Exoskeleton Intervention in Car Assembly Line to Minimize the Potential of Musculoskeletal Disorder Risk

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Intisari – Gangguan Muskuloskeletal (Musculoskeletal Disorders/MSDs) merupakan masalah kesehatan kerja yang umum terjadi dan disebabkan oleh gerakan berulang, postur kerja yang tidak ergonomis, serta beban fisik berlebihan. Di Indonesia, lebih dari 40% pekerja dari berbagai sektor industri dilaporkan mengalami gejala MSD. Penelitian ini mengkaji efektivitas eksoskeleton pendukung bahu pasif sebagai intervensi ergonomi tambahan pada aktivitas perakitan mobil. Sepuluh partisipan dewasa muda melakukan tugas pengencangan baut berulang dalam dua kondisi, yaitu dengan dan tanpa bantuan eksoskeleton. Gejala MSD dievaluasi menggunakan skala Borg CR-10, sementara risiko postur dinilai menggunakan Rapid Upper Limb Assessment (RULA). Selain itu, waktu penyelesaian tugas dan waktu pemulihan pascatugas dicatat untuk mengevaluasi efisiensi pelaksanaan tugas. Hasil penelitian menunjukkan bahwa penggunaan eksoskeleton menurunkan persepsi usaha otot terutama pada area pergelangan tangan serta menurunkan waktu penyelesaian tugas sebesar 13,6%. Penurunan waktu pemulihan pascatugas sebesar 19,08% juga diamati pada kondisi tugas dengan eksoskeleton. Skor RULA keseluruhan menurun dari 7 (risiko tinggi) menjadi 5,5 (risiko sedang), yang menunjukkan adanya penurunan risiko ergonomis. Secara umum, eksoskeleton pendukung bahu pasif menunjukkan potensi untuk meningkatkan keselamatan, kenyamanan, dan efisiensi kerja pada aktivitas perakitan otomotif berulang dengan posisi kerja di atas bahu (kondisi kerja elevasi).

Kata kunci – eksoskeleton pasif, gangguan muskuloskeletal, NBM, RULA, perangkat lunak detektor sudut

Abstract – Musculoskeletal Disorders (MSDs) remain one of the most prevalent occupational health issues worldwide, commonly caused by repetitive motions, awkward postures, and excessive physical load. In Indonesia, more than 40% of workers from various industries report MSD symptoms. Although ergonomic control measures aligned with international standards (e.g. ISO) have been implemented, these strategies are often insufficient to ensure safer postures sustained during work activities. Exoskeletons have been developed as a promising supplemental ergonomic intervention through its biomechanical mechanisms. This study examined the effectiveness of a passive shoulder-support exoskeleton adoption in one of the car assembly activities. Ten young adults performed repetitive bolt-tightening under two conditions: with and without exoskeleton assistance. MSD symptoms were assessed using the Borg CR-10 exertion scale, while postural risk was evaluated using the Rapid Upper Limb Assessment (RULA). Additionally, task completion and recovery times were recorded to evaluate task efficiency. Subjective perception regarding acceptability and safety perception towards the device were assessed through a questionnaire. Based on the experimental results, the exoskeleton reduced perceived muscle exertion mainly in the wrist region and reduced task completion time by 13.6%. A notable reduction in post-task recovery time (19.08%) was also observed under the exoskeleton condition. The overall RULA score decreased from 7 (high risk) to 5.5 (medium risk), indicating a reduction in ergonomic risk. Furthermore, questionnaire responses revealed positive perceptions related to task speed and mobility support, although some usability challenges were noted. Overall, these findings suggest that passive shoulder-support exoskeletons have the potential to enhance worker safety, comfort, and task efficiency in repetitive elevated automotive assembly tasks.

Keywords – passive exoskeleton, musculoskeletal disorder, NBM, RULA, angle detector software

I. INTRODUCTION

Musculoskeletal disorders (MSDs) are among the most prevalent occupational injuries across various industries, posing a significant threat to worker health, safety, and productivity. According to the European Agency for Safety and Health at Work, 60% of workers reported experiencing musculoskeletal disorders caused by work in 2015 [1]. Approximately 47% of plant and machine operators and assemblers indicated suffering from muscular discomfort in their shoulders, neck, and upper limbs [1]. Recent studies further supported EU-OSHA's findings, reporting high prevalence of MSDs among automotive assembly workers, particularly in the neck (44.5%), lower back (44.1%), and shoulders (34.6%) [2]. These work-related musculoskeletal disorders lead to a decrease in the worker's productivity. Addressing these disorders requires a multifaceted approach, integrating ergonomic assessments, employee training, engineering controls, and organizational policies [1].

In Indonesia, evidence also indicates that MSDs are a widespread occupational health issue. A survey of production workers in Bandung found that MSD prevalence reached 24.7%, while clinical diagnoses indicated a prevalence of 11.9% [3]. A study of MSD prevalence among office workers, janitors, and farmers during the last 12 months is relatively high, ranging from 40%-70% of the

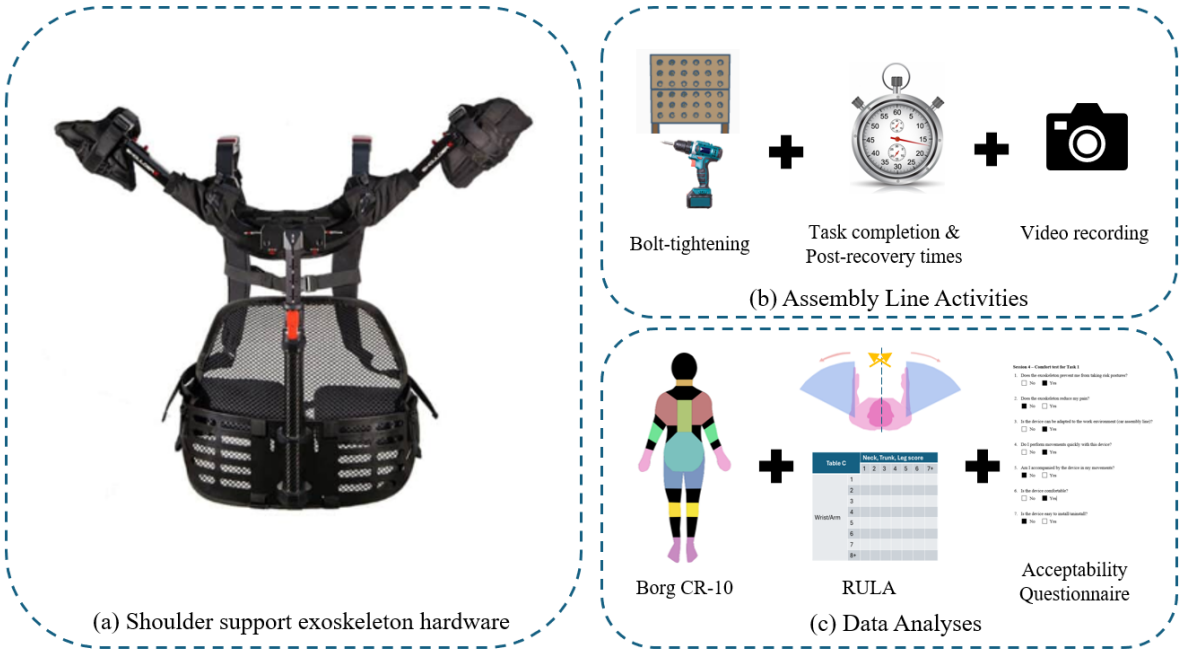

Figure 1. Illustration of the Proposed Method

respondents [4]. An assessment of bakery workers in Jakarta also noted MSD symptoms on neck, feet, low back, and upper back among 6 workers [5], while automotive workshop workers reported the highest MSD symptoms in the waist (65.8%) and back (63.2%) [6].These studies suggest that MSDs are common across diverse industries in Indonesia.

To prevent such injuries and promote a safety work environment, ergonomics-centered approaches have been widely recommended. ISO 6385:2016, "*Ergonomics principles in the design of work systems,"* outlines fundamental ergonomic principles as basic guidelines for designing work systems. Establishing effective and sustainable MSD prevention should include training for engineers and social stakeholders, as well as developing production organization guidelines that prioritize safety consideration [7]. Furthermore, ergonomic assessments typically involve evaluating workstations and task demands to identify risk factors such as repetitive motions, awkward postures, and forceful exertions [8]. These assessments form the basis for developing targeted interventions aimed at reducing physical strain and preventing MSD-related injuries including RULA, REBA, ROSA, and NIOSH. For instance, a one-year longitudinal study implementing ergonomic training programs, auxiliary tools improvements, and distribute the ergonomic educational brochure, resulting in a significant reduction of risk factors for the neck, back, shoulder or arms, and wrists ($p < 0.01$) through a Quick Exposure Check (QEC) [9]. Rotational work schedules are also commonly implemented to minimize prolonged exposure to repetitive tasks, thereby reducing the likelihood of cumulative trauma [10]. Additionally, engineering controls such as Personal Lift-Assist Device (PLAD) have been shown to significantly reduce low back muscular activity in performing forward bending and static holds during assembly task [11]. Another promising ergonomic intervention for MSD prevention is exoskeleton.

Exoskeletons are assistive wearable devices that enhance humans' posture, motion, or physical activity, and serve as ergonomic control measures by minimizing physical effort. Many shoulder support exoskeletons are already available commercially [12]. Most are designed as passive systems to ensure these devices remain lightweight, comfortable, and cost-effective [12], [13]. Potential application areas include industrial assembly, construction, healthcare, and personal care industries. Several studies have revealed positive result in reducing MSDs prevalence [13], [14].

Despite growing interest, existing research on exoskeletons in automotive assembly and related industrial tasks shows significant gaps. Most studies have assessed the impact of exoskeletons in preventing work related musculoskeletal disorders on muscle activities through Electromyography (EMG) or postural assessment [12], while subjective assessment of user comfort, overall acceptance, and usability are less consistently integrated [15]. From a managerial perspective, there are also limited studies of exoskeletons' effects on task completion times and their capability of reducing injury-related absenteeism [15]. Furthermore, exoskeleton research remains underexplored in developing-country work environments, particularly in Indonesia, where manual labor in automotive assembly remains highly prevalent.

To address these gaps, this study examines the impact of a shoulder-support exoskeleton on localized perceived exertion, task completion time, and post-task recovery time during a simulated repetitive car assembly task. While these

evaluation metrics align with established exoskeleton research [13, 16, 17], the contribution of this study lies in providing an integrated evaluation of performance, postural risk, and perceived exertion, representing an early adoption study of exoskeleton device in local context. This work contributes baseline evidence to support informed decision-making regarding ergonomic interventions in developing-country manufacturing environments.

II. METHODOLOGY

A. *Proposed Method*

Figure 1 shows the illustration of the proposed methodological framework for evaluating the effectiveness of exoskeleton intervention in car assembly line to minimize the potential of MSD risks. The framework consists of (a) shoulder support exoskeleton hardware, (b) assembly line activities, and (c) ergonomic assessments. To replicate the real car assembly line, this study employed a quasi-experimental design using a passive shoulder exoskeleton during repetitive manual tasks. The device is designed to reduce shoulder strain during elevated tasks by transferring the load of the arms and tools from the shoulders to the hips.

Through its biomechanical mechanism, it stores and releases mechanical energy to provide dynamic support [16], [17], offering greater assistance as the arms are raised and minimal resistance when lowered (See Figure 2). Lightweight, breathable, and adjustable, the exoskeleton has been demonstrating reduction in muscle activity by up to 81% in laboratory tests, with real world effectiveness depending on the specific task and peak torque amplitude (PTA) [18].

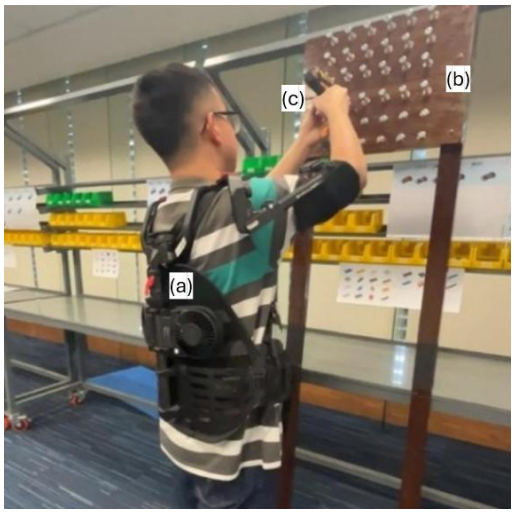

Figure 3. Simulated Assembly Line: (a) Exoskeleton, (b) Simulation Board, (c) Drill hardware.

B. *Experimental Study*

Ten young adults (8 males and 2 females) participated in the study, with an average age of 21 ± 1 years and an average height of 167.92 ± 6.57 cm. Participants were selected based on their physical capability to perform repetitive assembly tasks and their willingness to participate, ensuring voluntary involvement according to the adapted Informed Consent of Research Ethics from Iowa State University. Each participant performed the task under two experimental conditions without and with the ShoulderX V3 exoskeleton (3.17 kg). The core activity simulated was a bolt-tightening task chosen for its high repetition and upper-limb demand, which are common in automotive production lines.

To replicate assembly line condition, a custom simulation board based on the participants' anthropometric data (stature, standing shoulder height, and overhead reach height) was developed for elevated bolt-tightening task (See Figure 3). The board's maximum height was set at 180 cm from the floor, which is above participants' average shoulder height (~140 cm) and close to head level, thereby requiring arm elevation beyond 90° flexion. This ensured the task simulated realistic elevated working postures. The panel contained 36 M10 bolts (1 cm diameter) arranged with an inter-hole spacing of 8 cm.

The experiment consisted of two conditions, which are unassisted task (Condition A) and assisted task (Condition B). Each condition was repeated three times per subject and video recorded to ensure consistency and reliability of the measurements. Posture, assembly time, and recovery time were documented for each trial. During the task, participants stepped forward and lifted a 1.88 kg drill from a desk and tightened all bolts on the panel. The task design was adapted from a study in which the total length of cycle is 160 s/20 screws [19]. They assume that the time per screw needed is 5 s (20 screws x 5 s/screw + 60 s = 160 s). However, in this study, the focus was placed on the task completion time average rather than the number of bolts tightened, as the exoskeleton intervention was hypothesized to affect overall task duration These metrics were included to provide a managerial perspective on operational efficiency and worker recovery, ensuring that the ergonomic intervention benefits the industrial productivity [15]. The experimental session lasted approximately 60 minutes. To ensure that muscle fatigue did not influence the subsequent trials, a recovery

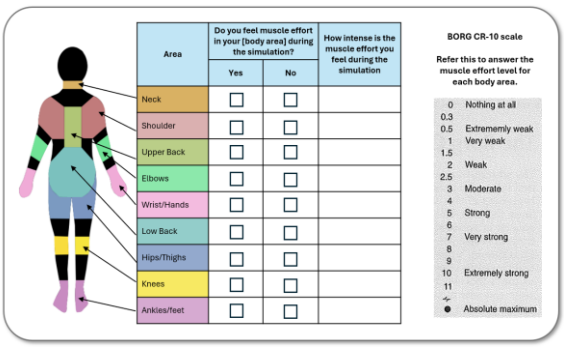

Figure 2. Borg CR-10

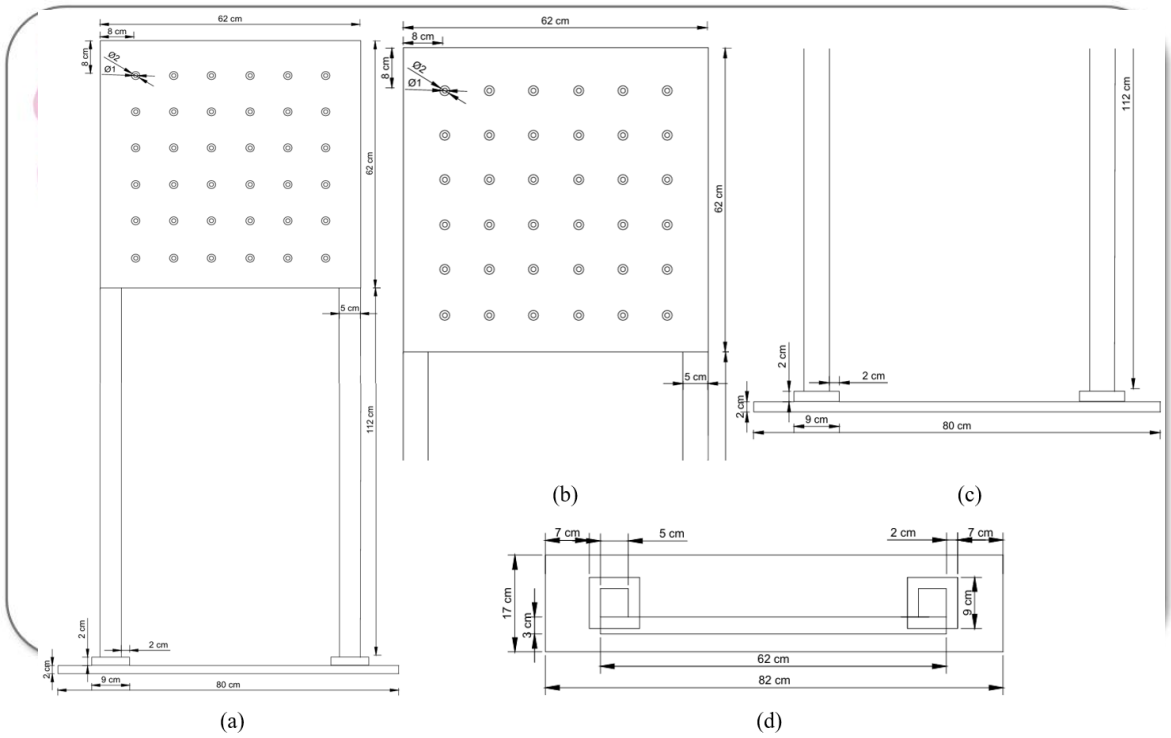

Figure 4. Simulation Board Design: (a) Full Design, (b) Front View Upper Part, (c) Front View Lower Part, (d) Top View.

period was provided between repetitions and conditions, based on the participant's subjective recovery. On average, participants took 2 minutes of rest between trials.

C. Evaluation Method

1) *Borg Category Ratio (CR) 10:* In this study, localized muscle effort was assessed using Borg Category Ratio (CR) 10 scale [20]. The CR-10 scale was selected due to its capability to capture intensity of effort immediately after completion of each experimental condition, making it suitable for experimental settings [20]. The Borg CR-10 consists of scores ranging from 0 to 10, with 0 representing no pain exertion and 10 represented extremely strong exertion [20]. Furthermore, to support accurate localization, participants were provided with a body chart adapted from the Nordic Body Map [21] and instructed to indicate the specific body regions where exertion was experienced as shown in Figure 4.

For each marked region, they provide a Borg CR-10 score. Complementary instructions for perceived exertion using the Borg CR-10 scale [20] also explained to the participants prior to the simulation to ensure they understand how to accurately use the scale. To minimize participant cognitive load and response fatigue, Borg CR-10 ratings were collected once after completion of each experimental condition. This approach enabled a consistent, condition-level assessment of localized perceived musculoskeletal effort during the simulated bolt-tightening activity. Borg CR-10 has been validated and shown to be a reliable tool for assessing perceived exertion in various physical task settings [22]. Additionally, the Bonferroni correction was applied to adjust the alpha level due to the multiple comparisons conducted across nine body regions. This adjustment was utilized to control the Family-Wise Error Rate, ensuring a robust statistical inference.

2) *Rapid Upper Limb Assessment:* To determine the risk level of MSD, the Rapid Upper Limb Assessment (RULA) was conducted during task simulations, which is depicted in Figure 5. RULA is an ergonomic tool developed to evaluate the exposure of individual workers to ergonomic risk factors associated with upper extremity MSD and uses a systematic process to evaluate required body posture, force, and repetition for the job task [23]. This ergonomic tool was selected due to its capability to evaluate upper limb risks in tasks involving repetitive arm movements and awkward postures, mainly in manufacturing sector [24], [25]. In this study, participants' postures were recorded, and the joint angles were measured with angle-detection software shown in Figure 5b. The software will automatically calculate the angle at critical joints, such as shoulder, elbow, wrist, trunk, and knee. These measured angles were subsequently transferred to the RULA worksheet.

The RULA scoring process could be expressed in the simplified mathematical equations, although the

original method is based on categorical scoring tables [23].

$$W_A = f_A(\alpha, \beta, \gamma) \quad (1)$$

$$S_A = W_A + \mu + \lambda \quad (2)$$

$$N_B = f_B(\theta, \phi, \delta) \quad (3)$$

$$S_B = N_B + \mu' + \lambda' \quad (4)$$

$$RULA\ score = f_C(S_A + S_B) \quad (5)$$

W_A is the arm and wrist analysis in Table A, which represents the combined score of the upper limb postures. It consists of upper arm (α), lower arm (β), and wrist (γ) scores. Additionally, N_B, which is the postural scores in Table B, represents the combination of neck postures (θ), trunk (ϕ), and legs (δ) scores. The adjustments for muscle use and load are both denoted by μ and λ respectively in total score A (S_A) and score B (S_B). Final RULA score is a function of *fc* that consists of the combination between S_A and S_B, which is mapped from a standardized reference table C. The MSD risks ranged from 1 (acceptable risk) to 7 (high risk), indicating the urgency of ergonomic intervention [23].

3) *Acceptability and Safety Perception Questionnaire:* A custom comfort questionnaire was used as a quick-check tool to evaluate the perceived comfort and general acceptance of the imported exoskeleton prototype among participants. The questionnaire consisted of ten binary questions (see Figure 6), covering aspects such as ergonomic outcome, muscle effort, workplace fit, task efficiency, motion support, overall comfort, ease of setup, physical load, safety, and subjective assistance. To ensure content clarity and relevance, the questionnaire underwent face validity review by two subject-matter experts in human factors. For analysis, responses were summarized using frequency distributions (%) for each question, which allows a direct comparison of positive and negative user perceptions.

Questions	Answer	
	Yes	No
Does the exoskeleton help me avoid risky postures?	☐	☐
Does the exoskeleton reduce my muscle effort?	☐	☐
Can the device be adapted to the work environment (e.g. car assembly line)?	☐	☐
Can I perform my tasks quickly while using the device?	☐	☐
Does the device allow me to move naturally?	☐	☐
Is the device comfortable to wear during work?	☐	☐
Is the device easy to don and doff?	☐	☐
Is the weight of the device acceptable for daily use?	☐	☐
Do I feel safe while using the device?	☐	☐
Do I feel supported by the device during the task?	☐	☐

Figure 6. Acceptability and Safety Perception Questionnaire

4) *Data Analysis:* The Shapiro-Wilk normality tests were conducted to check the differences for all paired datasets including RULA, Borg CR-10, and task completion and post-recovery time due to its capability and robustness to check the normal distribution for small sample sizes (n < 50). The key findings for normality analyses were:
   - If the normality test revealed a non-significant result ($p \geq 0.05$), indicating that the differences are normally distributed. Then, the paired-*t* test will be utilized for continuous data and Wilcoxon Signed-Rank for ordinal data.
   - Otherwise (p < 0.05), indicating that the differences are not normally distributed. The Wilcoxon Signed-Rank Test will be utilized to determine the significance of the results.

Due to the ordinal nature of RULA and Borg CR-10, median values were used for analysis. For RULA, the median score across the three repetitions was calculated to represent each participant's postural risk condition. Borg CR-10 ratings were collected once after completion of each experimental condition and used to represent perceived exertion per condition. All statistical calculations compiled in Excel and were analyzed using SPSS software.

III. RESULTS AND DISCUSSION

After conducting the experiment, data analysis was done to analyze the effectiveness of exoskeletons using both objective and subjective measurements. Participants were asked to share their perspective about the usability of shoulder support exoskeleton during the assembly simulation.

A. Task Completion and Post-task recovery time

Normality tests were performed to check the task completion and post-task recovery time. It revealed that both task completion and post-task recovery times are not normally distributed (p < 0.05), therefore a Related-samples Wilcoxon Signed-Rank Tests were performed.

Table 1. Statistics for Task Completion and Recovery Times

Variable (Cond. A vs Cond. B)	W	Z	*p*
Task Completion	7.00	-2.09	0.037
Post-recovery time	9.00	-1.599	0.110

Table 1 demonstrates a summary of the Related-samples Wilcoxon Signed-Rank Test. According to the table, a statistically significant result is shown in task completion time following the use of the shoulder support exoskeleton. By looking at the average of total assembly time, it decreased from 127.13 s to 109.83 s for 36 bolts. This reflects a reduction of 13.% in task completion time, highlighting the exoskeleton's potential to enhance workflow efficiency in repetitive manual operations. In contrast, the statistics showcases a non-significant result in terms of post-task recovery time (p = 0.110), indicating no

differences between both conditions. Although the Wilcoxon signed-rank test indicated no significant result, a noticeable decrease is shown under the exoskeleton condition (t_2 = 204.12 s) compared to the baseline condition (t_1 = 252.25 s), indicating a 19.08% reduction in recovery time. This suggests a potential benefit for post-task physical recovery. The lack of significance is likely due to the small sample size (n = 10) and inter-individual variability in biomechanical recovery responses.

B. Borg CR-10

A summary of Borg CR-10 normality test is depicted in **Table 2**. Based on Table 2, some of the body regions are not normally distributed, thus Wilcoxon Signed-Rank tests were performed.

Table 2. Normality Test of Borg CR-10

Body Parts	W	df	*P*
Neck	0.640	10	< 0.001
Shoulder	0.904	10	0.245
Elbow	0.949	10	0.645
Wrist	0.847	10	0.053
Upper Back	0.751	10	0.004
Low Back	*	10	*
Hips	0.366	10	< 0.001
Knee	*	10	*
Ankle/foot	0.366	10	< 0.001

Table 3. Wilcoxon rank Test Borg CR-10

Body Parts	Cond. A (Q1-Q3)	Cond. B (Q1 – Q3)	Z	*P*
Neck	0.5 (0.0 – 3.0)	0.0 (0.0 – 3.0)	-1.00	0.317
Shoulder	3.0 (0.0 – 6.0)	3.0 (0.0 – 6.0)	-0.24	0.810
Elbow	2.0 (0.0 – 6.0)	1.0 (0.0 – 5.0)	-1.02	0.306
Wrist	3.0 (2.0 – 5.0)	2.0 (0.0 – 3.0)	-2.21	0.027
Upper Back	0.0 (0.0 – 1.0)	0.0 (0.0 – 2.0)	-0.82	0.414
Low Back	0.0	0.0	0.00	1.000
Hips	0.0 (0.0 – 1.0)	0.0 (0.0 – 2.0)	-1.00	0.317
Knee	0.0	0.0	0.00	1.000
Ankle/ foot	0.0 (0.0 – 1.0)	0.0 (0.0 – 2.0)	-1.00	0.317

The descriptive statistics, presenting the Median and Interquartile Range, along with the results of the Wilcoxon signed-rank test for Borg CR-10 scores are summarized in Table 3. To account for the risk of Type I errors due to multiple comparisons, a Bonferroni correction was applied, shifting the significant threshold to $\alpha = 0.0055$.

The analysis revealed an overall downward trend in perceived exertion in Condition B, which is assisted activities. The most prominent reduction was observed in the wrist region, where the median score decreased from 3.0 (moderate) to 2.0 (weak). While this change indicated a notable trend toward improvement (p = 0.027), the score did not reach statistical significance under the new Bonferroni's threshold. Similarly, the elbow region showed a decrease in median exertion from 2.0 (weak) to 1.0 (very weak), while the neck region showed a slight reduction from 0.5 (extremely weak) to 0.0 (nothing at all). In contrast, the median of exertion for shoulder region remained stable with a score of 3.0 (moderate) in both conditions. This suggests that while the shoulder exoskeleton provided distal support, the physical load on the shoulders remained unchanged during the task. Furthermore, lower body regions including low back, hips, knees, and ankles, reported consistently low exertion 0.0 in both conditions.

C. Rapid Upper Limb Assessment Results

Following the analysis of muscle exertion, a Rapid Upper Limb Assessment (RULA) was conducted to further identify the associated risk level during the simulated task under both conditions. During the measurements, the load of the exoskeleton was also considered in evaluating the load scores for the neck, trunk, and legs. The medians of RULA scores from each participant are shown in Table 4. Although the differences did not violate normality assumption (p = 0.172), RULA scores were treated as ordinal; therefore, the Wilcoxon Signed-Rank test was applied.

Table 4. Summary of RULA Median Scores

Subject	Cond. A	Cond. B
1	7	5
2	7	6
3	7	7
4	7	5
5	6	4
6	7	6
7	7	5
8	7	6
9	7	4
10	7	5

Based on the final RULA scores summarized in Table 4, participants experienced a notable reduction in postural risk during assisted simulation task. The median of RULA score in Condition A is 7, which corresponds to a high level of MSD risk requiring immediate investigation and change. In contrast, the median in Condition B decreased to 5.5, indicating a shift to moderate risk level, suggesting that the use of the exoskeleton helps in improving upper limb posture during the simulated assembly task. A Wilcoxon Signed-Ranked then revealed a highly significant result ($Z = -4.287$, $p < 0.001$) in RULA scores between the two conditions. These findings demonstrate that the

implementation of the exoskeleton can significantly reduce postural strain, as quantified through RULA, and therefore mitigate MSD risks in repetitive upper limb tasks.

D. Acceptability and Safety Perception Questionnaire

After completing all stages of the simulation, participants were asked to fill out a questionnaire to evaluate the general acceptability and safety perceptions using the exoskeleton device, which is illustrated in Figure 7. Results indicated high positive responses in task efficiency (90%), subjective assistance (90%), workplace fit (80%), and motion support (80%). Moderate scores in ergonomic outcomes which represent the risk posture prevention (60%), muscle effort reduction (50%), and the exoskeleton load (50%) suggest areas for design enhancement. Comfort (70%) and perceived safety (70%) were generally favorable but highlight user concerns requiring further improvement according to the local anthropometric data. Ease of donning and doffing has a score of 70%, emphasizing the potential to optimize device usability in time-sensitive situations. These results provide a robust baseline metric for exoskeleton adoption, reflecting its targeted advancement to enhance safety and user satisfaction in elevated task environments.

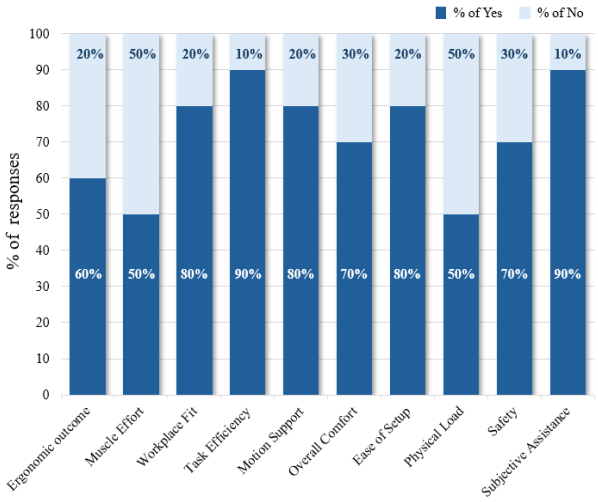

Figure 7. Summary of Acceptability and Safety Perception Questionnaire Result

E. Discussion

Overall, the results demonstrate the beneficial impact of shoulder support exoskeleton to reduce the MSD risks during semi-overhead assembly tasks. The significant reduction in task completion time and post-task recovery time aligns well with prior research by Maurice *et al*. [13], which reported a 3% decrease in the task-completion time for an overhead precision task wearing an exoskeleton. Similarly, Kim *et al.* [26] found a 20% reduction in the duration of a drilling task with an exoskeleton. In contrast, a study revealed there is no differences in the task completion time without exoskeleton, instead increased the duration to complete static holding M12 nut with a spanner and flexed elbow and shoulder [14]. The study indicates that the efficacy of exoskeletons may be task specific. Tasks involving static or constrained posture may limit the benefexoskeletonkeleton, underscoring the need to evaluate such technologies across varied occupational activities. This is also due to the originality of the passive exoskeleton itself which stores and releases mechanical energy to provide dynamic support. Additionally, the average post-recovery time, which the duration required for participants to no longer feel pain or discomfort after the simulated activities, also showed a notable reduction. The marked decrease in average post-recovery time further supports the exoskeleton's effect in accelerating physical recovery. This feature is critical in industrial environments, where minimizing downtime between repetitive tasks can help maintain worker productivity and reduce the risk of cumulative musculoskeletal strain.

In addition, in terms of physiological perspective, this study revealed a contradictory result with some previous studies. For instance, a study by Van Engelhoven *et al.* [18] noted while the activity of the primary shoulder muscles (e.g., anterior deltoid and upper trapezius) decreased by up to 54%, antagonist muscle activity increased by 22% to maintain shoulder stability and balance in a study of combination of ShoulderX V1 arms and ShoulderX V2 torso frame. This complexity is reflected in the current subjective data; while the shoulder remained stable in median exertion score of 3.0 (moderate) in both conditions, the wrist region showed a notable reduction from moderate to weak. Although this reduction in wrist region did not meet statistical significance criteria after Bonferroni correction, the shift in median values and the reduction in maximum reported score 5.0 to 3.0 suggest a practical significance in reducing distal effort.

Another finding is further revealed the usage of passive DeltaSuit exoskeleton which reduced the muscle activity up to 56% in the Trapezius Descendens and 64% in the deltoid during working with arms over shoulder level [27]. The participants also have no experienced in physical discomfort on their upper or lower back, since the erector spinae and latissimus dorsi muscles were not significantly affected by exoskeleton [28]. While this shift in muscles activity results in increased load on certain shoulder muscles, causing a slight rise in shoulder discomfort. The balance between reduced agonist muscle activity and increased antagonist activation is important for preventing fatigue and improving posture, but the alignment of exoskeleton can oppose natural muscle action in certain postures due to improper adjustments, design limitations, movement efficiency, and muscle overload [17].

Users' feedback on acceptability and safety perceptions further illustrates the interaction between hardware performance and user experience. The generally positive reports on mobility support and ease of donning and doffing indicate high potential for practical adoption in industrial settings, consistent with observations by Van Engelhoven *et al.* [18]. Another systematic review highlights the heterogeneity in subjective measurements yet consistently

finds that comfort, ease of use, perceived exertion, and fatigue are key factors influencing user acceptance of shoulder support exoskeletons. Masood *et al.* [29], in the Groupe PSA study, reported that participants valued comfort attributes such as fit, freedom of movement, and prolonged wearability. Furthermore, Baldassarre *et al.* [30] in their systematic review noted that while passive exoskeletons reduced perceived exertion and improved comfort in static or repetitive tasks, some users cited moderate usability challenges in dynamic tasks. Nonetheless, many users reported enhanced endurance and decreased shoulder discomfort, reinforcing acceptance in specific task contexts.

IV. CONCLUSION

This study demonstrates that the implementation of a passive shoulder-support exoskeleton was associated with a substantial reduction in perceived muscle effort, particularly in the wrist region, during repetitive elevated assembly tasks. In addition, the exoskeleton was associated with a reduction in postural risk, as evidenced by a decrease in the RULA score from 7 (high risk) to 5.5 (medium risk), suggesting an improvement in occupational postural safety. Task efficiency also improved under the exoskeleton condition, as demonstrated by a 13.6% reduction in task completion time. Although a decreasing trend in post-recovery time was noted by 19.08%, this change was not statistically significant. Furthermore, subjective evaluations revealed generally positive user perceptions regarding postural support, reduced muscular exertion, and enhanced mobility, notwithstanding several reported usability concerns. Overall, these findings suggest that passive shoulder-support exoskeletons have the potential to enhance worker safety, comfort, and task efficiency in repetitive elevated assembly tasks. However, further studies involving longer-term use and a more diverse worker population are recommended to confirm these findings and evaluate long-term applicability.

FUTURE WORKS

This study has several limitations. The relatively small sample size (n = 10) consisting of young adults may limit generalizability of the findings to an actual industrial population due to its aim as a preliminary study of the passive exoskeleton adoption in developing countries, especially Indonesia. Short-term simulation also may not capture long-term musculoskeletal prevalence that might occur in real work settings. As an initial investigation of passive shoulder exoskeleton effectiveness towards repetitive activities, future studies should involve larger and more representative samples of automotive assembly workers and draw on local anthropometric databases. Further product design refinement is also essential to better accommodate Indonesian anthropometric diversity, ensuring improved ergonomic fit and user comfort across diverse user populations. Moreover, integrating the standardized psychometric questionnaire such as Usability, Satisfaction, and Ease of Use (USE) questionnaire with physiological measures such as Electrical Impedance Tomography (EIT) [31], [32] is strongly recommended to provide muscle activity mapping and user acceptance of the localized exoskeleton device, offering deeper insights into exoskeleton's biomechanical impact and guiding targeted improvements.

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