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Evaluating the Impact of Exoskeletons on Muscle Fatigue under Time Pressure: A Pilot Study

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ABSTRACT: Construction workers perform strenuous tasks requiring long hours of physical labor and constant movement in a fast-paced environment. The time pressure induced by construction operations greatly contributes to Work-Related Musculoskeletal Disorders (WMSD) and muscular fatigue, as it forces workers to perform tasks at a faster pace, often resulting in unsafe behaviors, reduced work quality, and poor decision-making. To address WMSDs in construction, researchers have studied the impact of exoskeletons, wearable devices designed to enhance worker productivity, health, and safety on worker safety and efficiency. However, limited research has explored how time pressure affects exoskeleton performance, particularly in relation to muscle fatigue. This study examines the combined effects of time pressure and exoskeleton use on muscle fatigue in specific muscle groups. Participants performed drywall installation tasks in a controlled environment, simulating construction work using an upper arm exoskeleton, while surface electromyography (sEMG) sensors collected muscle fatigue data. Results indicated that the Anterior Deltoid right muscle group, under 90% time pressure with an exoskeleton, experienced a 38% reduction in fatigue, whereas the Thoracic Es left muscle group exhibited a threefold increase in muscle activation compared to the no-exoskeleton condition under 80% time pressure. The study highlights that using an exoskeleton in a fast-paced environment can significantly strain muscle groups that the device is not designed to support. This research enhances the understanding of how time pressure and exoskeleton use influence muscle fatigue, providing valuable insights for mitigating fatigue among workers across various industries.

1. INTRODUCTION

The construction industry is widely recognized as one of the most critical sectors globally, driving economic growth through job creation and infrastructure development. However, due to its complex and dynamic nature, approximately 90% of manual tasks in construction are physically demanding, often leading to Work-Related Musculoskeletal Disorders (WMSDs) (CPWR, 2016). Construction workers frequently perform tasks in awkward positions that strain muscles, injure tendons, and cause tissue damage. Since most construction tasks rely on manual labor, workers are frequently exposed to muscle fatigue and overexertion during long shifts, further exacerbating the risk of WMSDs. WMSDs are a major health concern in the industry, with a 2024 study reporting that 53.9% of construction workers experienced WMSD symptoms in the past 12 months. Additionally, the prevalence of WMSDs in construction is 9% higher compared to all other industries combined (Dong et al.). Beyond the physical toll on workers, WMSDs also impose a significant financial burden on companies, with worker fatigue-related performance issues costing an estimated $136 billion annually (National Safety Council, 2022).

To address these challenges, researchers in the construction field have recently explored the use of exoskeletons to mitigate WMSDs. Exoskeletons are wearable devices designed to support and enhance human movement, much like tools tailored for specific tasks. They come in various types, including upper-limb, lower-limb, full-body, and hand exoskeletons. Upper-limb exoskeletons assist with overhead tasks such as drilling, lifting, and bending (Gopura & Kiguchi, 2009), while lower-limb or back exoskeletons provide support for activities like lifting, carrying, and bending. Full-body exoskeletons are versatile, aiding tasks that engage the entire body, with adjustable features to focus on either the upper or lower body. Hand exoskeletons enhance grip strength and reduce vibrations when using tools like drills (Ibrahim et al., 2024). Additionally, exoskeletons are classified by their functionality into Active and Passive types (de Vries et al. 2021). Active exoskeletons require an external power source, such as electricity, to operate, while Passive exoskeletons function solely through manual human motion without external power.

Exoskeletons are believed to enhance worker performance by reducing fatigue, enabling tasks to be completed more efficiently. However, time pressure plays a crucial role in muscle fatigue by increasing strain, limiting recovery time, and causing overexertion. It also impairs decision-making and induces mental fatigue, potentially leading to harmful or even life-threatening consequences. While exoskeletons have been studied for their effects on muscle fatigue, no research has specifically examined their impact under time pressure. This study aims to analyze and compare muscle activation with and without exoskeletons to reduce fatigue in construction workers. In workplace settings, exoskeletons are expected to enhance efficiency while minimizing fatigue. By examining their impact under time pressure, this research evaluates how specially designed exoskeletons influence overall muscle activation and endurance.

In this study, the researchers aim to address and answer the following question: How do exoskeletons impact worker muscle fatigue under time pressure?

1. LITERATURE REVIEW

The Construction industry is known to be complex and dynamic in nature which may lead construction workers to develop Work related musculoskeletal disorders or WMSD from repetitive, physically intensive tasks over long periods of time. Previous researchers analyzed how construction workers fatigue mentally and physically for specific muscle groups, but few have offered insight on the effects of time pressure and exoskeletons have on the body. Many people used subjective and objective data combined to receive the most accurate data on fatigue. Several research studies analyzed the fatigue in construction workers using Heart Rate Variability (HRV) analysis for objective data and the Borg-20 scale for subjective data (Anwer et al. 2023; Umer et al. 2022; Umer et al. 2020; Aryal et al. 2017). These studies used an EQ02 system or body device that collected data from the participants performing strenuous tasks, resembling those in the construction industry (Anwer et al. 2023; Umer et al. 2022; Umer et al. 2020). One study had the participants wear helmets with infrared sensors to collect data such as skin temperature, heart rate and brainwave signals instead of the body EQ02 device (Aryal et al. 2017) while another study utilized flexible sensors and motion capture system to track physical movements of participants (Yin et al. 2023).

In addition to collecting data, previous research investigated different powered types of exoskeletons and their applications. For instance, Walter et al. (2023) examined how active exoskeletons affect muscle activity, focusing on back muscles while lifting weights and Ibrahim et al. (2024) analyzed active hand exoskeletons effectiveness when performing drilling tasks. de Vries et al. (2021) explored passive exoskeleton effect on the arms when performing plastering tasks while Rafique et al. (2024) investigated advantages and disadvantages on passive exoskeletons. Examples like these show the diverse range and applications of exoskeletons along with their future practicality for many industries.

Some studies that have analyzed the effects of time pressure on risk-taking behaviors and situational awareness, used questionnaires and some form of virtual mixed-reality simulations on construction tasks such as electrical lines (Pooladvand & Hasanzadeh. 2022, 2023). These studies used 3d models and multi-modal Mixed Reality (MR) environment which provided sounds and feeling of tasks simulating those performed on real electrical lines (Pooladvand & Hasanzadeh. 2022, 2023). Participants completed three tests: one at their normal pace, one under time pressure, and one with time pressure plus an additional task (Pooladvand & Hasanzadeh. 2022). Results revealed a 13% decline in performance under time pressure and indicated an increased reliance on safety equipment as fatigue levels rose (Pooladvand & Hasanzadeh. 2022). Supporting this idea, a group of construction workers with various levels of experience participated in a questionnaire-based survey on mental effects of scheduling pressure on tasks. Nepal et al. (2006) found that 59.1% and 21.5% of construction workers work under high and very high schedule pressures while 1.1% and 18.3% of construction workers performed tasks under low and normal time pressures. Many workers stated that tasks were given a near impossible amount of short time. Existing studies provide evidence that time pressures deceases performance. Therefore, it is equally important to investigate its impact on muscle fatigue using objective data while performing tasks with and without an exoskeleton.

2. METHODOLOGY

2.1 Data Collection

Ten healthy participants were recruited to participate in the research experiment. The participants were between 19 and 30 years, primarily students from Texas A&M University. Before the in-person experiment, participants completed initial screening through a phone call, which included a medical history review to confirm they were in good health, non-smokers, and had little to no pain in their limbs or body. Participants then completed the consent process approached by the Institutional Review Board. Subsequently, the researchers collected anthropometric measurements, in person, such as the participant's height, weight, BMI, visceral fat muscles, muscle percentage, and body fat percentage using the Omron HBF-514C device.

This study integrates both qualitative and quantitative data to provide a comprehensive and precise measurement of fatigue. Qualitative data is gathered using the Borg Scale (0 to 10), in line with previous studies (Anwer et al. 2023; Umer et al. 2022; Umer et al. 2020; Aryal et al. 2017; Khan et al., 2024). This process relies on participants' self-reported fatigue levels based on personal perception, introducing potential bias. To mitigate this, quantitative data is collected using Noraxon sEMG sensors, which provide objective, numerical measurements of localized muscle activity and physical exertion. These sensors were placed on specific muscle groups on the participant's body after the anthropometric measurements were recorded. The combination of qualitative and quantitative data allows researchers to compare self-reported fatigue levels with measurable physiological responses, enhancing the accuracy and reliability of the findings. Data was collected from muscle groups such as Anterior deltoid, Lateral gastrocnemius, Brachioradialis, Thoracic erector spinae, and Rectus Femoris. This provided an overall view of the muscles fatiguing over time.

The Borg Scale (0 to 10) was used to collect each participant's opinion on their experience with exertion levels after tests were completed after 30 total cycles under constant room temperature. Participants performed a Maximum Voluntary Contraction (MVC) which captures the maximum force produced by a muscle group. This was done after placing the sensors on the participant, but before each experimental session started, providing a baseline to compare to other time intervals throughout the tests. Participants performed drywall installation tasks at 90% and 80% of their baseline time, with and without the use of an exoskeleton, to evaluate changes in productivity and muscle fatigue. The research team selected ninety percent to mimic minimal time pressure as would be expected on a jobsite. Eighty precent was selected to mimic pursuit for increased productivity.

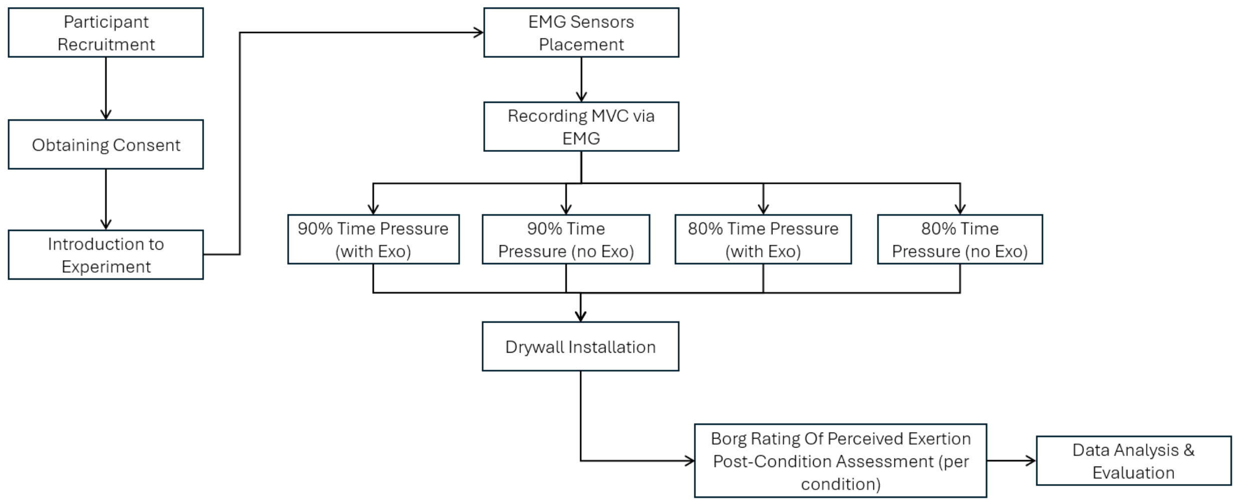

Figure 1: Experimental design process.

Figure 1 presents an overview of the experimental procedure. The process began with participant recruitment, informed consent, and an introduction to the study. Following this, EMG sensors were placed, and Maximum Voluntary Contraction (MVC) measurements were recorded before starting the main tasks. Participants then performed drywall installation tasks under four experimental conditions, which varied by time pressure (80% and 90%) and exoskeleton (Exo) use (with and without). For each condition, participants completed 30 cycles of drywall installation while continuous EMG data was collected. After each condition, participants rated their perceived exertion using the Borg RPE scale to capture subjective assessments of workload and fatigue. The final step involved analyzing the collected data to evaluate both physiological responses and perceived effort associated with exoskeleton use under different time pressure conditions.

The drywall installation tasks involved lifting and carrying plywood from a stacking location to the installation location. Next, a drilling activity was simulated by holding and pressing a drill against pre-drilled holes in a rung for about 5 seconds per hole (12 holes) as depicted in Figure 2, shown below. This process was repeated 30 times while measuring muscle fatigue. The NORAXON software was used to record, annotate videos of participants performing the tasks, and analyze the data. An upper limb support exoskeleton (Skelex) was used in this experiment to assist the arms and shoulder muscles. Assessing the effectiveness of exoskeletons in reducing fatigue requires a range of tools and techniques. For example, researchers use techniques like collecting subjective data through questionnaires and rating scales. While this may be helpful in analyzing a person's overall fatigue, it is time-consuming and contains bias due to a person’s feelings and personal experience (Zhang et al. 2015; Chan et al. 2012). Objective measurements are another technique that analyzes the physiological or kinematic movements of a person. Examples of machines or devices include, but are not limited to, Surface Electromyography (sEMG), Electrodermal Activity (EDA), and Inertial Measurement Units (IMU) (Aryal et al., 2017; Khan et al., 2024). Research studies like Anwer et al. (2021) have found that combining both subjective and objective measures provided the most accurate assessment of an individual's fatigue levels, as it provides insight into personal feedback and feelings alongside real-time data recorded through machines and devices.

Figure 2: Drywall installation tasks being performed.

2.2 Data Processing

For data analysis, after the participants completed the experiments, each recorded data set was processed using Noraxon software as seen in Figure 3. First, the data were normalized by comparing the measured values to the maximum voluntary contraction (MVC) activation tests, which served as a baseline for muscle contraction force. Normalizing to the MVC allows for standardization across participants by accounting for individual differences in strength, ensuring that the recorded muscle activations are relative to each participant's maximum capacity. Next, the data underwent a smoothing process. Smoothing was applied to reduce noise and short-term fluctuations that can occur due to sensor imperfections or transient movements. By minimizing these inconsistencies, smoothing helps in revealing the true underlying trends in muscle activation. After smoothing, the data were further cleaned by filtering within a frequency range of 20 to 450 Hz. This filtering step removed any remaining artifacts and isolated the relevant signal frequencies associated with muscle activity. The chosen frequency range is supported by previous research using similar filter parameters (Zhuang et al. 2018). Finally, the cleaned and normalized data were used to compare muscle activation across the experimental conditions, including the exoskeleton condition and time pressure.

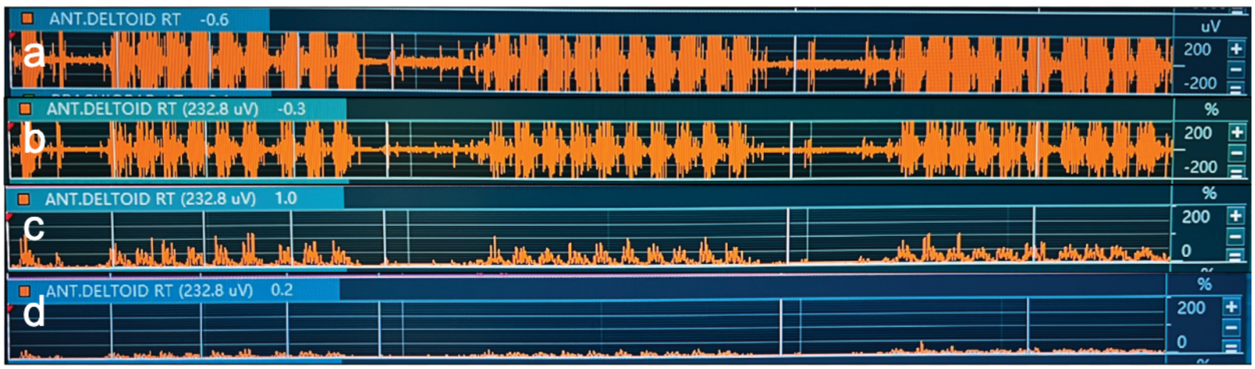

Figure 3: Overview of the raw Ant Deltoid RT data pre-cleaning process: starting with raw data (a), followed by normalization (b), then smoothing (c), and finally complete processing with filtering (d).

3. RESULTS

The analysis of the impact of time pressure on muscle groups, both with and without the use of an exoskeleton, is presented in Figure 4. Participants experienced 90% and 80% of their baseline time under both exoskeleton (exo) and no-exoskeleton (no exo) conditions, providing valuable insight into the effects of time pressure across these two variables. Analysis of the Anterior Deltoid Right muscle group revealed a 38% reduction in muscle fatigue when using the upper limb support exoskeleton under 90% time pressure, compared to no exoskeleton measurements. At 80% time pressure, the Anterior Deltoid Right muscle group activation reduced by 5.8% when using the exoskeleton (compared to the no exoskeleton condition). However, a 62.9% increase in muscle activation was recorded in the left Anterior Deltoid when using the exoskeleton compared to the no-exoskeleton condition in 90% time pressure. Moreover, in the Thoracic Es LT muscle group, the same exoskeleton under 80% time pressure resulted in a threefold increase in muscle activation compared to the no-exoskeleton condition. These findings challenge the common assumption that exoskeletons universally reduce muscle fatigue. Instead, the results indicate that while exoskeletons effectively reduce fatigue in the specific muscle groups they are designed to support—such as the upper limb in this study—they can inadvertently increase strain in other muscle groups, especially under time pressure, potentially leading to unintended physical stress.

The Kruskal-Wallis test was utilized to analyze the objective data. Performing the Kruskal-Wallis test over the same conditions or sessions, which is a nonparametric test used to analyze if there are any significant differences between two or more groups, resulted in the P-value probability being 0.075 which is greater than 0.05, indicating there was no significant difference. When analyzing and comparing specific muscle groups, the P-value on average was 0.936, indicating no significant difference.

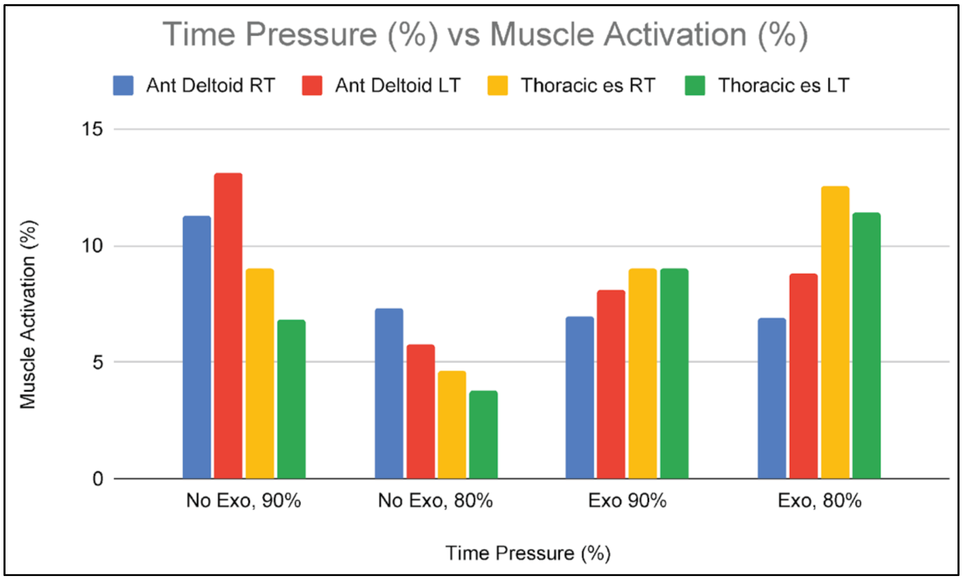

Figure 4: Variation in muscle group activation across different sessions.

The subjective data was analyzed using the Rate of Perceived Exertion (RPE) scale, which is used to rate individuals' fatigue levels based on their personal physical and emotional experiences. Again, the Kruskal-Wallis test was performed and yielded an H-statistic of 3.0 and a P-value of 0.3916, following the trend that fatigue levels were similar across test conditions, as depicted in Figure 5. Exoskeletons designed to support specific muscle groups were found to reduce fatigue in targeted areas; however, they also contributed to increased fatigue in other muscle groups.

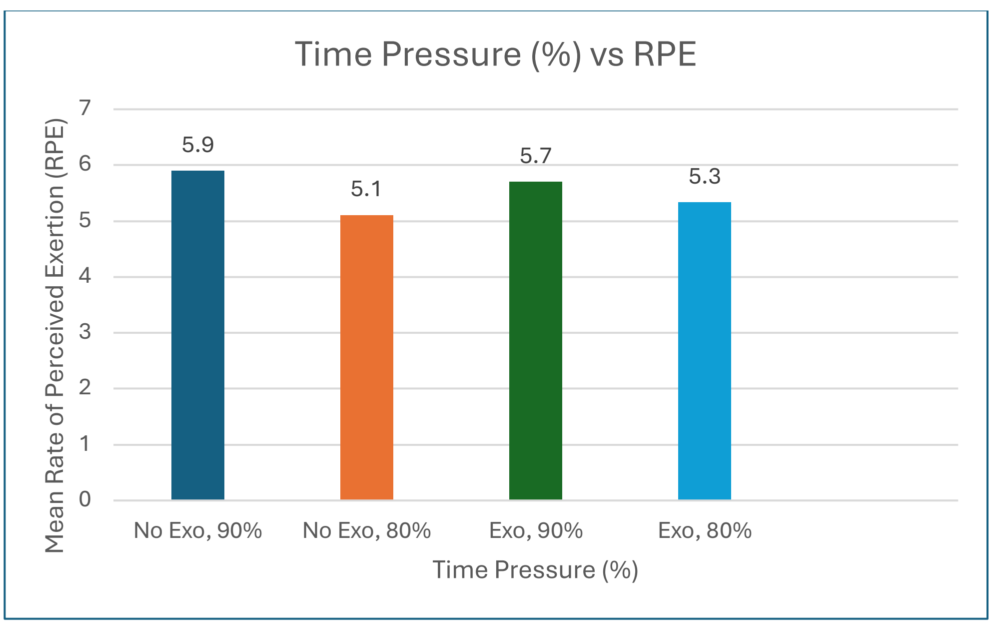

Figure 5: Mean Rate of Perceived Exertion Across Varying Time Pressures.

4. DISCUSSION AND CONCLUSIONS

Fatigue is a critical yet often overlooked issue in the construction industry, affecting both frontline workers and management. The fast-paced nature of construction sites marked by tight deadlines and constant activity often leads to significant time pressure, a key contributor to fatigue. Under these circumstances, workers may be driven to adopt unsafe practices or shortcuts to meet deadlines, thereby heightening the risk of accidents and adversely affecting both mental and physical well-being. Previous studies have investigated how various exoskeleton designs and data collection methods influence muscle fatigue, as well as the accuracy of these methods in predicting it. Exoskeletons, which assist in performing physically demanding tasks, are hypothesized to boost efficiency and productivity by enabling workers to complete more work in less time. Building on these insights, the present study examines the effects of exoskeletons on muscle fatigue in both targeted and adjacent muscle groups under varying degrees of time pressure.

The experimental results demonstrated that targeted muscle groups experienced reduced activation when using exoskeletons specifically designed for those groups. However, under higher time pressure, surrounding muscle groups showed increased activation (Figure 4). These results suggest that while exoskeletons can mitigate fatigue in the primary muscles they are designed to support, they may inadvertently shift the workload to adjacent muscles, particularly under time-constrained conditions. When analyzing both objective and subjective data for any differences across tests, performing the Kruskal-Wallis test showed P-values to be greater than 0.05, which indicated no significant difference in sensor measurements and that fatigue levels were similar across tested conditions for RPE ratings (Figure 5). Factors that may have influenced these results include the limited duration of the physical experiments and the lower intensity of tasks, which may not have accurately reflected the high-stress conditions of typical on-site workdays. This could explain the lack of significant differences observed between the tested groups. This pilot study consisted of 10 healthy participants, a sample size that may have also contributed to the absence of significant differences across testing levels and thus limits the generalizability of the findings. Additionally, the experiments were conducted in a controlled environment where factors such as weather variations, temperature fluctuations, and external disturbances were minimized, allowing participants to maintain full concentration on the tasks. This setting contrasts markedly with real-world conditions, which are often far more chaotic and less predictable.

Overall, this research approach was intended to simulate a typical drywall installation process, consisting of three primary tasks: (1) picking up, placing, and transporting drywall sheets to the installation point, (2) installing the drywall, and (3) returning to retrieve additional drywall sheets as needed. Of these tasks, the Skelex exoskeleton is specifically designed to support only one—the overhead installation activity. Unfortunately, this task accounted for only about 30% of the total cycle time, which is consistent with real-world drywall installation workflows. Conversely, plastering required minimal movement, allowing the exoskeleton to remain in an activated state for majority of the experiment.

As a result, while the overall method accurately reflected a critical work function, the effectiveness of the exoskeleton likely diminished over time. This is because workers also performed tasks not directly supported by the exoskeleton, potentially reducing its impact (muscle activation) throughout the full work cycle. Through this research design, we discovered a key phenomenon: exoskeletons may impair muscle function in unsupported areas and negatively intensifies as time pressure increases. This finding suggests a promising area for future research, particularly in construction and other industries that rely on exoskeletons and face time pressure.

Expanding upon these limitations, future research could include people with longer background experience from the industry, people older in age who performed these tasks, and could include changes in the testing environment to simulate real world conditions outside. By lengthening the testing period or raising task intensity, researchers may better evaluate the significance of time pressure’s effects on muscle fatigue. In the future, additional research studies are needed to evaluate the effects exoskeletons have on muscle fatigue with added time pressure for both individual muscle groups and groups as system. This can eventually lead to the reduction and prediction of fatigue with the use of exoskeleton for workers in all industries across the world.

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