Quantification of cognitive ergonomic factors and task performance for the use of passive upper limb exoskeleton while performing overhead tasks

Muhammad Hadri Aziz[1], Nurul Izzah Abd Rahman[1*], Hazreen Harith[2]
[1]Department of Mechanical Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang, Selangor, Malaysia.
[2] Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang, 43400, Selangor, Malaysia.
*Correspondence: chaijak.pimprapa@gmail.com

Received 21 June, 2023; Revised 6 August, 2023; Accepted 7 Auguat, 2023
Available online: 7 August, 2023 at www.atlas-tjes.org, doi: 10.22545/2023/00231

Abstract: *Exoskeleton has been proposed as a solution for musculoskeletal problems. Designed for physical attributes, it is crucial to determine the effect of its usage on cognitive aspects during task execution. This study aims to quantify cognitive ergonomic factors and task performance for the use of passive upper limb exoskeleton while performing overhead tasks. Ten male participants (mean age of 23.2 years (SD= 0.6)) took part in single and dual-task experiments. Subjective ratings using NASA Task Load Index (NASA-TLX) and Situation awareness rating technique (SART), physiological measure using Heart Rate Variability (HRV) and task performance (number of error) were measured. The dual-task setup reveals that there were strong positive correlations between the overall workload and number of errors percentage, which was statistically significant ($r = 0.822$, $n = 10$, $p = 0.004$). This finding is crucial as a reference for designers, developers, and policymakers in optimizing and sustaining task performance.*

Keywords: Cognitive ergonomics, passive upper limb exoskeleton, cognitive workload, situation awareness, task performance.

1 Introduction

Musculoskeletal disorders (MSDs) are one of the most prevalent occupational diseases in Malaysia [1]. According to a recent Global Burden of Disease Study 2019, over 1.71 billion people globally suffer from musculoskeletal problems [2]. The course of the disease might be acute or chronic, and the pain might be localized or widespread. Pain, body soreness, and fatigue that persist for an extended period may result in MSDs. World Health Organization reported that, musculoskeletal disorders are the leading cause of disability worldwide, with symptoms restricting mobility and dexterity to the point of early retirement, impaired well-being, and diminished social involvement [3].

Significant contributors to work-related musculoskeletal disorders (WMSD) of the neck, shoulder, elbow, hand, wrist, and back in the manufacturing industry include the routine lifting of heavy objects, daily exposure to whole-body vibration, routine overhead work, work with the neck in a chronic flexion position, and manual materials handling (MMH) [4, 5]. It was reported In Germany that 16.9% of employees report working in forced positions (e.g., working overhead) on a regular basis [6].

Currently, one available solution for work-related musculoskeletal disorders (WMSD) is an exoskeleton. In 2019, Alabdulkarim and Nussbaum [7] have reported that industrial exoskeletons reduce shoulder muscle loading in overhead tasks. During tasks execution, wearable exoskeleton enhances, facilitates, assists, or boosts the wearer's physical activities through enhancing movement, posture, or body position [8].

However, despite the encouraging effects of exoskeleton usage on task performance in the short term and from muscular activities perspective, its effects on users' cognitive load require further investigations. For example, in the event of physical degeneration, as in aging industrial workers, exoskeleton might seem to be a promising solution, but the aging industrial workers also experiencing declining function of physiologic and cognitive capabilities.

Theurel et al. [9] found that industrial exoskeletons had increased muscular activity, lumbar spine biomechanical stresses, and metabolic cost, all of which can exacerbate known workplace WMSD hazards. It was also found that these exoskeletons introduced additional concerns, such as cognitive overload [10]. Some exoskeletons are designed without considering cognitive ergonomics elements and the risk of cognitive load during the task performance. Although ergonomics interventions have shown promising potential to reduce the risk of WMSD, new research found that the cognitive fitness (operator's mental capacity to accurately operate exoskeleton while performing a task) may impose new risk on user or worker at a workplace and could result in a decline in performance as well as a diminished ability to prevent WMSDs [11].

1.1 Overview of Exoskeletons

In general, exoskeletons can be divided into two categories: passive and active [12]. Pneumatic muscles, hydraulics, and electric motors are among the technologies that can be employed to increase human strength. This enhancement in passive devices is made possible by spring, damper, or other materials that can store and effectively discharge energy generated by user movements. Active devices, on the other hand, provide a larger degree of enhancement, but are more expensive and heavier [7]. Considering the large industrial application potential, the advent of new technologies, and the complexity of designing exoskeletons from an ergonomics standpoint, this study focused on passive exoskeleton designs. The use of exoskeletons in the workplace should collectively considering ergonomics, biomechanical and physiological perspectives. Exoskeletons in the industrial sector able to reduce workers' exposure to biomechanical hazards by lowering musculoskeletal stresses and fatigue. When forces are transported to the ground via limbs, weight redistribution may also demand an evaluation to determine if it results in increased physical stress on other sections of the body or excessive stimulation of limbs.

1.2 Cognitive Workload and Human-Machine Interfaces

Cognitive ergonomics scrutinize mental processes, such as perception, memory, reasoning, and motor response, as they affect interactions among humans and other elements of a system [13]. Cognitive ergonomics focuses on getting human-system interactions compatible with human cognitive abilities and limits, especially in a workplace. It consists of elements and principles related to prototype development such as user understanding, recognition, automated behavior, and intentional action and predictable reaction [14]. As part of cognitive ergonomics, cognitive workload focuses on the cognitive capacity and task demand placed upon the individual [15]. Cognitive workload is one of the crucial factors that can exhibit the working memory. It can be measured by subjective evaluation, objective (physiological) and task performance measures. Subjective judgments can accurately quantify a broad range of load levels with condition the participant must first understand the various load scales utilized.

There are three main methods to measure cognitive workload namely objective, subjective and performance measurement. Objective or physiological measurement has been very viable in the assessment of cognitive workload [16]. The widely used measurements are Electroencephalogram (EEG) which quantify brain signal activities, eye blinking, and heart rate variability (HRV). A recent study has demonstrated the relationships between cognitive workload and HRV, where variation in cognitive loads alter cardiovascular function leading to increased cardiovascular risk [17].

The situation awareness rating technique (SART)[18] is a subjective rating method that was developed to quantify pilot situation awareness. SART measures operator situation awareness (SA) on ten dimensions: scenario familiarity, attention focusing, information quantity, information quality, situation instability, attention concentration, situation complexity, situation variability, arousal, and mental reserve. To establish a subjective assessment of SA, SART is administered post-trial and participants are required to score each dimension on a seven-point scale (1 = Low, 7 = High). The 10 SART dimensions can also be simplified into the 3-D SART, which requires participants to rate their attentional demand (D), supply (S), and understanding (U).

The NASA Task Load Index (NASA-TLX)[19] is a widely used subjective and multidimensional evaluation that rates perceived workload to analyze the effectiveness or other aspects of performance of a job, system, or team. It was developed by NASA's Ames Research Center's Human Performance Group over a three-year development cycle that comprised more than 40 laboratory simulations [20]. The NASA-TLX methodology consists of six subscales: mental demand (MD), physical demand (PD), Temporal demand (TD), performance (OP), effort (EF), and frustration (FR) and is the basis for workload comparison cards. Each subscale ranges from 0 to 100, with 0 indicating "extremely low" and 100 representing "very high" values. In contrast, the OP subscale featured a scale spanning from "success" to "failure." The source of workload comparison card consists of 15 questions that permit a binary comparison of the contributions of these subscales to the workload of a certain task, then the mean (raw TLX) of the six subscales and the mean overall workload were determined (OWL).

The quantification of performance is through efficiency and accuracy measurements [21]. According to the literature, there are two types of task performance measurement, namely direct and indirect measurements. Measurement of direct performance focuses on primary task execution, while indirect measurement focuses on the relationship between secondary task and primary task. The measurement is mainly on monitoring the capacity to handle mental workload and quantifying performance of the task in relation to another event during task execution. The secondary task frequently demands memory, mental calculation, and attention [22]. For example, an individual is assigned a one-page typing task (primary task), while at the same time, he is required to answer verbal questions from the researcher (secondary task). The tasks outcomes are measured separately and categorized into different levels. In this study, we investigated the cognitive ergonomics factors in the design of passive upper limb exoskeletons. The main objective of this study was to quantify cognitive ergonomic factors and task performance for the use of passive upper limb exoskeleton while performing overhead tasks.

2 Methodology

2.1 Participants

Ten male participants (mean age: 23.2 +/- 0.6) were recruited to participate in the study through advertisements and social media. All participants were in good health and had no musculoskeletal issues, hence minimizing the differences between individual cognitive workload and performance. All participants declared that they did not suffer from any musculoskeletal injury or disorder that had an impact on their everyday lives in the previous year. At least two hours before the experiment, each participant refrained from any task.

2.2 Exoskeleton and Cognitive Workload Measurement

V3 ShoulderX as depicted in Figure 1 is composed of a waist belt and arm belts together with energy storage units and back straps. The overall weight of the system is 3.17 kg (SuitX, 2021). The system was selected for this study as it suits the purpose of this study in simulating the overhead task with the use of an exoskeleton.

Figure 1: Participants equipped with the V3 ShoulderX.

The heart rate of each participant was recorded every 30 seconds throughout the experiment using Polar H10 (version, Polar Electro Oy) and its mobile app, Polar Beat (3.5.5, Polar Electro).

Self-rating techniques were used to acquire a participant's subjective assessment of their Situation awareness (SA) and workload. Post-trial self-rating procedures required participants to provide a subjective rating of their perceived SA using an SA-related rating scale (SART). A SART composite score is calculated using the formula as follows:

$$\mathrm{SA} = \mathrm{U} - (\mathrm{D} - \mathrm{S}) \tag{1}$$

where SA: Situation awareness; D: attentional demand; S: supply; U: Understanding.

The NASA-TLX was utilized to determine the operator's subjective workload. After completing each primary course activity, participants were required to self-report their workload. Each participant had around 5–10 minutes to complete the subjective evaluation.

2.3 Experimental Setup

The experimental setup consists of four settings namely: i) Single-task without Exoskeleton (SWoE), ii) Single-task with Exoskeleton (SWE), iii) Dual-task without Exoskeleton (DWoE) and iv) Dual-task with Exoskeleton (DWE).

In each setting, participants were required to lift and lowered 3kg loads back and forth onto the shelf. The arms initially were at 0^{o}, then elevated to 135^{o} at around head height without moving the feet substantially throughout the experiment as illustrated in Figure 2. Table 1 presents the details of the experimental setup.

Figure 2: The arms were initially at 0 degree, then elevated to 135 degrees at around head height.

Table 1: Details of the experimental setup.

Descriptions	Number of task (lifting/lowering) per minute	Degree of arm elevation	Other conditions
Single-task without Exo (SWoE)	6	90 - 135	No verbal communication
Single-task with Exo (SWE)	6	90 - 135	No verbal communication
Dual-task without Exo (DWoE)	6	90 - 135	Involved verbal communication to complete arithmetic tasks
Dual-task with Exo (DWE)	6	90 – 135	Involve verbal communication to complete arithmetic tasks

The single task requires participants to raise and lower 3kg loads back and forth between 90 and 135 degrees of arm elevation. For ten minutes, participants must complete the task at a rate of six lifts/lowers per minute. Meanwhile, during dual-task, participants were given the identical instruction as in the single-task condition but were also instructed to serially subtract 17 from a random value between 300 and 500. Participants were randomly assigned a new number for repeated subtraction once the difference approached zero. This approach was repeated until completion of the ten-minute physical cognitive task. Their responses were recorded for speed and accuracy analysis. This study's primary outcome measure was cognitive performance on the dual-task test. The following parameters were analyzed: Total arithmetic questions answered and number of errors percentage. This method was adapted based on validated study done by Zhu et al., 2021[23].

Based on manual handling guidance and regulations (Health and Safety Executive, 2016), 3 kg loads are within the safe limit and suffice to fulfill heart measurement, thus 3 kg loads were used in this study. Throughout the experiment, two cameras were used to record the participants and a Polar H10 heart rate monitor was used to record participant's heart rate. All experiments were conducted at Malaysian Agricultural Research and Development Institute (MARDI) research laboratory.

2.4 Experimental Procedure

In this study, informed consent was obtained from the participants. They were briefed on the experiment's details upon arrival at the setup station. All participants were instructed to complete the tasks in four different days.

In addition, it was highlighted to the participants that completing the assigned task was their main priority. Before each task, each participant was supplied with Polar H10 heart rate sensors to monitor their heart rate during the session. To achieve reliable measurements, the research assistant and participants are prohibited from speaking during heart rate monitoring, unless they are performing dual activities. The participants must then appropriately complete the subjective assessments namely SART & NASA-TLX for each session. Participants were instructed to rate the scores objectively and were given sufficient time and space to make subjective evaluations without intervention from the research assistant. Then, for the dual tasks, all participants were required to execute the same physical asymmetrical lifting/lowering task protocol as in Study 1, but with the addition of a cognitively challenging arithmetic subtraction problem. At the beginning of the task, participants were required to repeatedly deduct 17 from a random number between 300 and 500. As the difference approached zero, participants were assigned a new number at random for repeated subtraction. This approach was repeated until completion of the 10-minute physical cognitive task. Participants were then told to rate the scores objectively when completing the subjective evaluations. They were given sufficient time and space to undertake subjective judgement without interference from the research assistant. Before the following session, participants can rest for at least one day to prevent fatigue and increase the precision of the results. Figure 3 illustrates the overall experimental procedure.

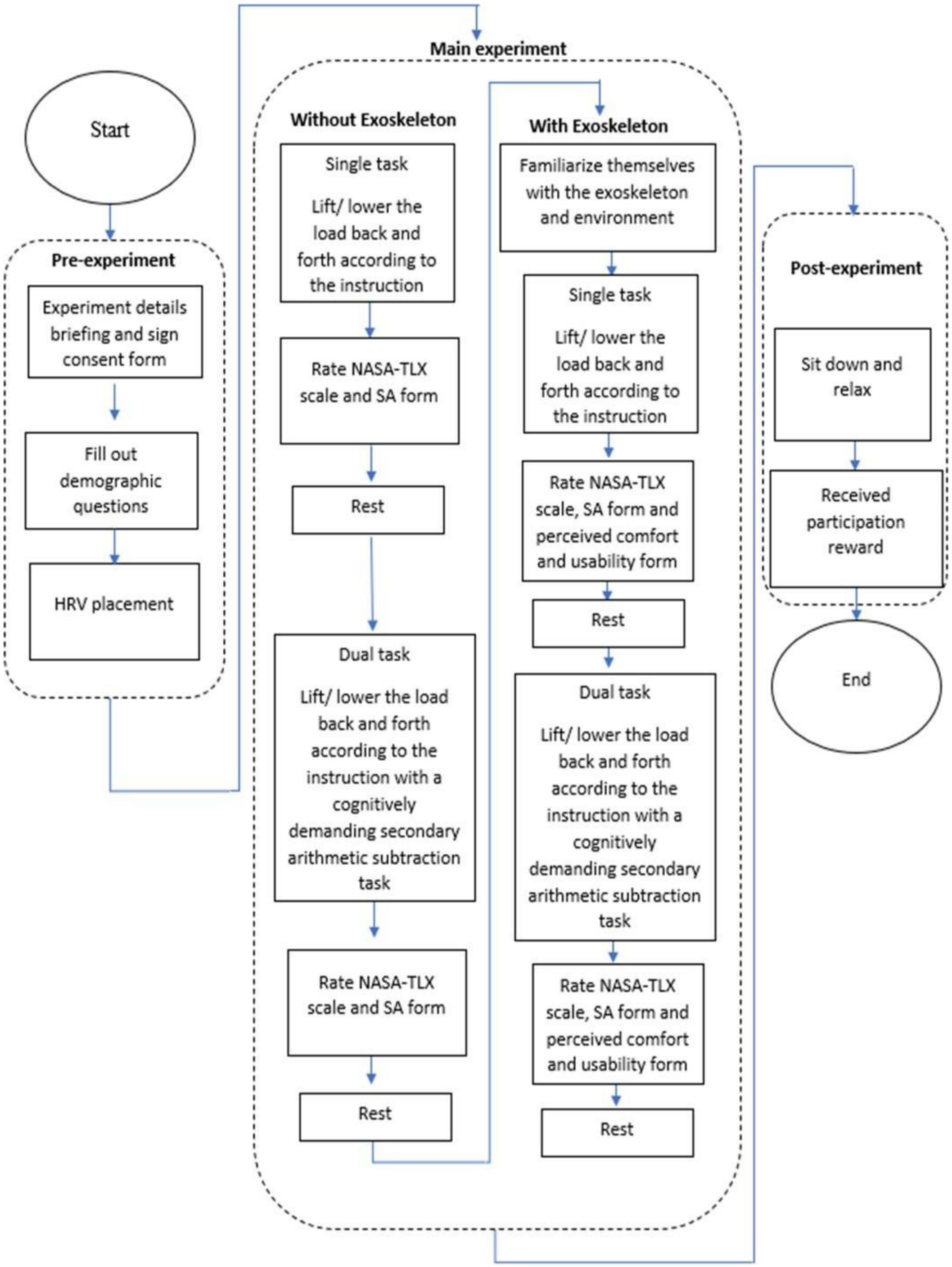

Figure 3: Overall experimental procedure.

2.5 Data Processing and Analysis

The cognitive load, situation awareness, HRV and task performance data were analyzed with IBM SPSS for Windows version 23.0 (IBM SPSS) (IBM Corporation, 2018). Prior to data analysis, skewness and kurtosis were used to determine the normality of all variables. The results showed that all variables in the study were normally distributed. Polar Beat application provided the raw data for HRV output. The data were analyzed using the repeated measures ANOVA to obtain the main effect of tasks setups on participants' workload levels. The link between each measure variables was discovered by Pearson correlation analysis.

3 Results and Discussions

3.1 NASA-TLX, SART and Heart Rate Variability (HRV) between Experimental Setups

Results of the subjective ratings of participants on workload measured using NASA-TLX in SWoE, SWE, DWoE and DWE are summarized in Figure 4. NASA-TLX scores ranged from 0 (no demand) to 100 (maximum demand). The two highest OWL scores were found in DWE (M= 70.03, SD= 12.50) and DWoE (M= 70.00, SD= 17.60). For single task, task performed without exoskeleton scored higher (M=54.50, SD=18.97) than with exoskeleton (M= 52.67, SD= 17.55). The mean MD score obtained was the highest compared to other scores in DWoE (M= 82.00, SD= 14.76) and DWE (M= 83.00, SD= 14.18).

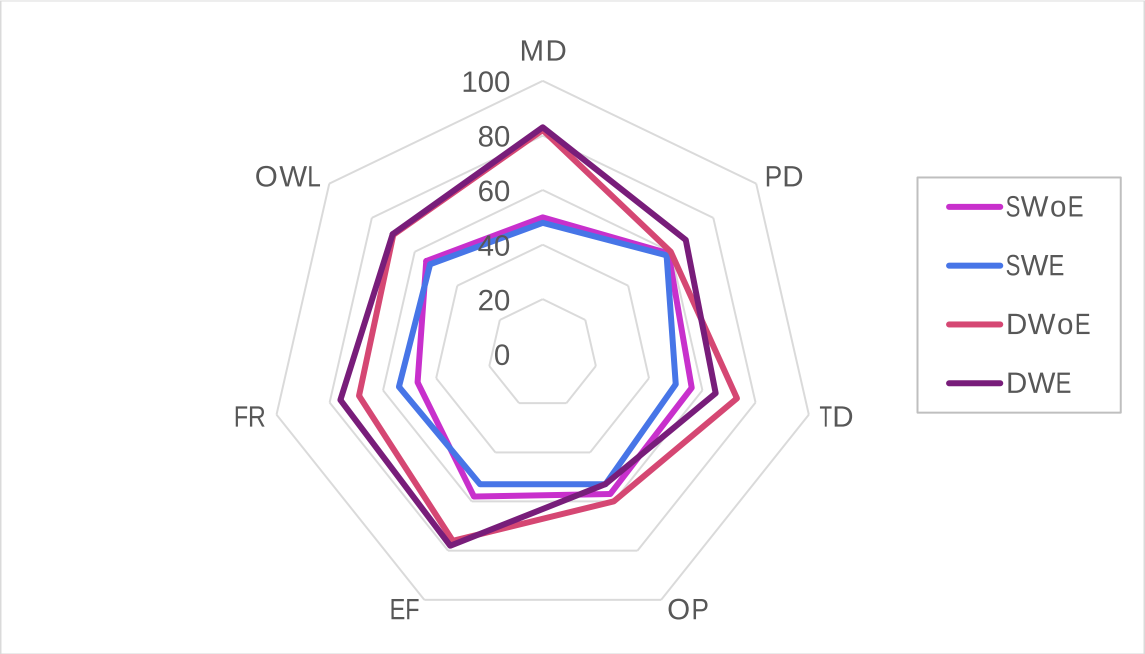

Figure 4: Classification of NASA-TLX mean scores between experimental settings/groups.

MD: Mental Demand, PD: Physical Demand, TD: Temporal Demand, OP: Own Performance, EF: Effort, FR: Frustration, OWL: Overall Workload SWoE : Single-task Without Exoskeleton, SWE : Single-task With Exoskeleton, DWoE : Dual-task Without Exoskeleton, DWE: Dual-task With Exoskeleton.

The repeated measures ANOVA test reveals a significant main effect of tasks setups on almost all participants' subjective workload score. There were significant differences between the experimental task setups ($p < 0.05$) and all variables except PD and OP (Table 2).

Table 2: Significant differences between the experimental task setups ($p < 0.05$) for majority of the scores.

		MD		**PD**		**TD**		**OP**		**EF**		**FR**		**OWL**	
Experimental Setup		M.df	*p*	M.df	*p*	M.df	*p*	M.df	*p*	M.df	*p*	M.df	*p*	M.df	*p*
SWoE	SWE	2.00	> 0.05	1.00	> 0.05	6.00	> 0.05	4.00	> 0.05	5.00	> 0.05	-7.00	> 0.05	01.83	> 0.05
	DWoE	-32.00*	0.017	-1.00	> 0.05	-17.00*	0.002	-3.00	> 0.05	-18.00	0.112	-22.00*	0.024	-15.50*	0.045
	DWE	-33.00*	0.035	-8.00	> 0.05	-9.00	> 0.05	4.00	> 0.05	-20.00*	0.013	-29.00*	0.021	-15.83*	0.031
SWE	SWoE	-2.00	> 0.05	-1.00	> 0.05	-6.00	> 0.05	-4.00	> 0.05	-5.00	> 0.05	7.00	> 0.05	-01.83	> 0.05
	DWoE	-34.00*	0.042	-2.00	> 0.05	-23.00	0.112	-7.00	> 0.05	-23.00	0.140	-15.00	> 0.05	-17.33	0.117
	DWE	-35.00	0.052	-9.00	> 0.05	-15.00	0.545	0.000	> 0.05	-25.00	0.076	-22.00	0.464	-17.67	0.195
DWoE	SWoE	32.00*	0.017	1.00	> 0.05	17.00*	0.002	3.00	> 0.05	18.00	0.112	22.00*	0.024	15.50*	0.045
	SWE	34.00*	0.042	2.00	> 0.05	23.00	0.112	7.00	> 0.05	23.00	0.140	15.00	> 0.05	17.33	0.117
	DWE	-1.00	> 0.05	-7.00	> 0.05	8.00	> 0.05	7.00	> 0.05	-2.00	> 0.05	-07.00	> 0.05	-00.33	> 0.05
DWE	SWoE	33.00*	0.035	8.00	> 0.05	9.00	> 0.05	-4.00	> 0.05	20.00*	0.013	29.00*	0.021	15.83*	0.031
	SWE	35.00	0.052	9.00	> 0.05	15.00	0.545	0.000	> 0.05	25.00	0.076	22.00	0.464	17.67	0.195
	DWoE	1.00	> 0.05	7.00	> 0.05	-8.00	> 0.05	-7.00	> 0.05	2.00	> 0.05	7.00	> 0.05	0.33	> 0.05

M.df: Mean difference = Task i – Task j

** The mean difference is significant at the 0.05 level.*

Subjective ratings and HRV of participants on situation awareness by SART across tasks in the SWoE, SWE, DWoE and DWE are summarized in Figure 5. SART dimensions scores ranged from 0, representing low, to 7, high. Based on the data from participants, overall, the highest SA score was from SWoE (M= 15.60, SD= 4.99). The repeated measures ANOVA test reveals no significant main effect of tasks setups on all participants' subjective situation awareness score ($p > 0.05$).

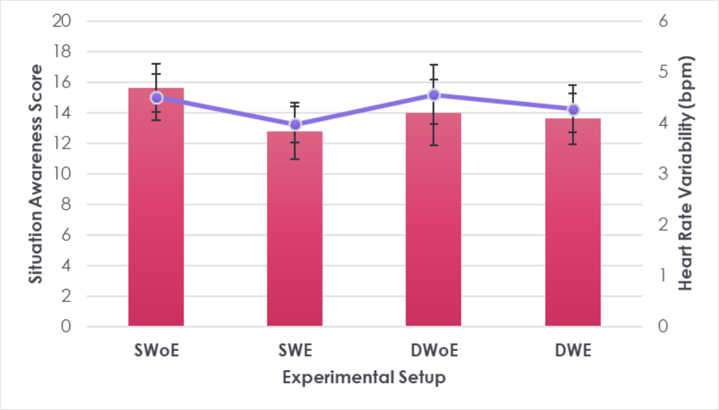

Figure 5: SART and HRV mean scores between experimental setups.

The highest HRV was from DWoE (M= 4.56, SD= 1.82) followed closely by SWoE (M= 4.51, SD= 1.42). The repeated measures ANOVA test reveals no significant main effect of tasks setups on all participants' HRV (p > 0.05).

3.2 Task Performance: Total Arithmetic Questions Answered and Number of Errors Percentages.

The task performance of the participants in Dual-tasks experimental setup were represented by the total of arithmetic questions answered within specified time and number of errors. Independent sample T-test test were executed to compare between DWoE and DWE. For the total of arithmetic questions answered, there were no statistically significant difference between DWoE (M = 42.8, SD=14.32) and DWE (M=41.3, SD=17.02), t=0.834, $p > 0.05$. For the number of errors percentage, there were no significant difference between DWoE (M = 14.7, SD=11.29) and DWE (M=14.0, SD=10.65), t=0.143, $p > 0.05$.

3.3 Relationship between the Cognitive Ergonomics Measures

The variations of subjective and objective measures were further investigated to quantify their relationships with the task performance. Correlation analyses were carried out for this purpose and the results are presented in Table 3. The experimental results of the participant in the DWE reveal that there were strong positive correlations between the OWL and number of errors percentage, which was statistically significant (r = 0.822, n = 10, p = 0.004). When the overall mental workload increases, the number of errors increases as well while performing task using exoskeleton. This is in line with the findings by Zhu et al., [23] which indicated that a wearer's biomechanical response to increased cognitive demands in the workplace. This situation may offset the mechanical advantages of exoskeletons.

Table 3: Correlation of the subjective and objective measures with the task performance

Experimental Setup	Cognitive ergonomics measures		Total arithmetic questions answered	Number of errors percentage
DWoE	OWL	r-value	-0.559	0.306
		p-value	0.093	0.39
	SA	r-value	0.114	-0.041
		p-value	0.754	0.912
	HRV	r-value	-0.044	-0.048
		p-value	0.904	0.896
DWE	OWL	r-value	-0.563	0.822**
		p-value	0.09	0.004
	SA	r-value	-0.208	0.303
		p-value	0.565	0.395
	HRV	r-value	-0.22	0.082
		p-value	0.541	0.822

** The correlation is significant at the 0.01 level.*

4 Conclusion

The cognitive ergonomics component in passive upper limb exoskeleton when performing overhead tasks has been quantified by using different cognitive ergonomics components approach which are subjective ratings, objective ratings, and task performance measure. Based on the correlation analysis, when the overall mental workload increases, number of error increases as well while performing task using exoskeleton. This finding may benefit as a reference for designers, manufacturers, developers, and policymakers in designing better exoskeleton using cognitive ergonomics approach to optimizing and sustaining the task performance. There is a need for human workers who can adapt to production variations and possess enhanced strength and stamina as well as cognitive performance, which might be provided by the proper application of exoskeletons. This project is aligned with Sustainable Development Goals (SDGs) number 8 which promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all.

Authors' Contribution: All authors contributed equally to this work.

Funding Statement: There was no external funding received for the conduction of this study.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

Acknowledgments: We would like to thank Mr. Hasmin Hakim Hasbullah from Malaysian Agricultural Research and Development Institute (MARDI) for the support and cooperation during the data collection for this project.

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About the Author

Muhammad Hadri bin Aziz is a mechanical maintenance engineer with problem solving and management skills and works for a hi-tech energy company. The company manufactures and distributes rechargeable batteries used for electric vehicles, IT, Energy Storage System (ESS), as well as materials for semiconductors and displays. As a mechanical maintenance engineer, he is responsible for analysing and doing improvement for reducing machines failure and downtime to increase the product efficiency. Muhammad Hadri has a bachelor's degree in mechanical engineering from Universiti Putra Malaysia (2022).

Dr. Nurul Izzah Abd Rahman received her Ph.D. from the University of Malaya in 2020 and currently works as Senior Lecturer at Universiti Putra Malaysia (UPM). She is a Graduate Engineer of Board of Engineers Malaysia and an Ergonomic Trained Person endorsed by Department of Occupational Safety & Health, Malaysia. Before joining UPM, she served in the industry as the Operation Manager and Ergonomist. Previously, she played strategic researcher roles in numerous transdisciplinary engineering projects involving innovative Mobile Applications and data models in fatigue and mental workload management for service sector workers and ageing population. She has also been involved in engineering design projects related to small and medium-sized enterprises productions, transportation (railway), and the special needs population (elderly & disabled person). Currently she is working on research grant projects that are towards Cognitive Ergonomic Technologies in manufacturing and office settings.

Dr. Hazreen Harith had her Ph.D. from Queensland University of Technology, Australia in 2014. She is a Senior Lecturer at Universiti Putra Malaysia. Her research interests include Biomechanics, motion analysis, 3D modelling and graphics.