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IMPACTS OF WEARABLE ROBOTS IN MITIGATING MUSCULOSKELETAL DISORDERS AMONGST MASONS: COGNITIVE STATES, PRODUCTIVITY, AND DISCOMFORT

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Joshua Ofori, M.Sc.
Georgia Institute of Technology, Atlanta, GA 30332
ORCID: https://orcid.org/0000-0002-6610-7703
joshoforinsiahaddo@gatech.edu

Mariam Tomori, M.Sc.
Georgia Institute of Technology, Atlanta, GA 30332
ORCID: https://orcid.org/0009-0004-8150-3554
mtomori3@gatech.edu

Omobolanle Ogunseiju*, PhD. (corresponding author)
Georgia Institute of Technology, Atlanta, GA 30332
ORCID: https://orcid.org/0000-0002-3852-4032
omobolanle@gatech.edu

SUMMARY*: Masonry is one of the most labour-intensive construction trades due to the repetitive, fast-paced, and strenuous tasks involved, which increase the risk of musculoskeletal disorders (MSD). While exoskeletons have been proposed as a means of reducing MSDs, few studies have investigated their impact on productivity, physical discomfort, and cognitive states during masonry tasks. To close this gap, the current study looks into the effects of active and passive exoskeletons on productivity, physical discomfort, and cognitive states while performing masonry tasks. The study consists of three rounds of masonry tasks performed by 19 participants, both with and without exoskeleton support, to determine the effects of exoskeletons on productivity and perceived discomfort. Using subjective and objective measures, the study found that active exoskeletons increase productivity during masonry tasks by 15.3% and 16.2%, respectively, compared to non-exoskeleton and passive exoskeleton conditions. In terms of physical discomfort, the findings revealed that both active and passive exoskeletons reduced low back discomfort while causing discomfort in the upper extremities during masonry tasks. The cognitive state analysis also revealed that active exoskeletons increased participants' levels of relaxation (58.40%), focus (53.10%), excitement (68.54%), and attention (46.31%) compared to other conditions. Both active and passive exoskeletons reduced stress during masonry tasks. This study provides a novel, multidimensional understanding of human-exoskeleton interaction in the construction industry by integrating productivity metrics, physical discomfort, and neurophysiological indicators (EEG-based cognitive states) to evaluate both the cognitive and emotional well-being of workers. The study assesses the impacts of passive and active exoskeletons on task productivity and perceived discomfort across different body parts using subjective and objective evaluations , offering new insights into the holistic impact of wearable robotics on construction labor. Understanding these may tend to assist construction firms in their selection of exoskeletons for specific construction activities and may also guide exoskeleton manufacturers in providing exoskeletons which are more tailored to the construction industry.*

KEYWORDS*: Masonry construction, Wearable robots, Ergonomics, Workers' safety, Exoskeletons, Cognitive states.*

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1. INTRODUCTION

The construction industry continues to face significant health and safety risks (Owoniyi et al., 2025). In 2019, there were 5,333 fatal occupational injuries in the United States, up 2% from the previous year ((BLS), 2020). Among the industry's various hazards, one major concern is the risk of musculoskeletal disorders (MSDs) (Antwi-Afari et al., 2023; Bamfo-Agyei & Atepor, 2018), which are caused by work-related activities such as prolonged work, uncomfortable body postures, excessive strain from heavy manual material handling, repetitive tasks, and exposure to whole-body vibrations (Ogunseiju et al., 2021). Masonry occupations, such as bricklayers and stone masons, are especially vulnerable to MSDs due to the required repetitive motions, physical strain, and manual material handling, leading to low back pain, shoulder injuries, and knee osteoarthritis, which account for more than one-third of all lost-time injuries in the construction industry (Anwer et al., 2021; Kaur, 2021). Dong et al. (2019) reported that masonry had one of the top ten highest rates of work-related musculoskeletal disorders in the construction industry in 2017, with 380 cases per 10,000 full-time equivalent workers. These statistics highlight the critical need for effective interventions to improve the health and safety of masonry workers.

Wearable robots (also known as exoskeletons) are a promising intervention that has the ability to augment human strength and reduce biomechanical stress (Antwi-Afari et al., 2023; Tomori et al., 2024). According to Ogunseiju et al. (2025), exoskeletons can be categorized as active or passive. Ogunseiju et al. (2025) and Anwer et al. (2023) revealed that while active exoskeletons use motors to facilitate dynamic movement, passive exoskeletons rely on mechanical elements like springs and dampers to minimize muscle strain and fatigue. Due to these professed benefits, several studies have investigated wearable robots for the construction industry. For instance, Anwer et al. (2023) found that a low-cost passive exoskeleton resulted in a 30% decrease in lumbar erector spinae (LES) muscle activation and a 12% reduction in thoracic erector spinae (TES) muscle activity. The same study also revealed that kinematics improved significantly, with reductions of 23% in neck movements, 11% in low back movements, 5% in hip movements, and 36% in knee movements. Ogunseiju et al. (2021) examined the effectiveness of passive back-support exoskeleton in flooring work using subjective evaluation. The findings showed a significant reduction in discomfort in the lower leg, lower back, and thigh by 28%, 21.74%, and 3.13%, respectively. Similarly, a recent study by Gonsalves et al. (2023) examined how concrete workers interacted with a passive back-support exoskeleton. The results showed that the system reduced stress on the lower back and provided less discomfort in the lower leg, lower back, and +thighs. Nevertheless, Gonsalves et al. (2023) observed that the exoskeleton caused discomfort in other body parts, indicating the need for design changes. Aside from the biomechanical effects of exoskeletons reported, recent studies have also recommended investigating cognitive states when exoskeletons are utilized on construction sites (Akanmu et al., 2024; Okunola, Akanmu, et al., 2024a). Rodriguez et al. (2020) elucidated that this is significant because construction workers frequently encounter elevated cognitive demands due to the complexities of their tasks, which impact their efficiency, decision-making, and attention, among other factors. In particular, masonry tasks are physically demanding and necessitate adequate cognitive resources for precise measurement, spatial reasoning, and quality control (Mitropoulos & Memarian, 2013). Therefore, due to the potential impact of the bidirectional relationship between physical exertion and cognitive performance on construction workers' efficiency and decision-making (Mehta & Parasuraman, 2014), it is essential to investigate discomfort levels and cognitive states experienced by masonry workers during exoskeleton use.

Consequently, existing research has been evaluating the cognitive demands associated with the use of exoskeletons for construction tasks. Most of these assessments have employed either subjective measures, such as NASA TLX, or objective measures, such as electroencephalography (EEG), or a combination of both. For example, the study by Okunola, Akanmu, et al. (2024b) employed NASA TLX and EEG to examine the cognitive load detection of users of an active back-support exoskeleton. Akanmu et al. (2024) evaluated the influence of an active back-support exoskeleton on cognitive load during a carpentry framing task. Conversely, utilizing EEG for a maintenance task with a passive exoskeleton, Kim et al. (2024) discovered that it effectively mitigated cognitive decline, as demonstrated by an enhanced hit-to-signal ratio (8% increase: 81.3 (EXO-Off) versus 87.9 (EXO-On)) in the information integration task and diminished perceived cognitive load. While these studies have been conducted to assess the cognitive demand of using either passive or active exoskeletons for construction tasks, there has been relatively little research into the effects of active and passive exoskeletons on productivity, comfort, and cognitive states during masonry tasks. This study seeks to fill this gap by assessing the effects of passive and active exoskeletons on task productivity, perceived discomfort, and cognitive states across different body parts using subjective and objective evaluations. The study's findings contribute to a better understanding of how exoskeletons affect productivity, physical discomfort, and cognitive states during masonry tasks. This could pave the way for more widespread adoption of wearable robots in construction, which can culminate in improved workers' safety, productivity, and the sustainability of the aging masonry community.

2. BACKGROUND

This section provides a review of the application of exoskeletons in construction, examines their impacts on users' comfort, productivity, and cognitive load, and presents the theoretical framework, research gaps, and significance.

2.1 Exoskeletons and User Comfort

Several studies have shown that both active and passive exoskeletons can reduce muscle activity and range of motion in body parts during various construction tasks. For example, Anwer et al. (2023) conducted a pilot study on a low-cost passive exoskeleton that used both subjective and objective assessments to demonstrate the efficacy of passive exoskeletons in reducing muscle activity. From the findings of the study, objective measures such as heart rate decreased by 13%, while perceived fatigue levels dropped by 67%. A recent field-based pilot study conducted by Bennett et al. (2023) also found that passive exoskeletons reduce exertion and muscle fatigue during manual tasks. Likewise, Okunola, Afolabi, et al. (2024) conducted one of the few studies on active exoskeletons and emphasized the need for additional research in this area. While most studies have focused on passive exoskeletons in the construction industry, there has been little research into evaluating the potential of active exoskeletons in the construction industry, especially for physically demanding and repetitive tasks like masonry. Therefore, to address this gap, this study aims to assess the impacts of passive and active exoskeletons on task productivity and perceived discomfort across different body parts using subjective and objective evaluations.

2.2 Exoskeletons and Productivity

Previous studies present various methodologies for assessing productivity during interactions with exoskeletons. Most of these studies have utilized task completion time, endurance duration, and error frequency to assess the impact of exoskeletons on productivity. For example, Miura et al. (2018) employed endurance time as a metric to evaluate the efficacy of exoskeletons in enhancing efficiency during repetitive drilling tasks. Alabdulkarim et al. (2019) in their study, which evaluated the effect of passive exoskeletons during repetitive tasks, utilized the number of errors as a metric for productivity. In addition to measuring productivity, the findings from these studies indicate that exoskeletons reduce physical strain while also enhancing productivity. Brosque and Fischer (2022) discovered that exoskeletons decrease the duration of repetitive site work by 25-90% and hazardous tasks by an average of 72%. Furthermore, Miura et al. (2018) evaluated the effects of utilizing a hybrid assistive limb (HAL) for repetitive lifting tasks, revealing that HAL diminished lumbar load during these movements. Additionally, performance metrics related to lifting exhibited significant enhancement, with substantial statistical power for lumbar fatigue (0.99), the number of lifts (0.92), and lifting duration (0.93). The study by Kim et al. (2018) on exoskeletons assessed the impact of overhead drilling tasks while utilizing the EksoVest, revealing a 19% reduction in movement completion time. Conversely, Maurice et al. (2019) found that exoskeletons either enhance or diminish the productivity of construction workers. This suggests that the productivity effects of the exoskeleton are contingent upon the specific task. Therefore, it is essential to evaluate the impact of exoskeletons on a physically strenuous task such as masonry.

2.3 Evaluation of Cognitive Load Associated With Exoskeletons

Recent studies have examined the impact of exoskeletons on the cognitive load of users in diverse sectors, including rehabilitation, automotive, and construction. For example, in medical rehabilitation, Afzal et al. (2017) examined the extent of variation in cognitive demands among individuals with multiple sclerosis during both exoskeleton-assisted and unassisted ambulation. The findings from the study by Afzal et al. (2017) revealed that individuals with multiple sclerosis could ambulate using an exoskeleton without significant cognitive demands. In the automobile industry (Kurt, 2024), the exoskeleton's effect on fatigue metrics during welding tasks is also quantified. Kurt (2024) discovered that the use of an exoskeleton led to markedly elevated indicators of fatigue in comparison to the absence of an exoskeleton. Numerous studies have examined the cognitive demands linked to exoskeletons in various construction tasks, including material handling (Liu et al., 2024), painting (Afolabi et al., 2024), framing (Akanmu et al., 2024), and flooring work (Okunola, Akanmu, et al., 2024b). All these studies indicated that cognitive load is associated with exoskeletons and attributed it to the repetitive nature of construction work (Akanmu et al., 2024). A critical examination of the previously mentioned studies indicates that subjective measures such as NASA TLX and objective measures like EEG are the most prevalent methods for assessing cognitive load related to exoskeleton use in the construction industry. Although the majority of these studies examined various construction activities, the masonry task, which is highly physically demanding, has been insufficiently explored, necessitating an investigation into the cognitive load associated with the use of exoskeletons for masonry tasks.

2.4 Theoretical Framework

This study is grounded in the Technology Acceptance Model (TAM) and Cognitive Load Theory (CLT). TAM is the fundamental model supporting the adoption and utilization of new technologies (Davis, 1989). As explained by Davis (1989), TAM is based on two core tenets: (1) the perceived usefulness and (2) the perceived ease of technology. The perceived usefulness tenet in the TAM model evaluates the degree to which an individual believes that utilizing a particular technology would enhance their job performance (Davis, 1989). Marangunić and Granić (2015) explained that an individual's inclination to embrace new technology is affected by their attitudes and the characteristics of the technology in question. Therefore, if an individual perceives technology as comfortable to use with minimal effort, it will likely lead to positive attitudes, increasing the likelihood of its adoption and subsequently aiding in improving productivity. In recent years, the TAM has been extensively used in various studies to forecast the adoption and utilization of novel technologies within the construction industry. This study leverages the tenets of TAM to perceive the comfort levels induced by exoskeletons on users and how they impact their work. The study further leveraged the CLT, which includes a framework for evaluating cognitive load associated with physically demanding tasks such as masonry. CLT contends that people are most effective when tasks are compatible with the brain's limited cognitive load (Sepp et al., 2019). The CLT considers three cognitive loads: intrinsic cognitive load (ICL), extraneous cognitive load (ECL), and germane cognitive load (GCL) (Klepsch et al., 2017). ICL emphasizes the learning curve and adaptation phase for users, during which they must invest additional cognitive resources to comprehend the exoskeleton's functions and control, especially if they are unfamiliar with it (Akanmu et al., 2024), while ECL focuses on processing irrelevant information unrelated to the tasks (Poupard et al., 2025). For instance, operating an exoskeleton may necessitate users to modify their movements and remain vigilant of their surroundings (Akanmu et al., 2024). GCL also emphasizes the cognitive load experienced by individuals as they acquire knowledge and develop schemas for knowledge retention during task execution (Haji et al., 2015). Hence, this study employed the CLT to understand the impact of exoskeletons on cognitive states during masonry tasks.

2.5 Research Gaps

The reviews conducted have revealed the paucity of research on the impact of exoskeletons on masonry tasks, despite it being considered physically demanding and having one of the ten highest rates of work-related musculoskeletal disorders in the construction industry in 2017 (i.e. with 380 cases per 10,000 full-time equivalent workers) (Dong et al., 2019; Mitropoulos & Memarian, 2013). Likewise, while there is an urgent necessity to comprehend the cognitive load related to exoskeletons in the construction sector, limited research has been undertaken to compare the cognitive load associated with different types of exoskeletons (i.e., active and passive). This includes the influence of exoskeletons on cognitive states such as attention, engagement, excitement, stress, relaxation, interest, and focus. Addressing this gap will enhance understanding of how exoskeletons affect cognitive load, emotional response, and overall usability. To address this gap, this study seeks to answer the following research questions (RQ):

i. ***RQ 1:*** *What are the impacts of passive and active exoskeletons on productivity during masonry tasks?*
ii. ***RQ 2:*** *How do passive and active exoskeletons affect the discomfort across different body parts during masonry tasks?*
iii. ***RQ3:*** *How do cognitive states vary across exoskeleton conditions, and how do they relate to task performance or discomfort across different body parts during masonry tasks?*

3. METHODOLOGY

This section describes the approach adopted to address the aforementioned research questions. As illustrated in Figure 1, the research framework is divided into five phases: participants' recruitment, experimental design, instrument and data collection, data processing, and data analysis.

3.1 Participants' Recruitment

Participants were recruited based on inclusion criteria related to age, health status, and experience in construction. Previous studies have demonstrated that for experimental procedures, a sample size of 10 or above is adequate (Antwi-Afari et al., 2021; Anwer et al., 2023). Upon recruitment, each participant signed a consent form and completed demographic questionnaires via Qualtrics. A total of nineteen (19) participants were involved in the study. The study participants predominantly consisted of male participants (14) compared to female participants (5). Among the participants, 12 were aged between 18 and 34 years, with six specifically in the 18-24 and 25-34 age brackets, respectively. Participants' heights were evenly distributed between 156-165 cm, 166-175 cm, and 176-185 cm. The majority of participants were within the 100-149 lb range, representing 50% of the sample, 33.3%, weighing between 150-199 lb, while two participants (16.7%) were in the 200 lb and above category, and lastly, one participant (8.3%) weighed below 100 lb, indicating the presence of a lighter individual. Notably, 18 participants reported no recent musculoskeletal injuries, while 1 participant mentioned experiencing shin splints.

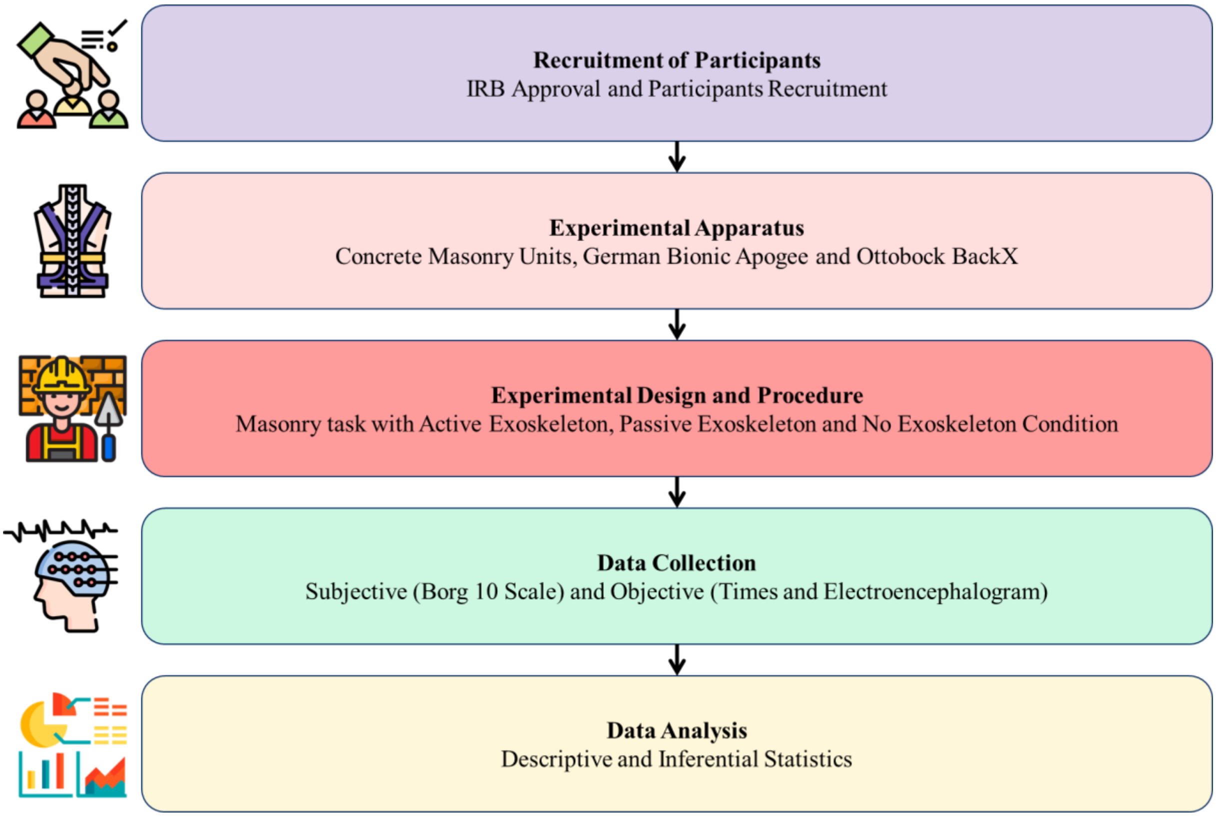


Figure 1: Study Approach.

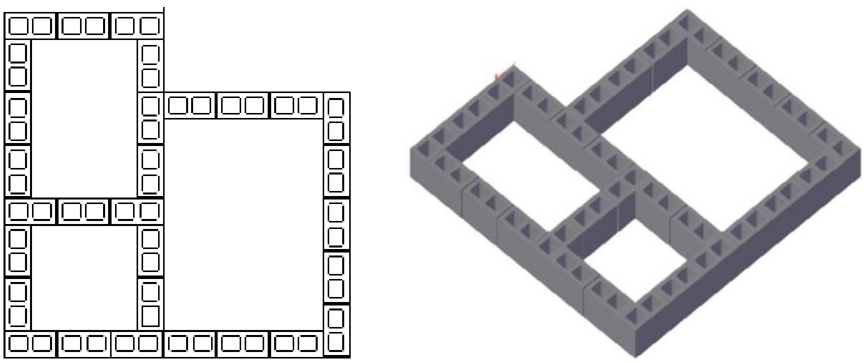
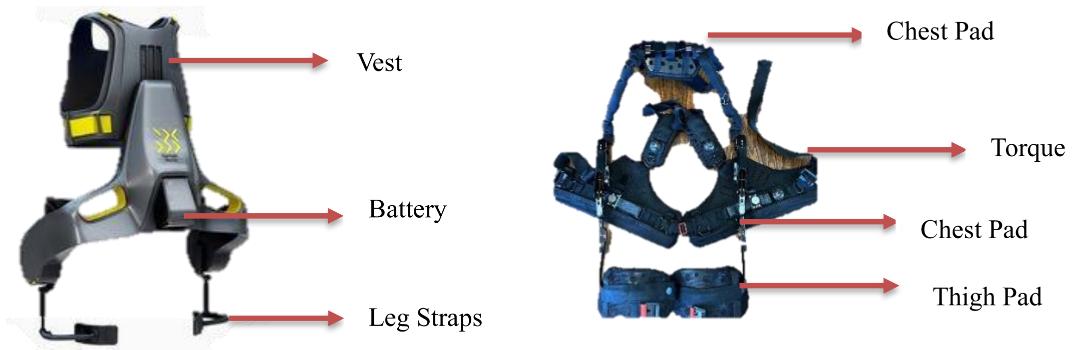


Figure 2: Mansory Task Model.

3.2 Experimental Apparatus

This study utilized standard concrete masonry units (CMUs) measuring 1.33 ft in length, 0.67 ft in width, and 0.67 ft in height. Each CMU weighted 37.49 pounds. The CMUs were situated at floor level and were in proximity to the task area. The total area of the masonry model was approximately 53 square feet. Thirty CMUs were necessary to accomplish the task depicted in Figure 2. The initiation and conclusion of executing this task (i.e., lifting, transporting, and positioning CMU to create a floor plan) are derived from the description provided by Mitropoulos and Memarian (2013) egarding masonry tasks.

The study also adopted a passive (i.e., Ottobock BackX) and an active (i.e., German Bionic's Apogee) exoskeleton. The Ottobock BackX, is a passive exoskeleton designed to reduce lower back strain during manual labor. It operates without batteries and uses mechanical means to provide support (Figure 3b). It aims to reduce the physical demands on workers during tasks such as lifting and bending. The study also adopted the German Bionic Apogee, an active, smart, and robotic exoskeleton that uses batteries to provide powered assistance to the lower back. It is designed to enhance the user's strength and endurance by reducing the physical effort required during strenuous tasks, as shown in Figure ea. This exoskeleton also adjusts to fit various body sizes and aims to improve overall work performance and safety (Toxiri et al., 2019).



(a) German Bionic Apogee *(b) Ottobock BackX*

Figure 3: Exoskeleton Types (Ottobock BackX and German Bionic Back).

a. No Exo *b. With Ottobock BackX* *c. With German Bionic Apogee*

Figure 4: Experimental Procedure.

3.3 Experimental Design and Procedure

As seen in Figure 4, the study involves three rounds of masonry tasks performed by participants, with and without exoskeleton support, to understand the impacts of exoskeletons on productivity and perceived discomfort and cognitive states. Participants performed a standardized masonry task, which involved picking up and placing concrete masonry units (CMUs) to form a floor plan (Figure 2). Participants were handed the blueprint of the floor plan and required to lay the CMUs to form the floor plan. Subsequently, the participants were acquainted with the Ottobock BackX and German Bionic Back utilized in the experiment and received training on the device's operation. The masonry task was demonstrated to the participants to mitigate the impact of task difficulty during the experiment (Akanmu et al., 2024). The experiment began once the participants comprehended the functionality

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of the Ottobock BackX and German Bionic Back, as well as the execution of the task. The first round of masonry tasks was conducted without any exoskeletons to serve as a control condition. After completing the task, participants completed a questionnaire assessing their perceived level of discomfort across different body parts. Participants repeated the same masonry task while wearing the Ottobock BackX and the German Bionic Back exoskeleton, respectively.

3.4 Data Collection

3.4.1 Research Question 1

To address research question 1, productivity was quantified using timers derived from the video recordings of the experiment. This yielded a quantitative assessment of the duration required to accomplish the masonry task under each experimental condition (without an exoskeleton, with the passive exoskeleton, and with the active exoskeleton). This approach is similar to previous studies that have investigsted productivity, such as Kim et al. (2018).

3.4.2 Research Question 2

To address the second research question, Borg's CR10 scale, a well-known subjective questionnaire, was adopted to evaluate the impacts of passive and active exoskeletons on discomfort across different body parts. The questionnaires were administered immediately after each task. Participants were asked to gauge their discomfort in different body regions (e.g., lower back, shoulders, legs) on a Likert scale, from 0 – 10, where 0 means no discomfort and 10 means maximum discomfort.

3.4.3 Research Question 3

To investigate how cognitive states vary across exoskeleton conditions and how they relate to task performance or discomfort across different body parts during masonry tasks, the EEG was utilized. This section describes the EEG used and how the data were procured and filtered.

Figure 5: Epoc+ 14 EEG Headset ((Emotiv, 2025)

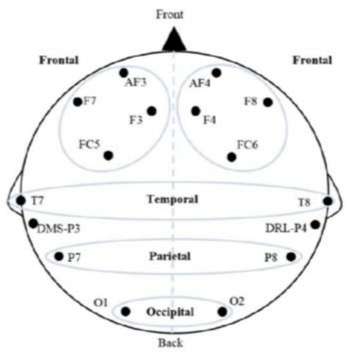

Figure 6: Location of Channels on Scap (Adopted from Afolabi et al. (2024))

Electroencephalography (EEG) Utilized

This study utilized the Epoc+ 14 EEG Headset manufactured by Emotiv (See Figure 5). The EEG headset comprises 14 channels and operates at sampling rates of 128 and 256 Hz for EEG data acquisition (Emotiv, 2025). This study employed a sampling rate of 128 Hz. The EEG captures the electrogram of electrical activity via electrodes positioned in different areas of the headset and the scalp. The electrodes detect activations in channels situated in four cerebral regions: the frontal, temporal, parietal, and occipital areas (Figure 6). In this research, the EEG device was positioned on the participants' scalps as this benefits the cerebral cortex, which exhibits the highest electrogram of electrical activity. Data was transmitted from the Epoc+14 to a laptop via Bluetooth. And yielded signals composed of specific neural rhythms associated with brain activities during task performance (Cheng et al., 2022). These rhythms are categorized into frequency bands: delta (0.5–4 Hz), theta (4–7 Hz), alpha (8–13 Hz), beta (14–30 Hz), and gamma waves (>30 Hz) (Cheng et al., 2022). Existing research has identified a substantial relationship between the alpha band and cognitive load (Akanmu et al., 2024; Liu et al., 2021). Therefore, in this

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study, the data collected was focused on the alpha band of the frontal lobe channels (F7, F3, AF3, AF4, F4, F8), the temporal lobe (T7 and T8), the parietal lobe (P7 and P8), and the occipital lobe (O1 and O2).

Data Processing

The recorded EEG signals underwent artifact removal techniques to eliminate intrinsic and extrinsic artifacts. Intrinsic artifacts originate from the body and arise from participants' eye blinking, facial muscle movements, and other factors during the simulated task, while external sources, including electromagnetic interference, electrode popping, environmental noise, and wiring noise, constitute extrinsic artifacts (Akanmu et al., 2024). The emergence of these artifacts was unavoidable, as participants engaged in masonry tasks that required excessive movements during data collection, thereby necessitating their removal to preserve data quality. Similar to previous related studies, the EEG data from the 14 channels were pre-processed utilizing MATLAB. Specifically, independent component analysis (ICA) was utilized to eliminate intrinsic artifacts, while a bandpass filter was applied to remove extrinsic artifacts. The ICA decomposed the data into 14 components based on the channels. A bandpass filter with cut-off frequencies of 0.5 Hz and 45 Hz was employed to eliminate undesirable frequencies.

3.5 Data Analysis

3.5.1 Research Question 1

The data collected from the timers were analyzed with descriptive statistics using SPSS. Descriptive statistics were calculated for the time each participant took to complete the task across the various conditions. Measures such as mean (sec), standard error, median, standard deviation, sample variance, kurtosis, skewness, and range were used to summarize the central tendency and variability of the data.

3.5.2 Research Question 2

In a manner akin to the analysis conducted in research question 1, SPSS was employed to evaluate data obtained from the Borg CR10 through descriptive statistics. Mean scores were computed for the perceived level of discomfort across various body parts, including the hands/wrists, upper arms, shoulders, lower back, thighs, neck, and lower legs/feet.

Table 1:Shapiro-Wilk Normality test.

Cognitive States, Productivity, and Low Back Discomfort	Without Exoskeleton		With Passive Exoskeleton		With Active Exoskeleton	
	Statistic	Sig.	Statistic	Sig.	Statistic	Sig.
Attention	0.956	0.592	0.911	0.142	0.927	0.315
Engagement	0.900	0.081	0.961	0.706	0.960	0.751
Excitement	0.952	0.515	0.946	0.458	0.947	0.559
Stress	0.992	1.000	0.923	0.212	0.904	0.154
Relaxation	0.827	0.006	0.853	0.019	0.824	0.013
Interest	0.936	0.308	0.958	0.649	0.842	0.022
Focus	0.970	0.833	0.945	0.446	0.924	0.281
Productivity	0.941	0.366	0.933	0.298	0.943	0.499
Low Back Discomfort	0.945	0.416	0.880	0.048	0.907	0.165

3.5.3 Research Question 3

To determine the normality of the processed EEG data, the Shapiro-Wilk test was used. As seen in Table 1, the Shapiro-Wilk test confirmed that the data met the normality assumption under all conditions. Given this, the EEG data were analyzed using descriptive statistics, correlation analysis, and analysis of variance (ANOVA), as well as post-hoc comparisons with SPSS. Descriptive statistics were calculated for each cognitive state. EEG-derived cognitive states were summarized using percentage ratings, which include attention, engagement, excitement, stress, relaxation, interest, and focus. Following that, a Pearson correlation analysis was used to investigate the relationships between various cognitive states, body discomfort, and productivity. Furthermore, a Spearman correlation matrix was used to investigate the relationships between dependent variables (cognitive states, body discomfort, and time) across exoskeleton conditions. To compare the effects of various exoskeleton conditions on cognitive state, productivity, and low back discomfort, repeated-measure ANOVA within-subject factor was used. The ANOVA tests determined whether the differences observed between the groups were statistically significant, and posthoc tests were used to determine whether specific group differences were significant. The data analysis focused on the lower back region for discomfort variables because it plays an important role in physical tasks and is often prone to strain, injury, and MSD risk. Following that, the pairwise comparisons looked at the differences in mean cognitive state, productivity, and low back discomfort variables between the three exoskeleton conditions.

4. RESULTS

4.1 Impacts of passive and active exoskeletons on productivity (RQ1)

The study examined the impacts of passive and active exoskeletons on the productivity of masons, specifically in tasks involving manual handling of CMUs. The productivity was assessed by measuring the time taken (in seconds) to complete the task under three conditions: without an exoskeleton, with a passive exoskeleton, and with an active exoskeleton. The results reveal that the active exoskeleton significantly improved productivity, with the lowest mean completion time of 302.42 seconds, compared to 357.05 seconds without an exoskeleton and 360.95 seconds with a passive exoskeleton, showing a reduction of approximately 55 and 59 seconds, respectively. Additionally, the active exoskeleton condition exhibited the lowest performance variability, as reflected by a standard deviation of 121.36 seconds, compared to 136.33 and 157.04 seconds in the no-Exo and passive Exo conditions, respectively. This suggests that active exoskeletons not only improve average performance but also enhance consistency. Furthermore, distribution metrics show that active exoskeleton use resulted in a more peaked (kurtosis = 0.91) and positively skewed (skewness = 1.03) distribution. In contrast, the passive exoskeleton showed the highest range (561 seconds) and variability, indicating inconsistent performance across participants. Overall, the findings support that active exoskeletons enhance both the speed and consistency of masonry task performance, outperforming both passive exoskeletons and no exoskeleton use. Table 2, and Figure 6 show the completion time distribution across all participants.

Table 2: Descriptive statistics per Exoskeleton completion time.

	Without Exoskeleton	Passive Exoskeleton	Active Exoskeleton
Mean (sec)	357.05	360.95	302.42
Standard Error	31.28	36.03	27.84
Median	340.00	363.00	262.00
Standard Deviation	136.33	157.04	121.36
Sample Variance	18586.27	24662.39	14727.48
Kurtosis	-0.57	-0.41	0.91
Skewness	0.48	0.51	1.03
Range	448.00	561.00	467.00

4.2 Effects of passive and active exoskeletons on body discomfort (RQ2)

Investigating the discomfort by body parts revealed that the active exoskeleton caused the most discomfort in the hand/wrist (2.26) and upper arm (2.34), indicating potential ergonomic issues despite their productivity benefits (Figure 7). Shoulder discomfort increased slightly with both exoskeletons, with the active condition (1.97) causing more discomfort than the no exoskeleton (1.79), and the passive exoskeleton causing the least discomfort (1.63). In contrast, both passive and active exoskeletons reduced lower back discomfort compared to no exoskeleton use, with passive offering slightly more relief (2.63 vs. 2.42, compared to 3.29 without exoskeleton). Thigh discomfort increased with both devices, with passive (2.03) and active (2.00) conditions both higher than no exoskeleton (1.58). Neck discomfort saw minimal changes, though a slight improvement was observed with the active exoskeleton (1.21), while passive exoskeleton slightly increased discomfort (1.26). Notably, lower leg and foot discomfort was lowest with the active exoskeleton (1.34), whereas passive slightly increased discomfort beyond the no-exoskeleton condition (1.58 vs. 1.53). Overall, these results suggest that while exoskeletons, particularly active types, can alleviate lower back and leg fatigue, they may introduce new discomforts in the upper limbs (Figure 8).

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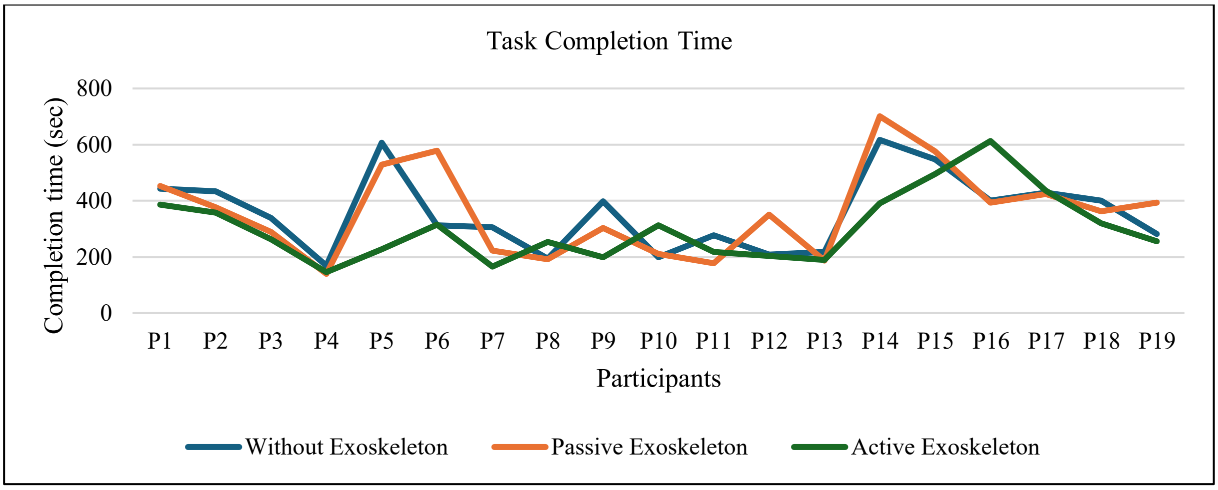

Figure 6: Impact of exoskeleton types on task completion time across participants.

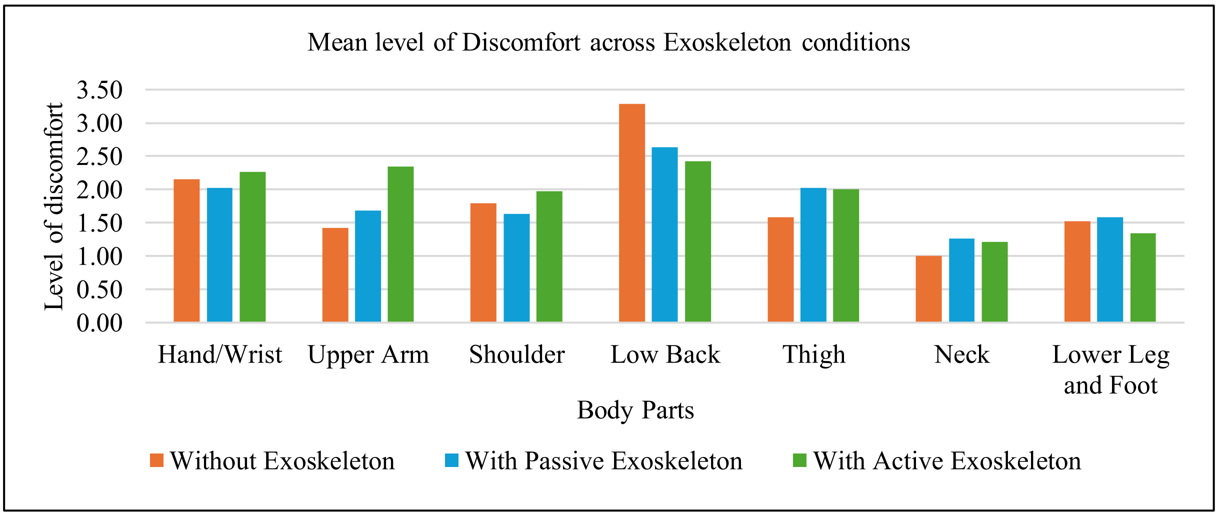

Figure 7: Mean rating for discomfort across different body parts.

4.3 Cognitive states across exoskeleton conditions, and their relationship to task performance and discomfort (RQ3)

This section presents the results of participants' cognitive states, as measured by EEG-derived metrics, during the masonry task across three exoskeleton conditions: Control (without exoskeleton), passive exoskeleton, and active exoskeleton.

4.3.1 Descriptive Statistics

Without Exoskeleton Condition: With the control condition (without exoskeleton), participants demonstrated moderate levels of cognitive engagement across EEG performance metrics while performing the masonry task (Figure 8). The average attention level was 45.09%, with relatively low variation (SD = 4.00%), suggesting consistent focus across participants. Engagement averaged 61.64%, indicating sustained involvement in the task, though it varied moderately (SD = 8.16%). Excitement levels were more variable, with an average of 55.72% and a higher standard deviation of 17.11%, reflecting differences in emotional arousal among participants. Stress levels were comparatively high (M = 66.46%), with some participants experiencing significant mental strain (SD = 13.88%). Interestingly, relaxation also averaged at a moderate 55.70% level, suggesting that some participants might have maintained calmness despite stress. Interest levels remained consistently high (M = 63.78%, SD =

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8.83%), indicating the task was cognitively engaging. Finally, focus was moderate (M = 50.47%, SD = 9.67%), aligning with attention levels.

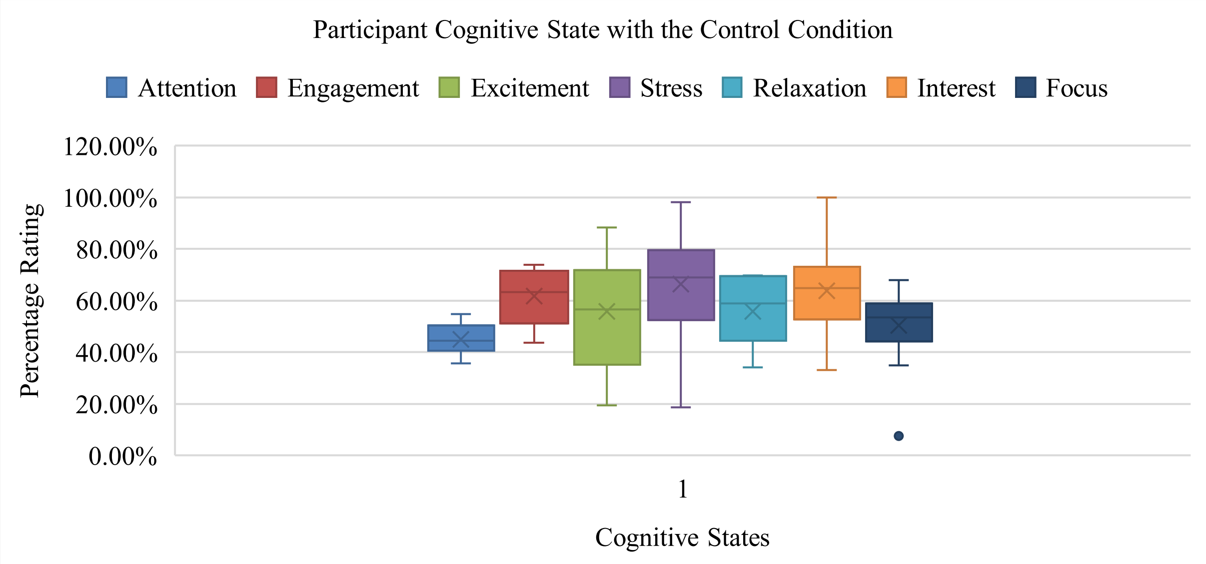

Figure 8: Participants' Cognitive States without Exoskeleton Condition.

With passive exoskeleton: With the passive exoskeleton condition, participants exhibited a moderate level of cognitive engagement across various EEG-based performance metrics (Figure 9). The overall average attention level was 44.30%, with a median of 46.99%, indicating a generally consistent yet slightly below-optimal focus during the task. Engagement and excitement yielded higher averages (60.80% and 62.38%, respectively), suggesting that the passive support may have facilitated steady involvement and emotional arousal, possibly due to the novelty or physical comfort provided by the exoskeleton. Notably, excitement showed the highest variability (standard deviation = 15.58%), reflecting considerable individual differences in emotional stimulation. Stress and relaxation levels averaged 53.84% and 48.47%, respectively, while focus levels averaged 48.41%, with relatively low variability (SD = 8.44%), showing that most participants maintained a similar level of task-directed mental effort. While some individuals showed heightened interest and attention (e.g., ratings above 70%), others recorded substantially lower levels, such as one participant with attention and engagement around 11–12%.

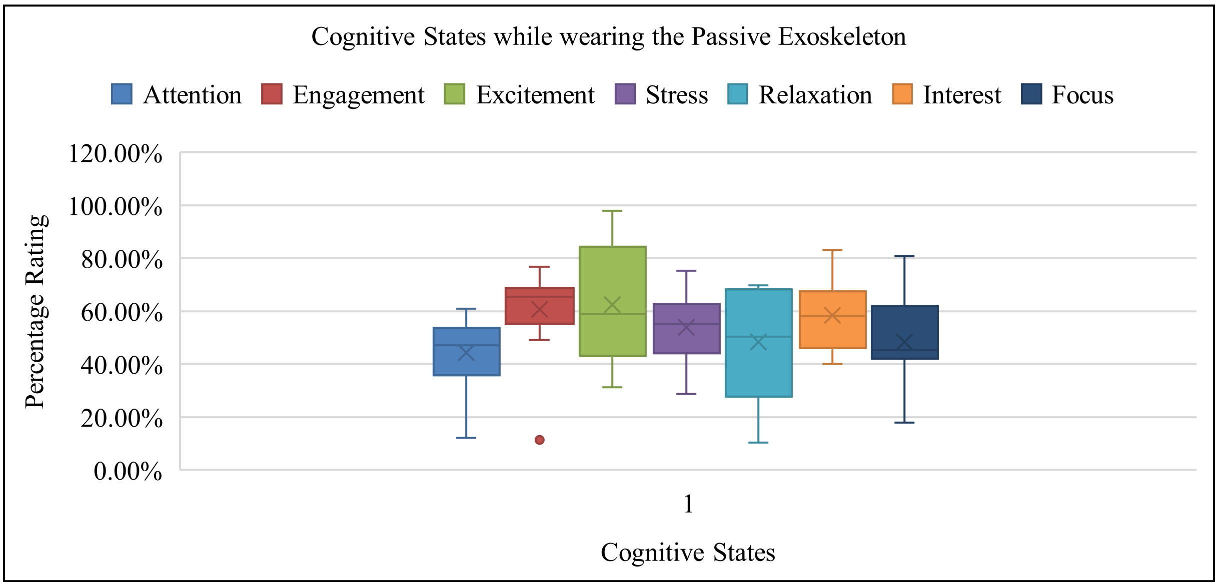

Figure 9: Cognitive States During Passive Exoskeleton Use.

With active exoskeleton: Under the active exoskeleton condition, participants demonstrated relatively high levels of cognitive activation across EEG-derived performance metrics. On average, excitement was the highest among all measured states, with a mean of 68.54% (SD = 15.19%), indicating that the active exoskeleton elicited strong emotional arousal during task execution (Figure 10). Engagement (M = 61.52%) and interest (M = 58.18%) also showed elevated values, suggesting that participants remained attentive and mentally invested in the masonry activity while wearing the active exoskeleton. Stress levels averaged 55.74%, reflecting a moderate cognitive load, possibly due to the mechanical support's impact on task complexity or movement adaptation. Relaxation scores (M = 58.40%) were moderate, with some variability (SD = 6.41%), implying that while participants were cognitively stimulated, they did not experience high mental strain. Focus and attention averaged 53.10% and 46.31%, respectively, showing that participants were mentally engaged in the tasks.

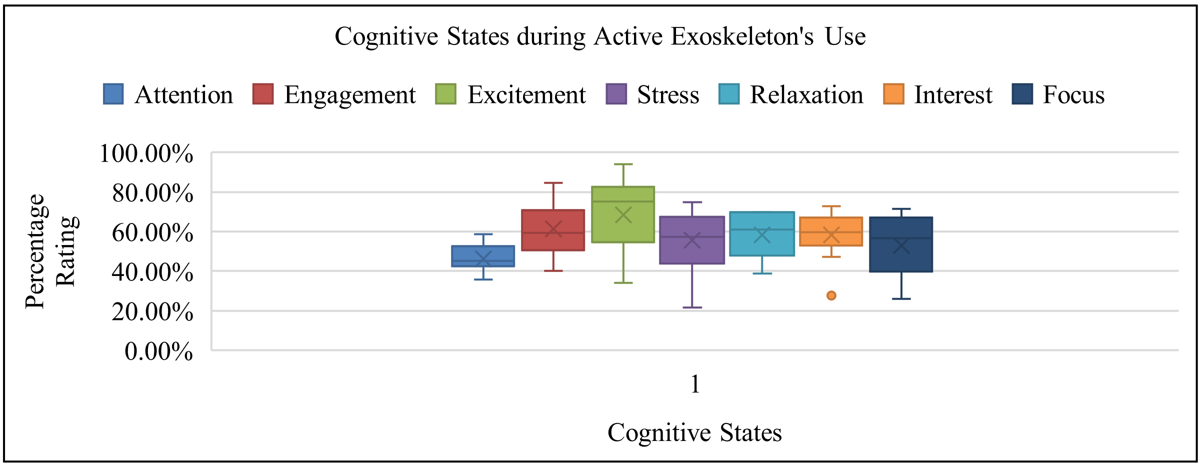

Figure 10: Cognitive States During Active Exoskeleton's Use.

The active exoskeleton appears to offer a balanced profile, enhancing excitement, focus, and relaxation, while reducing stress, though it may slightly dampen interest compared to the no-exoskeleton condition. Figure 11 shows the breakdown.

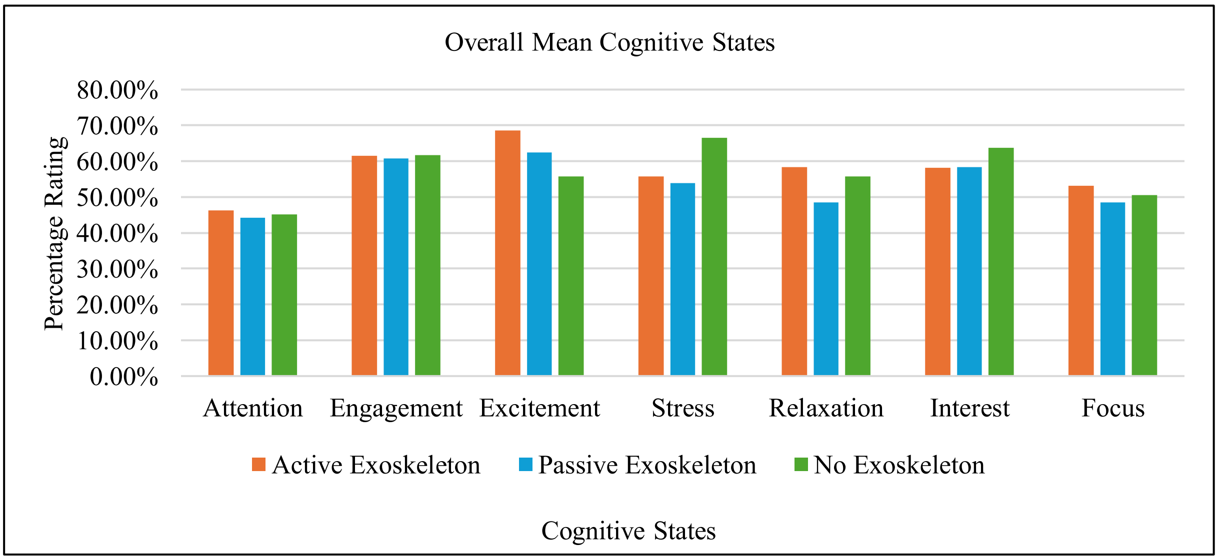

Figure 11: Overall Average Cognitive States Across All Exoskeleton Conditions.

Attention. Participants exhibited the highest average attention level when using the active exoskeleton (46.31%), followed by the no-exoskeleton condition (45.09%), and the passive exoskeleton (44.30%). This suggests that active exoskeletons may help users remain more attentive during task execution. **Engagement** levels were relatively consistent across all three conditions, with no exoskeleton slightly higher (61.64%), followed closely by the active (61.52%) exoskeleton conditions, indicating that both conditions were equally effective in sustaining user engagement, with the passive exoskeleton slightly lower (60.80%). For **excitement,** the active exoskeleton had the strongest emotional arousal (68.54%), followed by passive (62.38%) and no exoskeleton (55.72%), highlighting the stimulating nature of the active assistive device. Excitement was lowest in the no exoskeleton condition (55.72%), indicating that the more interactive the system, the more emotionally stimulated the user tends to be. Interestingly, **stress** levels were highest under the no-exoskeleton condition (66.46%), indicating the potential cognitive and physical demands of completing tasks without support. In contrast, both passive (53.84%) and active (55.74%) exoskeletons reduced stress, with the passive condition providing the most relief. **Relaxation** was highest in the active exoskeleton condition (58.40%), closely followed by no exoskeleton (55.70%), while the passive exoskeleton condition showed the lowest relaxation (48.47%). This may indicate that active support helps users feel physically and mentally more at ease, while passive support may create ambiguity or discomfort, reducing the sense of relaxation. **Interest** peaked in the no-exoskeleton condition (63.78%), suggesting more curiosity or novelty when completing the task unaided, though both exoskeleton conditions maintained comparable levels (active: 58.18%, passive: 58.33%). Finally, **focus** was highest in the active exoskeleton condition (53.10%), followed by no exoskeleton (50.47%) and passive (48.41%), indicating that active support may help maintain mental concentration during complex physical tasks.

4.3.2 Correlations between cognitive states, body discomfort, and productivity

The study adopted Pearson correlation to examine the correlations between the dependent variables (cognitive states, body discomfort, and time) (Table 3) across the exoskeleton conditions. The correlation matrix (Table 3) reveals that engagement positively correlates with relaxation (r = .352*), suggesting that participants who were more engaged also felt more relaxed. Excitement showed strong positive correlations with both focus (r = .677**) and relaxation (r = .284*), indicating that a heightened sense of excitement may promote mental clarity and calmness during tasks. Similarly, stress was significantly correlated with multiple variables, including interest (r = .700**), focus (r = .651**), and relaxation (r = .495**). Interestingly, productivity was negatively correlated with relaxation (r = –.293*) and interest (r = –.26). Additionally, productivity was only weakly correlated with most cognitive states and discomfort metrics, with the exception of a positive correlation with neck discomfort (r = .370, $p < .01$).

On the physical discomfort, low back pain was strongly associated with discomfort in other body parts, including the thigh (r = .416), upper arm (r = .425), and hand/wrist (r = .535), implying systemic physical strain during activity. Likewise, shoulder discomfort was highly correlated with pain in the upper arm (r = .648), neck (r = .451), and hand/wrist (r = .435). This underscores the importance of designing exoskeletons that not only enhance task performance but also minimize physical discomfort while supporting positive cognitive states.

4.3.3 Pairwise Comparisons in Cognitive States, Productivity, and Low Back Discomfort Variables

The pairwise comparisons (Tables 4, 5, and 6) investigated the differences in mean cognitive states, productivity, and low back discomfort variables across the three exoskeleton conditions (without exoskeleton, with a passive exoskeleton, and with an active exoskeleton). Each comparison shows the mean difference and significance level (p-value). In this analysis, only the pairwise comparisons that reveal significant differences were presented, as indicated by low p-values ($p<0.05$). Attention was consistently and significantly related to engagement, stress, interest, productivity, and low back discomfort across all conditions. Notably, the strength of these associations appeared more pronounced when participants used exoskeletons, especially active models, suggesting enhanced cognitive alignment and reduced physical strain during task performance. However, the relationship between attention and stress was only significant in the "without exoskeleton" and "active exoskeleton" conditions, while attention and interest showed significance in the "without" and "passive" conditions, but not in the active condition. Other cognitive states, such as excitement, relaxation, and focus, all demonstrated strong and consistent associations with productivity and low back discomfort across all conditions. Stress was significantly associated with productivity and low back discomfort in the "without" and "passive" exoskeleton conditions, but this relationship became non-significant in the "active" exoskeleton condition. Interest, while generally related to productivity and low back discomfort, showed a less consistent pattern under the passive exoskeleton condition, where its relationship to both outcome variables was not significant. The results from Table 5 further corroborate these findings by showing that productivity had strong positive relationships with all measured cognitive variables across all exoskeleton conditions, and with reduced low back discomfort. The strongest associations were seen in the "without exoskeleton" condition, although the trends remained significant with both passive and active exoskeletons. Similarly, low back discomfort (Table 6) was significantly and inversely associated with all cognitive states and productivity in all exoskeleton conditions.

Table 3: Spearman Correlation: Discomfort across body parts, productivity, and Exoskeleton Conditions.

	Att	Eng	Exc	Str	Rel	Int	Foc	Prod	LB	Sh	Th	Ne	UA	HW	LLF
Att	1.0	.34*	-0.03	-0.24	0.06	-0.26	-0.10	0.11	-0.25	-0.02	-0.08	-0.26	-0.08	-0.03	-0.06
Eng	.34*	1.0	0.02	0.18	.35*	0.06	0.04	0.19	-0.04	0.02	-0.24	-0.01	-0.03	0.01	-0.25
Exc	-.03	0.02	1.0	0.25	.28*	0.23	.68**	-0.25	0.10	0.23	0.23	-0.01	0.25	.28*	0.02
Str	-.24	.18	0.25	1.0	.50**	.70**	.65**	0.02	0.19	0.09	-0.21	0.13	-0.11	0.13	-0.03
Rel	.06	.35*	.284*	.50**	1.0	.66**	0.25	-.29*	0.03	0.08	-0.16	-0.03	0.07	0.12	0.00
Int	-.26	.06	0.23	.70**	.66**	1.0	.38**	-0.26	0.20	0.06	-0.11	-0.17	0.01	-0.05	0.14
Foc	-.10	.04	.68**	.65**	0.25	.38**	1.0	0.02	0.18	0.13	0.13	0.10	0.08	0.23	-0.10
Prod	.11	.19	-0.25	0.02	-.29*	-0.26	0.02	1.0	0.00	0.13	-0.01	.370**	0.04	0.05	-0.23
LB	-.25	-.04	0.10	0.19	0.03	0.20	0.18	0.00	1.0	.27*	.42**	.336*	.43**	.54**	0.18
Sh	-.02	.02	0.23	0.09	0.08	0.06	0.13	0.13	.27*	1.0	.37**	.451**	.65**	.44**	.38**
Th	-.08	-.24	0.23	-0.21	-0.16	-0.11	0.13	-0.01	.42**	.37**	1.0	.391**	.56**	.38**	.40**
Ne	-.26	-.01	-0.01	0.13	-0.03	-0.17	0.10	.37**	.34*	.45**	.40**	1.0	.38**	.57**	0.05
UA	-0.08	-0.03	0.25	-0.11	0.07	0.01	0.08	0.04	.43**	.65**	.56**	.380**	1.0	.61**	.39**
HW	-.03	0.01	.28*	0.13	0.12	-0.05	0.23	0.05	.54**	.44**	.38**	.568**	.61**	1.0	.32*
LLF	-.06	-.25	0.02	-0.03	0.00	0.14	-0.10	-0.23	0.18	.38**	.40**	0.05	.39**	.32*	1.0

*The Table includes the following abbreviations for the variables: Att (Attention), Eng (Engagement), Exc (Excitement), Str (Stress), Rel (Relaxation), Int (Interest), Foc (Focus), Prod (Productivity), LB (Low Back), Sh (Shoulder), Th (Thigh), Ne (Neck), UA (Upper Arm), HW (Hand/Wrist), and LLF (Lower Leg/Foot). Legend for Significance: * = p < .05, ** = p < .01. Color Legend: Green = Perfect correlation, Red = Negative correlation, Yellow = Low correlation, and White = Significant correlations.*

Table 4: Pairwise comparison of Cognitive States Variables with other Variables.

Variable * Variable		**Without Exo: Mean Diff**	**Sig.**	**With Passive Exo: Mean Diff**	**Sig.**	**With Active Exo: Mean Diff**	**Sig.**
Attention	Engagement	-16.883	0.033	-20.699*	0.003	-23.702*	0.001
Attention	Stress	-19.146	0.043	Not sig		-18.405*	0.024
Attention	Interest	-18.041	0.017	-20.186*	0.048	Not sig	-
Attention	Productivity	-337.868*	0.000	-334.099*	0.002	-322.498*	0.000
Attention	Low Back	42.814*	0.000	41.856*	0.000	39.866*	0.000
Excitement	Productivity	-328.557*	0.001	-314.603*	0.004	-293.501*	0.001
Excitement	Low Back	52.125*	0.000	61.351*	0.000	63.568*	0.000
Stress	Productivity	-318.722*	0.001	-316.631*	0.002	Not sig	-
Stress	Low Back	61.960*	0.000	59.323*	0.000	68.862*	0.000
Relaxation	Productivity	-330.305*	0.001	-320.000*	0.003	-305.885*	0.000
Relaxation	Low Back	50.377*	0.000	55.955*	0.000	56.479*	0.000
Interest	Productivity	-319.827*	0.001	Not sig	-	-305.474*	0.000
Interest	Low Back	60.855*	0.000	Not sig	-	56.890*	0.000
Focus	Productivity	-332.428*	0.001	-324.011*	0.002	-309.254*	0.000
Focus	Low Back	48.254*	0.000	51.943*	0.000	53.110*	0.000

*Note-Significant Result Presented "*p < .05 for all comparisons"*

Table 5: Pairwise comparison of Productivity with other Variables.

Variable	Variable	Without Exo	Sig.	With Passive Exo	Sig.	With Active Exo	Sig.
Productivity	Attention	337.868*	0.000	334.099*	0.002	322.498*	0.000
	Engagement	320.985*	0.001	313.401*	0.002	298.795*	0.000
	Excitement	328.557*	0.001	314.603*	0.004	293.501*	0.001
	Stress	318.722*	0.001	316.631*	0.002	304.093*	0.000
	Relaxation	330.305*	0.001	320.000*	0.003	305.885*	0.000
	Interest	319.827*	0.001	313.913*	0.003	305.474*	0.000
	Focus	332.428*	0.001	324.011*	0.002	309.254*	0.000
	Low Back	380.682*	0.000	375.955*	0.001	362.364*	0.000

*Note-Significant Result Presented "*p < .05 for all comparisons"*

Table 6:Pairwise comparison of Low back with other Variables.

Variables		Without Exo	Sig.	With Passive Exo	Sig.	With Active Exo	Sig.
Low Back	Attention	-42.814*	0.000	-41.856*	0.000	-39.866*	0.000
	Engagement	-59.697*	0.000	-62.554*	0.000	-63.568*	0.000
	Excitement	-52.125*	0.000	-61.351*	0.000	-68.862*	0.000
	Stress	-61.960*	0.000	-59.323*	0.000	-58.271*	0.000
	Relaxation	-50.377*	0.000	-55.955*	0.000	-56.479*	0.000
	Interest	-60.855*	0.000	-62.042*	0.000	-56.890*	0.000
	Focus	-48.254*	0.000	-51.943*	0.000	-53.110*	0.000
	Productivity	-380.682*	0.000	-375.955*	0.001	-362.364*	0.000

*Note-Significant Result Presented "*p < .05 for all comparisons".*

5. DISCUSSIONS

This section presents the discussions of the research findings and the contributions to the body of knowledge. The findings of each research question were presented in sub-headings and discussed below.

5.1 Impacts of passive and active exoskeletons on productivity (RQ1)

The first research question sought to understand the impacts of passive and active exoskeletons on masons' productivity. The results indicate that participants utilizing active exoskeletons, with a mean time (MT) of 302.42 seconds, executed masonry tasks 15.3% and 16.2% more efficiently than under no exoskeleton (MT = 357.05 seconds) and passive exoskeleton conditions (MT = 360.95 seconds), respectively. These findings align with the research conducted by Kim et al. (2019) and (Tomori et al., 2025g), which demonstrated a decrease in task completion time when utilizing active exoskeletons for a one-arm load-handling task. The diminished completion time associated with the utilization of an active exoskeleton can be ascribed to various factors. For instance, active exoskeletons, according to Poliero et al. (2022), provide dynamic support that responds to the user's movements, potentially resulting in reduced fatigue and physical exertion. With this, users are likely to sustain consistent performance throughout their tasks. Furthermore, the motorized assistance offered by active exoskeletons, as noted by Toxiri et al. (2019), enhances biomechanical movements, thereby enabling users to perform their tasks with greater efficiency and effectiveness. Conversely, the passive exoskeleton exhibited slightly increased task completion time. The findings contradict those of Gonsalves et al. (2021), who reported that a passive exoskeleton decreased the completion time for rebar work by 50%. This contradiction may be ascribed to the type of exoskeleton employed for the masonry activity. Kim et al. (2018) clarified that certain exoskeleton types may inhibit the natural movement patterns of participants, indicating the necessity for more standardized design solutions.

In terms of variability, the results indicate that the active exoskeleton exhibited the lowest standard deviation (SD=121.36 seconds), in contrast to the passive exoskeleton (SD=157.04 seconds) and the no exoskeleton condition (SD=136.33 seconds). The distribution metrics additionally corroborated this. For instance, the kurtosis and skewness of the active exoskeleton condition exhibited a more peaked distribution (See Table 2). The low standard deviation for the active exoskeleton condition during the masonry task suggests that the active exoskeleton may facilitate standardized performance in this task. The high standard deviation of passive exoskeletons may result from device adaptations, individual anthropometry, working techniques, and preferences (Alabdulkarim et al., 2019; Theurel et al., 2018). Overall, the findings challenge the notion that ergonomic interventions typically result in diminished productivity (Li & Buckle, 1999) and indicate the necessity for more industry-specific designs and thorough evaluation of appropriate tasks for exoskeleton application.

5.2 Effects of passive and active exoskeletons on body discomfort (RQ2)

The study further explored the impacts of passive and active exoskeletons on body discomfort and revealed a more intricate pattern of discomfort redistribution across body parts when utilizing exoskeletons for masonry tasks. The results demonstrated that both active and passive exoskeletons, with mean scores of 2.63 and 2.4, respectively, alleviated lower back discomfort. These findings align with prior research that identified comparable reductions in discomfort associated with lumbar load back exoskeletons (Ogunseiju et al., 2024). In the study by Antwi-Afari et al. (2021), participants reported a 42.40% decrease in lower back discomfort. The sensor-based data indicated an 11-33% decrease in lumbar erector spinae muscle activity. However, the findings indicated high perceived discomfort levels in the upper body regions, excluding the hands and wrists. The active exoskeleton produced high discomfort levels at the hand/wrist (2.26) and upper arm (2.34), whereas the passive exoskeleton exhibited comparatively minimal discomfort. In contrast, when evaluating the passive exoskeleton condition against the no exoskeleton condition, the passive condition exhibited a lower discomfort level in the hand/wrist and the shoulder compared to the no exoskeleton condition. The findings corroborate those of Alabdulkarim et al. (2019), who clarified that upper body exoskeletons possess the capacity to alter muscular demands, generating new stress points in the shoulder and upper arm. Consequently, it was unsurprising that the perceived discomfort in the shoulder went up for the active exoskeleton conditions during the masonry tasks. Kim et al. (2018) explained that the utilization of upper extremity exoskeletons restricts the shoulder joint's range of motion, potentially causing compensatory movements and altered recruitment patterns, which may lead to discomfort in the upper body.

In addition to the upper extremities, the lower extremities exhibited distinct patterns of discomfort under different conditions. The discomfort scores in the thigh were elevated for both active (2.00) and passive exoskeletons (2.03) in comparison to the no-exoskeleton condition (1.58). This contradicts the findings of Amandels et al. (2019), who discovered no significant difference in discomfort levels between exoskeleton and non-exoskeleton conditions. The perceived discomfort in the lower leg and foot was minimal with the active exoskeleton (1.34), while the passive exoskeleton resulted in increased discomfort compared to the no-exoskeleton condition (1.58 vs. 1.53). The advantageous impact of the active exoskeleton on the lower leg and foot may stem from the load distribution mechanisms and partial weight-bearing support offered by the powered joints in the active exoskeleton (Hyun et al., 2017). Finally, in contrast to other body parts, the perceived discomfort scores for the neck exhibited minimal fluctuation across the three conditions, with a slight enhancement noted in the active exoskeleton condition (1.21) and the passive exoskeleton condition (1.26). The enhancement in active exoskeleton condition indicates that specific active controls assist users in sustaining improved body postures, particularly in head and neck alignment, as posited by Picchiotti et al. (2019) in their analysis of two postural assist exoskeletons concerning biomechanical loading of the lumbar spine. Overall, the observed perceived discomfort indicates the necessity for optimizing exoskeleton interactions to mitigate discomfort at contact points and to design hybrid systems that integrate the advantages of both passive and active exoskeletons.

5.3 Cognitive states across exoskeleton conditions, and their relationship to task performance and discomfort (RQ3)

The third research question investigated the impacts of exoskeletons on cognitive states and their relationship with task performance and discomfort. The findings indicated that the type of exoskeleton employed affects users' cognitive states. Significantly, in all three conditions of this study, executing masonry tasks with the active exoskeleton resulted in increased levels of attention (46.31%), excitement (68.54%), relaxation (58.40%), and focus (53.10%). These findings indicate that an active exoskeleton offers the most cognitively balanced experience. The noted enhancement in attention and focus corroborates the notion that suitable physical assistance can liberate cognitive resources (Afzal et al., 2017), enabling individuals to concentrate on their tasks rather than being preoccupied with managing work-induced strain. This phenomenon aligns with cognitive resource theory, which

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asserts that cognitive resources are more accessible when physical demands diminish for task-related processing (Wickens, 2008). The significant percentage increase in excitement observed in the active exoskeleton (68.54%) and passive exoskeleton (62.38%) conditions, compared to the no exoskeleton condition (55.72%), may indicate the novelty effect described by (Gilotta et al., 2019). Gilotta et al. (2019) elucidated that when users are unfamiliar with a technology, their enthusiasm and involvement are heightened. Additionally, this can be explained by the technology acceptance model, wherein perceived usefulness and ease of use engender positive affective behaviors. Also, the increased levels of stress in the absence of an exoskeleton condition (66.46) relative to the exoskeleton condition (active = 55.74% and passive = 53.84%) highlight the physically arduous nature of the masonry task. This suggest that both active and passive exoskeletons can alleviate physical strain during masonry tasks, corroborating the conclusions of Ofori et al. (2025), who found that exoskeletons can diminish physical exertion and physiological stress indicators. The nuanced distinction between active and passive exoskeletons may stem from the dynamic support provided by active exoskeletons, enabling users to execute tasks with greater comfort and freedom (Huysamen et al., 2018).

Table 3 illustrates that the correlation analysis yielded significant insights regarding the relationship among cognitive states, productivity, and physical discomforts. The positive correlation between engagement and relaxation (r=.352*) indicates that participants experienced relaxation while undertaking the masonry task. The positive correlation of focus (r=.677**) and relaxation (.284*) with excitement suggests that heightened emotional arousal is linked to enhanced mental clarity and diminished tension. This finding aligns with the results of Kim and Nussbaum (2019), which indicate that positive emotions enhance cognitive performance. Moreover, although the positive correlations of stress with relaxation (r=.495**), interest (r=.700**), and focus (r=.651**) may seem counterintuitive, they imply that stress can activate attentional resources for task engagement. The findings also indicated multiple correlations regarding physical discomforts. For example, low back discomfort exhibited a strong correlation with upper arm (r=.425), thigh (r=.416), and hand/wrist (r=0.535) discomforts, while shoulder discomfort correlated with upper arm (r=.648), hand/wrist (r=.435), and neck (r=.451). The identified correlations validate Marras (2012)'s conceptualization of musculoskeletal disorders (MSDs) as systemic, indicating that strain in one bodily region is transmitted to other interconnected areas. As indicated in Table 3, productivity exhibited a negative correlation with relaxation (r = -0.293) and interest (r = -0.26), implying that productivity may detrimentally impact relaxation and interest in task engagement. This contradicts the premise that a positive cognitive state augments productivity (Niemiec & Lachowicz-Tabaczek, 2015). Nonetheless, it corresponds with the theory proposed by Hancock and Szalma (2008), which posits that performance enhancement frequently transpires at moderate rather than maximal levels of specific cognitive states.

Finally, the pairwise analysis highlighted the correlation between productivity and cognitive states, as well as physical discomfort and cognitive states across the three conditions (See Table 5). The pairwise correlation indicated that productivity exhibited a robust positive association with all cognitive factors across the three conditions. The most significant correlation was observed in the no-exoskeleton condition, indicating that cognitive states and productivity may be more direct without assistive devices. Stress exhibited a positive correlation with both the passive exoskeleton condition and the condition without an exoskeleton; however, this was not the case for the active exoskeleton condition. This indicates that advancing exoskeletons can partially alleviate psychological strain from physical performance (Mukherjee et al., 2024). Furthermore, as illustrated in Table 6, the results indicated that low back discomfort exhibited a significant inverse correlation with all cognitive states and productivity across all exoskeleton conditions. This aligns with the findings of Martin et al. (2024), which indicate that physical discomfort adversely affects cognitive function and task performance.

6. CONCLUSIONS, LIMITATIONS, AND FUTURE WORK

This study investigated the effects of active and passive exoskeletons on productivity, body discomfort, and cognitive states during simulated masonry tasks. To accomplish this goal, subjective (Borg CR10 scale) and objective (timers and EEG device) measures were used. The data gathered were analyzed using descriptive and inferential statistics. The findings indicated that active exoskeletons increased productivity. In terms of physical discomfort, the study found that both active and passive exoskeletons reduced lower back discomfort during masonry tasks. However, the findings also revealed that using both exoskeletons resulted in increased discomfort in a few body parts, particularly the upper extremities. In terms of cognitive states, EEG data revealed that active exoskeletons, in particular, tend to buffer cognitive load and emotional strain by increasing attention, engagement, and relaxation compared to passive exoskeletons. The correlations analysis revealed a complex relationship between physical discomfort, particularly in the lower back, productivity, and cognitive states. Specifically, physical discomfort had a significant inverse correlation with cognitive across all passive and active conditions, but no exoskeleton conditions. Overall, the findings indicate that exoskeletons, particularly active exoskeletons, have a significant potential to improve manual labor by increasing productivity, reducing back pain, and improving cognitive states.

This study contributes novel insights by providing a multidimensional evaluation of human-exoskeleton interaction, an approach that has not been explored in construction ergonomics research. Unlike prior studies that focus singly on either physical strain, cognitive load, or productivity outcomes, this work uniquely integrates neurophysiological evidence (an EEG-based cognitive states) to examine emotional well-being (e.g., stress, engagement, and excitement) alongside physical performance. Moreover, it is among the first to contrast active versus passive exoskeletons in a construction-specific context, offering comparative evidence on their trade-offs. This ensures that exoskeletons are not only biomechanically effective but also cognitively and socially sustainable across varied construction contexts. Furthermore, this study contributes to the growing body of literature by informing future workforce training programs and guiding industry-wide adoption strategies. These findings enhance the theoretical comprehension of human-wearable robot interaction, emphasizing the correlation between physical exertion and cognitive performance. The findings extend the technological acceptance theory by demonstrating how the characteristics of the device, specifically active and passive exoskeletons, influence user experience and performance. From a practical point of view, the findings offer a means for construction firms to substantiate their investment in exoskeletons. Moreover, the reported discomfort levels may assist construction firms in choosing exoskeletons for construction activities. The results of this study can also assist manufacturers in developing exoskeletons specifically designed for the construction industry.

Notwithstanding the significant contributions of this study, several evident limitations are present. The study was conducted in a controlled laboratory setting with a relatively small sample size of participants who had minimal experience in construction tasks, which may limit the generalizability of the findings. The gender imbalance among participants (14 males and 5 females) may also influence the diversity of experiences and perspectives recorded. As a result, future studies should aim for more balanced gender representation. This can reveal significant differences in exoskeletons' impacts based on gender differences. It can also ensure that the findings reflect a broader range of perspectives and are more applicable across different groups. Furthermore, the participants were comparatively younger, rendering the findings less generalizable to older workers who comprise a significant portion of the masonry workforce. Future research could undertake longitudinal studies by engaging construction professionals with expertise in masonry tasks within actual construction sites. Ultimately, the EEG employed for the assessment of cognitive data is susceptible to movement artifacts, notwithstanding meticulous processing. Future studies could benefit from additional validation through complementary measures.

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REFERENCES

(BLS), B. o. L. S. (2020). National Census of Fatal Occupational Injuries in 2019. https://www.bls.gov/news.release/pdf/cfoi.pdf

Afolabi, A., Akanmu, A., & Yusuf, A. (2024). Cognitive Load Assessment of Shoulder Support Exoskeleton Users in Overhead Construction Painting Tasks. The International Conference of Sustainable Development and Smart Built Environments,

Afzal, T., Kern, M., Tseng, S.-C., Lincoln, J., Francisco, G., & Chang, S.-H. (2017). Cognitive demands during wearable exoskeleton assisted walking in persons with multiple sclerosis. 2017 International symposium on wearable robotics and rehabilitation (WeRob), Akanmu, A., Okunola, A., Jebelli, H., Ammar, A., & Afolabi, A. (2024). Cognitive load assessment of active back-support exoskeletons in construction: A case study on construction framing. Advanced Engineering Informatics, 62, 102905. https://doi.org/https://doi.org/10.1016/j.aei.2024.102905

Alabdulkarim, S., Kim, S., & Nussbaum, M. A. (2019). Effects of exoskeleton design and precision requirements on physical demands and quality in a simulated overhead drilling task. Applied ergonomics, 80, 136-145. https://doi.org/https://doi.org/10.1016/j.apergo.2019.05.014

Amandels, S., Eyndt, H. O. h., Daenen, L., & Hermans, V. (2019). Introduction and testing of a passive exoskeleton in an industrial working environment. Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018) Volume III: Musculoskeletal Disorders 20,

Antwi-Afari, M. F., Li, H., Anwer, S., Li, D., Yu, Y., Mi, H.-Y., & Wuni, I. Y. (2021). Assessment of a passive exoskeleton system on spinal biomechanics and subjective responses during manual repetitive handling tasks among construction workers. Safety science, 142, 105382. https://doi.org/https://doi.org/10.1016/j.ssci.2021.105382

Antwi-Afari, M. F., Li, H., Chan, A. H. S., Seo, J., Anwer, S., Mi, H.-Y., Wu, Z., & Wong, A. Y. L. (2023). A science mapping-based review of work-related musculoskeletal disorders among construction workers. Journal of safety research, 85, 114-128. https://doi.org/https://doi.org/10.1016/j.jsr.2023.01.011

Anwer, S., Li, H., Abdul-Rahman, M., & Antwi-Afari, M. F. (2023). Development and evaluation of a low-cost passive wearable exoskeleton system for improving safety and health performance of construction workers: A pilot study. ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction,

Anwer, S., Li, H., Antwi-Afari, M. F., & Wong, A. Y. L. (2021). Associations between physical or psychosocial risk factors and work-related musculoskeletal disorders in construction workers based on literature in the last 20 years: A systematic review. International Journal of Industrial Ergonomics, 83, 103113. https://doi.org/https://doi.org/10.1016/j.ergon.2021.103113

Bamfo-Agyei, E., & Atepor, L. (2018). The Impact of Ergonomics Interventions on Musculoskeletal Injuries Among Construction Workers. Advances in Physical Ergonomics and Human Factors: Proceedings of the AHFE 2017 International Conference on Physical Ergonomics and Human Factors, July 17-21, 2017, The Westin Bonaventure Hotel, Los Angeles, California, USA 8,

Bennett, S. T., Han, W., Mahmud, D., Adamczyk, P. G., Dai, F., Wehner, M., Veeramani, D., & Zhu, Z. (2023). Usability and Biomechanical Testing of Passive Exoskeletons for Construction Workers: A Field-Based Pilot Study. Buildings, 13(3), 822. https://doi.org/https://doi.org/10.3390/buildings13030822

Brosque, C., & Fischer, M. (2022). Safety, quality, schedule, and cost impacts of ten construction robots. Construction Robotics, 6(2), 163-186. https://doi.org/https://doi.org/10.1007/s41693-022-00072-5

Cheng, B., Fan, C., Fu, H., Huang, J., Chen, H., & Luo, X. (2022). Measuring and computing cognitive statuses of construction workers based on electroencephalogram: a critical review. IEEE Transactions on Computational Social Systems, 9(6), 1644-1659. https://doi.org/https://doi.org/10.1109/TCSS.2022.3158585

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. MIS quarterly, 319-340. https://doi.org/https://doi.org/10.2307/249008

Dong, X. S., Betit, E., Dale, A. M., Barlet, G., & Wei, Q. (2019). Trends of musculoskeletal disorders and interventions in the construction industry.

Emotiv. (2025). EPOC X - 14 Channel Wireless EEG HeadsetEPOC X - 14 Channel Wireless EEG Headset. Retrieved May 16, 2025 from https://www.emotiv.com/collections/all/products/epoc-x

Gilotta, S., Spada, S., Ghibaudo, L., Isoardi, M., & Mosso, C. (2019). Acceptability beyond usability: a manufacturing case study. Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018) Volume VII: Ergonomics in Design, Design for All, Activity Theories for Work Analysis and Design, Affective Design 20, Gonsalves, N. J., Ogunseiju, O. O., Akanmu, A. A., & Nnaji, C. A. (2021). Assessment of a passive wearable robot for reducing low back disorders during rebar work. J. Inf. Technol. Constr., 26(2021), 936-952. https://doi.org/https://dx.doi.org/10.36680/j.itcon.2021.050?

Gonsalves, N. J., Yusuf, A., Ogunseiju, O., & Akanmu, A. (2023). Evaluation of concrete workers' interaction with a passive back-support exoskeleton. Engineering, Construction and Architectural Management. https://doi.org/https://doi.org/10.1108/ECAM-12-2022-1156

Haji, F. A., Rojas, D., Childs, R., de Ribaupierre, S., & Dubrowski, A. (2015). Measuring cognitive load: performance, mental effort and simulation task complexity. Medical education, 49(8), 815-827. https://doi.org/https://doi.org/10.1111/medu.12773

Hancock, P. A., & Szalma, J. L. (2008). Performance under stress. Ashgate Publishing, Ltd.

Huysamen, K., de Looze, M., Bosch, T., Ortiz, J., Toxiri, S., & O'Sullivan, L. W. (2018). Assessment of an active industrial exoskeleton to aid dynamic lifting and lowering manual handling tasks. Applied ergonomics, 68, 125-131. https://doi.org/https://doi.org/10.1016/j.apergo.2017.11.004

Hyun, D. J., Park, H., Ha, T., Park, S., & Jung, K. (2017). Biomechanical design of an agile, electricity-powered lower-limb exoskeleton for weight-bearing assistance. Robotics and Autonomous Systems, 95, 181-195. https://doi.org/https://doi.org/10.1016/j.robot.2017.06.010

Kaur, H. (2021). Workers' compensation claim rates and costs for musculoskeletal disorders related to overexertion among construction workers—Ohio, 2007–2017. MMWR. Morbidity and Mortality Weekly Report, 70. https://doi.org/http://dx.doi.org/10.15585/mmwr.mm7016a1

Kim, J., Kang, S. H., Li, J., Mirka, G. A., & Dorneich, M. C. (2024). Effects of a Passive Back-Support Exosuit on Postural Control and Cognitive Performance During a Fatigue-Inducing Posture Maintenance Task. Human factors, 66(11), 2451-2467. https://doi.org/https://doi.org/10.1177/00187208231221890

Kim, S., Lawton, W., Nussbaum, M. A., & Srinivasan, D. (2019). Effects of using a prototype whole-body powered exoskeleton for performing industrial tasks. Proceedings of the Human Factors and Ergonomics Society Annual Meeting,

Kim, S., & Nussbaum, M. A. (2019). A follow-up study of the effects of an arm support exoskeleton on physical demands and task performance during simulated overhead work. IISE Transactions on Occupational Ergonomics and Human Factors, 7(3-4), 163-174. https://doi.org/https://doi.org/10.1080/24725838.2018.1551255

Kim, S., Nussbaum, M. A., Esfahani, M. I. M., Alemi, M. M., Alabdulkarim, S., & Rashedi, E. (2018). Assessing the influence of a passive, upper extremity exoskeletal vest for tasks requiring arm elevation: Part I– "Expected" effects on discomfort, shoulder muscle activity, and work task performance. Applied ergonomics, 70, 315-322. https://doi.org/https://doi.org/10.1016/j.apergo.2018.02.025

Klepsch, M., Schmitz, F., & Seufert, T. (2017). Development and validation of two instruments measuring intrinsic, extraneous, and germane cognitive load. Frontiers in psychology, 8, 1997. https://doi.org/https://doi.org/10.3389/fpsyg.2017.01997

Kurt, J. (2024). Examining the effects of a passive upper extremity exoskeleton on shoulder fatigue during a simulated automotive overhead weld inspection task University of Waterloo]. http://hdl.handle.net/10012/20507

Li, G., & Buckle, P. (1999). Current techniques for assessing physical exposure to work-related musculoskeletal risks, with emphasis on posture-based methods. Ergonomics, 42(5), 674-695. https://doi.org/https://doi.org/10.1080/001401399185388

Liu, Y., Gautam, Y., Ojha, A., Shayesteh, S., & Jebelli, H. (2024). Studying the Effects of Back-Support Exoskeletons on Workers' Cognitive Load during Material Handling Tasks. Construction Research Congress 2024,

Liu, Y., Habibnezhad, M., & Jebelli, H. (2021). Brainwave-driven human-robot collaboration in construction. Automation in Construction, 124, 103556. https://doi.org/https://doi.org/10.1016/j.autcon.2021.103556

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Marangunić, N., & Granić, A. (2015). Technology acceptance model: a literature review from 1986 to 2013. Universal access in the information society, 14, 81-95. https://doi.org/https://doi.org/10.1007/s10209-014-0348-1

Marras, W. S. (2012). The complex spine: the multidimensional system of causal pathways for low-back disorders. Human factors, 54(6), 881-889. https://doi.org/https://doi.org/10.1177/0018720812452129

Martin, K., Flood, A., Pyne, D. B., Périard, J. D., Keegan, R., & Rattray, B. (2024). The impact of cognitive, physical, and psychological stressors on subsequent cognitive performance. Human factors, 66(1), 71-87. https://doi.org/https://doi.org/10.1177/00187208211065548

Maurice, P., Čamernik, J., Gorjan, D., Schirrmeister, B., Bornmann, J., Tagliapietra, L., Latella, C., Pucci, D., Fritzsche, L., & Ivaldi, S. (2019). Objective and subjective effects of a passive exoskeleton on overhead work. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 28(1), 152-164. https://doi.org/https://doi.org/10.1109/TNSRE.2019.2945368

Mehta, R. K., & Parasuraman, R. (2014). Effects of mental fatigue on the development of physical fatigue: a neuroergonomic approach. Human factors, 56(4), 645-656. https://doi.org/https://doi.org/10.1177/0018720813507279

Mitropoulos, P., & Memarian, B. (2013). Task demands in masonry work: Sources, performance implications, and management strategies. Journal of Construction Engineering and Management, 139(5), 581-590. https://doi.org/https://doi.org/10.1061/(ASCE)CO.1943-7862.0000586

Miura, K., Kadone, H., Koda, M., Abe, T., Endo, H., Murakami, H., Doita, M., Kumagai, H., Nagashima, K., & Fujii, K. (2018). The hybrid assisted limb (HAL) for care support, a motion assisting robot providing exoskeletal lumbar support, can potentially reduce lumbar load in repetitive snow-shoveling movements. Journal of Clinical Neuroscience, 49, 83-86. https://doi.org/https://doi.org/10.1016/j.jocn.2017.11.020

Mukherjee, T. R., Tyagi, O., Wang, J., Kang, J., & Mehta, R. (2024). Neural, Muscular, and Perceptual responses with Shoulder Exoskeleton use over days. arXiv preprint arXiv:2403.08044. https://doi.org/https://doi.org/10.48550/arXiv.2403.08044

Niemiec, T., & Lachowicz-Tabaczek, K. (2015). The moderating role of specific self-efficacy in the impact of positive mood on cognitive performance. Motivation and Emotion, 39, 498-505. https://doi.org/https://doi.org/10.1007/s11031-014-9469-3

Ofori, J. N. A., Tomori, M., & Ogunseiju, O. (2025). Assessing the ethical, social and psychological risks of active and passive exoskeletons in the construction industry: trust, productivity and stress levels. Smart and Sustainable Built Environment.

Ogunseiju, O., Cho, Y. K., Tomori, M., & Rudraraju, L. (2025). Virtual Boundaries: Investigating the Ethical and Social Risks of Exoskeletons in the Construction Industry.

Ogunseiju, O., Gonsalves, N., Akanmu, A., & Nnaji, C. (2021). Subjective Evaluation of Passive Back-Support Exoskeleton for Flooring Work. EPiC Series in Built Environment, 2, 10-17.

Ogunseiju, O., Tomori, M., Ofori, J., Rudraraju, L., & Skourup, E. E. (2024). Examining the Impacts of Wearable Robots in Mitigating Musculoskeletal Disorders Amongst Masons. The International Conference of Sustainable Development and Smart Built Environments,

Okunola, A., Afolabi, A., Akanmu, A., Jebelli, H., & Simikins, S. (2024). Facilitators and barriers to the adoption of active back-support exoskeletons in the construction industry. Journal of safety research. https://doi.org/https://doi.org/10.1016/j.jsr.2024.05.010

Okunola, A., Akanmu, A., & Jebelli, H. (2024a). Cognitive Load and Fall Risk Dynamics in Human-Exoskeleton Interaction for Construction Workers. The International Conference of Sustainable Development and Smart Built Environments,

Okunola, A., Akanmu, A., & Jebelli, H. (2024b). Detection of Cognitive Loads during Exoskeleton Use for Construction Flooring Work. Construction Research Congress 2024, Owoniyi, M., Scissum, W., Tomori, M. A., Lawal, K., Oyetola, T., & Adedeji, A. (2025). Global Assessment of Advanced Technology and Safety Management in the Construction Industry. Faculty of Engineering and Technology Conference (FETiCON), Kwara, Nigeria.

Picchiotti, M. T., Weston, E. B., Knapik, G. G., Dufour, J. S., & Marras, W. S. (2019). Impact of two postural assist exoskeletons on biomechanical loading of the lumbar spine. Applied ergonomics, 75, 1-7. https://doi.org/https://doi.org/10.1016/j.apergo.2018.09.006

Poliero, T., Fanti, V., Sposito, M., Caldwell, D. G., & Di Natali, C. (2022). Active and passive back-support exoskeletons: a comparison in static and dynamic tasks. IEEE Robotics and Automation Letters, 7(3), 8463-8470. https://doi.org/https://doi.org/10.1109/LRA.2022.3188439

Poupard, M., Larrue, F., Sauzéon, H., & Tricot, A. (2025). A systematic review of immersive technologies for education: Learning performance, cognitive load and intrinsic motivation. British Journal of Educational Technology, 56(1), 5-41. https://doi.org/https://doi.org/10.1111/bjet.13503

Rodriguez, F. S., Spilski, J., Hekele, F., Beese, N. O., & Lachmann, T. (2020). Physical and cognitive demands of work in building construction. Engineering, Construction and Architectural Management, 27(3), 745-764. https://doi.org/https://doi.org/10.1108/ECAM-04-2019-0211

Sepp, S., Howard, S. J., Tindall-Ford, S., Agostinho, S., & Paas, F. (2019). Cognitive load theory and human movement: Towards an integrated model of working memory. Educational Psychology Review, 31, 293-317. https://doi.org/https://doi.org/10.1007/s10648-019-09461-9

Theurel, J., Desbrosses, K., Roux, T., & Savescu, A. (2018). Physiological consequences of using an upper limb exoskeleton during manual handling tasks. Applied ergonomics, 67, 211-217. https://doi.org/https://doi.org/10.1016/j.apergo.2017.10.008

Tomori, M., Gnanaprakasam, S., & Ogunseiju, O. (2025g). Leveraging Machine Learning and Wearable Sensor for Cognitive Risk Assessments in Human-Wearable Robot Interactions. The International Conference of Sustainable Development and Smart Built Environments, Auckland, New Zealand.

Tomori, M., Ogunseiju, O., & Nnaji, C. (2024). A Review of Human-Robotics Interactions in the Construction Industry. Construction Research Congress 2024, 903-912. https://doi.org/doi.org/10.1061/9780784485262.092

Toxiri, S., Näf, M. B., Lazzaroni, M., Fernández, J., Sposito, M., Poliero, T., Monica, L., Anastasi, S., Caldwell, D. G., & Ortiz, J. (2019). Back-Support Exoskeletons for Occupational Use: An Overview of Technological Advances and Trends. IISE Transactions on Occupational Ergonomics and Human Factors, 7(3-4), 237-249. https://doi.org/10.1080/24725838.2019.1626303

Wickens, C. D. (2008). Multiple resources and mental workload. Human factors, 50(3), 449-455. https://doi.org/https://doi.org/10.1518/001872008X288394