Assessment of a passive exoskeleton system on spinal biomechanics and subjective responses during manual repetitive handling tasks among construction workers

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Highlights

- A manual repetitive handling task in construction was simulated in a laboratory.
- Effects of a passive exoskeleton system are examined.
- The exoskeleton system significantly reduced Lumbar Erector Spinae muscle activity.
- The developed passive exoskeleton system was rated as having acceptable usability.
- It could serve as an ergonomic intervention tool to mitigate WMSDs risks.

Abstract

An exoskeleton system can be an effective ergonomic intervention for mitigating the risks of developing work-related musculoskeletal disorders, yet little attention is given to the effects of its application on physical risk factors and subjective responses. Therefore, the objective of this study was to examine the effects of a passive exoskeleton system on spinal biomechanics and subjective responses during manual repetitive handling tasks among construction workers. Muscle activity of the Thoracic Erector Spinae (TES), Lumbar Erector Spinae (LES) at L3 vertebrae level, Rectus Abdominis (RA), and External Oblique (EO) during the repetitive handling tasks were measured by surface electromyography (sEMG). Additionally, the Borg categorical rating scale (Borg CR 10), local perceived pressure (LPP), and system usability scale (SUS) were used to measure the ratings of perceived discomfort, perceived musculoskeletal pressure, and system usability, respectively. Our results found that: (1) the use of the passive exoskeleton system significantly reduced LES muscle activity (11-33% MVC), with a greater reduction in LES muscle activity (32.71% MVC) for the heaviest lifting load; (2) the use of the passive exoskeleton system significantly reduced perceived discomfort scores (42.40%) of the lower back for the heaviest lifting load; (3) increased lifting load significantly increased LPP scores of the shoulder, lower back, and leg body parts; and (4) majority of the participants rated the passive exoskeleton system as having acceptable usability. The findings of these results indicate that the developed passive exoskeleton system could reduce the internal muscle force, extensor moments, and spinal forces in the lumbar region.

Keywords: Construction workers; Ergonomic intervention; Exoskeleton; Manual repetitive handling tasks; Muscle activity

1. Introduction

1.1. Work-related musculoskeletal disorders and manual repetitive lifting tasks among construction workers

Work-related musculoskeletal disorders (WMSDs) represent a major health issue and the leading cause of occupational injuries in many industries like construction, transport, and automotive (Waters, 2004; Kong et al., 2018). In the automotive manufacturing industry, a 13-year cohort study found WMSDs as the main cause of injuries, representing approximately 27.8% of 46,094 work-related injuries (Sadi et al., 2007). Similarly, Wang et al. (2017) reported that the number of WMSDs among the United States' construction industry dropped by 66% from 1992 to 2014, while the proportion of WMSDs among older workers increased during this period. WMSDs are associated with work-related physical risk factors such as repetitive lifting, work environment, and psychosocial stressors, and individual factors (Wang et al., 2015a; Antwi-Afari et al., 2017b; Umer et al., 2017b; Colim et al., 2020). WMSDs contribute to high direct and indirect costs resulting from worker's compensation, health care needs, lost time, retraining, administrative costs, and productivity and quality reductions (Umer et al., 2017a; Anwer et al., 2021; Umer et al., 2020; Yu et al., 2021). Therefore, it is important to provide effective interventions that can help to prevent WMSDs' risk factors and further improve the working efficiency by reducing the adverse effects of construction workers.

Manual repetitive handling tasks (e.g., lifting, carrying, pulling, pushing) are widely known as physical risk factors that expose construction workers to substantial biomechanical strains which may lead to developing WMSDs (Grzywiński et al., 2016; Antwi-Afari et al., 2018f; Antwi-Afari et al., 2020a). Manual repetitive handling tasks involve biomechanical movements like forward flexion and lateral bending of the trunk muscles which exert compression forces and extensor moments on the lumbar spine (Chaffin and Baker, 1970; Garg and Chaffin, 1975). Repetition, forceful exertion, speed of movement, and lack of recovery time during manual repetitive handling tasks increased mechanical spinal loading, and they have been identified as important risk factors for developing WMSDs such as low back disorders (LBDs) (Norman et al., 1998; Albers and Hudock, 2007). Previous studies have demonstrated numerous work-related ergonomic interventions (e.g., workers' training, task-specific tool design, administrative control; use of mechanical aids like cranes) to prevent workers from developing WMSDs (Nussbaum et al., 2001; Garg et al., 2006; Lavender et al., 2013; Lowe and Dick, 2015). Despite these effective ergonomic interventions in the construction industry, many construction workplace activities are still performed by workers in manual repetitive handling tasks. To mitigate the high prevalence of WMSDs' physical risk factors among construction workers, there is a need to introduce other potential ergonomic interventions like an exoskeleton system, which can be used as an assistive system to support the mechanical loading during manual repetitive handling tasks.

1.2.Applications of exoskeleton systems on spinal biomechanics and subjective responses

An exoskeleton is a wearable assistive system designed to provide physical assistance through torque to support the human body. Generally, exoskeletons, also known as wearable robots, can be classified into two main systems, namely: (1) active and (2) passive (de Looze et al., 2016; Zhu et al., 2021). Active exoskeleton systems use actuators such as pneumatic muscles, hydraulics, or electric motors that augment the power to support the human body. Examples include "Muscle suit" (Kobayashi et al., 2009), BLEEX (Berkeley Lower Extremity Exoskeleton) (Kazerooni et al., 2005), "Hybrid Assistive Limb (HAL) lumbar support" (von Glinski et al., 2019; Sankai, 2010), and "Wearable Stooping-Assist Device (WSAD)" (Luo and Yu, 2013). Kobayashi et al. (2009)

studied the changes in muscle activation with and without an active exoskeleton system during a load-holding task in an automobile factory. The results showed that muscle suit reduced muscle activation in the biceps brachii (BB), trapezius, and lumbar erector spinae (LES) muscles by 85%, 85%, and 50% MVC, respectively. By using HAL lumbar support, von Glinski et al. (2019) investigated the effect of muscle activity of the thoracic erector spinae (TES), LES, and quadriceps femoris muscles and perceived discomfort during repetitive lifting tasks. Surface electromyography (sEMG) signals and Borg rating of perceived exertion scale were used to measure muscle activity and subjective discomfort, respectively. The results found no significant difference in subjective discomfort with a mean score of 2.5. In addition, muscle activity was significantly reduced at the LES (4.5% mean root mean square) TES (11% 4.5% mean root mean square) and while using HAL lumbar support. Luo and Yu (2013) evaluated the effectiveness of an ergonomic intervention (i.e., WSAD) on muscle activity during a stooped work. It was reported that sEMG amplitudes of the thoracic erector spinae (TES), the lumbar erector spinae (LES), the latissimus dorsi (LD), and the rectus abdominis (RA) were reduced by 42%, 47%, 28%, and 9% respectively. Although active exoskeleton systems have been applied in rehabilitation, automobile, and other industrial disciplines, the major drawbacks of these systems include higher degree of augmentation, expensive and users' discomfort due to the heavyweight and inadequate torque transmission. Alternatively, passive exoskeleton systems utilize mechanical actuators such as springs, dampers for storing or releasing elastic energy during movement from one part of the body to another.

There are several commercially available passive exoskeleton systems such as PAEXO (Ottobock, Duderstadt, Germany) (Schmalz et al., 2019), EksoVest™ (Ekso Bionics®, Richmond, CA, USA)

(Kim et al., 2018a; Kim et al., 2018b), Levitate Airframe™ (Levitate Technologies, San Diego, CA, USA) (Gillette and Stephenson, 2019), ShoulderX (SuitX, Emeryville, CA, USA) (Alabdulkarim and Nussbaum, 2019; Van Engelhoven et al., 2019), Laevo® (Laevo, Delft, The Netherlands) (Bosch et al., 2016; Baltrusch et al., 2018; Koopman et al., 2019), SkelEx (Skel-Ex, Rotterdam, The Netherlands) (de Vries et al., 2019), Bending Non-Demand Return (BNDR) (Ulrey and Fathallah, 2013) and Personal Lifting Assistive Device (PLAD) (Abdoli-Eramaki et al., 2006; Abdoli-Eramaki and Stevenson, 2008; Graham et al., 2009; Lotz et al., 2009). Schmalz et al. (2019) investigated the biomechanical and metabolic effects of a passive exoskeleton during laboratory simulated overhead work activities. The results indicated that the use of an exoskeleton system could provide an ergonomic intervention to mitigate shoulder WMSDs among workers who usually conduct overhead activities. Kim et al. (2018a) evaluated the effects of a passive upper extremity exoskeletal vest on perceived discomfort, shoulder muscle activity, and task performance during a simulated repetitive overhead drilling and light assembly task. The findings showed no changes in perceived discomfort for the body parts considered, but a reduced shoulder muscle activity and mixed effects on drilling task performance. Graham et al. (2009) assessed the effectiveness and user acceptance of a PLAD exoskeleton during forward bending and static holding tasks in an automotive manufacturing industry. These authors measured trunk inclination and muscle activity by using accelerometer and sEMG, respectively. It was reported that a PLAD exoskeleton can significantly reduce low back muscle activity and ratings of perceived exertion, but without significant changes in abdominal activity or trunk flexion.

Compared with active exoskeleton systems, these passive exoskeleton systems are not powered to support the human body, thus, are lighter in weight, and present fewer safety risks to users. The main application disciplines of passive exoskeleton systems are rehabilitation (Viteckova et al., 2013), military (Walsh et al., 2006; Anam and Al-Jumaily, 2012), and automotive manufacturing industries (Graham et al., 2009). Consequently, they are applied to either assist individuals with disabilities or disorders in their daily living activities or carrying capabilities of soldiers or during on-line assembly tasks. In addition, most of these passive exoskeleton systems are designed to assist with trunk flexion to prevent LBDs or upper extremity injuries during dynamic lifting, bending, and static holding tasks (Abdoli-Eramaki et al., 2006; Abdoli-Eramaki and Stevenson, 2008; Graham et al., 2009; Wehner et al., 2009; Ulrey and Fathallah, 2013; Bosch et al., 2016).

1.3.Research rationale and objective

Given the countless potentials of passive exoskeleton systems, the effects of these passive exoskeleton systems have been demonstrated in industrial applications that mainly required static holding tasks and forward bent trunk postures other than the construction industry, where workers are exposed to physically demanding activities such as manual material handling tasks that require dynamic lifting, carrying, and walking in different postures. In other words, these empirical studies based on passive exoskeleton systems cannot be generalized to environments with more versatile working tasks. In addition, adopting commercially available passive exoskeleton systems may not be applicable in the construction industry due to user discomfort (Abdoli-Eramaki et al., 2006; Bosch et al., 2016), excessive force application (Abdoli-Eramaki et al., 2006), loss of range of motion (Abdoli-Eramaki et al., 2006; Toxiri et al., 2016; Baltrusch et al., 2018), not easy to use, kinematic incompatibility (Ulery and Fathallah, 2013), and lack of versatility to be used in a variety of real-world settings (Baltrusch et al., 2018; Cardoso et al., 2020). Moreover, little information is known on the effects of passive exoskeleton systems on spinal biomechanics (i.e., muscle activity) during manual repetitive handling tasks among construction workers. These drawbacks raise the need to assess the effects of a passive exoskeleton system during manual repetitive handling tasks in construction that may result in developing WMSDs among workers. As such, evaluating the use of a novel passive exoskeleton system that can augment human capabilities in different postures (squat and stoop lifting), lower metabolic cost of human locomotion, provide effective control to reduce discomfort and interference, and prevent WMSDs risks during manual repetitive handling tasks is essential in the construction domain.

Therefore, the objective of the current study was to evaluate the effects of a passive exoskeleton system on spinal biomechanics (i.e., muscle activity) and subjective responses (i.e., ratings of perceived discomfort, perceived musculoskeletal pressure, and system usability) during manual repetitive handling tasks among construction workers. The hypothesis tested was whether a passive exoskeleton system reduces muscle activity and subjective response during a simulated manual repetitive handling task. Muscle activity of the Thoracic Erector Spinae, Lumbar Erector Spinae at L3 vertebrae level, Rectus Abdominis, and External Oblique during the repetitive handling tasks were measured by sEMG. In addition, the Borg categorical rating scale (Borg CR 10), local perceived pressure (LPP), and system usability scale (SUS) were used to measure the perceived discomfort, perceived musculoskeletal pressure, and system usability, respectively. The findings of this study could help safety managers to develop a passive exoskeleton system that would serve as an ergonomic intervention to mitigate the risks of developing WMSDs among construction workers.

2. Research methods

2.1. Participants

Ten healthy male participants were voluntarily recruited to participate in this study. The participants’ mean age, weight, and height were 33 ± 3 years, 72 ± 3 kg, and 172 ± 3 cm, respectively. Each participant had basic construction engineering knowledge and experience in conducting manual repetitive handling tasks on construction sites. All participants had no history of mechanical pain/injury of the upper extremities, back, or lower extremities. The detailed experimental procedures, including research objective, protocol, and possible risks were explained to each participant. They were trained to perform the experimental tasks in two sessions, with and without a passive exoskeleton system. Participants provided their demographic characteristics and informed written consent in accordance with the procedure approved by the Human Subject Ethics Subcommittee of the Hong Kong Polytechnic University (reference number: HSEARS20191008004).

2.2. Experimental apparatus

A standard wooden box measuring (L: 30, W: 30, and H: 25 cm) and three lifting loads (5 kg, 15 kg, and 25 kg) were used in this study. The wooden box with hand-holes was positioned at floor level with dumbbell weights equivalent to each lifting load. The 5 kg was equivalent to carrying floor tiles whilst the 15 kg and 25 kg lifting loads were equivalent to carrying cement bags. As suggested by Jaffar et al. (2011), the loads studied reflect a range from low risk (< 8 kg) to moderate risk (8 to 23 kg) to high risk (> 23 kg) in construction tasks, which fall within the weights of objects involved in lifting, lowering and carrying activities in construction. Moreover, the origin and destination of lift/lower/carry were based on guidelines by ISO standards (ISO 14738, 2002).

The designed exoskeleton system is a passive trunk exoskeleton system aimed to reduce lumbar back loadings during awkward postures (i.e., stoop and squat postures) and lifting/lowering/carrying events in manual repetitive handling activities. To achieve the given goal, the passive trunk exoskeleton system was designed to assist both the physiological/biomechanical and functional considerations of human-robot interaction at the user's hip and knee joints. From the biomechanical perspective, the passive exoskeleton system is of interest to help mitigate lumbar back injuries when performing manual repetitive handling activities (Antwi-Afari et al., 2018a). On the other hand, the functional considerations of the passive exoskeleton system were designed to allow a wearer to ambulate freely during normal walking speed (i.e., 1.3 m/s) and natural motions (i.e., the lateral bending of 20º in the frontal plane and axial rotation of 90º in the transverse plane) (Yang et al., 2019). Moreover, it poses no restrictions to lumbar or knee flexion (approx. 60º) during awkward working postures. Furthermore, it is characterized as a simple, lightweight, economical passive trunk exoskeleton system. Fig. 1 represents an overview of the developed passive exoskeleton system. This novel passive exoskeleton system is attached to the shoulder, trunk, and thighs and articulated to coincide with rotation about the hip region. The passive exoskeleton system consists of four segments: a shoulder, trunk, and two leg units for both thighs connected with Velcro straps. There are two springs attached from the shoulder to the hip region to release elastic energy through eccentric or concentric muscle contractions during repetitive movement (Robertson et al., 2008). Without physical assistance from the experimenter, the participants were able to securely adjust the passive exoskeleton system to their bodies by using straps. The harnesses and cuffs were chosen to reduce weight, easily adapted to different users, and the possibility of internal joint injuries due to misalignments. The total setup time for each participant was approximately 1 min.

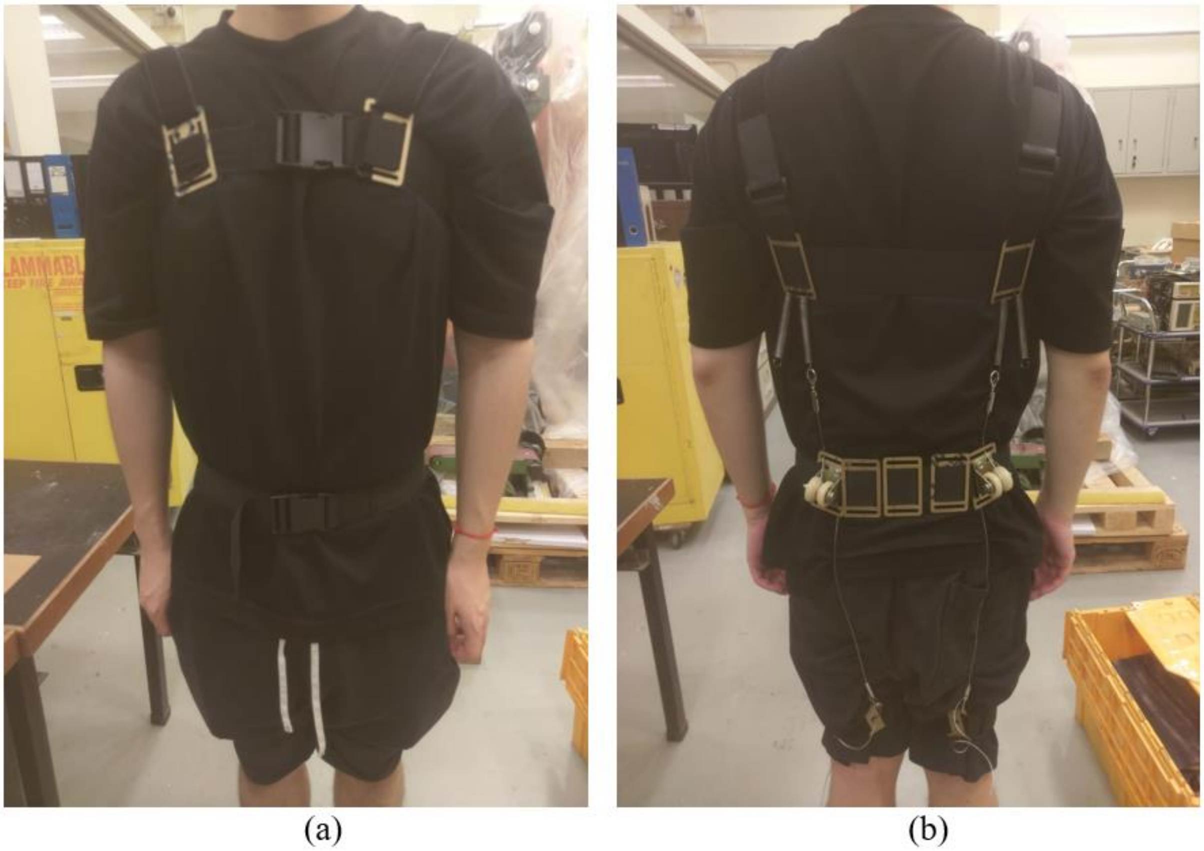


Fig. 1. An overview of a passive exoskeleton system: (a) Front view; and (b) Back view

2.3.Experimental design and procedures

The current study adopted a randomized crossover study design in a single testing session. The independent variables were lifting loads (5 kg vs. 15 kg vs. 25 kg), lifting postures (stoop vs. squat), and systems (with vs. without passive exoskeleton). The dependent variables were muscle activity (i.e., left and right sEMG: Thoracic Erector Spinae (TES), Lumbar Erector Spinae (LES) at L3 vertebrae level, Rectus Abdominis (RA), and External Oblique (EO)), and subjective responses (i.e., perceived discomfort scores, LPP scores, and system usability).

Fig. 2 shows the laboratory experimental setup. The experimental task was a manual repetitive handling activity involving—lifting the weighted box from the floor level in a specific posture (i.e., stoop or squat) onto a table at waist level for inspection (Fig. 2a); carrying the weighted box along a path (Fig. 2b); and lowering the weighted with the same posture to a marked destination (Fig. 2c). Upon arrival, the experimental procedures and equipment were explained to the participants. All participants gave their informed consent and demographic characteristics followed by the preparation and attachment of surface sEMG electrodes. After a detailed explanation and prior to actual data collection, each participant could practice the experimental task—a manual repetitive handling task—using different levels of lifting load, posture, and system. To simulate a realistic experimental task in construction, the participants were allowed to watch representative videos and practice the two lifting/lowering postures (i.e., stoop and squat) with the lifting loads before the testing sessions until they became experts in using them during the manual repetitive handling activity at the laboratory setting. In addition, the study investigator reminded the participants each time to adopt the required lifting posture before starting an experimental trial. However, each participant’s feet position, lifting height, and loading destination were defined to maintain the lifting load close to the body during the experimental trials. The purpose of the training session was to ensure that the participants understood the experimental procedure and satisfied with the testing equipment. The training session lasted approximately 25 minutes.

A completed experimental trial lasted for approximately 2 minutes. At the end of a completed experimental trial, each participant gave their perceived discomfort and LPP scores of the shoulder, lower back, and leg body parts. The participants performed each lifting load in four experimental conditions, including a combination of two levels of lifting posture (stoop vs. squat) and two levels of the system (with vs. without the exoskeleton). Consequently, a total of twelve randomized experimental conditions were performed by two separate groups of participants for six repeated experimental trials. The participants were divided into two separate groups to enable the test of a between-subject factor during data analysis. Accordingly, five randomized participants were asked to perform a stoop lifting posture in a sagittal plane at waist level. The other group of participants conducted a squat lifting posture in a sagittal plane while using the same experimental procedures and set-up. The sequence of conducting the experimental conditions was randomized for each participant by using a random number generator (an n × n × n array). The primary purpose of randomization was to prevent the accumulative effect of physical fatigue during the experimental task.

Each participant performed a manual repetitive lifting/carrying/lowering task using either a stoop lifting, or squat lifting posture based on the randomized conditions. After training, each participant performed six repeated experimental trials for each randomized experimental condition. To reduce fatigue, the participants could also rest for 5 minutes between two successive experimental trials. The actual experimental data collection lasted for approximately 2.7 h for each participant. Upon completion, each participant was asked to provide his thoughts on the usability of the passive exoskeleton system. After completing the experimental task, the participants were instructed to perform two trials of Maximum Voluntary Contractions (MVCs) against manual resistance of each muscle. For the TES and LES muscles MVC trials, the participants relaxed in a prone position with their torso hanging over the edge of a physiotherapy table and were asked to extend their trunk upward and to twist left and right against manual resistance applied by the study investigator. Conversely, to measure the MVC trials of the EO and RA muscles, the participants relaxed in a supine position and were asked to flex their trunk upward and to twist left and right against manual resistance. Notably, the MVCs trials were conducted at the end of the entire experiment to avoid fatigue before the testing session. Each muscle was maximally contracted for 5 seconds, with 2 minutes rest period between trials (Hermens et al., 1999; Wong et al., 2016). The purpose of the MVCs trials was to obtain a maximum amplitude of sEMG activity for normalizing the collected sEMG signals, thus, enabling comparison of muscle activity between different muscles, lifting postures, and systems.

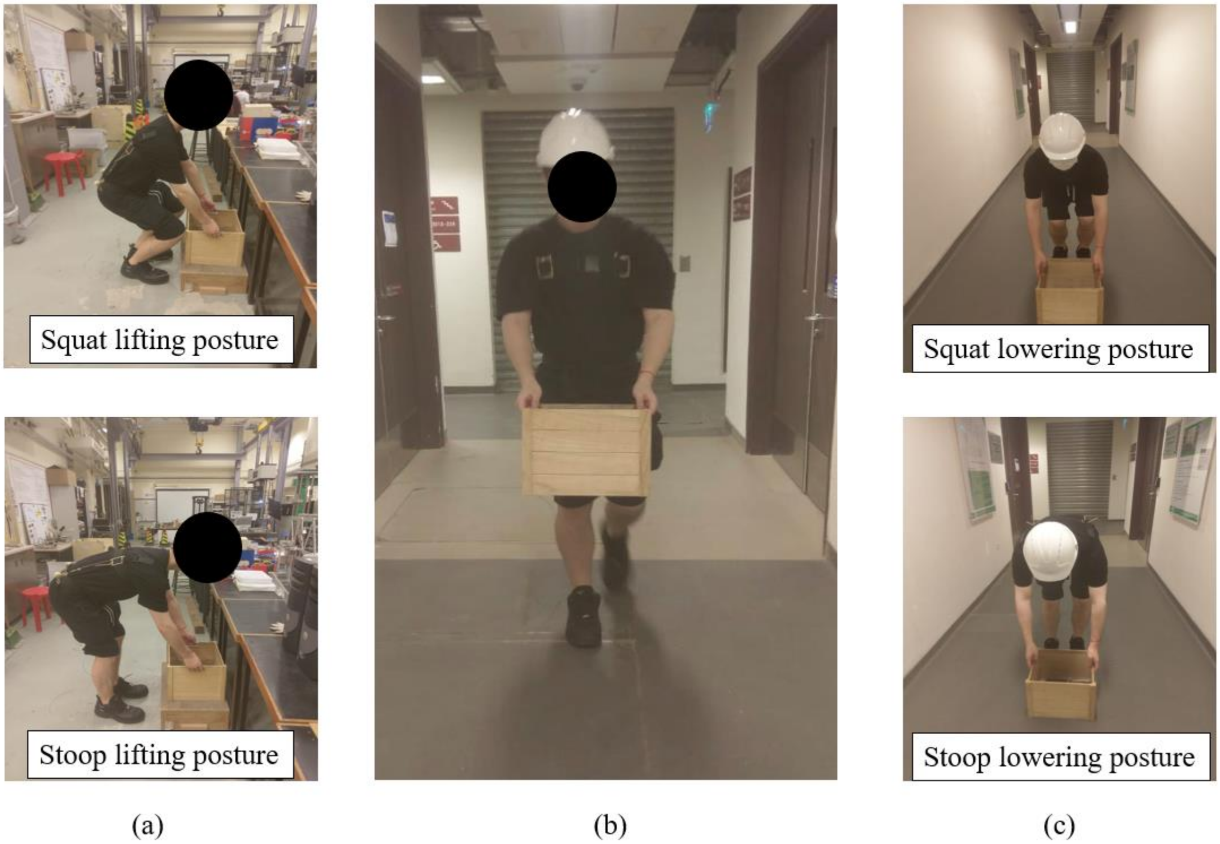


Fig. 2. Laboratory experimental setup: (a) Lifting postures; (b) Carrying task; (c) Lowering postures

2.4.Instrumentation, data processing, and analysis

2.4.1. Surface electromyography (sEMG)

Fig. 3 illustrates the placement of the sEMG electrodes. Both the left and right sides of the four muscles, namely: TES, LES, RA, and EO were studied. These muscles were selected because they do not present high fat mass accumulation, which could compromise the sEMG data acquisition (Colim et al., 2019). From the biomechanical perspective, the selected muscle groups aim to analyze the performance of trunk muscle activation and identify the role of the lumbar joint to generate mechanical energy during manual repetitive lifting tasks. To measure muscle activity, two pairs of wireless bipolar Ag/AgCl surface electrodes (Noraxon TeleMyo sEMG System, Noraxon USA Inc., USA) were attached bilaterally to each muscle in accordance with the guidance in the surface EMG for non-invasive assessment of muscle (SENIAM) protocol (Hermens et al., 1999). In addition, a standardized skin preparation procedure, including skin abrasion with light sandpaper, cleaning with alcohol, and shaving of hair if necessary was undertaken to ensure the skin impedance was below 10 kΩ (Hermens et al., 1999; Antwi-Afari et al., 2017b; Antwi-Afari et al., 2018a). The diameter of the electrode was 15 mm and the inter-electrode distance was 20 mm. Raw electrocardiography signals were sampled for all sEMG signals at a frequency of 1,500 Hz with the common-mode rejection ratio of 100 db, and then digitized by a 16-bit analog to digital (A/D) converter using an electrocardiography-reduction algorithm (Konrad, 2005; Antwi-Afari et al., 2018a). The maximum root mean square (RMS) of sEMG signal of each muscle was identified using a 1000 ms moving window passing through the sEMG signals during the two MVCs. The highest RMS sEMG signal of each muscle was chosen for normalization.

Each experimental trial was visually inspected for artefact effects. Subsequently, all sEMG signals were processed with a band-pass filter between 20 and 500 Hz. A notch filter centered at 50 Hz was used to eliminate power-line interference. The rectified and processed sEMG signals with an averaging constant window of 1,000 ms were used to estimate the RMS sEMG signals. The RMS sEMG signals from the left and right of each muscle were averaged because the paired *t*-test found no significant difference ($p > 0.05$) in sEMG signals between both sides. The mean RMS sEMG activity was calculated from the collected sEMG signals. As mentioned, the participants performed two trials of MVCs at the end of the experiments. The sampled RMS sEMG data were normalized to the maximum amplitude of RMS sEMG during MVC and expressed as a percentage MVC (max % MVC) sEMG. In this study, the highest amplitude (i.e., max % MVC) was selected because it is sensitive to momentary variations in body loading, thus, a good measure of human exoskeleton interaction for short periods (Huysamen et al., 2018a). The signals from sEMG electrodes were recorded and analyzed using the Noraxon MR 3.8 software (Noraxon USA Inc., USA). The sEMG activity levels during manual repetitive handling tasks were analyzed as averaged Standard Amplitude Analysis (SAA). As such, the mean SAA was used for further statistical analyses. It is worth mentioning that the processes of data processing and analyses were similar to the authors' previous studies (Antwi-Afari et al., 2017b; Antwi-Afari et al., 2018a).

Fig. 3. Placement of the sEMG electrodes

2.4.2. Subjective responses

Participants were asked to rate their level of perceived discomfort on a 11-point (0 to 10) Borg CR 10, where 0 indicates “no discomfort” and 10 indicates “maximal discomfort” (Borg, 1998). It was used to quantify the perceived level of local discomfort by each participant when they conducted the experimental trials with or without an exoskeleton. In this study, the perceived discomfort score was separately assessed for shoulder, lower back, and leg body parts at the end of each randomized condition.

Perceived musculoskeletal pressure was also rated using the LPP (Van der Grinten and Smitt, 1992). The LPP is a subjective scale from 0 (no pressure at all) to 10 (extremely strong pressure). Unlike the perceived discomfort score, the LPP score was only assessed for shoulder, lower back, and leg body parts after using the exoskeleton system.

In addition, the system usability of the passive exoskeleton system was rated from 1 (strongly disagree) to 5 (strongly agree) using the SUS, a subjective rating scale consisting of ten questions (Bangor et al., 2008). The purpose of the SUS was to evaluate the efficacy, effectiveness, and user's satisfaction of the system during performing the experimental tasks. A score over 70 is deemed to indicate acceptable usability. Like the LPP, the SUS score was also only assessed after using the exoskeleton system.

2.4.3. Statistical analyses

The Shapiro-Wilk test was used to assess the normality of data. A separate three-factor (3 × 2 × 2) mixed-model repeated-measures analysis of variance (ANOVA) was then adopted to evaluate the effects of lifting load (within-subject factor) with three levels (5 kg vs. 15 kg vs. 25 kg), lifting posture (between-subject factors) with two levels (stoop vs. squat), and system (within-subject factor) with two levels (with vs. without exoskeleton system) on muscle activity. A separate two-way (3 × 2) repeated measures ANOVA was also used to evaluate the effects of lifting load and system on perceived discomfort scores. Moreover, a one-way repeated measures ANOVA was applied to evaluate the effect of lifting loads on LPP scores. The average SUS scores of each participant were also assessed. Post hoc pairwise comparisons were conducted with the Bonferroni adjustment. All statistical analyses were analyzed by the Statistical Package for the Social Science version 20.0 (IBM, USA). Statistical significance was set at $p < 0.05$.

3. Results

3.1. Effects of lifting load, lifting posture, and system on muscle activity

Table 1 denotes the ANOVA results for muscle activity. Statistically significant differences in sEMG activity were found for the main effects of either lifting load ($p < 0.05$) or system ($p < 0.05$) in all muscles studied ($p < 0.05$). However, the main effect of lifting posture revealed no significant difference in sEMG activity for all muscles studied, except the EO muscle. In addition, the results showed a significant interaction in sEMG activity between lifting posture × system for either LES or EO muscles. Furthermore, mixed ANOVA results found a significant interaction in sEMG activity between lifting load × system for LES muscle. However, no significant difference in muscle activity was found for lifting load × lifting posture interaction. Similarly, the lifting load × lifting posture × system interaction revealed no significant difference in muscle activity (Table 1).

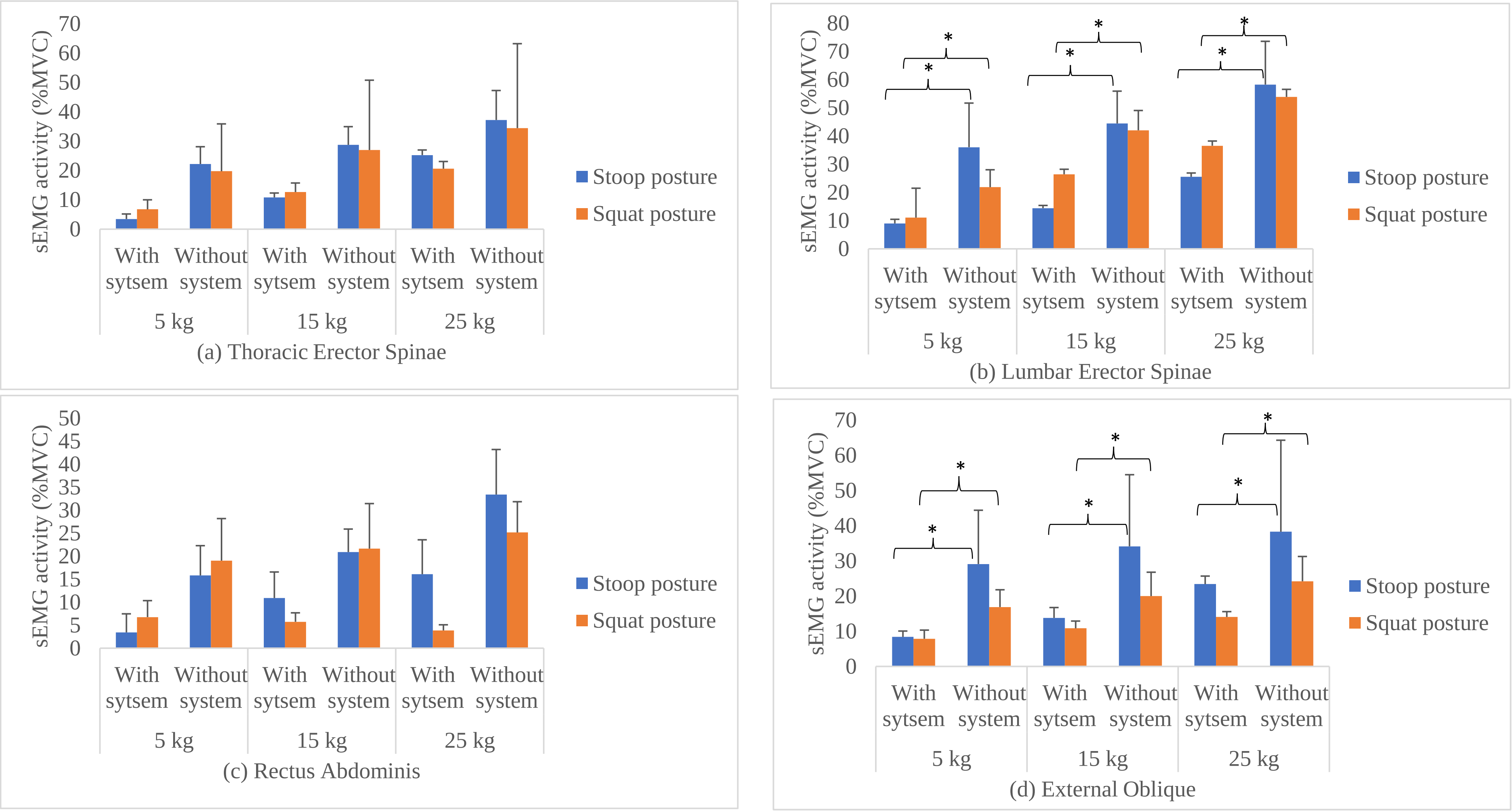
Fig. 4 represents the interaction effects of muscle activity for each muscle. It was found that the muscle activity of all muscle groups (i.e., TES, LES, RA, and EO) increased with increasing lifting load with or without the exoskeleton system. In each muscle group, the heaviest lifting load (i.e., 25 kg) had the highest sEMG activity with or without the exoskeleton system. Regardless of each lifting load, the LES muscle displayed the highest sEMG activity as compared to other muscles. Alternatively, the RA muscle showed the lowest sEMG activity. The results only showed significant interactions in sEMG activity for either LES muscle or EO muscle. Between the two lifting postures, the results showed that squat posture had higher LES sEMG activity than stoop posture while using the exoskeleton system. Conversely, stoop posture showed consistent higher LES sEMG activity than squat posture without the exoskeleton system. With a significant interaction of lifting posture × system, stoop posture had greater EO sEMG activity than squat posture either with or without system.

In this study, the results showed that lifting posture × system interaction significantly affected sEMG activity for either LES muscle ($F = 2.960$, $p = 0.022$, $\eta_p^2 = 0.058$) or EO muscle ($F = 5.596$, $p = 0.022$, $\eta_p^2 = 0.104$). For the LES muscle, post hoc analysis revealed that the participants had significantly greater sEMG activity (79.44% MVC, $p < 0.05$) without system when compared to with exoskeleton system during stoop posture. With the squat posture, without exoskeleton system also found a significant increase in sEMG activity (67.84% MVC, $p < 0.05$) when compared to with exoskeleton system. In summary, using the exoskeleton system reduced LES muscle activity to a greater extent during each lifting posture. For the EO muscle, post hoc analysis revealed that sEMG activity differed significantly (71.95% MVC, $p < 0.05$) for without exoskeleton system when compared to with exoskeleton system during stoop posture. With the squat posture, without exoskeleton system also found a significant increase in sEMG activity (57% MVC, $p < 0.05$) when compared to with the exoskeleton system. Taken together, using a passive exoskeleton system reduced EO muscle activity to a greater extent during each lifting posture.

The LES muscle showed a significant difference in sEMG activity between lifting load × system interaction ($F = 3.619$, $p = 0.034$, $\eta_p^2 = 0.131$). Post hoc analysis revealed that participants had significantly higher LES sEMG activity for the 25 kg load during without exoskeleton system condition when compared to with the exoskeleton system. The percentage mean differences in LES muscle activity of the 5 kg, 15 kg, and 25 kg lifting loads between the two levels of the exoskeleton system were 64%, 77.63%, and 78.60%, respectively.

Table 1. Summary of ANOVA Results for Muscle Activity

Independent variable	Thoracic Erector Spinae (TES)		Lumbar Erector Spinae (LES)		Rectus Abdominis (RA)		External Oblique (EO)	
	F ratio	*P-value*	*F ratio*	*P-value*	*F ratio*	*P-value*	*F ratio*	*P-value*
Main effect								
Lifting load	1.461	0.001	1.789	0.010	0.107	0.012	0.497	0.020
Lifting posture	0.100	0.995	0.212	0.647	0.053	0.818	5.506	0.023
System	45.433	0.000	308.308	0.000	88.834	0.000	56.674	0.000
Interaction								
Lifting load × Lifting posture	0.055	0.475	0.272	0.763	0.488	0.617	0.118	0.889
Lifting posture × System	0.518	0.475	2.960	0.022	0.381	0.540	5.596	0.022
Lifting load × System	2.123	0.131	3.619	0.034	0.117	0.890	0.961	0.390
Lifting load × Lifting posture × System	0.027	0.974	0.120	0.887	0.205	0.815	0.025	0.975



(a) Thoracic Erector Spinae

(b) Lumbar Erector Spinae

(c) Rectus Abdominis

(d) External Oblique

Fig. 4. Interaction effects of muscle activity for each muscle: (a) Thoracic Erector Spinae (TES); (b) Lumbar Erector Spinae (LES); (c) Rectus Abdominis; (d) External Oblique (EO). **Note:** sEMG = Surface electromyography; MVC = Maximum voluntary contraction; Error bars indicate standard deviation; * indicates a significant difference (*p* < 0.05) between the levels of interactions

3.2.Subjective responses

3.2.1. Ratings of perceived discomfort

Since the main effect of lifting posture showed no statistically significant difference, the collected data were pulled together to evaluate the effect of lifting load and system on perceived discomfort scores. Table 2 shows the ANOVA results (*F* ratios and *p*-values) of perceived discomfort for shoulder, lower back, and leg. Significant main effects of lifting load were found on perceived discomfort of the shoulder ($F = 201.000$, $p = 0.000$, $\eta_p^2 = 0.957$), lower back ($F = 290.302$, $p = 0.000$, $\eta_p^2 = 0.970$), and leg ($F = 115.239$, $p = 0.000$, $\eta_p^2 = 0.928$). The main effect of the 25 kg load on mean perceived musculoskeletal discomfort of the lower back was the highest as compared to 15 kg load [mean difference = 1.050% (95% confident interval (CI) = 0.903% to 1.197%), standard error = 0.050; $\eta_p^2 = 0.986$; $p = 0.000$] and 5 kg load [mean difference = 2.150% (95% CI = 1.837% to 2.463%), standard error = 0.107; $\eta_p^2 = 0.986$; $p = 0.000$]. Similarly, significant main effects of system were found on perceived discomfort scores of the shoulder ($F = 441.000$, $p = 0.000$, $\eta_p^2 = 0.980$), lower back ($F = 561.623$, $p = 0.000$, $\eta_p^2 = 0.984$), and leg ($F = 6.318$, $p = 0.033$, $\eta_p^2 = 0.412$). When compared to without exoskeleton system, it was found that using the exoskeleton system reduced the mean perceived musculoskeletal discomfort scores for the shoulder by 48.73% [mean difference = 5.133% (95% CI = 4.580% to 5.686%), standard error = 0.244; $\eta_p^2 = 0.986$; $p = 0.000$], the lower back by 49.84% [mean difference = 5.167% (95% CI = 4.673% to 5.660%), standard error = 0.218; $\eta_p^2 = 0.984$; $p = 0.000$], and leg by 11.48% [mean difference = 1.167% (95% CI = 0.117% to 2.217%), standard error = 0.464; $\eta_p^2 = 0.412$; $p = 0.033$], respectively.

Fig. 5 depicts the perceived discomfort scores of the shoulder, lower back, and legs with or without an exoskeleton system. As shown in Fig. 5, increased lifting load increased perceived discomfort of the shoulder, lower back, and leg only during the without exoskeleton system condition. Significant interaction of lifting load × system was found on perceived discomfort of the lower back (F = 4.465, p = 0.005, η_p^2 = 0.140) (Table 2, Fig. 5). Post hoc analysis revealed that the participants had significant reduction in perceived discomfort of the 25 kg load while using the exoskeleton system when compared to without exoskeleton system (p = 0.03). In particular, the use of the exoskeleton system reduced the mean perceived musculoskeletal discomfort on the lower back by 60.98% [mean difference = 5.00% (95% CI = 1.231% to 1.969%), standard error = 0.163; η_p^2 = 0.923; p = 0.04], 48.15% [mean difference = 5.20% (95% CI = 2.231% to 2.969%), standard error = 0.133; η_p^2 = 0.948; p = 0.02], and 42.40% [mean difference = 5.30% (95% CI = 3.231% to 3.969%), standard error = 0.100; η_p^2 = 0.957; p = 0.03] for the 5 kg, 15 kg, and 25 kg loads, respectively.

Table 2. Summary of ANOVA Results for Ratings of Perceived Discomfort

Independent variable	Shoulder		Lower back		Leg	
	F ratio	*P-value*	*F ratio*	*P-value*	*F ratio*	*P-value*
Main effect						
Lifting load	201.000	0.000	290.302	0.000	115.239	0.000
System	441.000	0.000	561.623	0.000	6.318	0.033
Interaction						
Lifting load × System	1.465	0.257	4.465	0.005	2.441	0.142

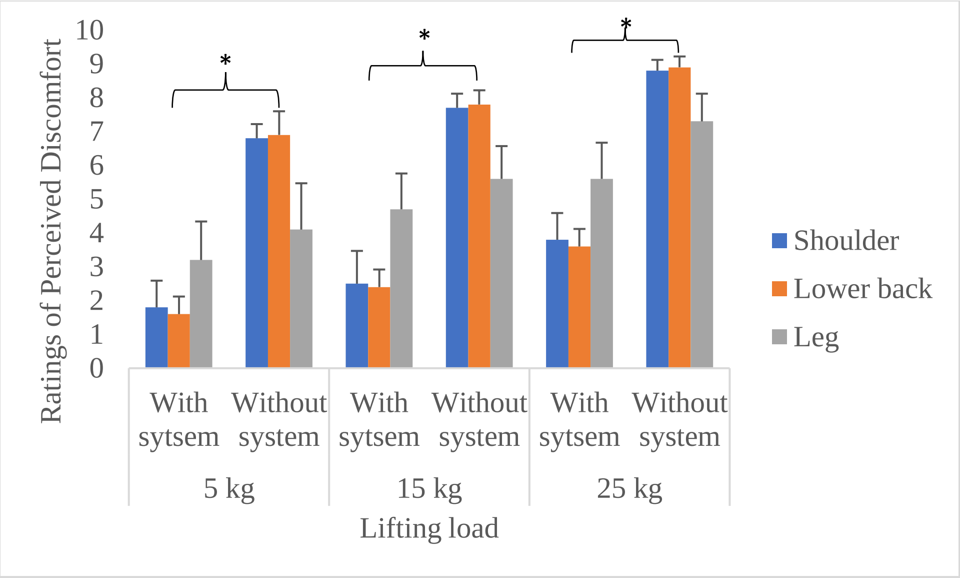


Fig. 5. Ratings of perceived discomfort scores of the shoulder, lower back, and leg with or without the exoskeleton system. **Note:** Error bars indicate standard deviation; * indicates a significant difference ($p < 0.05$) between the levels of interactions

3.2.2. Local perceived pressure (LPP)

ANOVA results revealed significant effects of lifting load on LPP scores of the shoulder (F = 311.548, p = 0.000, η_p^2 = 0.972), lower back (F = 252.111, p = 0.000, η_p^2 = 0.966), and leg (F = 211.154, p = 0.000, η_p^2 = 0.959). Fig. 6 illustrates the LPP scores of the shoulder, lower back, and leg body regions for different lifting loads while using the exoskeleton system. There was a significant increase in LPP scores ($p < 0.01$) with an increase in lifting loads across the studied body regions. As shown in Fig. 6, perceived musculoskeletal pressure was higher for the 25 kg load as compared to either the 15 kg or 5 kg load. In particular, the effect of 25 kg load on LPP scores of the shoulder was the highest as compared to 15 kg load [mean difference = 2.700 (95% CI = 2.252% to 3.148%), standard error = 0.153; η_p^2 = 0.988; p = 0.000] and 5 kg load [mean difference = 5.800 (95% CI = 5.068% to 6.532%), standard error = 0.249; η_p^2 = 0.988; p = 0.000].

The average LPP scores of the 5 kg, 15 kg, and 25 kg loads were rated as 15.57%, 34.13%, and 50.30% for the shoulder, 13.24%, 33.09%, and 53.68% for the lower back, and 14.16%, 31.86%, and 53.98% for the leg, respectively.

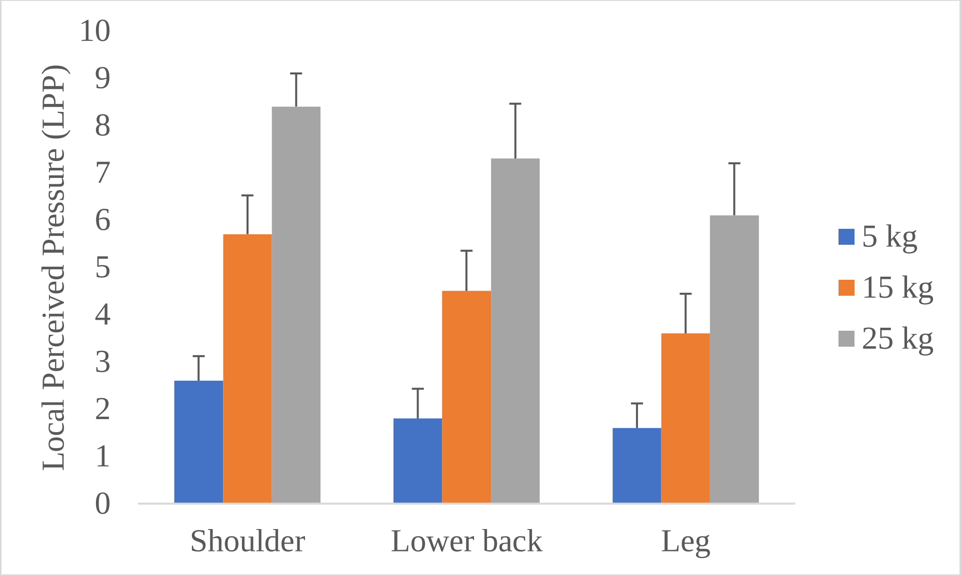


Fig. 6. Local perceived pressure (LPP) of the shoulder, lower back, and leg body regions for different lifting loads while using the exoskeleton system

3.2.3. System usability scale (SUS)

Fig. 7 represents the SUS scores (%) of the participants. As shown in Fig. 7, seven participants had their SUS scores rated above the criterion for acceptable usability.

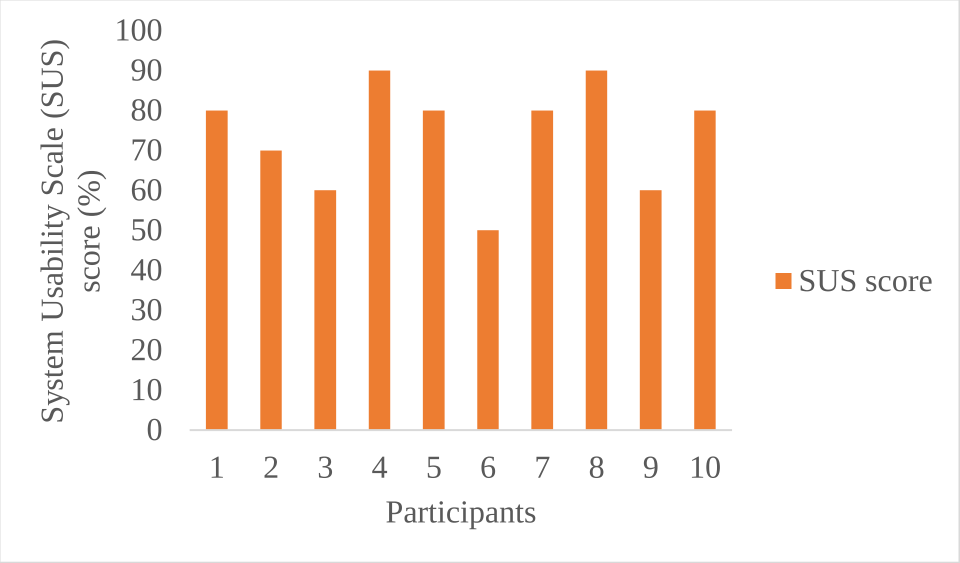


Fig. 7. System Usability Scale (SUS) scores of the exoskeleton system

4. Discussion

To mitigate WMSD's risk in construction, this study aimed to evaluate the effects of a passive exoskeleton system on muscle activity and subjective responses (i.e., perceived discomfort, LPP, and SUS scores) during manual repetitive handling tasks among construction workers. The results found that: (1) the effects of either lifting load or exoskeleton system had a statistically significant difference in sEMG activity of all muscles studied; (2) lifting posture showed no statistically significant difference in sEMG activity for all muscles, except the EO muscle; (3) the effects of lifting load or exoskeleton system showed a statistically significant difference in perceived discomfort of the shoulder, lower back and leg body parts; (4) the effect of lifting load, especially 25 kg load found a significant difference in LPP scores of the shoulder, followed by lower back and leg body parts; and (5) majority of the participants in this study rated the passive exoskeleton system as having acceptable usability. Given the above results, the findings of this study elucidated that the passive exoskeleton system could serve as an ergonomic intervention tool to assist construction workers during manual repetitive handling tasks on construction sites, thus, preventing workers from developing WMSDs.

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

Muscle activity (sEMG activity) of all muscles studied (i.e., TES, LES, RA, and EO) was found to increase significantly ($p < 0.05$) with increased lifting load either with or without the exoskeleton system (Table1, Fig. 4). Amongst the different lifting loads, the 25 kg load obtained the highest sEMG activity, thus, (with exoskeleton system: 25.25% MVC, 36.57% MVC, 16.08%MVC, and 23.39% MVC) and (without exoskeleton system: 37.20% MVC, 58.26% MVC, 33.41% MVC, and 38.27% MVC) in TES, LES, RA, and EO muscles, respectively. As such, the LES muscle showed the highest sEMG activity—with exoskeleton system (36.57% MVC) or without exoskeleton system (58.26% MVC)— amongst all muscles. More importantly, the results found that the use of the exoskeleton system significantly ($p < 0.05$) reduced sEMG activity in all muscles as compared to without using the exoskeleton system during manual repetitive handling tasks. In particular, the LES muscle activity was reduced by 11-33% MVC, with a greater reduction in LES sEMG activity (i.e., 32.71% MVC) for the heaviest lifting load. Overall, the findings from these results suggested that the use of the passive exoskeleton system reduced sEMG activity and may reduce the risk of developing WMSDs among construction workers. These findings were consistent with the findings of previous studies in which a reduction in LES muscle activity was found while using an exoskeleton system during manual repetitive handling tasks (Abdoli-E. and Stevenson, 2008; Graham et al., 2009; Wehner et al., 2009; Ulrey and Fathallah, 2013; Bosch et al., 2016; Huysamen et al., 2018a). In a simulated assembly work during a prolonged forward bending task, Bosch et al. (2016) reported a reduction by 35-38% MVC in muscle activity while wearing an exoskeleton system. Huysamen et al. (2018a) evaluated the effect of an industrial exoskeleton on muscle activity, finding a significant reduction in muscle activity of the LES muscle by 12% to 15% MVC. During an industrial trunk bending tasks in a furniture manufacturing industry, Cardoso et al. (2020) reported a decrease in muscle activity between 0.8% and 3.8% of the back muscles when wearing a passive exoskeleton system. Taken together, the results indicate the great potential of the passive exoskeleton system to reduce internal muscle forces and spinal forces, thus, could be useful to mitigate the risk of developing WMSDs among construction workers.

Unlike the main effects of lifting load or exoskeleton system, the main effect of lifting posture revealed inconsistent results in sEMG activity (Table 1). Apart from the EO muscle, all other muscles studied found no significant difference in sEMG activity between lifting postures (Table 1, Fig. 4). Muscle activity of the EO muscle was higher during stoop posture as compared to squat posture while using or without using the exoskeleton system. This result might be explained by the fact that in forward bending posture—while using or without using the exoskeleton system—high compressive forces and extensor moments are exerted on the EO muscle unlike other trunk muscles considered in this study. Conversely, no significant difference in sEMG activity of the TES, LES, and RA muscles was found between lifting postures could indicate that the passive exoskeleton system provides little support to observe changes in muscle loading while participants adopted a specific posture. However, future studies should be conducted to evaluate the effect of the passive exoskeleton system on spinal kinematics while adopting a stoop or squat lifting posture. From the spinal kinematic data perspective, a better understanding of the effect of lifting posture could be envisaged on changes in flexion, lateral, and axial movements while performing manual repetitive handling tasks with or without an exoskeleton system.

While the results showed a significant interaction of lifting posture × system on sEMG activity for either LES or EO muscles, a significant interaction of lifting load × system on sEMG activity was only reported for the LES muscle (Table 1, Fig. 4). It was found that the stoop posture obtained higher sEMG activity during the without exoskeleton condition as compared to using the exoskeleton system for either the LES muscle (79.44% MVC) or EO muscle (71.95% MVC) (Fig. 4). These results suggested that high spinal loading and compressive forces are exerted on both the LES and EO muscles during stoop posture than squat posture. Thus, increased spinal loading during the stoop lifting posture may lead to an increased risk of developing LBDs (Wang et al., 2000).

Given the above, we conclude that increased lifting load increased LES muscle activity while performing manual repetitive handling tasks without the exoskeleton system. However, the LES muscle activity was significantly reduced while using an exoskeleton system. Since the muscle activity of the LES muscle is closely related to the spinal compressive force, it is plausible to conclude that a passive exoskeleton system has a great potential to significantly reduce the risk of developing WMSDs among construction workers, especially in forward bending posture for longer time durations.

4.2.Effect of a passive exoskeleton system on subjective responses

The results revealed a significant main effect of either lifting load or exoskeleton system on perceived discomfort of the shoulder, lower back, and leg body parts (Table 2). It was also found that increased lifting load increased perceived discomfort of the shoulder, lower back, and leg body parts while performing manual repetitive handling tasks without using the exoskeleton system (Fig. 5). By comparing the different lifting loads, the 25 kg load had the highest perceived discomfort of the lower back (Fig. 5). These results indicate that the participants experienced greater perceived musculoskeletal discomfort on their lower back while conducting the experimental tasks with a higher lifting load without using the exoskeleton system. Therefore, this study's findings suggest that increased lifting load increased perceived discomfort at the lower back and may increase the risk of developing LBDs. Alternatively, the results found a significant reduction in perceived discomfort of the lower back than all other studied body parts while conducting the experimental tasks with the exoskeleton system. Accordingly, the participants experienced reduced muscular discomfort in their lower back when using the exoskeleton system. Consequently, the findings of this result indicate that the passive exoskeleton system could aid construction workers in manual repetitive handling tasks, thus, mitigating the risk of developing LBDs. This study's findings are consistent with the findings of previous studies that found reduced perceived discomfort of the lower back when using an exoskeleton system (Bosch et al., 2016). Bosch et al. (2016) reported significantly lower discomfort values in the lower back when comparing with or without the exoskeleton condition.

Interestingly, the results only found a significant interaction of lifting load × system on the perceived discomfort of the lower back (Table 2). More specifically, the participants observed a significant reduction in mean perceived discomfort scores (42.40%) of the lower back for the 25 kg load while using the exoskeleton system (Fig. 5). The findings of these results indicate that with an increased lifting load, the participants rated a reduced level of perceived discomfort in their lower back while using an exoskeleton system. However, the perceived discomfort of the shoulder and leg body parts were not affected by the increased lifting load while using an exoskeleton system (Fig. 5). As such, these findings indicate that the passive exoskeleton system could serve as an ergonomic intervention tool for reducing internal muscle forces and spinal forces in the lower back region than either the shoulder or leg body part. These findings of perceived discomfort in the lower back are consistent with the objective findings of muscle activity of the LES muscle. As stated, this study not only found a significant reduction in muscle activity of LES muscle, but also a significant reduction in perceived musculoskeletal discomfort of the lower back when using the exoskeleton system with the highest lifting load. Nevertheless, further analysis is still needed to test the correlation between perceived discomfort scores and muscle activity to obtain better performance.

The results revealed a significant effect of lifting load on LPP scores of the shoulder, lower back, and leg body parts (Fig. 6). It was also reported that increased lifting load significantly increased LPP scores for all three body parts (Fig. 6). These results indicate that the passive exoskeleton system does not provide excessive perceived musculoskeletal pressure and tissue damage while conducting manual repetitive handling tasks. These results of higher perceived musculoskeletal pressure for the three body parts with increased lifting loads are likely to be expected. However, perceived musculoskeletal pressure was most likely expected on the shoulder region while using the passive exoskeleton system as compared to either the lower back or leg body parts. This is because the transfer of force was distributed from the shoulder followed by the lower back and leg body parts. In addition, few participants complained that the connection straps at the shoulder region were too tight while wearing the exoskeleton system. The muscle circumference of the shoulder region increased during forward bending. These could explain why increased LPP scores were found for the shoulder region. A study by Huysamen et al. (2018a) found higher perceived pressure on the thighs and shoulders with increased lifting load. Taken together, these findings are likely due to differences in the types of exoskeleton systems that led to an increased moment and muscle circumference of specific body parts generated by the participants to lift a heavier load.

Majority of the participants rated the passive exoskeleton system as having acceptable usability (Fig. 7). This is because they classified the passive exoskeleton system as being lightweight, simple, and easily wearable. Even though there are differences in experimental conditions and types of exoskeleton, previous studies also found accepted usability (Huysamen et al., 2018a; Huysamen et al., 2018b). Besides, the participants that rated the passive exoskeleton system below the required criterion, found it to be either bulky to use or that their range of movements (e.g., flexion, lateral, axial) were not always consistent with their normal movements. As such, future studies are needed to examine the effect of this passive exoskeleton system on spinal kinematics. In addition, the sensor placement while wearing the exoskeleton system needs to be addressed. These could provide a better assessment of the overall usability as well as the perceived musculoskeletal effort of this exoskeleton system. Undoubtedly, the SUS scores may have been negatively influenced by the endurance time, thus the estimated time taken to complete a given task. Thus, the participants may have rated the passive exoskeleton system to be not useful if the experimental tasks were conducted for longer periods. Consequently, further studies are needed to examine the relationship between endurance time and usability of the system.

5. Study implications and potential applications

The findings have theoretical implications and potential applications in the construction industry. First, the results showed that LES muscle activity was reduced by 11-33% MVC, with a greater reduction in LES sEMG activity (i.e., 32.71% MVC) for the heaviest lifting load. These results indicate that the use of a passive exoskeleton system reduced sEMG activity during manual repetitive handling tasks, thus, may reduce the risk of developing WMSDs. Consequently, this study has a great potential to enable safety managers to use the passive exoskeleton system as a proactive ergonomic intervention tool to mitigate the risk of developing WMSDs among construction workers. Second, the results found a significant reduction in perceived musculoskeletal discomfort of the lower back while using the exoskeleton system. In addition, the results revealed that increased lifting load significantly increased LPP scores for all three body parts, but perceived musculoskeletal pressure was most likely expected on the shoulder region while using the exoskeleton system. Moreover, a greater number of participants (7 out of 10) rated the passive exoskeleton system as having acceptable usability. Taken together, these subjective results provided complimentary findings to the objective results of the reduction in LES muscle activity. Thus, the use of the passive exoskeleton system during manual repetitive handling tasks in construction would not only reduces the biomechanical strain of the studied body parts but also increased workers’ acceptance. Third, the passive exoskeleton system has numerous advantages when compared to existing exoskeletons. For instance, it is characterized as being lightweight, simple, flexible, and easy-to-use, thus, enabling a full range of movement and providing comfortable postures for its application in the construction industry.

6. Limitations and future directions

The results indicated that using the passive exoskeleton system during manual repetitive handling tasks has great potential in the construction industry. Nonetheless, some limitations need to be addressed in future research. First, this study was conducted by a small sample of student participants in a laboratory setting. As such, there is a lack of diversity in participants' anthropomorphology and biomechanical effects since construction workers often have more experience in work activities than novice participants. Future research is warranted to compare the findings of this study with a large sample of expert construction workers from different construction trades on construction sites. Second, the participants only conducted a manual repetitive lifting/carrying/lowering task using either a stoop or squat posture. Other physical WMSDs risk factors such as overhead tasks, pushing, pulling that are performed by workers should be considered. In addition, the present study focused on the risk of developing WMSDs while conducting a manual repetitive handling task. However, the use of an exoskeleton system may affect postural balance and muscle fatigue due to the additional weight of the exoskeleton system and prolonged task duration, respectively. These risk factors may lead to an increased risk of fall injuries among construction workers. As such, future research is needed to investigate the effects of the passive exoskeleton system while conducting other construction activities and different risk factors. Moreover, the current study does not consider the association between individual WMSDs risk factors (e.g., age, gender, height, weight, body composition) and manual repetitive lifting tasks. Consequently, the evaluation of fat mass accumulation which may affect sEMG data acquisition was not considered. By adopting a suitable indicator (e.g., body fat mass, abdominal circumference, body mass index) (Paniagua et al., 2008; Colim et al., 2020), future studies should collect relevant individual WMSDs risk factor data to evaluate body fat distribution during sample characterization. Third, the present study focused on evaluation criteria such as muscle activity and subjective responses to assess the feasibility of the passive exoskeleton system. Notably, there are other objective evaluation criteria such as endurance time, spinal kinematics (e.g., flexion, lateral, axial), and physiological metrics (e.g., heart rate, oxygen consumption). Future studies should examine the effects of these evaluation criteria to provide an overall assessment and validation of the passive exoskeleton system as a proactive ergonomic intervention tool.

7. Conclusions

The objective of the present study was to examine the effects of a passive exoskeleton system on spinal biomechanics (i.e., muscle activity) and subjective response (i.e., perceived discomfort, LPP, and SUS scores) during manual repetitive handling tasks among construction workers. The results of this study revealed that: (1) the main effects of either lifting load or exoskeleton system showed a statistically significant difference in sEMG activity of all muscles studied; (2) the use of the exoskeleton system significantly reduced LES muscle activity (11-33% MVC), with a greater reduction in LES muscle activity (32.71% MVC) for the heaviest lifting load; (3) the main effect of lifting posture had no statistically significant difference in sEMG activity for all muscles studied, except the EO muscle; (4) the main effects of either lifting load or system showed statistically significant difference in perceived discomfort of the shoulder, lower back, and leg body parts; (4) the use of the exoskeleton system significantly reduced perceived discomfort scores (42.40%) of the lower back for the heaviest lifting load; (5) increased lifting load significantly increased LPP scores of the shoulder, lower back, and leg body parts; and (6) majority of the participants in this study rated the passive exoskeleton system as having an acceptable usability.

The findings of these results indicate that the use of the passive exoskeleton system reduced sEMG activity and, thus, may reduce the risk of developing WMSDs. In addition, the participants observed a reduced level of perceived discomfort in the lower back while using the exoskeleton system with increased lifting load, implying reduced lower back loading. Moreover, the passive exoskeleton system could be widely adopted by construction workers while performing manual repetitive handling tasks since the usability scores reached acceptable levels. The main contributions of this study include the fact that the passive exoskeleton system: (1) has a great potential to serve as an ergonomic intervention tool to assist construction workers while performing manual repetitive handling tasks; (2) has been demonstrated as being a simple, lightweight, comfortable and easy-to-use by workers; (3) could help safety managers to mitigate the risks of developing WMSDs among construction workers to enhance workers' safety. Despite these potential contributions, future research is needed to assess the effects of this passive exoskeleton system on spinal kinematics, physiological metrics, and work task performance with diverse construction trades.

Data Availability Statement

All raw data that support the findings of this study are available from the corresponding author upon reasonable request.

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Declarations of Interest

None

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