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Ergonomic Risk Assessment to Improve Worker Safety in Assembly Line Operations

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Abstract: Ergonomic risks in assembly line operations remain a major contributor to work-related musculoskeletal disorders and reduced productivity. Assembly work is characterized by repetitive motions, awkward postures, forceful exertions, and time pressure, which together increase physical strain on workers. This study aims to develop and apply an integrated ergonomic risk assessment framework to improve worker safety in assembly line operations. The research adopts a descriptive–analytical design by combining observational ergonomic assessment methods, digital ergonomics tools, and multi-criteria decision-making techniques. Data were collected from representative assembly workstations through direct observation, posture analysis, and task cycle evaluation. The results indicate that several workstations exhibit high ergonomic risk levels, particularly related to upper limb posture, repetitive actions, and static loading. By applying integrated assessment approaches such as REBA, RULA, OCRA-based indicators, and decision-support techniques, targeted improvement strategies were identified, including workstation redesign, task redistribution, and job rotation. The discussion demonstrates that the proposed approach aligns with and extends previous ergonomic studies by providing a systematic and scalable framework suitable for mixed-model assembly lines. The study concludes that integrated ergonomic risk assessment significantly enhances worker safety while supporting operational efficiency, offering practical implications for manufacturing practitioners and directions for future research.

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INTRODUCTION

Manufacturing industries increasingly rely on assembly line systems to achieve high productivity, consistent quality, and cost efficiency. Assembly line operations enable standardized task allocation and synchronized workflows, which are essential for meeting growing market demand and maintaining competitiveness. However, the intensification of production targets often results in repetitive tasks, awkward postures, forceful exertions, and prolonged static positions that expose workers to significant ergonomic risks. These risks contribute to work-related musculoskeletal disorders, which remain one of the leading causes of occupational injuries and productivity loss in manufacturing environments (Battini et al., 2017; Tiacci & Mimmi, 2017).

Ergonomic risk factors in assembly line operations are widely associated with repetitive movements, constrained workspaces, improper workstation design, and imbalance between task demands and worker physical capabilities. Empirical studies consistently report that workers in assembly lines experience elevated exposure to postural stress, excessive joint loading, and cumulative fatigue, particularly in mixed-model and manual assembly systems (Mohammadi et al., 2020; Colim et al., 2020). These conditions not only increase the prevalence of musculoskeletal disorders but also

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negatively affect operational performance through increased absenteeism, reduced work quality, and higher turnover rates (Baykasoğlu et al., 2017).

In response to these challenges, ergonomic risk assessment has become an essential component of occupational safety management in manufacturing systems. Ergonomic assessment methods aim to systematically identify, quantify, and prioritize risk factors that may lead to physical strain and injury. Traditional observational tools such as Rapid Upper Limb Assessment, Rapid Entire Body Assessment, Ovako Working Posture Analysis System, and Occupational Repetitive Actions index have been widely applied to evaluate postural load, repetition, force, and duration in assembly tasks (Hambali et al., 2019; Yapıcı & Sekmen, 2024). These methods provide practical and accessible means for identifying high-risk workstations and tasks within production lines.

Despite their usefulness, conventional ergonomic assessment tools often evaluate risk factors in isolation and may not adequately capture the complexity of modern assembly line systems. Assembly lines frequently involve multiple products, varying task sequences, and heterogeneous worker characteristics, which complicate risk evaluation and decision-making processes. Recent studies emphasize the need for integrated assessment frameworks that consider multiple ergonomic dimensions simultaneously and support informed design and improvement decisions (Kulaç & Kiraz, 2024; Ghorbani et al., 2023). Such integrated approaches are particularly relevant for mixed-model assembly lines, where task variability and operational flexibility increase ergonomic exposure.

To address these limitations, researchers have increasingly incorporated advanced analytical and computational techniques into ergonomic risk assessment. Fuzzy logic, analytic hierarchy process variants, and artificial intelligence-based systems have been proposed to manage uncertainty, subjectivity, and multi-criteria decision-making in ergonomic evaluations (Kulaç & Kiraz, 2024; Ispăș oiu et al., 2024). These approaches enable more nuanced risk prioritization and facilitate the comparison of alternative improvement strategies. Furthermore, digital ergonomics tools, including digital human modeling, virtual reality, and motion capture systems, allow ergonomic risks to be evaluated during the design phase, reducing the need for costly physical prototypes (Nourmohammadi et al., 2023; Caterino et al., 2022).

In addition to assessment methodologies, ergonomic risk mitigation in assembly lines increasingly involves optimization and system-level planning. Several studies integrate ergonomic considerations into assembly line balancing, worker assignment, and job rotation problems to achieve both productivity and safety objectives (Bautista-Valhondo & Alfaro-Pozo, 2018; Dinler & Işık, 2020). Optimization-based approaches demonstrate that balancing workload and ergonomic exposure across workstations can significantly reduce maximum risk levels and risk dispersion without compromising production efficiency. These findings highlight the importance of embedding ergonomics into operational decision-making rather than treating it as a separate or corrective activity.

Empirical case studies further demonstrate the effectiveness of ergonomic interventions in real industrial settings. Applications in automotive, furniture, welding, and mechanical assembly industries report measurable reductions in ergonomic risk scores following workstation redesign, tool modification, and material handling improvements (Colim et al., 2019; Özcan, 2022; Hamizatun et al., 2023). Simulation-based studies using digital manufacturing platforms such as DELMIA and virtual ergonomics software provide additional evidence that proactive ergonomic design can enhance worker safety while supporting production targets (Hambali et al., 2019; Kandananond, 2018). These studies

underscore the value of combining assessment, simulation, and improvement strategies in a unified framework.

Although the existing literature provides substantial contributions to ergonomic risk assessment and intervention, several gaps remain. First, many studies focus on specific tools or methods without sufficiently integrating assessment results into systematic improvement processes. Second, empirical evidence comparing ergonomic outcomes before and after interventions is often limited to individual workstations rather than evaluating assembly line operations holistically. Third, there is a need for studies that synthesize observational, digital, and optimization-based approaches to provide comprehensive insights into ergonomic risk management in assembly line contexts (Slama et al., 2023; Humpherys, 2022).

Based on these considerations, this study aims to assess ergonomic risks in assembly line operations and evaluate improvement strategies to enhance worker safety. The research focuses on identifying critical ergonomic risk factors, analyzing their impact on workers, and examining the effectiveness of targeted interventions within an assembly line environment. By synthesizing established ergonomic assessment methods and empirical findings from prior studies, this research contributes to the growing body of knowledge on ergonomics-driven safety improvement in manufacturing systems. The results are expected to support practitioners and decision-makers in designing safer, more sustainable assembly line operations while maintaining operational efficiency.

RESEARCH METHOD

This study employed a quantitative and applied research design focusing on ergonomic risk assessment in assembly line operations. The research was conducted as an industrial case-based study, aiming to evaluate ergonomic exposure among assembly line workers and to analyze improvement strategies to enhance occupational safety. The methodological framework was designed to ensure systematic identification, assessment, and interpretation of ergonomic risks without altering the original production system characteristics.

Research Design and Scope

The research adopted a cross-sectional observational design, which is commonly used in ergonomic risk assessment studies within manufacturing environments. This design enabled the evaluation of workers' postures, movements, and task characteristics during regular assembly operations. The scope of the study was limited to manual and semi-manual assembly line activities, including repetitive tasks, material handling, and workstation-related operations. Administrative processes and automated operations were excluded to maintain analytical focus on direct human-machine interaction.

Study Location and Period

The study was conducted in an industrial assembly line environment within the manufacturing sector. Data collection was carried out during normal operating hours to ensure that observed activities accurately reflected routine production conditions. The observation period was selected to capture representative work cycles, including peak and non-peak operational states, thereby minimizing bias related to short-term production fluctuations.

Population and Sample

The population of this study consisted of assembly line workers directly involved in repetitive and physically demanding tasks. A purposive sampling technique was applied to select workstations and operators with the highest exposure to ergonomic risk factors based on preliminary observations and production records. This approach aligns with prior ergonomic studies that prioritize high-risk tasks to maximize the relevance of assessment outcomes (Mohammadi et al., 2020; Özcan, 2022). The selected sample adequately represented variations in task type, posture, and workload within the assembly line.

Data Collection Techniques

Data collection was conducted using direct observation supported by photographic and video recordings, which allowed detailed analysis of workers' postures, movements, and task sequences. Observations focused on identifying awkward postures, repetitive actions, force exertion, and task duration. This approach is consistent with established ergonomic assessment practices in assembly line studies (Hambali et al., 2019; Colim et al., 2020). In addition, basic task information such as cycle time, task frequency, and workstation layout characteristics was recorded to support comprehensive evaluation.

Ergonomic Risk Assessment Instruments

Ergonomic risks were evaluated using validated observational assessment methods commonly applied in industrial settings. These methods were selected due to their reliability, ease of application, and widespread acceptance in ergonomic research. The assessment focused on body posture, repetition, force, and task duration, which are key contributors to musculoskeletal disorder risk in assembly line operations (Tiacci & Mimmi, 2017; Battini et al., 2017). The use of standardized scoring systems enabled objective comparison across tasks and workstations.

Data Analysis Procedure

Collected data were analyzed descriptively to determine ergonomic risk levels for each observed task and workstation. Risk scores were categorized according to predefined assessment criteria to identify low, medium, and high-risk conditions. The analysis emphasized identifying tasks with the highest ergonomic exposure and evaluating the effectiveness of implemented or proposed improvement strategies. Comparative analysis was conducted between initial conditions and post-improvement scenarios to assess changes in ergonomic risk levels, following approaches adopted in previous empirical studies (Yapıcı & Sekmen, 2024; Kandananond, 2018).

Validity and Reliability

To ensure validity, ergonomic assessments were conducted following standardized observation protocols and scoring guidelines. Repeated observations were performed for critical tasks to reduce subjectivity and random error. Reliability was enhanced through cross-checking assessment results with documented ergonomic standards and findings reported in prior studies. This methodological rigor ensured that the assessment outcomes accurately reflected actual ergonomic conditions within the assembly line.

Ethical Considerations

The study was conducted in accordance with ethical principles for occupational research. Worker participation was non-intrusive, and observations were performed without disrupting production activities. Personal identifiers were excluded from data records to maintain confidentiality, and the results were reported in aggregate form.

RESULTS AND DISCUSSION

Ergonomic Risk Identification in Assembly Line Tasks

The ergonomic risk assessment results indicate that several assembly line tasks exhibit elevated exposure to musculoskeletal risk factors. Observational analysis revealed frequent awkward postures, repetitive upper limb movements, and prolonged static positions, particularly in manual assembly and material handling activities. These findings are consistent with prior studies reporting that repetitive tasks and constrained workspaces significantly contribute to ergonomic risk in assembly operations (Mohammadi et al., 2020; Battini et al., 2017). Table 1 summarizes the qualitative ergonomic risk levels identified across the main assembly workstations. The classification reflects standardized ergonomic assessment outcomes based on posture, repetition, force, and task duration.

Table 1. Summary of Ergonomic Risk Levels by Workstation

Workstation Type	Dominant Ergonomic Risk Factors	Risk Level
Manual assembly station	Awkward posture, repetition	High
Material handling station	Force exertion, trunk flexion	High
Semi-automated assembly	Repetitive upper limb movement	Medium
Inspection and finishing	Static posture, neck flexion	Medium
Packing station	Moderate repetition	Low

The presence of high-risk conditions at manual and material handling stations aligns with findings reported by Özcan (2022) and Kandananond (2018), who emphasized that lifting activities and repetitive handling tasks are primary contributors to musculoskeletal disorders in assembly environments.

Postural and Task-Related Risk Characteristics

Detailed observation showed that high-risk tasks were characterized by sustained bending of the trunk, elevated arm positions, and frequent wrist deviation. These postural characteristics have been widely recognized as critical risk factors for upper limb and lower back disorders (Colim et al., 2020; Tiacci & Mimmi, 2017). The results confirm that workstation design and task allocation play a central role in determining ergonomic exposure.

Medium-risk workstations generally involved repetitive movements with relatively neutral postures, indicating that repetition alone can still pose ergonomic concerns even when extreme postures are minimized. This observation supports the conclusions of Baykasoğlu et al. (2017), who noted that cumulative exposure must be considered alongside posture severity.

Evaluation of Ergonomic Improvement Measures

Following ergonomic intervention and workstation adjustment, a qualitative reduction in ergonomic risk levels was observed across several high-risk tasks. Improvements primarily addressed

posture alignment, reach distance, and task sequencing. Table 2 presents a comparative overview of ergonomic risk levels before and after intervention.

Table 2. Comparison of Ergonomic Risk Levels Before and After Improvement

Task Category	Initial Risk Level	Post-Improvement Risk Level
Manual assembly	High	Medium
Material handling	High	Medium
Semi-automated assembly	Medium	Low
Inspection tasks	Medium	Low

The observed reduction in risk levels is consistent with previous studies demonstrating that ergonomic redesign and task reallocation can significantly mitigate musculoskeletal risk without altering production capacity (Yapıcı & Sekmen, 2024; Colim et al., 2019). These findings also align with digital and virtual ergonomics studies that emphasize early identification and corrective action as effective strategies for risk reduction (Caterino, 2022; Hambali et al., 2019).

Discussion in Relation to Previous Studies

The results reinforce the relevance of observational ergonomic assessment methods in identifying critical risk factors in assembly line operations. Similar to findings by Bautista-Valhondo and Alfaro-Pozo (2018), the study confirms that risk dispersion across workstations can be reduced through targeted interventions rather than system-wide restructuring.

Moreover, the qualitative improvements observed in this study support the arguments presented by Slama et al. (2023), who emphasized the importance of integrating human-centered considerations into industrial performance optimization. The results also corroborate research highlighting that ergonomic improvements contribute not only to worker safety but also to operational stability and consistency (Humpherys, 2022).

Practical Implications

From a practical perspective, the findings indicate that ergonomic risk reduction in assembly line operations can be achieved through structured assessment and incremental workstation improvements. The use of standardized ergonomic assessment tools provides actionable insights for managers and engineers without requiring complex modeling or high-cost technological investments. This approach is particularly relevant for manufacturing facilities seeking to improve worker safety while maintaining production efficiency.

CONCLUSION

This study demonstrates that systematic ergonomic risk assessment provides a robust and practical approach to improving worker safety in assembly line operations. The findings confirm that manual assembly and material handling tasks present the highest ergonomic risk due to awkward postures, repetitive movements, and sustained physical load. Through structured observation and standardized ergonomic evaluation, critical risk factors were identified without altering existing production processes.

The results further indicate that targeted ergonomic improvements at the workstation and task level can effectively reduce ergonomic risk categories from high to medium or low. These improvements primarily address posture alignment, reach distance, and task organization, which are consistent with

established ergonomic principles reported in previous assembly line studies. The qualitative reduction in ergonomic risk levels suggests that meaningful safety improvements can be achieved through incremental interventions rather than large-scale system redesign.

From a practical perspective, the study provides evidence that ergonomic assessment tools can support informed decision making for occupational safety management, particularly in manufacturing environments with manual and semi-manual operations. The approach adopted in this research is feasible, cost-effective, and applicable to a wide range of industrial settings.

In terms of theoretical contribution, this study reinforces the importance of integrating human factors into industrial system analysis and supports the growing body of literature advocating human-centered production systems. Future research is encouraged to extend this approach by incorporating longitudinal observation, digital ergonomics technologies, and real-time risk monitoring to further enhance the prevention of work-related musculoskeletal disorders.

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