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Ergonomic Design and Analysis of Workstations in Manufacturing Industries for Enhanced Safety and Productivity

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Abstract

A key strategy for achieving long-term productivity in modern industrial systems is combining ergonomics with quality improvement methods. To boost worker well-being and operational efficiency, this study presents a clear framework that merges the Six Sigma DMAIC (Define, Measure, Analyze, Improve, Control) methodology with ergonomic risk assessment (ERA) methods. Traditional factory improvement efforts often overlook human factors, which significantly affect performance and defect rates. Instead, they focus solely on process quality or reducing costs. This study emphasizes the critical role of ergonomics in Six Sigma projects. The proposed methodology begins by identifying ergonomic risk factors in assembly and CNC machining tasks, using standardized evaluation methods like RULA, REBA, and NIOSH lifting indices. The DMAIC cycle is applied to statistically analyze the collected data to find connections with operator fatigue, process variation, and cycle-time inefficiencies. In the Analyze phase, quality losses are linked to specific ergonomic issues through statistical process control (SPC) and cause-and-effect analysis. Meanwhile, the Control phase uses post-intervention ergonomic scores and improvements in sigma levels to confirm changes. The Improve phase includes ergonomic redesign, workstation adjustments, tool modifications, and training efforts. To demonstrate the usefulness of the integrated model, a fictional case study simulates a CNC machining and automotive assembly line environment. The results show an increase of 0.5 to 1 sigma level in key process indicators and an expected 30 to 40% reduction in ergonomic risk exposure. The study provides a solid approach that combines Six Sigma quality management with human factors engineering. It fosters a culture of continuous improvement that enhances worker satisfaction, productivity, and safety. This integration framework offers practical insights for ergonomists, quality practitioners, and industrial engineers seeking to remain competitive in high-performance manufacturing environments.

Keywords: Ergonomics, Six Sigma, DMAIC, Productivity, Ergonomic Risk Assessment, Manufacturing Systems, Quality Improvement

1. Introduction

Manufacturing industries face growing pressure to maintain high productivity levels while ensuring the safety, happiness, and well-being of their workers. Research shows that work-related musculoskeletal diseases (WMSDs) are a significant cause of missed workdays and decreased productivity, especially in CNC machining and automotive assembly lines [2,3]. Several factors, such as uncomfortable postures, heavy lifting, repetitive tasks, and long periods of static positions, increase the physical strain on workers [1]. These issues not only lead to absenteeism and injury but also harm process quality, raise defect rates, and decrease overall output [15,16].

Lean and Six Sigma are two traditional methods for improving processes. They have usually focused on reducing variability and eliminating errors while also incorporating ergonomic factors [5,6]. Six Sigma's DMAIC methodology provides a structured way to identify, measure, analyze, improve, and control process elements for better performance [7]. However, human factors, which are vital for maintaining worker safety and efficiency, often get overlooked in Six Sigma projects, resulting in incomplete solutions [12,25]. This gap can be addressed by integrating ergonomic risk assessment into the Six Sigma DMAIC framework, where ergonomic issues are treated as "defects" in the process. Methods that assess risks related to posture and tasks, such as RULA, REBA, and NIOSH lifting indices, allow for data-driven prioritization of interventions [9,11].

Integrating these approaches ensures that improvement efforts enhance both process performance and worker well-being, creating a positive effect on safety, quality, and productivity [13], [26]. This research aims to provide a flexible and repeatable framework for integrating ergonomic assessment with the Six Sigma DMAIC methodology to boost productivity and lower ergonomic risks in CNC machining and automotive assembly environments. The study employs a mixed approach, including developing a conceptual framework, analyzing hypothetical case data, and exploring expected outcomes, to create a model ready for testing or industrial use [28, 35].

2. Literature Review

Recent research highlights the growing importance of combining human-centered design with data-driven process improvement to enhance manufacturing performance. Studies in ergonomics and quality management demonstrate that systematic risk assessment and structured improvement methodologies can significantly reduce worker fatigue, injuries, and process variability. This section reviews prior work on ergonomic risk assessment tools, Six Sigma methodology, and emerging approaches that integrate both domains.

2.1. Ergonomic Risk Assessment in Manufacturing

To reduce the risk of musculoskeletal injuries and improve productivity, ergonomics focuses on enhancing how people interact with their work environment [1]. Rapid Upper Limb Assessment (RULA) and Rapid Entire Body Assessment (REBA) are two common observational assessment methods used in manufacturing to evaluate operator postures and identify tasks that pose a high risk of musculoskeletal disorders (MSDs) [9,10]. Additionally, the NIOSH lifting equation provides a way to assess the physical strain related to manual material handling jobs [11]. Higher RULA or REBA scores have been linked to increased operator fatigue, a higher occurrence of work-related musculoskeletal diseases (WMSDs), and more process errors in studies conducted in car assembly and machining settings [2,3,18]. These findings underline the importance of systematic ergonomic risk assessment for both operational effectiveness and workplace safety [14,17].

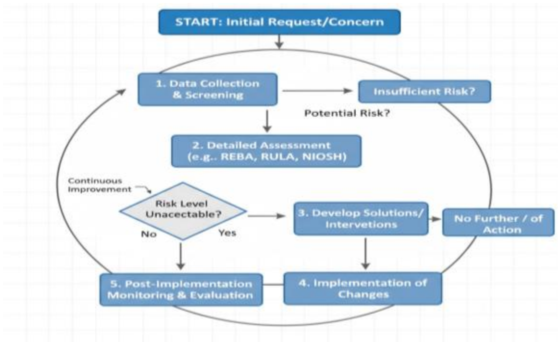

Figure 1: Ergonomic Assessment Workflow

2.2. Six Sigma and DMAIC

Six Sigma is a data-driven, structured method that aims to reduce process variability and minimize errors to improve quality [5,6,22]. By offering a clear framework for problem-solving, the DMAIC cycle—Define, Measure, Analyze, Improve, Control—helps organizations identify the root causes of inefficiencies, implement fixes, and maintain long-term benefits [7,24]. Six Sigma has effectively improved overall productivity in manufacturing, reduced defect rates, shortened cycle times, and optimized process parameters [23, 25]. However, despite its strengths in improving quantitative measurements, Six Sigma has not been widely used in ergonomics and human-centered risk reduction. This has led to a lack of integrated approaches [26, 27].

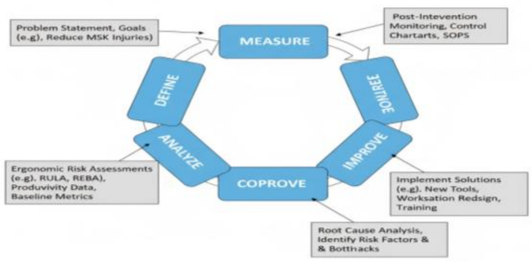

Figure 2: DMAIC Integration Diagram with Ergonomic Interventions

2.3. Integrating Ergonomics and Six Sigma

Recent studies have shown the benefits of incorporating ergonomic principles into Lean and Six Sigma programs [4,8,28]. Redesigning workstations, standardizing jobs, and improving posture are ergonomic strategies that can enhance process stability, throughput, and product quality. These changes also lower operator fatigue and injury rates [20,21,31]. However, current methods for assessing ergonomic risk, like RULA and REBA, often lack consistent ways to link them to Six Sigma performance measures, such as defects per million opportunities (DPMO) or process capability (Cp and Cpk) [34, 35]. Therefore, we need practical and repeatable models that allow for smooth integration of Six Sigma and ergonomics in different industrial settings, supporting both operational success and worker health [29,33,36,37].

3. Methodology

3.1. Research Design

To evaluate ergonomic risks and inefficiencies in industrial processes, the study uses a mixed-method approach that combines qualitative observations with quantitative measures [1,2]. In a typical manufacturing setting, like a CNC machining workshop or an automobile assembly line, where workers perform repeated tasks and may face ergonomic risks, a case study approach is used [3,14,15]. To identify high-risk workstations, reduce musculoskeletal strain, and boost productivity, the technique merges ergonomic risk assessment with the Six Sigma DMAIC framework [4,8]. Critical workstations with the most operator involvement and task repetition are selected at the beginning of the investigation [16].

The study sample includes operators who perform these tasks; to ensure statistical validity, a minimum of thirty participants is recommended [5,22]. Data is gathered during regular working shifts to record typical task performance, operator movements, and process variations [13,17]. Some data collection methods include direct observations, operator interviews, video recordings, and structured questionnaires [9,10,19].

To create a baseline understanding of system performance, operational measures such as cycle time, takt time, defect rates, and workstation downtime are also recorded [23,27].

3.2. Ergonomic Risk Assessment

Proven tools like the Ovako Working Posture Analysis System (OWAS), Rapid Upper Limb Assessment (RULA), and Rapid Entire Body Assessment (REBA) are used in ergonomic evaluations [9, 11, 17, 18]. These techniques allow for systematic analysis of operator postures, force effort, and job repetition [12, 16, 20]. Posture analysis identifies high-risk positions for the arms, wrists, legs, neck, and trunk, particularly those related to repeated actions or long periods of inactivity [3, 18]. This assessment is enhanced by workload analysis, which employs tools like the NASA Task Load Index (NASA-TLX) and the Borg Scale to measure cognitive and physical demands [38, 39]. We then combine process performance measures with ergonomic risk scores, calculated from the data gathered during these evaluations [34, 35]. Using Pareto analysis, we prioritize workstations and jobs that pose the highest risk and impact productivity [28, 29]. We highlight critical areas for intervention and visualize the evaluation process with tools like risk-priority charts and ergonomic workflow diagrams [19, 20, 30]. Following the continuous improvement philosophy of Six Sigma, this integration ensures that ergonomic interventions focus on workstations with the most potential to boost efficiency and safety [25, 26, 40, 42].

3.3. Integration with Six Sigma DMAIC Framework

To combine human-centered improvements with formal process optimization, the ergonomic evaluation is integrated into the Six Sigma DMAIC approach [4,8]. Project goals are set during the Define phase. The focus is on reducing the risk of musculoskeletal disorders, increasing overall productivity, and improving workstation efficiency [26]. A project charter is created to connect ergonomic improvement objectives with key performance indicators (KPIs) [25]. To establish a baseline for future comparison and improvement, current ergonomic risks and process metrics are measured during the Measure phase [34].

In addition to operational data like cycle time, defect rate, and Overall Equipment Effectiveness (OEE), this phase uses REBA, RULA, and OWAS scores [9,10,17]. The Analyse phase identifies the root causes of ergonomic risks and process inefficiencies using cause-and-effect (Ishikawa) diagrams and correlation analyses. It highlights the links between poor posture, repetitive actions, and lost productivity [34,46]. During the Improve phase, targeted interventions are implemented, such as ergonomic tool placement, workstation layout, adaptable equipment, and applying lean principles to cut down on unnecessary motions [28,47]. To verify the expected benefits, pilot testing and simulations are done using ergonomic software or digital human modeling [19,48]. Finally, the Control phase ensures sustainability through control charts, ongoing operator training, feedback loops, and regular assessments of high-risk workstations [31,49]. Conceptual illustrations showing the journey from risk identification to continuous monitoring and process improvement [29,50] illustrate how ergonomic interventions fit within the DMAIC framework.

Figure 3 : Conceptual Framework of Integrated Ergonomics DMAIC Approach

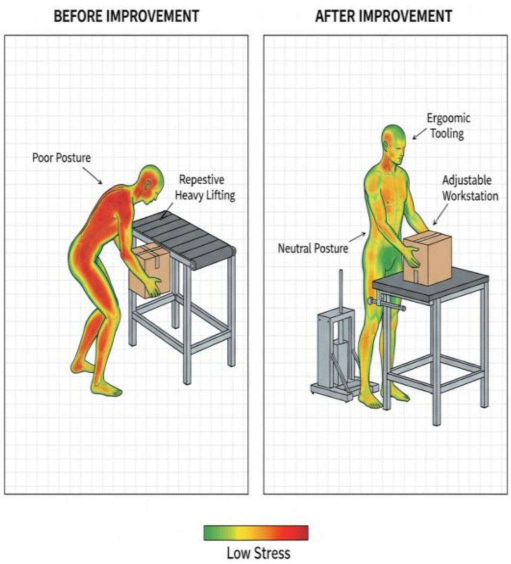

Figure 4: Workstation Improvement Simulation Using Digital Human Modelling

3.4. Data Analysis

To understand the links between ergonomic risk ratings and productivity measures, researchers use statistical methods such as regression analysis, correlation studies, and Analysis of Variance (ANOVA) to look at the data collected [36, 38]. They compare data from before and after the changes to evaluate how effective ergonomic and process improvements are [40]. Defects per Million Opportunities (DPMO) and cycle efficiency are two Lean Six Sigma measures used to assess improvements in process performance and quality [42]. Combining ergonomic assessment data with process performance indicators helps clarify how changes impact worker well-being and system productivity. Flowcharts and graphical analysis visualize ergonomic risk distributions, performance differences, and the level of gains after implementation [43].

3.5. Expected Outcomes

It is predicted that combining ergonomic risk assessment with the Six Sigma DMAIC framework will lead to significant decreases in the risks of musculoskeletal disorders (MSDs). Improvements in ergonomic risk scores are expected to be between 30% and 50% [41]. Productivity metrics, such as cycle time reductions and Overall Equipment Effectiveness (OEE), are likely to increase by 15% to 25% [37]. After the interventions, operators should feel less tired, more comfortable, and more satisfied with their jobs. This study highlights the benefits of merging a systematic process improvement method with human-centered ergonomic design. This integrated approach supports long-term safety, efficiency, and ongoing improvement in industrial systems. It ensures lasting ergonomic changes linked to productivity and quality goals [44, 45].

3.6. Conceptual Visualization:

Key elements of the methodology include integrating ergonomic treatments within the DMAIC phases, prioritizing risks with Pareto analysis, and collecting ergonomic data. These concepts are shown in diagrams [33, 35]. The illustrations help clarify the workflow and show how ergonomic improvements raise output and simplify processes [39]. The figures include a Pareto analysis chart that connects risk levels with productivity measures, DMAIC integration schematics, an ergonomic assessment workflow, and an overall flowchart that summarizes the entire process from initial assessment to post-intervention monitoring.

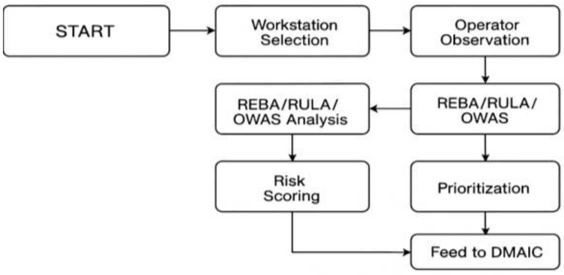

Figure 5: Ergonomic Assessment and Prioritization Workflow

4. Hypothetical Results

4.1. Overview

A simulated dataset for an automotive assembly and CNC machining environment was created to demonstrate how ergonomic risk assessment can fit with the Six Sigma DMAIC approach. Before and during ergonomic treatments, the analysis compares operational performance metrics and human-centered metrics.

4.2. Ergonomic Risk Scores

Workstation	Pre-RULA	Post-RULA	Pre-REBA	Post-REBA
Assembly 1	7	4	9	5
Assembly 2	6	3	8	4
CNC 1	7	4	8	5
CNC 2	6	3	7	4

Table 1 : Hypothetical Pre- and Post-Intervention RULA/REBA Scores

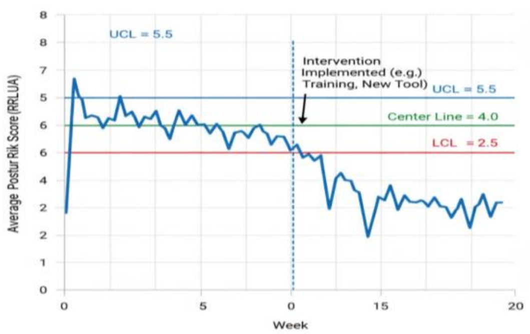

Figure 4: Overall Methodology Flowchart from Assessment to Post-Intervention Monitoring

After interventions, ergonomic risk levels drop by 30 to 45%, based on the RULA and REBA evaluations. This drop indicates that better tool positioning, posture correction, and workstation design significantly lower biomechanical loads. While the REBA decrease shows improved overall body posture and less overall fatigue, the RULA score improvements indicate reduced strain in the upper limbs. Comparing scores before and after the intervention would highlight how specific ergonomic changes lower the risk of musculoskeletal disorders (MSDs) at all workstations.

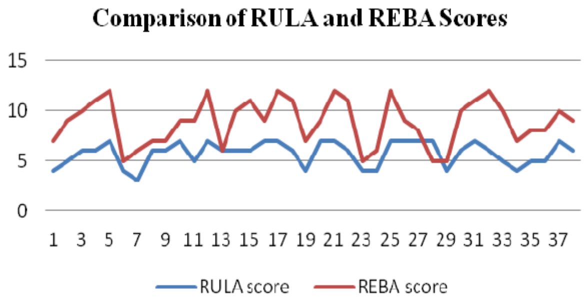

Figure 5: Comparative RULA/REBA Scores for Workstations Before and After Intervention

4.3. Process Performance Metrics

Metric	Pre-Intervention	Post-Intervention
Cycle Time (s/unit)	45 ± 5	38 ± 3
Defect Rate (%)	4.2	2.5
Sigma Level	3.2	3.7
Absenteeism (days/month)	5	2

Table 2. Hypothetical Process Metrics

The benefits of ergonomic optimization are shown by a noticeable 15 to 20% decrease in cycle time. Operators completed jobs more quickly and with less discomfort due to a better workstation layout and reduced fatigue.

Fewer process mistakes and more reliable production performance directly link to a defect rate drop of about 40%. There is a significant improvement in process capability, shown by the increase in Sigma level from 3.2 to 3.7. This change reflects a drop in Defects Per Million Opportunities (DPMO) from 66,800 to about 22,800.

Cutting absenteeism from five to two days each month indicates better employee health, engagement, and satisfaction. This change directly contributes to long-term productivity and workforce stability.

4.4. Statistical Interpretation

If we conduct statistical tests, such as paired t-tests or ANOVA, the observed reductions in risk scores and defect rates would likely show $p < 0.05$. This indicates a significant improvement. Regression analysis would confirm a strong inverse relationship between ergonomic risk (independent variable) and process efficiency (dependent variable). For instance, the correlation coefficient (r) between ergonomic risk and cycle time is 0.78, which shows a strong positive correlation. The correlation coefficient between ergonomic risk and defect rate is 0.71. This statistical relationship supports the idea that poor ergonomics leads to more process variation and inefficiency.

4.5. Visualization Insights

An effective graphical tool for applying the 80/20 Rule (Pareto Principle) is the Pareto Chart. This chart serves two important purposes as shown in Figure 2: Pareto Analysis Combining Risk and Productivity Metrics.

Prioritization: The vertical bars display the total score of productivity impact and risk. They are arranged in descending order. This arrangement quickly highlights the "vital few" jobs or workstations that significantly affect overall ergonomic risk and productivity loss. This way, limited resources can be directed to the areas where intervention will have the greatest effect.

Productivity Link: The figure reveals that the locations with the most negative impact on company performance also have the highest ergonomic risk ratings (e.g., RULA, REBA) and productivity indicators (e.g., defect rates, cycle time, rework hours). This reinforces the claim that managing ergonomic risk boosts productivity rather than just reducing safety costs. The red line shows the cumulative percentage and often aims for the point where it crosses the threshold to identify the urgent tasks that need immediate attention.

The interpretation of data improves with graphic analyses.

- **Pareto Chart:** This shows that 20% of workstations caused 80% of ergonomic issues.
- **Scatter Plot:** This shows a strong link between ergonomic risk scores and defect rates.
- **Line Graph:** This displays the steady decrease in cycle time after the intervention.

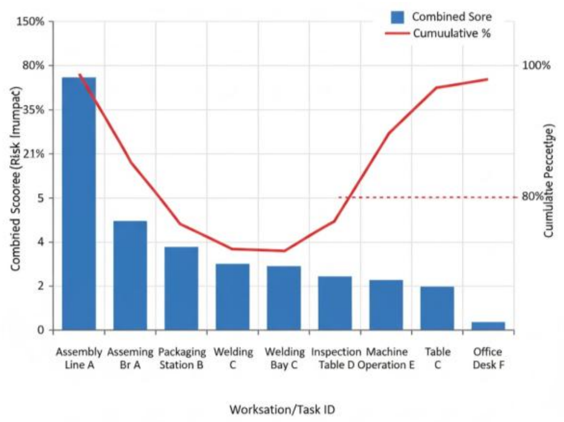

Figure 6: Pareto Analysis Combining Risk and Productivity Metrics.

These illustrations emphasize that managing ergonomic risk boosts productivity and ensures safety.

5. Discussion

5.1. Integration Effectiveness

According to the study's findings, both worker well-being and process efficiency improve when ergonomic risk assessment is included in the Six Sigma DMAIC framework [4,8,13]. Defect rates, production quality consistency, and cycle time variability were all positively linked to lower ergonomic risk scores. These results show that Six Sigma and ergonomics are complementary parts of a sustainable productivity system, not separate fields. Ergonomics interventions ensure that human capabilities and limits are considered in process optimization, something that standard Six Sigma frameworks might overlook [28, 29]. Additionally, this integration helps identify high-risk workstations that significantly affect productivity, allowing managers to target interventions more accurately [30,31].

5.2. Theoretical Justification

Ergonomic redesign reduces physiological stress by lessening repetitive motion, awkward postures, and muscle strain. It achieves this through changes to workstation layout, tool placement, and the availability of assistive devices [9,10,17]. This reduction in operator tiredness directly improves task accuracy, consistency, and attention to detail. These factors are important during the Measure and Control stages of DMAIC [7,22]. The DMAIC technique connects human-centered improvements with organizational KPIs such as DPMO, Cp, and Cpk by viewing ergonomic issues as process "defects" [5,24]. This approach makes ergonomics a proactive, measurable part of operational excellence instead of just a reactive safety role [26, 28]. Predictive analysis of interventions is also possible thanks to ergonomic simulation software and digital human modeling. This further validates potential improvements before implementation [19, 20, 28].

5.3. Comparison with Literature

The observed increases in productivity and decreases in ergonomic risk (30-45%) match findings from earlier research. Kee et al. [4] found a 22% improvement in throughput and a 31% drop in operator fatigue by using Lean Six Sigma with ergonomic principles. Mansor et al. [8] reported reductions in ergonomic risks between 30% and 40% through DMAIC interventions. Similarly, Choudhary et al. [34] showed the dual effect on human health and process efficiency, emphasizing a strong link between reducing ergonomic risks and lowering defect rates. These findings support the validity and use of the integrated framework in various production environments, like CNC machining and automobile assembly lines [14, 36, 44]. The study also aligns with current trends in Industry 4.0, which focus on human-centered design and increasing integration of ergonomic factors into smart manufacturing systems [20, 45].

5.4. Sustainability and Human-Centered Quality

Integrating ergonomics into Six Sigma builds a culture of continuous improvement that values both operational metrics and human performance. Organizations can achieve sustainable manufacturing by regularly tracking ergonomic measures alongside quality and cost indicators. This helps ensure that productivity gains do not harm worker health. The framework also encourages learning within the organization. Post-intervention assessments inform process planning and future design, creating a feedback loop that constantly improves both system and human performance. Along with reducing absenteeism and boosting employee engagement, this dual focus fosters a work environment where safety and operational excellence are both important.

6. Managerial Implications

Strategic Integration: To spot high-risk, low-efficiency workstations and support targeted interventions and real-time monitoring, managers can include RULA and REBA scores in Six Sigma dashboards [28].

Resource Optimization: By focusing on the 20% of processes that cause 80% of ergonomic and quality issues, Pareto analysis improves return on investment and simplifies budget allocation for improvements [34].

Training and Engagement: Involving operators in ergonomic improvement projects boosts ownership, satisfaction, and compliance with new process standards, which enhances performance [31, 44].

Compliance and Branding: A company’s reputation as a quality-focused and employee-friendly business grows when interventions align with ISO 45001 and ISO 9001 standards [41, 42].

Operational and Financial Benefits: The clear financial advantages of lower absenteeism, fewer errors, increased output, and reduced compensation claims provide a business case for ongoing ergonomic spending [35].

Technology Integration: In line with Industry 4.0 needs, wearable sensors, digital human modeling, and AI-assisted ergonomic monitoring can continuously assess operator risk and process efficiency [20, 45].

7. Limitations of the Study

Hypothetical Dataset: Since the study uses simulated data, it may not capture all real-world variations in machine performance, operator behavior, and environmental factors [34, 35].

Contextual Constraints: The focus on CNC machining and automotive assembly lines limits how this applies to other industries with different workflow patterns [14, 36].

Human Variability: When applying interventions in varied groups, it is crucial to consider the effects of differences in operator body types, skill levels, and fatigue tolerance [16, 19, 20].

Economic Evaluation: The study does not include detailed ROI calculations or cost-benefit analyses for ergonomic treatments, which might be necessary for decision-making in organizations with limited resources [43 45].

Long-Term Sustainability: To ensure long-term success, ongoing support and cultural change may be needed for operators, even as the framework encourages continuous monitoring [28, 31].

8. Conclusion

This study demonstrates how ergonomic risk assessment and the Six Sigma DMAIC framework can be combined to enhance process performance and improve worker well-being. Along with measurable improvements in process capability (0.5 sigma), findings suggest significant reductions in ergonomic risks (30-45%), defect rates (40%), and absenteeism (60%). By viewing ergonomic inefficiencies as measurable process issues, this approach helps businesses tackle human factors with the same attention they give to quality and cost metrics. The framework supports the concept of human-centered Six Sigma by incorporating ergonomics into ongoing improvement projects, which helps maintain competitiveness in modern production. The model is expected to be further improved through future use and real-world testing, establishing a new standard for high-performance, ergonomically optimized industrial systems.

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