Assessing the Impact of Active Back Support Exoskeletons on Muscular Activity during Construction Tasks: Insights from Physiological Sensing

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ABSTRACT

Active exoskeletons are emerging as ergonomic solutions in the construction sector to reduce work-related musculoskeletal injuries. While the benefits of active exoskeletons are promising, they can also cause increased muscle activity, leading to local muscular fatigue. This study aimed to examine the impact of the active exoskeleton system on the muscular activity of construction workers during common construction activities. Ten subjects completed material handling tasks under two weight conditions (10 and 30 lbs) in a lab-controlled environment, with and without using an active exoskeleton. Portable electromyography (EMG) sensors were used to measure lumbar erector spinae (LES) muscle activity in each condition. Four descriptive statistics features in the time and frequency domains were extracted from the collected signals. Results of the t-test showed a significant difference in the physiological metrics extracted from the subjects' EMG signals of the LES muscle. Findings demonstrated that using active exoskeletons reduces the internal muscle force in the lower back regions of construction workers.

INTRODUCTION

Active exoskeletons are becoming an increasingly popular ergonomic solution in the construction industry to minimize the risk of work-related musculoskeletal injuries (WMSDs) by providing lift support, weight dispersion, and posture correction (Shein Esther 2019). Active exoskeletons are powered by actuators such as electric motors, pneumatics, or hydraulics and actively augment the power of the human body (Linner et al. 2018). While passive exoskeletons are typically less expensive and easier to implement, active exoskeletons are preferred in the construction sector due to their ability to actively aid workers in handling physical workloads during construction tasks (Shein Esther 2019). With the impending integration of active back-support exoskeletons (BSEs) on construction sites, new concerns are bound to arise due to the transformation from a human-centric work environment to a human-technological collaborative workplace. Studies have shown that exoskeletons could introduce new physical risk factors, including local muscular fatigue (de Looze et al. 2015). Several researchers have attempted to understand the changes in muscle activation with the use of exoskeletons (von Glinski et al.

2019; Kobayashi et al. 2009). For instance, Kobayashi et al. (2009) studied the impact of an active exoskeleton on the muscle activity of workers during the load-holding task. Results suggested that the active exoskeletons reduced the muscle activation in the biceps brachii, trapezius, and lumbar erector spinae (LES) by 85%, 85%, and 50% Maximum Voluntary Contractions (% MVC), respectively (Kobayashi et al. 2009). However, it's important to note that most of the studies on the impact of active exoskeletons on muscular activity have been mostly conducted in industrial settings that primarily involve static tasks and forward-bending postures, rather than the construction industry, where workers are exposed to physically demanding activities that require dynamic lifting, carrying and prolonged periods of stopping on unstructured and dynamic job sites.

Towards this end, this research aims to examine the impact of the active exoskeletons system on the muscular activity of construction workers while performing common construction activities. As evidenced by the empirical study on lower-back pain being the most prevalent of all musculoskeletal disorders in the construction sector (Wang et al. 2017), the scope of this study lies in focusing on the back muscle activation of construction workers. For this purpose, ten subjects were required to complete lightweight and heavyweight material handling tasks under two conditions (with and without using an active back-support exoskeleton). During each condition, muscle activity of the Lumbar Erector Spinae (LES) of the subjects was measured through surface electromyography (EMG) sensors. In addition, Borg categorical rating scale (Borg CR-10) was leveraged to assess the perceived musculoskeletal exertion of the subjects, which was used as a baseline for low muscle fatigue and high muscle fatigue. The elicited physiological signals were preprocessed by reducing signal noises. Likewise, various metrics were extracted from the physiological signals in the time and frequency domains. Lastly, the impact of the active exoskeletons system on the muscular activity of construction workers was assessed by statistically comparing the extracted physiological metrics for tasks performed with exoskeletons and without exoskeletons.

EXOSKELETON SYSTEM IN THE CONSTRUCTION SECTOR: BENEFITS AND RISKS

Prolonged periods of awkward bending and stooping during common construction tasks can weaken and compress the discs in the lumbar spine of construction workers (Ekpenyong and Inyang 2015). Such compression can cause irritation of the nerve and overloading of the spinal muscles (including the lumbar spinae), ultimately leading to lower back pain. A wide range of exoskeletons is emerging as ergonomic solutions in the construction sector to reduce work-related musculoskeletal injuries by providing lift support, weight dispersion, and posture correction (Shein Esther 2019). Depending on the type of load and movement strategy, however, exoskeletons can be responsible for increased muscle activity (de Looze et al. 2015). Exoskeletons assisting the user in performing a task can lead to the muscles being used differently than without the device (Weston et al. 2018). 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 back muscle 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 back muscles, such as the lumbar erector spinae, which play a critical role in stabilizing the spine during lifting and bending (Weston et al. 2018). The potential for increased muscle activity and localized muscle fatigue in the back muscle can be further exacerbated by factors such as prolonged use of the exoskeleton and poor posture (Godwin et al. 2009). Over time, increased muscle activity and localized fatigue can lead to muscular strain, pain, and injury (Godwin et al. 2009). Despite such risk factors, there is a lack of studies to understand the impact of the exoskeleton system on the muscular activity of construction workers while performing common construction activities.

EMG-BASED IMPACT ASSESSMENT OF ACTIVE EXOSKELETONS ON WORKERS' MUSCULAR ACTIVITY

Overview

This research aims to examine the impact of the active exoskeletons system on the muscular activity of construction workers while performing common construction activities. Figure 1 illustrates the methodology of the study.

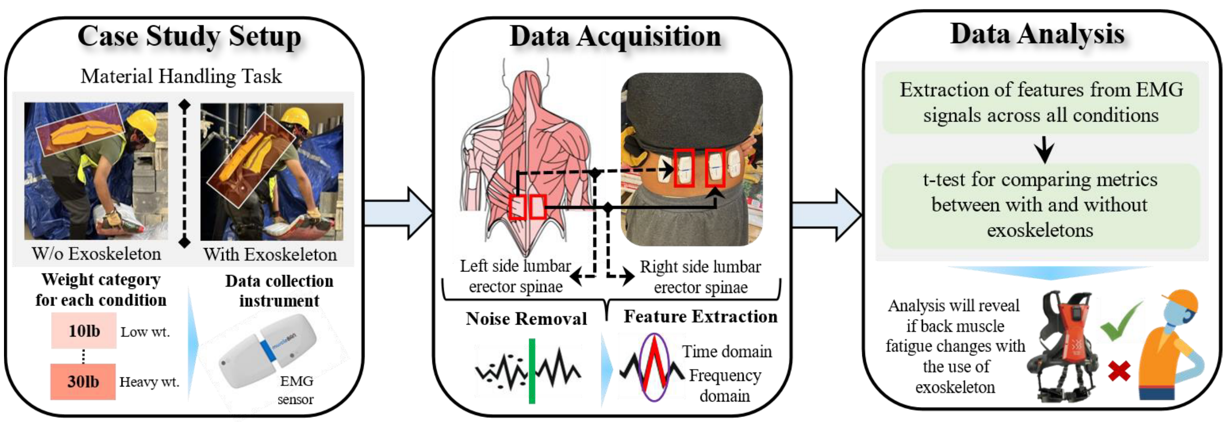

Figure 1. Steps for EMG-based impact assessment of active exoskeletons on workers' muscular activity

As shown in Figure 1, this research involved three main steps. In the first step, case study setup, ten subjects were required to complete manual handling tasks in a lab-controlled environment under two scenarios (with and without using an active exoskeleton) with varying weights of the cement bags, 10 lbs. (lightweight condition) and 30 lbs. (heavyweight condition) respectively. During each condition, subjects were equipped with EMG sensors to measure the muscular activity of LES muscle groups. Two EMG devices were used on either side of LES muscle groups, as shown in Figure 1. In addition, the Borg CR-10 scale was leveraged to assess the perceived musculoskeletal exertion of the subjects, which was used as a baseline for low muscle fatigue and high muscle fatigue. In the second step, data acquisition, the EMG signals were obtained from the sensors across the condition and processed to reduce signal noises and extract informative physiological metrics. Different metrics in the time domain [Mean Absolute Value (MAV) and Root Mean Square (RMS)] and frequency domain [Mean Frequency (MNF)] were extracted from the processed physiological signals. Finally, in the third step, data analysis, the authors assessed the impact of the active exoskeletons system on the muscular activity of construction workers by statistically comparing the extracted physiological metrics through a two-sample t-test for the tasks performed with and without using an exoskeleton. The following subsection will provide a detailed explanation of each step.

Case Study Setup

To assess the impact of the active exoskeletons system on the muscular activity of construction workers while performing common construction activities, a material handling task was designed, as shown in Figure 2. During the tasks, subjects were required to complete material handling tasks in a lab-controlled environment under two conditions (with and without using an exoskeleton) with varying weights of the cement bags, 10 lbs. (lightweight scenario) and 30 lbs. (heavyweight scenario), respectively.

Figure 2. Case Study Illustration: a) Material handling task setup; b) Task with and without exoskeleton c) Active back-support exoskeleton; d) Placement of EMG sensor

Twelve participants, comprising two females and ten males, executed the assigned material-handling task. The study used a randomized crossover design where each participant performed the task under two conditions: with and without the assistance of an active exoskeleton. The task involved lifting, carrying, and lowering a 10 lbs. bag of cement for 5 minutes (lightweight session) and a 30 lbs. bag of cement for another 5 minutes (heavyweight session) from the material storage area to the delivery location, as shown in Figure 2-a. Figure 2-b illustrates the performed material handling task under two conditions, and Figure 2-c shows an image of the implemented active exoskeleton. During the task sessions, the activity of the LES muscle groups of the subjects was measured through portable EMG sensors. From the biomechanical perspective, the LES muscle group was selected because of its role in generating mechanical energy during manual lifting tasks. To measure muscle activity, two pairs of wireless bipolar Ag/AgCl surface electrodes were attached bilaterally to each side of the LES muscle group. A standardized skin preparation procedure was followed to ensure that the skin impedance was below ten kΩ. Prior to the task sessions, the maximum voluntary contractions (% MVC) trial was performed for the LES muscle group for each subject, and the corresponding EMG data from each session was normalized to the % MVC. For the % MVC trials, the subjects were asked to extend their trunk upward against manual resistance applied by the study investigator while in a prone position, with their torso hanging over the edge of a table. Each MVC trial lasted for 10 seconds. All the subjects had basic construction engineering knowledge and experience in conducting manual handling tasks on construction sites. Moreover, none of the participants reported any history of mechanical pain or injury of the lower back extremities. Informed written consent was obtained from all the subjects following the procedure approved by the Institution Review Board (IRB) at Penn State.

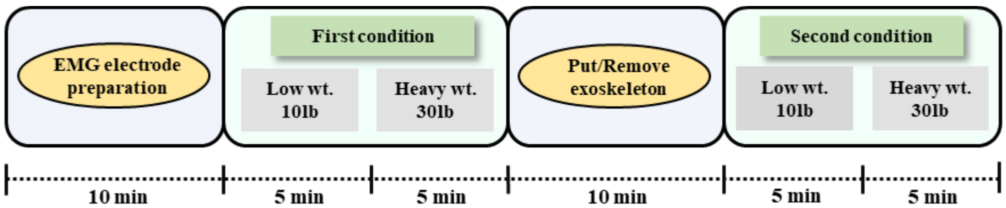

Figure 3. Case study protocol

The data collection for the case study lasted for an average of 40 minutes per subject, during which time they were given instructions on the task they were required to perform until the final session was completed and the electrodes were removed. Figure 3 outlines the steps taken during the case study. After each session, participants were asked to rate their level of musculoskeletal exertion on the Borg CR-10 scale. According to subjects' perceived musculoskeletal exertion, the recorded EMG signals were divided into: Low Muscle Fatigue (RPE scale between 0 to 4) and High Muscle Fatigue (CR 10 scale between 4 to 10).

Data Acquisition

The EMG signal was sampled at a sampling rate of 1 kHz. The collected signal from each session from all subjects was filtered, rectified, normalized, and averaged. Firstly, EMG signals were band-pass filtered between 0.5 Hz and 250 Hz to reduce external signal artifacts. To remove ambient noise that comes from external electromagnetic sources, a notch filter with a cutoff frequency of 60 Hz was applied. After filtering, EMG signals were rectified and, consequently, normalized. Since the intensity of the signal was different for each subject, the EMG was normalized to the % MVC, a commonly used method in previous studies (Mirka 1991). The % MVC data for the left and right EMG channels for LES muscle groups were averaged to produce one signal after a cross-correlation analysis showed high correlations (> 0.97) for both channel combinations. After applying signal processing algorithms, several metrics was extracted from the normalized EMG signal both in the time domain and frequency domain. Owing to the high temporal resolution of EMG recording (1000 data points in 1 second), a single EMG data point is not informative. In this regard, the authors extracted metrics from a block of 1000 consecutive data points (1 s) of the normalized EMG signal. In the time domain, MAV and RMS values from the normalized EMG signal were calculated via the corresponding equations: $MAV = \frac{1}{N}\sum_{i=1}^{N}|x_i|$; $RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N}x_i^2}$, where x_i indicates the i^{th} sample of the normalized EMG signal, and N is the total number of samples. In the frequency domain, MNF was calculated using the equation: $MNF = \frac{\int_0^{\frac{f_s}{2}} fP(f)df}{\int_0^{\frac{f_s}{2}} P(f)df}$; where $P(f)$ is the power spectral density (PSD) of the normalized EMG signal, and f_s is the sampling frequency.

Data Analysis

To analyze the impact of the active exoskeletons system on the muscular activity of construction workers while performing common construction activities, the two-sample t-test (with a significance level of 0.05) was used to determine the statistical differences between the extracted metrics. As the data satisfied the normal distribution assumption, a two-sample t-test was adopted to evaluate the impact of material handling tasks with varying loads [10 lbs. (lightweight condition) and 30 lbs. (heavyweight condition)] with two different scenarios (with and without using an active exoskeleton) on muscle activity.

RESULTS AND DISCUSSION

Figure 4 illustrates the calculated EMG-based metrics for LES muscle groups while subjects performed the experiment tasks under two conditions (with and without using an exoskeleton) with varying muscle fatigue levels.

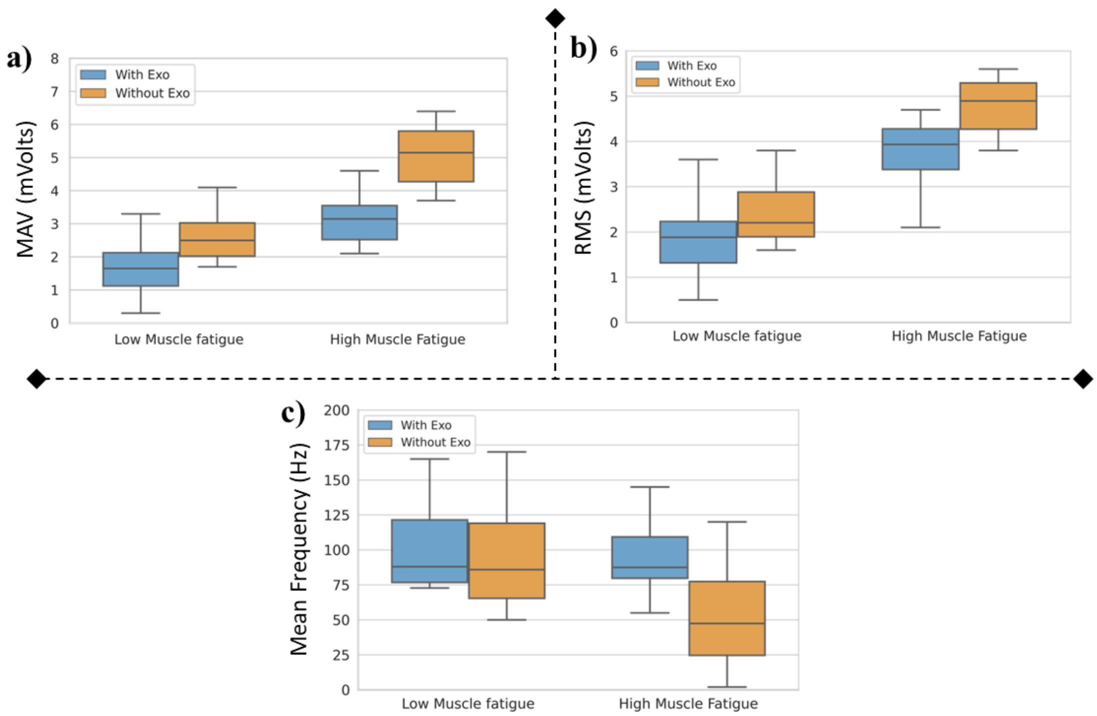

Figure 4. Metrics derived from EMG signals

Across all fatigue levels, the EMG metrics for tasks completed with the exoskeleton device resulted in a significant reduction. For metrics extracted from EMG signals, results indicated a significant difference (p-value < 0.05) in MAV, RMS value, and mean frequency values while subjects were performing the tasks with different setups (without exoskeleton and with exoskeletons) for the same fatigue level. Results show higher MAV, RMS values, and lower MNF values while subjects performed the tasks with the exoskeletons, compared to the situation without exoskeletons. As seen in Figures 4-a and 4-b, when the subjects use the exoskeletons to perform the tasks, the MAV and RMS value of EMG metrics exhibit a significant decrease. More specifically, the two-sample t-test indicated that the MAV and RMS value extracted from the EMG signals is significantly lower with the use of exoskeletons (p-value <0.05). Likewise, there was a clear difference in the metrics that were calculated in the frequency domain (MEF) when subjects performed the experiment tasks under two conditions (with and without using an exoskeleton. Particularly, the t-test delineated that the MEF value extracted from the EMG signals is significantly higher when subjects use the exoskeletons to perform the tasks with varying weights of cement bags (p-value <0.05). Since the previous researchers have asserted that lower MAV and RMS value, as well as higher MNF value, shows lower muscle exertion (Dideriksen et al. 2010), the results suggest that the exoskeletons offer significant support to lumbar erector spinae muscles. Although the study did not make a direct comparison between active and passive systems, the outcomes strongly suggest that active back support exoskeletons have a valuable role to play in physically demanding workplaces that involve lifting, carrying, lowering, and other awkward positions. By providing an external power source, active exoskeletons offer significant support to the lower back. In this vein, the additional weight of an active exoskeleton is offset by the added external energy from the device, which results in overall fatigue reduction.

CONCLUSION

This research aimed to investigate the effect of an active exoskeleton system on the muscular activity of construction workers during common construction activities. To accomplish this, twelve subjects completed material handling tasks with varying loads under two conditions - with and without using an active exoskeleton. The muscle activity of the lumbar erector spinae (LES) was measured using EMG sensors during each condition. The results showed a significant difference in EMG signal metrics when performing tasks with exoskeleton systems under varying weight conditions. Specifically, when using exoskeletons, the time-domain metrics of EMG signals (MAV and RMS values) were significantly higher, while the frequency-domain metric (MNF) was significantly lower. These findings suggest that using exoskeletons can reduce internal muscle force in the lumbar regions of construction workers. The findings of the study will help formalize standard regulations and guidelines for the widespread adoption of active exoskeletons in construction sites. Although the study was designed with a range of different testing procedures to mimic a broad range of working scenarios, there is still a need for long-term study in real-world scenarios.

ACKNOWLEDGEMENT

This material is based upon work supported by the National Science Foundation under Grant No. IIS-2221167 and IIS-2221166. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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