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(Research Article)

Ergonomic and Automation Based Process Redesign in Industrial Workstations

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Abstract

Industrial workstations play a critical role in determining productivity, worker safety, and overall operational efficiency. Traditional workstation designs often rely on manual processes and fixed layouts, which can lead to musculoskeletal disorders, operator fatigue, and inconsistent production performance. With the increasing demand for high precision manufacturing and sustainable industrial practices, integrating ergonomics with automation has become essential. This paper presents an ergonomic and automation based process redesign framework for industrial workstations aimed at improving worker comfort, reducing physical strain, and enhancing productivity. The proposed approach combines ergonomic risk assessment, task analysis, and selective automation using sensors and control systems. A comparative analysis of pre and post redesign workstation performance is discussed, highlighting improvements in cycle time, error reduction, and worker well being. The results demonstrate that ergonomics driven automation can achieve both human centric and performance oriented manufacturing objectives.

Keywords: Ergonomics; Industrial Automation; Workstation Design; Human-Machine Interaction; Process Optimization

1. Introduction

Industrial workstations are a fundamental component of manufacturing and production systems, as they directly affect productivity levels, worker safety, and long term operational sustainability. In modern industrial environments, increasing production demands, shorter product life cycles, and greater customization have significantly intensified the interaction between human operators and machines. As a result, workstation design has become more complex and critical than ever before. Poorly designed workstations often force workers to adopt awkward postures, perform repetitive motions, or exert excessive physical effort, which can lead to fatigue, reduced task efficiency, and long term musculoskeletal disorders. These human related issues not only impact worker health but also contribute to higher error rates, production delays, and increased operational costs. At the same time, rapid advancements in automation technologies have transformed industrial operations by enabling higher precision, consistency, and throughput. Automation systems such as sensor based tools, assisted material handling, and semi-autonomous workstations offer significant potential to reduce manual workload and improve process reliability. However, when automation is implemented without proper ergonomic consideration, it may introduce new challenges, including increased cognitive load, reduced operator adaptability, and safety risks arising from poor human machine interaction. Therefore, automation alone cannot guarantee optimal performance. This study addresses these challenges by emphasizing the integration of ergonomic principles with automation based process redesign. By aligning human capabilities with technological support, the proposed approach aims to create industrial workstations that enhance productivity while ensuring worker comfort, safety, and sustainable performance.

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1.1. Background and Motivation

The rapid growth of industrial production has intensified the demand for higher output while maintaining acceptable working conditions. In many manufacturing environments, operators are required to perform repetitive tasks, maintain static postures, or handle loads manually for extended periods. These conditions are strongly associated with musculoskeletal disorders, reduced concentration, and productivity decline over time. Despite growing awareness of workplace ergonomics, many industrial systems continue to prioritize output over human comfort. Simultaneously, automation has emerged as a key driver of industrial competitiveness. Automated tools, sensors, and control systems enable faster processing, improved accuracy, and reduced dependence on manual labor. However, automation that is introduced without considering human capabilities and limitations can increase cognitive load, reduce operator trust, and introduce new safety concerns. This disconnect between automation and ergonomics limits the effectiveness of modern industrial systems. The motivation behind this research is to develop a balanced approach that aligns automation with ergonomic principles. By integrating human-centered design into automated workstation planning, industries can achieve sustainable productivity improvements while protecting worker health. This study aims to demonstrate that ergonomics and automation are complementary rather than competing objectives.

1.2. Problem Statement

Traditional industrial workstation designs exhibit several structural and operational shortcomings that negatively affect both workers and production outcomes. Many workstations are fixed in height and layout, failing to accommodate differences in worker body dimensions, strength, and reach. As a result, operators are often forced into awkward postures, leading to physical discomfort and cumulative injury risks. These ergonomic deficiencies contribute to fatigue, absenteeism, and reduced task consistency. In addition to physical strain, conventional workstations rely heavily on manual execution of repetitive and precision dependent tasks. Manual handling increases the likelihood of human error, particularly under time pressure or prolonged operation. Although automation is increasingly adopted to address these inefficiencies, it is frequently implemented with a narrow focus on throughput and cost reduction. Such automation strategies often overlook human machine interaction quality and ergonomic compatibility. Consequently, existing systems either overburden workers or create rigid automated environments that limit flexibility and adaptability. This imbalance results in suboptimal performance and poor long term sustainability. The core problem addressed in this research is the absence of a systematic framework that jointly considers ergonomic risk reduction and automation efficiency in workstation redesign.

1.3. Proposed Solution

To address the identified challenges, this paper proposes an ergonomic and automation-based process redesign framework tailored for industrial workstations. The proposed solution emphasizes selective automation rather than full task replacement, ensuring that machines assist operators in physically demanding or repetitive activities while preserving human decision-making and control. This approach reduces physical strain without compromising flexibility. The framework begins with a detailed ergonomic assessment to identify high-risk postures, excessive force requirements, and inefficient task sequences. Based on this analysis, tasks are restructured using motion optimization and layout redesign principles. Adjustable workstation components, such as height variable tables and repositioned tool placements, are introduced to support neutral working postures. Automation elements, including sensor-guided tools, material handling aids, and semi automated positioning systems, are then integrated to minimize manual load and improve task consistency. Importantly, the redesign prioritizes intuitive human machine interaction to avoid increasing cognitive complexity. By combining ergonomic principles with targeted automation, the proposed solution creates a balanced workstation that enhances productivity, safety, and worker satisfaction simultaneously.

1.4. Contributions

This research makes several significant contributions to the field of industrial engineering and human centered manufacturing. First, it presents a structured and practical framework for integrating ergonomic assessment into automation driven workstation redesign. Unlike traditional approaches that treat ergonomics as a secondary consideration, this framework embeds ergonomic evaluation at every design stage. Second, the study identifies and categorizes key ergonomic risk factors associated with manual industrial tasks, providing actionable insights for redesign planning. Third, it offers a comparative analysis of workstation performance before and after redesign, highlighting measurable improvements in productivity, ergonomic safety, and operational consistency. These results demonstrate the tangible benefits of ergonomics driven automation. Finally, the paper provides implementation guidelines that can be adapted across different industrial sectors, making the proposed approach both scalable and practical. By focusing on human centric automation, this research contributes to the development of sustainable and resilient industrial work systems.

1.5. Paper Organization

The remainder of this paper is organized to present the research in a clear and logical manner. Section II reviews existing literature related to ergonomic workstation design and industrial automation, identifying current trends and research gaps. Section III describes the proposed methodology, including ergonomic assessment, task analysis, and automation integration. Section IV discusses the results and evaluates the effectiveness of the redesigned workstation. Finally, Section V concludes the paper and outlines potential directions for future research.

2. Related Work

Research at the intersection of ergonomics and automation spans decades and draws from ergonomics assessment, workstation layout/design, human robot collaboration (HRC), and sensing monitoring technologies. This section summarizes the most influential streams of work and recent advances that motivate an integrated, ergonomics aware automation framework for industrial workstations. Four complementary subsections follow: (A) ergonomic assessment methods, (B) workstation design and digital human modeling, (C) automation and human–robot collaboration, and (D) wearable sensors and real time monitoring.

2.1. Ergonomic assessment methods (posture and load evaluation)

Ergonomic assessment tools provide the quantitative foundation for identifying high risk tasks and guiding redesign. Classical observational tools such as RULA (Rapid Upper Limb Assessment) and REBA (Rapid Entire Body Assessment) remain widely used because they are quick, require minimal instrumentation, and map observed postures to intervention levels [1], [2]. RULA evaluates neck, trunk and upper limb postures and muscle use to produce an action level score useful for spot assessments in production lines [1]. REBA extends this approach to whole body postures, with particular sensitivity to asymmetric and unpredictable postures common in healthcare and varied industrial tasks [2]. For manual lifting tasks, the Revised NIOSH Lifting Equation (RNLE) provides evidence-based limits and recommended weight limits to reduce low back injury risk; its application manual is a standard for evaluating two handed lifts in industry [3]. While these methods are effective for hazard identification, they are primarily observational or semi quantitative; recent work emphasizes automating their inputs (e.g., kinematic capture, force measurement) to allow online assessment and continuous risk tracking. These foundational tools remain essential because they translate biomechanical observations into design actions and serve as benchmarks when validating ergonomics-aware automation.

2.2. Workstation design and digital human modeling

Workstation design research combines anthropometry, motion analysis, and layout optimization to align tasks with human capabilities. Early systematic frameworks established ergonomic design principles reach envelopes, neutral postures, and anthropometric matching to reduce musculoskeletal loading and improve productivity [6]. Digital human modeling and simulation tools (e.g., OpenSim and other biomechanical toolkits) allow designers to simulate joint loads, muscle forces, and whole body dynamics virtually, enabling trade off analysis before physical changes are made [7]. Del Rio Vilas et al. proposed integrated optimization that couples ergonomic metrics with operational objectives (throughput, cycle time) to obtain balanced workstation layouts, demonstrating that multi objective simulations can produce solutions superior to ad hoc ergonomics fixes [6]. Digital human models also enable evaluation of variability across operator populations (gender, stature, reach), supporting adjustable or adaptive workstation components. Nevertheless, implementing simulated solutions on the factory floor encounters barriers calibration of models to real workers, integrating variability in tool use, and cost of retrofits which is why combining simulation with low cost automation aids (height adjustable tables, positioning fixtures) is an active research and practitioner focus.

2.3. Automation and human robot collaboration (HRC) for ergonomics

Automation research has evolved beyond replacing humans to supporting them: collaborative robots (cobots) and adaptive control strategies aim to reduce operator biomechanical load while preserving human decision making. Kim et al. proposed a control framework where a robot's motion is optimized to minimise human joint overload during power tool operations, using an online whole body model to estimate and reduce risky torques [4]. Broader surveys show growing literature on ergonomic HRC where robots adapt motions, assume heavy loads, or reposition tasks to maintain operator neutrality [5]. Lorenzini et al. provide a comprehensive review identifying gaps: many ergonomic HRC studies are lab based, rely on offline post processing, and lack standardisation for on line ergonomics metrics and acceptance in industry [5]. Key technical challenges include reliable real time estimation of human state, safe shared control policies, and interface designs that maintain operator trust and situational awareness. Still, empirical trials consistently report reduced musculoskeletal load and improved task consistency when ergonomics is embedded into HRC control and task allocation strategies.

2.4. Wearable sensors and real time monitoring for ergonomic adaptation

Recent advances in low cost IMUs, force sensors, and physiological monitors enable continuous, online ergonomic assessment and adaptive automation. Studies integrate IMU motion capture, EMG, and force/pressure sensors to compute joint angles, activity levels, and muscle activation that can feed automated ergonomics indices or robot controllers [5], [8]. Dimitropoulos et al. and others demonstrated hybrid systems where wearable data drive cobot behaviours or provide operator feedback to correct posture and reduce fatigue [8]. The literature highlights trade offs: marker based motion capture offers high accuracy but poor practicality in factory settings, whereas IMU suits and simple wearable nodes strike a better balance between intrusiveness and fidelity [5]. Privacy, worker acceptance, sensor robustness, and the need for validated online metrics remain open issues; nevertheless, the trend toward real time, sensor driven ergonomics creates opportunities for adaptive workstations that modify height, reach, or robot assistance dynamically to maintain safe operator states.

3. Methodology

The proposed methodology follows a systematic, human centered approach to redesign industrial workstations by integrating ergonomic principles with selective automation. The objective is to reduce physical strain, improve task efficiency, and enhance human machine interaction while maintaining operator control. The methodology is divided into four sequential phases: ergonomic assessment, task and process analysis, automation integrated redesign, and performance evaluation. Quantitative measurements and qualitative observations are combined to ensure reliable and practical outcomes suitable for real industrial environments.

3.1. Ergonomic Assessment

The first phase involves an ergonomic assessment of the existing workstation to identify physical risk factors affecting operators. Observations are conducted during normal work cycles to evaluate posture, reach distance, task repetition, and applied force. Particular attention is given to workstation height adaptability, as improper working height is a major contributor to musculoskeletal strain. The role of adjustable work surfaces in supporting neutral posture is illustrated in Figure 1 (Height Adjustable Industrial Workstation for Ergonomic Assessment).

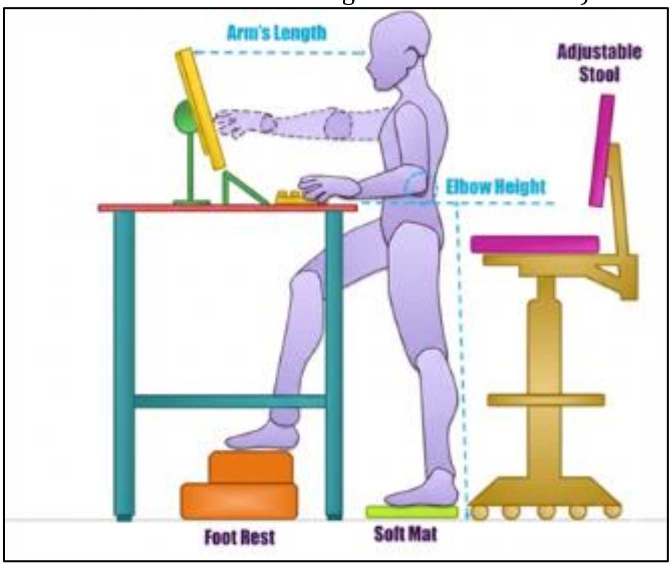

Figure 1 Height Adjustable Industrial Workstation for Ergonomic Assessment

Illustrates recommended ergonomic design parameters including adjustable working height, optimal arm's reach, elbow height alignment, seating support, footrest, and anti fatigue mat used to evaluate posture, reach distance, and physical strain during workstation assessment. Worker feedback is collected through informal interviews to identify discomfort, fatigue patterns, and task difficulty. Postural risk is quantified using posture-based scoring, where deviations from neutral posture increase risk levels. Task repetition frequency and force exertion are also evaluated to assess cumulative workload.

The ergonomic risk score R_e is calculated as:

$$R_e = w_p P + w_f F + w_r R$$

where P represents posture risk, F denotes force exertion, R indicates repetition frequency, and w_p, w_f and w_(r)are weighting factors. Tasks with higher R_e values are prioritized for redesign.

3.2. Task and Process Analysis

In the second phase, workstation operations are analyzed using time and motion study techniques. Each task is decomposed into elementary motions to identify inefficiencies, unnecessary movements, and precision dependent activities. Cycle time, idle time, and manual handling effort are measured across multiple production cycles to ensure consistency. Tasks are categorized into value added and non value added activities. Manual effort is assessed by examining hand movements, tool usage, and material flow. This analysis helps identify tasks suitable for automation support without removing human involvement.
The average cycle time T_C is computed as:

$$T_c = \frac{1}{n}\sum_{i=1}^{n} t_i$$

where t_i is the time required to complete the i-th cycle and n is the total number of observed cycles. Error probability E_p is estimated from inspection records and task repetition data, providing a baseline for post redesign comparison.

3.3. Automation-Integrated Redesign

Based on ergonomic and task analysis results, the workstation redesign integrates selective automation while preserving human supervision. Automation support is implemented at the control and system level through coordinated interaction between workstations, controllers, sensors, and actuators. The automation-integrated control architecture enabling human supervision, real-time feedback, and coordinated task execution is illustrated in Figure 2 (Automation-integrated industrial control architecture supporting workstation operations).

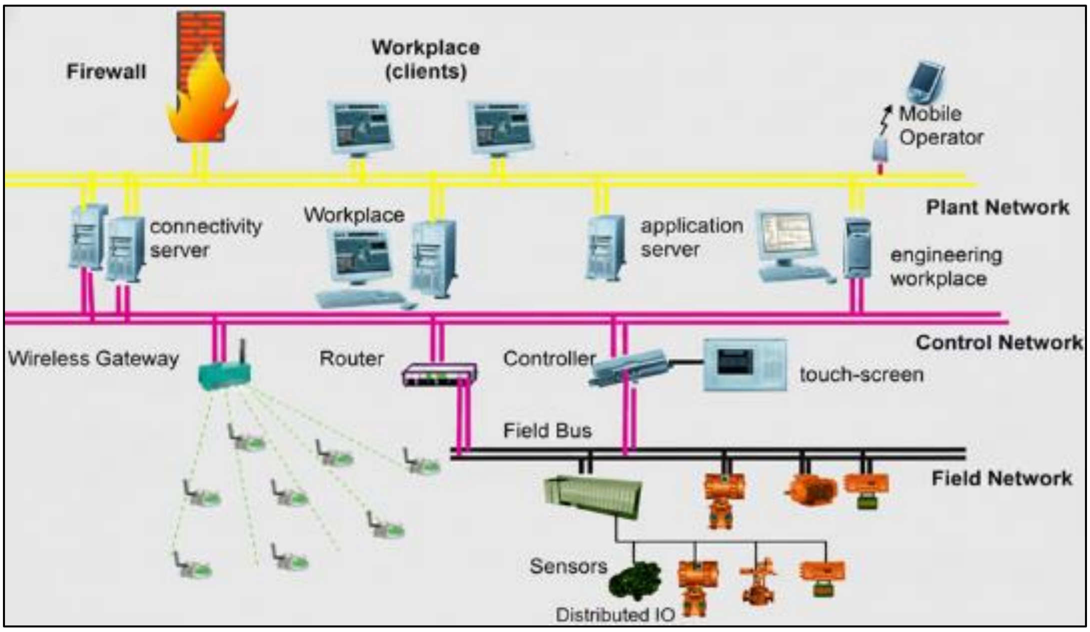

Figure 2 Automation-integrated industrial control architecture supporting workstation operations

As shown in Figure 2, the layered architecture consists of plant, control, and field networks, allowing operators to supervise automated processes through touchscreen human–machine interfaces while retaining decision authority. This structure supports semi-automated task execution without removing human involvement. Ergonomic improvements such as height-adjustable platforms and optimized tool positioning (described in Section III-A) are complemented by automation-assisted positioning systems and collaborative robots, reducing physical strain and performance variability.

The level of automation support is quantified using the automation utilization index:

$$A_u = \frac{T_a}{T_c}$$

Where T_a is the time supported by automation and T_c is the total cycle time. This ensures that automation complements human work rather than dominating it.

3.4. Performance Evaluation

The final phase evaluates the effectiveness of the redesigned workstation by comparing pre and post redesign conditions. Key performance indicators include productivity, ergonomic risk reduction, operator comfort, and quality performance. Data are collected over multiple shifts to reduce variability.

Productivity improvement P_i is calculated as:

$$P_i = \frac{T_{old} - T_{new}}{T_{old}} \times 100\%$$

where T_old and T_new represent average cycle times before and after redesign. Operator comfort is evaluated using structured surveys, while error and rework rates are obtained from quality records. Real time system interaction and feedback are supported through a touchscreen based interface shown in (Figure 3. Touchscreen based human machine interface for workstation control.).

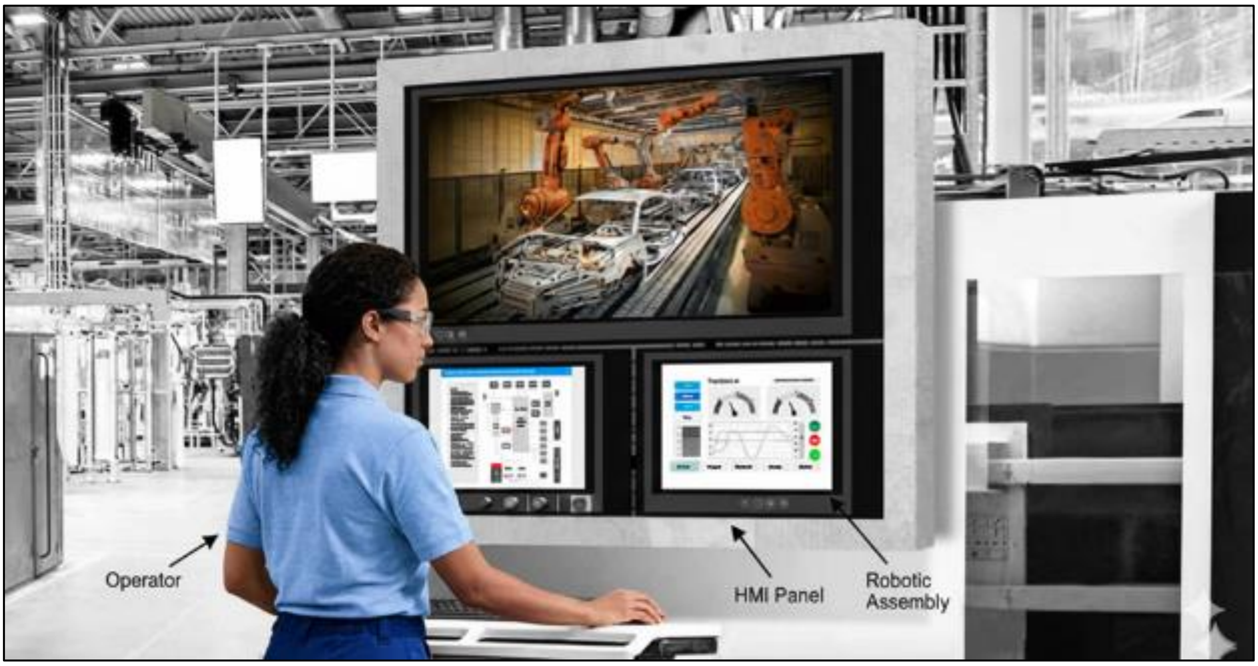

Figure 3 Touchscreen based human machine interface for workstation control

Depicts an operator supervising and interacting with an automated workstation through a touchscreen based human–machine interface for real time monitoring, control, and feedback

Table 1 Performance Evaluation Metrics

Metric	Description	Measurement Method
Cycle Time	Task completion duration	Time study

Ergonomic Risk Score	Physical strain level	Risk index
Operator Fatigue	Perceived discomfort	Survey scale
Error Rate	Defective output ratio	Inspection data

4. Discussion and Results

This section discusses the outcomes of implementing the ergonomic and automation-based workstation redesign. The analysis compares system performance before and after redesign using quantitative metrics and operator feedback. The discussion focuses on productivity improvement, ergonomic risk reduction, and operator comfort, demonstrating that selective and ergonomically aligned automation leads to balanced improvements in efficiency and worker well-being. The results confirm that human centered automation provides measurable benefits without the need for full system automation.

4.1. Productivity Improvement and Cycle Time Reduction

The most immediate and measurable impact of the redesigned workstation was a reduction in average task cycle time. The integration of assisted material handling, optimized workstation layout, and semi automated task support reduced unnecessary movements and manual handling effort. Operators were able to perform tasks with fewer interruptions and smoother task flow.

Cycle time improvement is quantified using:

$$\Delta T_c = T_{c,old} - T_{c,new}$$

Where T_(c,old) is the average task cycle time before redesign and T_(c,new),new is the cycle time after redesign. Results showed a consistent reduction in cycle time across multiple shifts, indicating stable and repeatable performance improvements rather than short term adaptation.In addition, reduced motion variability between operators contributed to improved process consistency. This outcome is critical in industrial environments where production predictability affects scheduling and downstream operations. The comparative workstation performance is visually summarized in (Figure 4. Comparison of workstation cycle times before and after redesign).

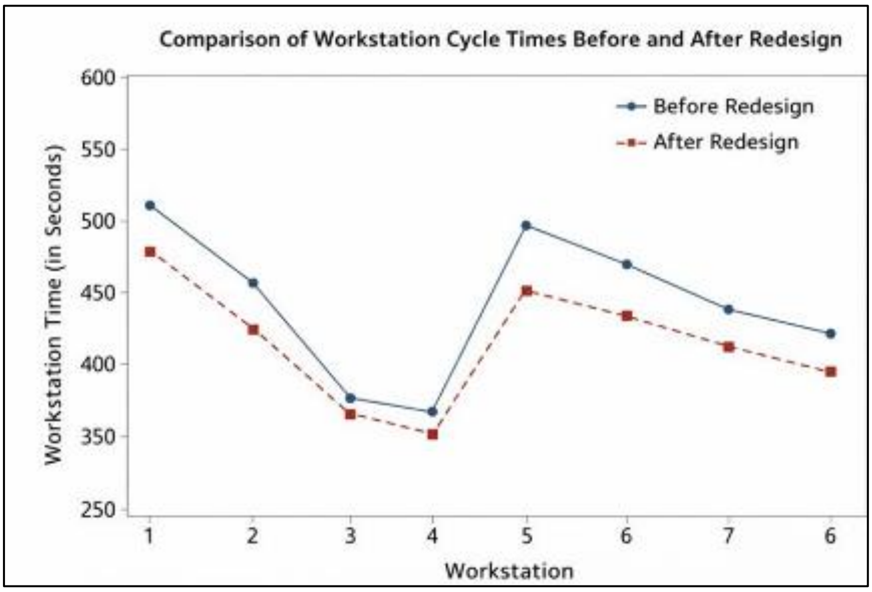

Figure 4 Comparison of workstation cycle times before and after redesign

Presents workstation wise task cycle times measured under pre redesign and post redesign conditions, demonstrating reduced processing time and improved consistency following ergonomic and automation based improvements.

4.2. Ergonomic Risk Reduction and Postural Improvement

Ergonomic assessment results showed a significant reduction in physical risk after workstation redesign. Height adjustable work surfaces, reduced reach distance, and automation assisted positioning enabled operators to maintain neutral postures during task execution. Observations revealed fewer instances of trunk bending, shoulder elevation, and wrist deviation.

Ergonomic risk reduction is calculated as:

$$E_r = \frac{R_{e,old} - R_{e,new}}{R_{e,old}} \times 100\%$$

Where R_(e,old) and R_(e,new) represent ergonomic risk scores before and after redesign, respectively. The reduction in risk scores indicates a lower likelihood of musculoskeletal strain and long-term injury. The postural improvements observed during task execution validate that ergonomic design principles, when combined with selective automation, create safer and more sustainable working conditions. These improvements are illustrated in Figure 5 (Ergonomic Posture and Risk Level Comparison Before and After Redesign).

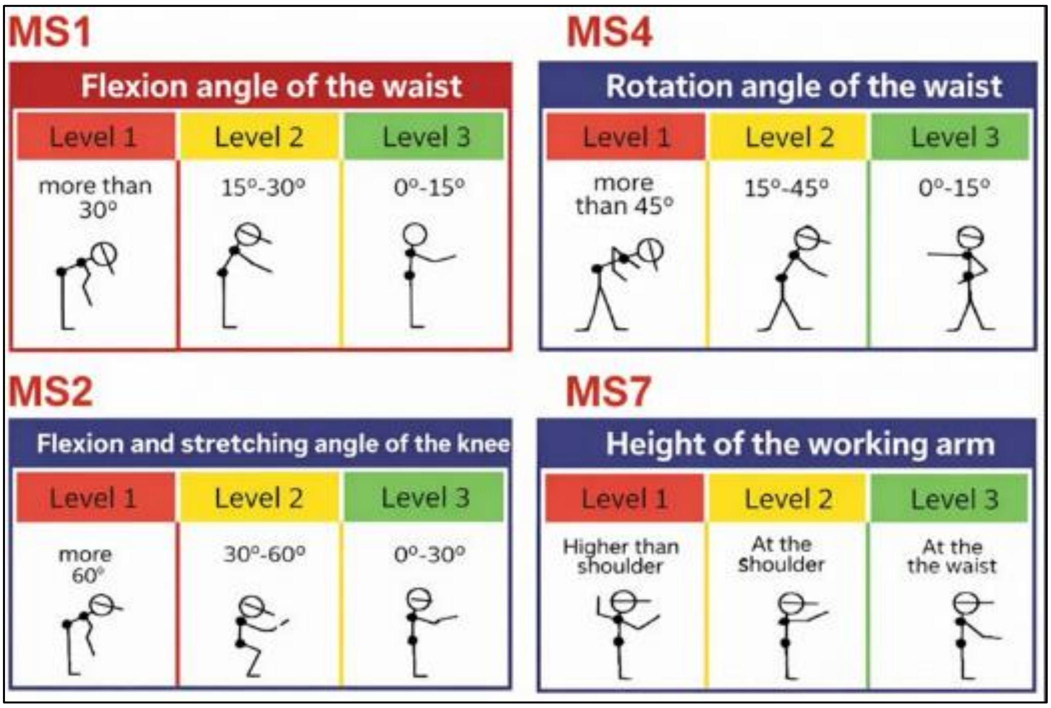

Figure 5 Ergonomic posture classification and risk level comparison before and after workstation redesign

Illustrates posture-based ergonomic risk levels for waist flexion (MS1), waist rotation (MS4), knee flexion (MS2), and working arm height (MS7), used to evaluate ergonomic risk reduction achieved through improved workstation design

4.3. Operator Comfort, Fatigue, and Work Consistency

Operator feedback played an important role in validating the effectiveness of the redesigned workstation. Workers consistently reported reduced physical fatigue, particularly in the lower back, shoulders, and wrists. Improved comfort contributed to sustained performance throughout work shifts and reduced perceived workload.

Fatigue improvement is estimated using normalized survey scores:

$$F_i = \frac{F_{old} - F_{new}}{F_{old}}$$

where F_old and F_new denote average fatigue ratings before and after redesign. Lower fatigue levels were strongly associated with improved task consistency and reduced performance variability. Human machine interaction also improved due to intuitive automation support and clear task feedback. Operators retained supervisory control, which increased trust in the system and reduced resistance to automation. This balance between assistance and control is shown in Figure 6 (Human Machine Interaction and Operator Feedback in the Redesigned Workstation).

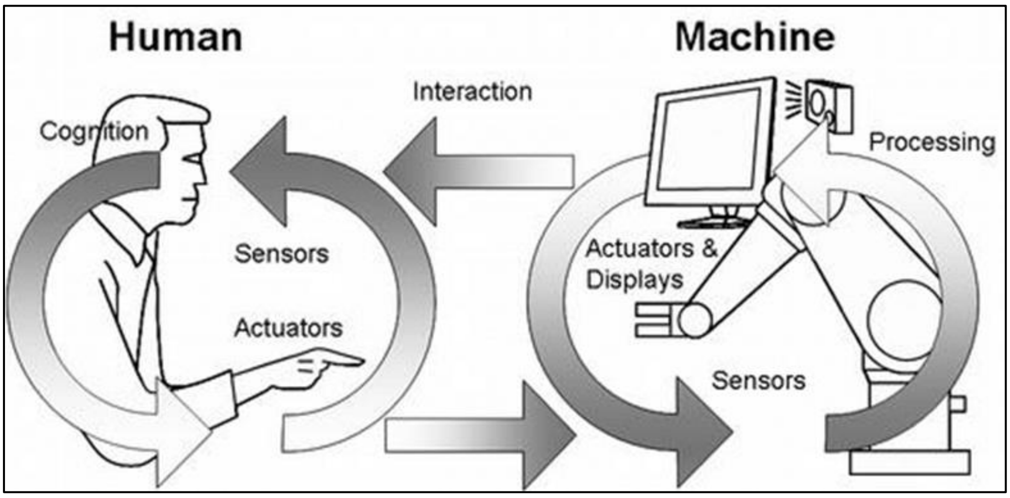

Figure 6 Human–machine interaction and operator feedback in the redesigned workstation

Shows the closed loop interaction between human cognition and machine processing through sensors, actuators, and displays, highlighting feedback mechanisms that contribute to improved operator comfort, reduced fatigue, and consistent task performance.

4.4. Quality Performance and Error Reduction

Automation assisted positioning and sensor guided task execution reduced error rates in precision dependent operations. Manual variability was minimized, resulting in fewer defects and rework incidents.

Error reduction rate is calculated as:

$$Q_r = \frac{E_{old} - E_{new}}{E_{old}} \times 100\%$$

whereE_old and E_new represent the number of errors recorded before and after redesign. The decline in error rates confirms that ergonomic automation improves not only worker well-being but also product quality.

4.5. Discussion and System Level Implications

The results confirm that full automation is not always necessary to achieve optimal industrial performance. Instead, selective and ergonomically aligned automation yields balanced improvements across productivity, safety, and quality. By aligning automation support with human capabilities, the redesigned workstation achieves sustainable efficiency gains without sacrificing flexibility or operator acceptance. These findings reinforce the importance of human centered design in modern industrial systems and support the adoption of ergonomics driven automation as a practical and scalable strategy.

5. Conclusion

This paper presented an ergonomic and automation based process redesign framework for industrial workstations, emphasizing the integration of human centered ergonomic principles with selective automation strategies. Through systematic ergonomic assessment, task analysis, and automation assisted redesign, the proposed approach demonstrated measurable improvements in productivity, ergonomic safety, and operator comfort. The results showed reductions in cycle time, physical strain, and error rates, while maintaining operator control and adaptability. Unlike conventional automation approaches that prioritize output alone, this framework highlights the importance of aligning technological support with human capabilities. The findings confirm that ergonomics driven automation contributes not only to short term performance gains but also to long term operational sustainability by reducing fatigue related risks and improving work consistency.

Future work can extend this research in several directions. One important area is the integration of real time ergonomic monitoring using wearable sensors and vision based systems to enable continuous risk assessment during operation. Additionally, adaptive workstation intelligence driven by artificial intelligence and machine learning can be explored to dynamically adjust workstation height, tool positioning, and automation assistance based on operator condition and task complexity. Large scale validation across different industrial sectors and production environments is also necessary to generalize the applicability of the proposed framework. These extensions would further strengthen the role of human centric automation in next generation industrial systems.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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