeleton was 2.16 ± 0.64 and subjects performing the tasks without exoskeleton was 2.45 ± 1.32 for lowering subtask. On the other hand, the COPv for subjects with exoskeleton was 39.79 ± 9.85 and subjects without exoskeleton was 41.07 ± 13.83 for rebar tying task. Likewise, rAcc for subjects with exoskeleton was 3.95 ± 1.33 and subjects performing the tasks without exoskeleton was 3.64 ± 1.73 for rebar tying tasks. The lower COPv and rAcc values during the lowering subtask and rebar tying for those with the exoskeleton could suggest more controlled or stable movement.

Table 4 summarizes the results of paired *t*-test in comparison of extracted metrics for subjects with exoskeleton and without exoskeleton assessed for all subjects during the stationary condition. The results suggest that was not any significant difference between the COPv and rAcc values for all the stationary tasks with exoskeleton and without exoskeleton ($p > 0.05$).

This study also compared the gait parameters of all the subjects' with and without the powered BSEs to explore the impact of using powered BSEs on construction workers' stability in dynamic conditions. Table 5 presents the mean and SD values for the gait stride length, height, gait stride time, Max LE in AP direction and Max LE in ML direction across all the conditions to elucidate differences between the gait parameters. As seen in the table, the use of active BSEs marginally increased stride length, stride time and Max LE in AP direction. On the other hand, the stride height and Max LE in ML direction slightly decreased with the use of active BSE during the dynamic condition. However, the results of the paired t-test demonstrated that there was a lack of statistically significant difference between the gait parameters ($p > 0.05$). The lack of significant differences in the examined gait parameters suggests that the powered BSEs neither enhance nor detract from the construction workers' gait stability under the dynamic condition.

5. Discussion

This study aimed to evaluate the physiological impacts of powered BSEs on construction workers performing common construction tasks. Firstly, a user-centered experiment was conducted to assess different interactions with active BSE during material handling and rebar-tying tasks for evaluation of potential physiological risks. During the experimental setup, subjects' muscular activity was extracted through EMG sensors, breath-by breath respiratory data was collected through indirect portable calorimetry, and subjects' bodily posture and movement was collected through IMU sensors. Secondly, the impact of exoskeletons on workers' physiological parameters, which includes local muscular fatigue, metabolic risks, fall risks and joint hyperextension from the collected metrics were statistically analyzed. The results suggested that the muscular activity across all the relevant muscle groups (LES, TES, RA, EO, RF) decreased consistently with the use of powered BSE. Notably, the significant decrease in %MVC for LES, TES, RA, and EO during lifting activities highlights the capability of powered BSE to significantly offload stress from the back and abdominal muscles. This is particularly important as lifting is a common source of back injuries in construction, often due to improper posture or excessive force exerted by pertinent muscle group. Likewise, the results indicated a significant reduction in %MVC for LES and TES muscle group during the carrying task. Carrying tasks often lead to postural deviations, such as leaning forward or sideways, which increase the strain on the back muscles. By encouraging the maintenance of a neutral spine posture, the results illustrate that powered BSEs reduce the muscle fatigue on the LES and TES muscle groups. Further, the result demonstrated a substantial decrease in %MVC for LES and EO muscle groups during the lowering activities. The substantial decrease during lowering tasks points to the role of powered BSE in aiding with load control and posture maintenance. In this vein, the result demonstrates the capability of powered BSEs on preventing back strain and enhancing stability during the lowering movement (descent of loads and materials), which requires precise postural adjustments. Likewise, the reductions in %MVC during the rebar tying task, especially for the TES and EO muscles, indicate the significant positive impact of powered BSE on tasks involving repetitive bending and twisting. The results across both material handling and rebar tying tasks of the significant reduction in energy expenditure and VO_2 max with the use of powered BSE underscores the effectiveness of exoskeletons in reducing the metabolic cost of construction workers during construction activities. By alleviating the need for overexertion, which typically results in higher oxygen consumption and energy usage, the powered exoskeleton allows muscles to operate more efficiently. The particularly noticeable reduction in energy expenditure during the rebar tying task suggests that the specific ergonomic challenges of this task, as sustained awkward postures are effectively mitigated by the powered BSE. Further, the results also indicated a notable decrease in ergonomic risk with the use of powered BSE. The ergonomic risk, assessed by REBA scores, was notably lower when tasks were executed with the assistance of BSEs. The elevated REBA scores observed without exoskeleton support highlight the intrinsic ergonomic risks associated with construction tasks. The observed reduction of REBA score was 47.6 % for lifting, 41.5 % for carrying, 45.3 % for lowering, and 57.5 % for rebar tying tasks. The high reduction in ergonomic risk in the rebar tying task suggests that tasks involving repetitive bending and twisting benefit most from exoskeleton use. Also, the consistent reduction in REBA scores suggests exoskeletons could be a valuable ergonomic intervention, potentially improving worker safety and reducing the risk of musculoskeletal injuries. It is important to note that while the primary function of the powered BSE is to provide support rather than directly correct posture, it indirectly influences posture, leading to reduced REBA scores. The support provided by powered BSE alleviates strain on the lower back and promotes more upright posture during bending or lifting tasks. By distributing physical load more evenly and reducing muscle fatigue, the exoskeleton enables workers to maintain better posture throughout their activities. Additionally, the physical constraint of the powered BSE encourages neutral spine alignment and limits extreme movements that contribute to higher REBA scores. These combined factors of support, load distribution, fatigue reduction, and postural feedback contribute to the observed improvements in ergonomic risk across various construction tasks. The findings from the analysis of COPv, rAcc, and gait parameters for assessing potential fall risks underscore the minimal effects of powered BSEs on workers' study while performing common construction tasks. In stationary lifting, lowering, and rebar tying tasks, the lack of significant difference in COPv and rAcc suggested that the use of

Table 4
Results of the *p*-values from t-test in comparison of subjects with exoskeleton and without exoskeleton assessed for all subjects during stationary condition.

Experimental Task	COPv	rAcc
Lifting Subtask- Material Handling	0.26	0.35
Lowering Subtask-Material Handling	0.33	0.65
Rebar Tying Task	0.83	0.55

Level of significance = 0.05.

Table 5
Results of the gait parameters assessed for all subjects during the dynamic condition.

Gait Parameters	With Exoskeleton	Without Exoskeleton	p-value[1]
Stride Length (m)	1.41 ± 0.12	1.37 ± 0.13	0.386
Stride Height (m)	0.065 ± 0.026	0.071 ± 0.019	0.355
Gait Stride Time (s)	1.40 ± 0.16	1.39 ± 0.15	0.437
MLE (AP)	0.13 ± 0.008	0.12 ± 0.023	0.572
MLE (ML)	0.30 ± 0.006	0.328 ± 0.027	0.447

[1] Level of significance = 0.05.

exoskeleton does not statistically alter the fundamental stability of users in stationary conditions. In dynamic carrying tasks, the minimal changes in gait parameters and the absence of significant impacts on MLE on AP and ML direction indicates that the use of powered BSE does not adversely affect gait stability.

The results indicated that muscular activity across all relevant muscle groups (LES, TES, RA, EO, RF) decreased consistently with the use of powered BSEs. This finding is consistent with Walter et al. [57], who reported a 25 % reduction in muscle activity in the lumbar erector spinae during lifting tasks with powered BSEs. Similarly, Toxiri et al. [58] found a 30 % reduction in lumbar spine muscle activity with powered BSEs during material handling tasks, which aligns closely with our observations of significant decreases in %MVC for LES and TES during lifting and carrying tasks. Kim et al. [59] demonstrated that custom-made powered BSEs decreased muscle activity in the lumbar erector spinae by 16 % and 11 %, without significantly affecting upper trapezius muscle activity. This study found similar reductions in LES muscle activity, suggesting that powered BSEs effectively offload stress from the back muscles. Blanco et al. [30] observed a more than 24 % decrease in oxygen consumption with upper-limb exoskeletons during repetitive tasks. This result is consistent with our findings, which suggest that the powered back-support exoskeleton reduces the energy expenditure of the user. The reductions in muscle activity observed in our study also align with findings from studies on passive exoskeletons. Antwi-Afari et al. [22] found reported that passive exoskeletons significantly reduced LES muscle activity by 11–33 % MVC during construction tasks, comparable to the reductions we observed with powered BSEs. Likewise, Madinei et al. [43] found that passive BSEs reduced trunk muscle activity in quasi-static assembly tasks by 24–42 % MVC, which is in line with results of this study, demonstrating decreased % MVC for TES during rebar tying task. However, some studies on passive exoskeletons reported mixed results regarding trunk flexor activity (RA and EO). For example, in static forward bent tasks, some studies found no changes [87], while others reported decreases [18]. In lifting tasks, trunk flexor activity either increased [88] or did not change [89] with passive BSE use. In contrast this study consistently observed reductions in muscle activity across different tasks, indicating the superior effectiveness of powered BSEs in reducing muscle strain. Further, Baltrusch et al. [89] found that the passive exoskeleton significantly reduced metabolic cost by 18 % when wearing the exoskeleton. This result is consistent with the findings, elucidating that both the passive and powered exoskeletons can effectively reduce the metabolic cost of construction tasks. Exoskeleton has also been used in the other sector, providing valuable insights for comparison. In the industrial sector, Slujis et al. [90] found that the passive BSE reduces the muscle activity of TES by 33 % and LES by 13.2 % during lifting tasks. This is consistent with findings of significant reductions in %MVC for LES and TES during lifting and carrying tasks, suggesting that powered exoskeletons effectively reduce muscle strain in both construction and industrial contexts. In the nursing sector, Hwang et al. [91] explored the use of exoskeletons for assisting nurses with patient handling tasks and found that muscle activities of the erector spinae were significantly lower (up to 11.2 %). This reduction is consistent with our results showing decreased muscle activity in construction tasks, highlighting the potential of exoskeletons to alleviate physical strain in various sectors. In the automotive assembly tasks, Gillete et al. [92] found that muscle activity for the erector spinae was not significantly changed with the exoskeleton compared to without it in automotive assembly tasks. This contrasts with findings of this study and those in the nursing sector and industrial sector, suggesting that the effectiveness of exoskeletons may vary based on task specificity and exoskeleton design. The consistent findings across various sectors demonstrate the broad applicability and benefits of powered exoskeletons in reducing physical strain and improving worker safety.

This study is expected to promote a deeper understanding of physiological benefits associated with the use of powered BSEs during construction tasks. By leveraging objective assessment methods, which includes EMG for local muscle fatigue, portable indirect calorimetry for metabolic risks, and IMU sensors for ergonomic risks of awkward postures and fall risks, this study showcases an integrated approach in assessing the diverse physiological impacts of exoskeleton use, setting a precedent for future ergonomic research that seeks to understand the holistic effects of wearable assistive devices. Further, the assessment of the impact of use of powered BSE across various construction tasks (lifting, carrying, lowering, and rebar tying) offers a task-specific analysis that is crucial for the development of BSEs tailored to specific tasks, which could further optimize their ergonomic benefits. Notably, the in-depth understanding of interaction of powered BSEs with workers' physiology and biomechanics can engender the development of more effective, user-centric exoskeleton solutions. Also, the study can inform guidelines and policy for the safe and efficient adoption of powered BSE in the construction sector.

While the findings of the study offered substantial insights into the efficacy of powered BSEs for reducing physiological risks and enhancing ergonomic safety during common construction activities, it's imperative to acknowledge certain limitations that can be explored in future research. Firstly, the scope of the study was limited to analyze the physiological impacts of powered BSEs. Psychological factors, including cognitive load, trust and vigilance play a crucial role in the successful implementation and sustained use of ergonomic interventions. Future research could include the quantitative assessment of psychological impacts of powered BSEs during construction activity. Secondly, the sample size of the subjects during the experimental study may not fully represent the full diversity of construction workforce, including variations in age, gender, physical fitness, and experience. To enhance the generalizability of findings, future research could involve a larger diverse sample size of subjects to provide a deeper understanding of the varied interactions between workers and powered exoskeletons and how different demographic and experiential backgrounds influence the benefits derived from exoskeleton use. Thirdly, this study was conducted using a specific model of commercially available powered BSE (Cray X), which could influence the findings. Future research should investigate a broader range of powered BSE, offering insights into the impact of diverse support mechanisms from varying commercially available powered BSEs on worker health and task performance, thereby, informing the development of more effective and adaptable powered wearable assistive devices.

6. Conclusion

This paper investigated the potential physiological impact of powered BSE on construction workers, focusing on local muscle fatigue, metabolic cost, joint hyperextension and fall risks. Through a user-centered experiment, employing EMG sensors, portable indirect calorimetry, and IMUs, the research uncovered significant findings in reduction of local muscle fatigue, metabolic cost, and ergonomic risks during common construction activities. Notably, the study demonstrated that powered BSEs could significantly alleviate the stress on back and abdominal muscle groups by an average of 60 %, during material handling and rebar tying tasks. Additionally, the study highlighted a substantial reduction in energy expenditure and maximal oxygen consumption by 17 %, attributed to the use of powered BSEs. Furthermore, ergonomic risks were notably minimized by above 40 % when tasks were performed with the assistance of powered BSEs, as evidenced by lower REBA scores for common construction activities. The study also demonstrated that powered BSEs do not adversely impact the stability of users during task execution. The observed reductions in muscular activity, metabolic cost, and ergonomic risk collectively highlight the effectiveness of BSEs in fostering a safer and more efficient working environment for construction workers. This study significantly advances the understanding of ways powered BSEs can be leveraged to improve the health, safety, and efficiency of construction workers. The findings of the study provide a strong empirical basis for the scalable adoption of powered BSEs in construction sites and other industries facing similar ergonomic challenges, paving the way for a safer and more productive work environment. However, it is also important to consider some limitations that could be addressed in future research endeavors. For instance, controlled experimental setup, while necessary for precise measurement, may not completely replicate the complexities of real-world construction sites. Future research could explore field studies to assess the practicality, and long-term effects of powered BSE use in actual work environments. Additionally, future studies could explore the range of commercially available powered BSEs to provide comprehensive insights into how the variations of design features influence both physiological and ergonomic outcomes. This exploration is crucial for understanding the effects of design variations on physiological impacts, guiding the development of more tailored and impactful powered exoskeleton solutions.

CRediT authorship contribution statement

Amit Ojha: Writing – original draft, Visualization, Validation, Methodology, Formal analysis. **Yogesh Gautam:** Validation, Investigation, Formal analysis. **Houtan Jebelli:** Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Abiola Akanmu:** Conceptualization, Funding acquisition, Validation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Houtan Jebelli reports financial support was provided by National Science Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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