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COBOT-LED ERGONOMIC OPTIMIZATION: A STRATEGIC APPROACH TO MITIGATING MSDS RISKS IN MANUFACTURING

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A B S T R A C T

Work-related musculoskeletal disorders are a growing concern in industrial environments, leading to increased interest in technologies that can improve workers' safety. Among these technologies, collaborative robots have gained attention due to their ability to reduce physical strain and support better ergonomic conditions. In this study, the impact of collaborative robots on musculoskeletal risk was examined through a combination of literature review, experimental observation, and ergonomic assessment of task design and operator's posture. The results show that the integration of collaborative robots leads to measurable improvements in workplace ergonomics, reduces physical workload, and increases operational efficiency. It was also observed that proper task design, including human–robot interaction, workstation adjustability, and operator training, plays an important role in achieving these improvements. Overall, the findings suggest that collaborative robotics can significantly reduce musculoskeletal risks and contribute to safer and more adaptable industrial work environments.

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1. INTRODUCTION

Work-related musculoskeletal disorders (WMSDs) are among the most common occupational health issues in manufacturing. According to the European Agency for Safety and Health at Work (2019), WMSDs are the main reason for 60% of employee complaints. Manual work, characterized by repetitive movements and prolonged duration, creates cumulative trauma to tendons, muscles, and nerves (da Costa & Vieira, 2010), and is typically analyzed based on deviations from the body's neutral posture. Beyond physical strain, repetitive tasks also lack cognitive engagement, which can lead to low job satisfaction, absenteeism and poor production quality (Cheshmehgaz et al., 2012). These challenges are closely related to the Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health and Well-being) and SDG 8 (Decent Work and Economic Growth) (Das et al., 2024).

Traditional ergonomic approaches are important, but new technologies can help create a broader approach to minimizing WMSDs. Collaborative robotics offers new possibilities in this context, considering that cobots are designed to operate alongside humans without physical separation, enabling synergy in human-robot

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collaboration (HRC). However, a key issue lies in the predominantly reactive nature of current ergonomic interventions. Most companies address risks only after they become visible or reported, rather than focusing on proactive risk prevention. This is an important issue considering occupational diseases develop gradually over a long period of time and are not easily noticed in the early stages. Based on the identified gap, the following research question and sub-questions are proposed:

RQ: *What are the effects of collaborative robot implementation in an ergonomically redesigned workstation?*

SQ1: *How does the cobot-assisted workstation influence workers' exposure to risk factors for WMSDs in terms of time spent in non-ergonomic postures and physical workload?*

SQ2: *What is the effect of the cobot-integrated workstation on operational performance indicators, reflected in cycle time and productivity?*

2. THEORETICAL BACKGROUND

2.1. Ergonomics and Musculoskeletal Disorders

Ergonomics, as defined by the International Ergonomics Association, is the scientific discipline based on understanding interactions among humans and other elements of a system, applying theory, principles, data, and methods to optimize human well-being and overall system performance (IEA, 2024). Physical ergonomics deals with the anatomical, anthropometric, physiological, and biomechanical characteristics of humans in relation to physical activities (Berlin & Adams, 2017). It includes elements such as working postures, material handling, repetitive movements, workplace layout, and physical safety and health. According to many authors, physical ergonomics represents one of the most important directions in ergonomic research (Karwowrski et al., 2020, Hedge, 2005). Methods such as RULA (Rapid Upper Limb Assessment) and REBA (Rapid Entire Body Assessment) enable quantitative evaluation of postural risks and have been widely validated for identifying WMSD risk factors (McAtamney & Corlett, 1993).

Ergonomic requirements for workplace design are based on adapting the work system to human capabilities and limitations, including physical, cognitive, and psychosocial characteristics (Djapan & Vukićević, 2025). From a physical perspective, workplace layout and spatial organization should enable natural movements and minimize awkward postures, while work surfaces and equipment should be adjustable according to anthropometric characteristics such as body height, reach, and field of vision. Proper design also involves controlling physical workload by reducing repetitive movements, limiting prolonged static postures, and introducing assistive devices where necessary. In addition to physical factors, ergonomic design must ensure appropriate environmental conditions, including temperature, lighting, noise, and vibration, all of which directly affect comfort, health, and performance. Equally important are cognitive aspects, where interfaces, controls, and information displays should be intuitive and easy to interpret in order to reduce mental workload and the likelihood of human error. Psychosocial factors, such as communication, teamwork, stress levels, and overall job satisfaction, play a significant role in shaping the effectiveness of the work system.

2.2. Collaborative Robotics

Collaborative robots are defined as robotic systems designed for direct interaction with humans in a shared workspace without physical barriers (ISO/TS 15066, 2016). Four operational modes ensure safe collaboration: safety-rated monitored stop, where the robot stops when the operator enters the collaborative workspace; hand guiding, where the operator manually guides robot movements; speed and separation monitoring, where robot speed adjusts based on operator proximity; and power and force limiting, where the robot limits force upon contact with the operator. These safety features enable cobots to take over physically demanding tasks while working alongside human operators, reducing biomechanical exposure and the risk of WMSDs (Villani et al., 2018; Gualtieri et al., 2021).

Related to safety aspects, human–robot interaction can be further understood through several classification criteria, including workspace, time, task, and the presence of physical contact. These criteria determine whether humans and robots operate in shared or separated environments, whether tasks are performed simultaneously or sequentially, and whether interaction involves direct physical contact. Based on these dimensions, different levels of interaction can be identified, ranging from fully separated autonomous systems to coexistence, synchronization, cooperation, and full collaboration (Weiss et al., 2021). The highest level, collaboration, involves real-time joint work on the same task, requiring advanced safety, adaptability, and awareness of the working environment. Human–robot systems can be organized into different team configurations, such as one human–one robot, one human–multiple robots, or multiple humans–multiple robots. These configurations vary in terms of autonomy, coordination complexity, and efficiency, with more complex systems offering greater flexibility but requiring advanced communication and control mechanisms.

In the same way as the human arm uses multiple joints to perform a range of movements, the cobot has several articulations (labeled J1–J6), each representing one degree of freedom. The base (J1) rotates the system around the vertical axis, analogous to the human shoulder. J2, located in the shoulder section, enables

forward/backward and up/down arm movements. J3 acts as the elbow, allowing flexion and extension, while J4, J5, and J6 simulate wrist and hand movements such as bending, rotation, and precise end-effector orientation (Quintana et al., 2022). This analogy is beneficial for operators, as it supports intuitive understanding of cobot behavior and facilitates more effective human–robot interaction (Figure 1).

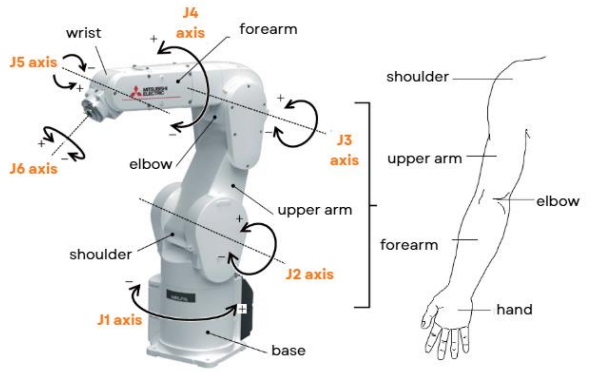


Figure 1. Analogy between 6-DOF cobot and the human arm

An important aspect of collaborative robotics is task allocation between humans and robots, which determines how activities are distributed based on their complementary strengths. The most common use is that cobots are assigned with repetitive, physically demanding, and ergonomically unfavorable tasks, while humans retain tasks that require cognitive flexibility, decision-making, and contextual awareness. Task allocation should not be viewed as a static process, but rather as a dynamic and adaptive mechanism that considers factors such as worker fatigue, safety constraints, and changing task requirements. Modern approaches emphasize capability-based and data-driven allocation, where tasks are assigned according to the real-time assessment of human and robot performance, as well as their reliability and limitations. In this context, integrating safety constraints and ergonomic criteria into task allocation models has been shown to simultaneously enhance productivity and ensure operator well-being. Additionally, advanced methods incorporate concepts such as trust and expected performance, enabling more intelligent distribution of tasks and improved overall system efficiency (Baratta et al., 2025; Langås et al., 2025).

2.2.1. Human-Machine Interface

The human-machine interface (HMI) plays a critical role in successful cobot implementation. Effective HMI design must minimize cognitive load, enable intuitive control, and provide clear feedback about robot intentions (Ionescu et al., 2020). Modern HMI solutions include hardware interfaces such as teaching pendants and software platforms that enable offline programming and simulation (Mitsubishi Electric Corporation, 2019). The Human–Machine Interface (HMI) represents a communication system between humans and machines, defining how users send commands to a system and receive feedback on its operation. In the context of collaborative robotics, HMI plays a central role by enabling interactive and safe cooperation between humans and robots within a shared workspace. The objective of HMI systems is not limited to robot control, but also includes creating an environment in which human intentions and robotic actions are naturally aligned.

A well-designed interface increases operator trust in technology, reduces the likelihood of errors, improves overall performance, and facilitates adaptation to different task requirements. In addition to hardware components such as teaching pendants, software-based HMI solutions allow operators, engineers, and programmers to plan and simulate robot activities in advance, combining safety, efficiency, and transparency in modern intelligent manufacturing systems. Furthermore, contemporary interaction systems enable intuitive and flexible control of robotic systems, while robots simultaneously adapt their behavior in response to human intentions and environmental conditions. In practice, multiple types of interfaces are used, differing in levels of autonomy, technological complexity, and modes of information exchange.

2.2.2. New Risks Related To Cobot Use

Even though cobots significantly reduce the risk of WMSDs, the integration of any new technology introduces a new set of hazards and risks. According to ISO/TS 15066:2016 and ISO 12100, hazard identification must include not only the technical characteristics of the cobot, but also its impact on the human operator, including attention, understanding, mental workload, body posture, and perception of safety. Some of the risks associated with the use of collaborative robots can be classified into two main categories (Amin et al., 2021):

a) Hazards related to the cobot and robotic system:

- Robot characteristics, such as payload, speed, force, torque, power, geometry, and the shape and material of contact surfaces, which directly influence the severity of potential interactions.
- Risks related to end-effectors and workpieces, including sharp edges, protrusions, risk of object dropping, and poor ergonomic design.
- Operator position and movement in relation to the robot and its components, including workplace layout, orientation, and exposure to hazardous zones.
- Conditions of potential human–robot contact, including whether the interaction is transient or quasi-static, as well as which body parts may be affected.
- Influence of the working environment and surrounding equipment, which may affect visibility, accessibility, and safe interaction.

b) Hazards related to specific applications:

- Process-related risks, such as exposure to high temperatures, mechanical stress, sparks (e.g., in welding), or other task-specific hazards.
- Limitations caused by personal protective equipment (PPE), which may restrict movement, reduce precision, and impair perception of the environment.
- Poor ergonomic design of the workplace or system, which can lead to reduced concentration, improper system use, and increased likelihood of operational errors.

In addition to these standardized hazards, particular attention should be given to cognitive and psychosocial risks, which include:

- continuous need for system monitoring,
- increased cognitive demands,
- dependence on user interfaces that may not be sufficiently intuitive,
- elevated sense of responsibility and stress,
- reduced trust in the system in cases of unpredictable robot behavior.

2.3. Lean Methodology and Workplace Optimization

Lean manufacturing principles, originating from the Toyota Production System, emphasize the elimination of waste (muda), unevenness (mura), and overburden (muri) (Sah et al., 2023). The 5S methodology provides a framework for organizing the workplace to reduce unnecessary movements and improve workflow efficiency (Pienkowski, 2014). Beyond operational efficiency, prior research has established strong links between lean practices and workers' well-being, showing that lean implementations can positively influence ergonomics, occupational health, and safety (Temple & Adams, 2000; Conti et al., 2006; Eswaramoorthi et al., 2010; Parker, 2003). This connection between different disciplines shows how multidisciplinary approach is important in the decision-making process and strategic optimization. Lean should not be viewed solely as a set of tools, but also as a strategic and systemic approach that integrates technological, organizational, and human factors. When viewed within the frameworks of Industry 4.0 and Industry 5.0, lean extends beyond its traditional focus on efficiency. In Industry 4.0, it is enhanced by digital technologies enabling real-time monitoring and more precise decision-making. In Industry 5.0, lean adopts a human-centric perspective, emphasizing worker well-being, ergonomics, and sustainable production.

3. RESEARCH METHODOLOGY

A case study was used to investigate the effects of collaborative robot implementation on ergonomic conditions and workplace performance. The experiment consists of two scenarios: a traditional manual workstation (Scenario 1) and an optimized workstation with a collaborative robot (Scenario 2).

3.1. Experimental Setup

The experiment was conducted in laboratory conditions with the following equipment:

- collaborative robot: Mitsubishi RV-5AS-D with 6 degrees of freedom (DOF),
- vacuum gripper for pick-and-place operations,
- height-adjustable workbench (740–1200 mm range),
- conveyor belt.

The experimental task simulates a real-world packaging operation from the food industry, involving packaging process of chocolate bars. This task was selected due to its prevalence in industrial practice and its characteristic repetitive movements and physical demands. The work cycle consisted of four activities: taking the packaging pallet (1), changing the packaging template (2), taking and packaging individual chocolate bars (3) and placing the packaged product on conveyor belt (4). One participant was involved in the study (male, 24 years, height 185 cm, body mass 82 kg). Anthropometric characteristics were considered when adjusting workstation parameters.

The collaborative robot was programmed using *RT Toolbox3* software, which enabled precise control over trajectory planning, speed modulation, and task sequencing. The software interface allowed for real-time monitoring of cobot behaviour. A particular safety feature implemented was collision detection (COD), which ensures that the cobot immediately stops or reduces speed upon sensing unexpected contact, thereby preventing potential collisions between the robot and the human operator.

The use of a cobot instead of a traditional industrial robot was central to the experimental design, as the study involved close physical interaction between the human operator and the robotic system, reflecting a semi-automated process where tasks are shared between the operator and the machine. Unlike conventional industrial robots, which typically operate within safety fences and lack real-time adaptability, a cobot is specifically used to ensure safe human–robot collaboration.

3.2. Experimental Procedure

Scenario 1: Traditional Workstation

Scenario 1 represented a traditional manual workstation without cobots. The workstation showed typical ergonomic deficiencies such as fixed work surface height, disorganized tool placement outside optimal reach zones, pallets stored on shelves beside the table. These conditions represented typical non-ergonomic workplace characteristics which are commonly found in real industrial settings. Such setup often forces workers

to adopt awkward postures, including excessive bending, reaching, and twisting, which increases physical strain and fatigue over time. The lack of adjustability and poor workplace organization can lead to reduced productivity, longer task execution times, and a higher risk of WMSDs. Inefficient layout and material flow contribute to unnecessary movements and interruptions.

Scenario 2: Optimized Workstation with Cobot

Scenario 2 showed the proposed ergonomically optimized workstation with cobot (Figure 2). The cobot was programmed to perform *pick-and-place* operation, precisely, task of delivering chocolate bars to the conveyor belt, while the operator remained focused on the packaging process.

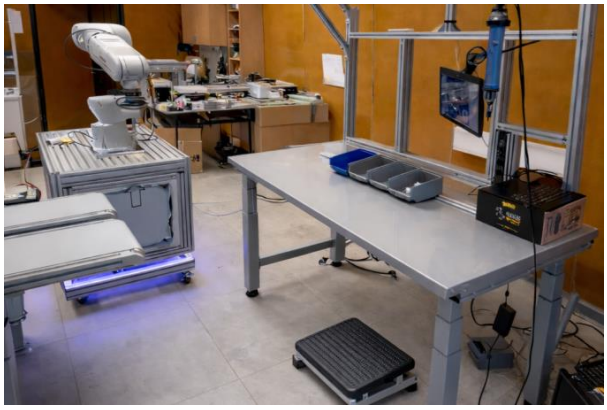


Figure 2. Optimized workstation

Workplace redesign was systematically implemented in alignment with the 5S methodology and advanced ergonomic design principles (Figure 3), with the objective of minimizing biomechanical load and optimizing operator performance. The workbench height was adjusted to match the operator's anthropometric characteristics (approximately 1050 mm), thereby enabling neutral postures and reducing static muscular strain. Material positioning was optimized by placing chocolate bar containers within the golden reach zone (≤400 mm), effectively eliminating excessive reaching and unnecessary movements.

To further enhance visual ergonomics and task efficiency, containers were oriented at an inclined angle, improving visibility and facilitating more natural hand movements. A color-coding system was used to support error prevention and cognitive clarity during task execution. Digitalization of work instructions was achieved through the implementation of a monitor for template display, which eliminated reliance on paper-based documentation and reduced non-value-added activities. The pallet was strategically positioned directly on the work surface, minimizing handling time and physical effort.

The overall layout was adapted to both the operator and the available workspace, ensuring maximum functional alignment between human capabilities and spatial constraints. It is important to note that, in real industrial environments, achieving an ideal layout is often not feasible due to limitations such as space, existing equipment, and process requirements. Therefore, workstation design must remain flexible, balancing ergonomic principles with practical constraints to achieve the best possible solution under given conditions.

3.3. Ergonomic Risk Assessment

HAPO LEA mobile application was used for ergonomic risk assessment, which implements the RULA method (HAPO, 2025). Entire process was recorded using standard video camera without the need for wearable sensors, markers, or physical contact with the operator. This approach allowed for natural worker behavior during the work cycle, minimizing interference with the task and ensuring authentic postural data collection. The assessment procedure involved:

1. video recording of the complete work cycle,
2. frame-by-frame analysis of postural parameters for neck, trunk, and upper limbs,
3. calculation of RULA scores for each body segment,
4. classification of risk levels: ≥80 (low risk), 50–79 (medium risk), <50 (high risk).

The percentage of work cycle time spent in low, medium, and high-risk postures was calculated for each body segment.

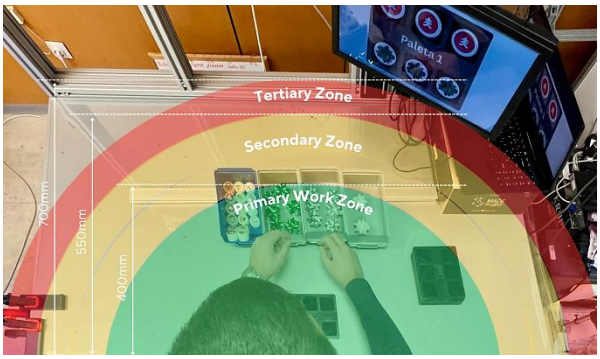


Figure 3. Ergonomic reach zone (golden zone)

3.4. Performance Metrics

Key performance indicators were measured for both experimental scenarios. Due to the nature of the experiment, the following metrics were measurable: *Cycle Time*: Total time required to complete one work cycle (5 packaged pallets), measured from video recordings. *Productivity*: Calculated as output per effective working hour:

- Assumptions: 8-hour shift, 0.5-hour break, effective working time 27,000 seconds.
- Productivity = (Total working time per shift / Cycle time per unit) / Effective working hours.

In addition to quantitative performance metrics, work activities were classified according to *Lean* principles into three categories (Mačužić & Djapan, 2016):

- *Value-Added Activities* (VAA) – actions that directly transform the product and increase its value from the customer's perspective,
- *Semi-Value-Added Activities* (SVAA) – actions necessary for process continuity but not directly adding value,
- *Non-Value-Added Activities* (NVAA) – actions that represent waste and add no value.

4. RESULTS

This section presents the findings from the ergonomic risk assessment, performance measurement, and activity classification for both experimental scenarios.

4.1. Postural Analysis

Scenario 1. Traditional Workstation

Analysis of the traditional workstation showed high ergonomic risk across all body segments. Total postural score was 48, which is classified as high risk requiring immediate intervention. Table 1 presents the percentage of work cycle time spent in different risk levels.

Table 1. Ergonomic risk assessment - Scenario 1

	% of time spent at a specific risk level		
Body segment	Low Risk	Medium Risk	High Risk
Neck	7	58	35
Trunk	12	61	27
Left shoulder	32	48	20
Right shoulder	14	50	36
Left elbow	28	49	23
Right elbow	33	46	21
RULA score	1-2	3-4	5-6

The neck showed the highest risk exposure, with 35% of the total work time spent in high-risk postures, primarily due to the fixed height of the work surface, which required sustained forward flexion. The trunk was also in the significant exposure to non-neutral postures, particularly flexion and rotation during pallet retrieval from the side shelf. These findings are further illustrated in Figure 4, which presents the distribution of body postures expressed through angular positions of different body segments during the observed work process in the pre-optimization scenario.

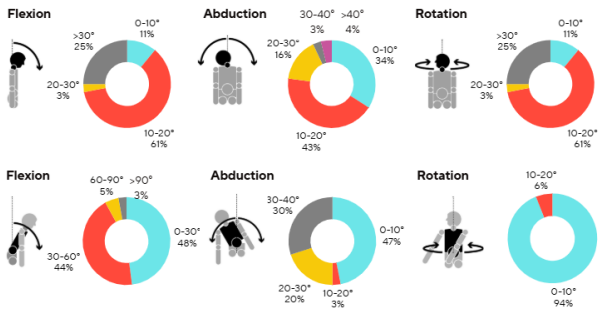


Figure 4. Body postures in Scenario 2

Each diagram represents a specific movement: flexion, lateral bending, or rotation, while the segments of the charts indicate the proportion of time spent within particular angular intervals (e.g., 0–10°, 10–20°, etc.). These angular categories correspond directly to ergonomic risk levels, where greater deviation from neutral postures is associated with increased musculoskeletal load and elevated risk of injury.

Both shoulders demonstrated elevated risk levels, with the right shoulder spending 36% of work time in high-risk postures due to reaching outside the golden zone. The observed risk was characterized by a combination of shoulder flexion and abduction, accompanied by forearm pronation during repetitive grasping and positioning tasks. HAPO LEA software also generates line models (stick figures) that visually represent the operator's posture during each phase of the work cycle (Figure 5). All four observed activities were classified as ergonomically risky; however, Activity 1 (pallet retrieval) was identified as the most critical, because of its pronounced trunk rotation, shoulder abduction, and forward flexion of the neck.

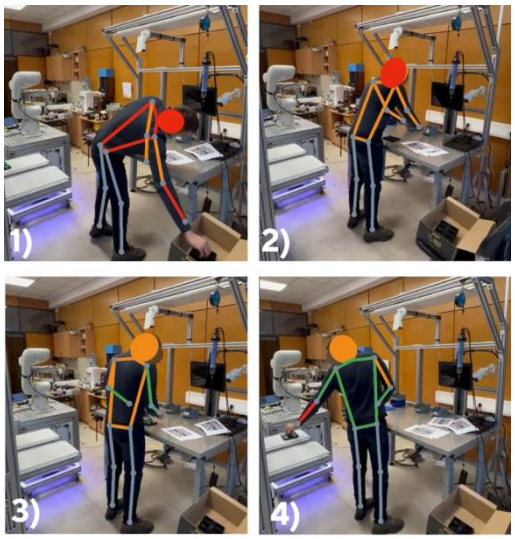


Figure 5. Body postures in Scenario 1

Scenario 2. Optimized Workstation with a Cobot

In the second scenario, following cobot implementation and optimization, the total postural score improved to 82, which is classified as good posture with low risk. Table 2 presents the ergonomic risk assessment results for the second scenario.

Table 2. Ergonomic risk assessment – Scenario 2

	% of time spent at a specific risk level		
Body segment	Low Risk	Medium Risk	High Risk
Neck	52	44	4
Trunk	95	5	0
Left shoulder	25	72	3
Right shoulder	82	18	0
Left elbow	59	36	5
Right elbow	58	39	3
RULA score	1-2	3-4	5-6

All body segments showed significant improvement. Neck time in high-risk postures decreased from 35% to 4%. Trunk remained in low-risk postures for 95% of the work cycle, eliminating high-risk trunk positions completely. Shoulder exposure improved dramatically, with the right shoulder spending no time in high-risk postures. Minimal residual risk was observed in the left elbow (5% high-risk) and left shoulder (3% high-risk), attributed to reaching toward the robot work zone (Figure 6). Stick figures for the second scenario are shown in Figure 7.

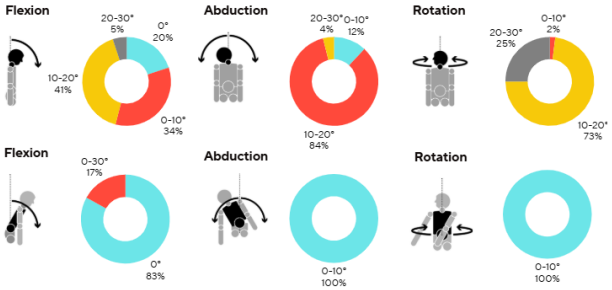


Figure 6. Body postures in Scenario 2

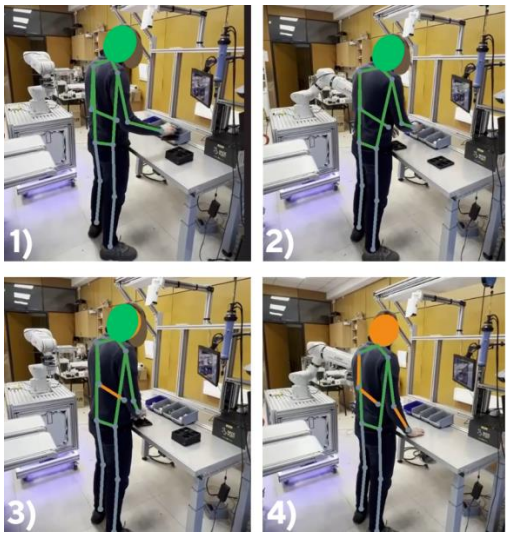


Figure 7. Body postures in Scenario 2

4.2. Operational Performance

Cycle time analysis was done using time measurement based on video recordings of the process. In the observed work cycle, the operator packaged five chocolate packages in both scenarios (before and after optimization). Table 3 presents the comparative analysis of cycle time for both scenarios.

Table 3. Cycle time and activity classification comparison between two scenarios

Activity/ *Lean* classification		**Scenario 1 (s)**	**Scenario 2 (s)**	**Reduction (%)**
1	VAA	16.39	7.83	52.21
2	NVAA	10.60	2.07	80.47
3	VAA	65.55	43.04	34.36
4	SVAA	14.46	8.06	44.26
Total cycle time		107.00	61.00	43.00

It is shown that total cycle time decreased from 107 seconds to 61 seconds for five packaged pallets, representing a 43% reduction. Cycle time per pallet decreased from 21.4 seconds to 12.2 seconds. The number of pallets per shift was obtained as the ratio of total available time to the time required per pallet. Based on this, the output per shift amounted to 1,260 pallets before optimization and 2,213 pallets after optimization. Productivity was then calculated as the number of pallets divided by effective working hours:

- Scenario 1: 1,260 ÷ 7.5 ≈ 168 pallets/hour
- Scenario 2: 2,213 ÷ 7.5 ≈ 295 pallets/hour

Productivity increased by 75% following the implementation of the collaborative workstation. In addition to productivity improvements, there is also a significant change in the structure of activities. The overall share of value-added activities (VAA) increased from 76.6% to 83.4%, representing a rise of 6.8 percentage points. Semi-value-added activities (SVAA) slightly decreased from 13.5% to 13.2%. The most notable improvement was observed in non-value-added activities (NVAA), which decreased from 9.9% to 3.4%, corresponding to a reduction of 6.5 percentage points. Taking into account the redistribution of activities, the reduction in NVAA directly contributed to the overall decrease in cycle time and improved process efficiency.

5. DISCUSSION

RQ: The results above demonstrate that the implementation of a cobot in an ergonomically redesigned workstation gives significant positive effects on ergonomic conditions and operational performance, thereby addressing the main research question. Regarding ergonomic conditions, the total postural score improved from 48 (high risk) to 82 (low risk), representing a 71% improvement. Time spent in high-risk postures decreased dramatically across all body segments. On the other hand, regarding operational performance, total cycle time decreased by 43% (from 107 seconds to 61 seconds), while productivity increased by 75% (from 168 to 295 pallets per hour).

SQ1: In response to the first sub-question, the findings provide clear evidence that the cobot-assisted workstation reduces workers' exposure to WMSD risk factors. This reduction in physical workload was achieved through task redistribution, where the collaborative robot assumed repetitive *pick-and-place* operations that previously required sustained awkward postures. Time spent in non-ergonomic postures decreased significantly across all observed body segments, directly mitigating the risk of specific musculoskeletal disorders. The neck exhibited the most notable improvement, with high-risk exposure decreasing from 35% to just 4% of the work cycle. This reduction in sustained neck flexion substantially lowers the risk of neck tension syndrome (cervical strain), a common condition associated with prolonged forward

head posture. The trunk showed complete elimination of high-risk postures (from 27% to 0%), primarily due to the reorganization of materials within the golden reach zone (≤400 mm), which eliminated the need for trunk flexion and rotation during pallet retrieval. This improvement reduces the risk of lower back pain and chronic spinal disorders, which are among the most prevalent WMSDs in manufacturing. Shoulder exposure improved as well, with the right shoulder spending no time in high-risk postures compared to 36% in the traditional setup. The reduction in shoulder flexion, abduction, and repetitive reaching directly mitigates the risk of rotator cuff syndrome, as well as medial and lateral epicondylitis (commonly known as golfer's and tennis elbow), conditions associated with repetitive gripping, wrist extension, and forearm pronation. It is important to mention that the ergonomic assessment in this study was conducted over a limited portion of the working time. The identified risk levels may underestimate the actual exposure that would occur during a full work shift. Prolonged task execution under non-ergonomic conditions would likely lead to fatigue accumulation, which could result in even greater use of unfavorable postures and an increased overall risk of musculoskeletal disorders.

SQ2: Regarding the second sub-question, the results show that the cobot-integrated workstation does improve operational performance. Total cycle time for five packaged pallets decreased from 107 seconds to 61 seconds, representing a 43% reduction. Consequently, productivity increased from 168 to 295 pallets per hour, a 75% improvement. The most substantial reductions were observed in non-value-added activities (NVAA), which decreased by 80.47% for template change activity and by 44.26% for conveyor placement activity. The overall share of value-added activities (VAA) increased from 76.6% to 83.4%, while NVAA decreased from 9.9% to 3.4%. These performance gains demonstrate that ergonomic optimization and collaborative robotics are complementary approaches that together enhance operational efficiency.

The findings support cobot integration not only as a technological investment. They also show its value as a strategic approach to workplace design. A strategic approach makes a shift from *reactive* ergonomic interventions (addressing risks after they have manifested) to a *proactive* design that integrates technological, operational, and human factors before the risk occurs. Three elements define the strategic nature of the approach in this study. First, the combination of ergonomic and operational goals shows that worker well-being and productivity do not conflict, but instead support each other. The 71% reduction in ergonomic risk and the 75% increase in productivity clearly demonstrate this. Second, combining *Lean* and 5S for workplace organization, golden zone principles for material placement, and collaborative robotics for task redistribution reflects a more holistic approach. Third, time-based RULA analysis enabled continuous and objective data. Overall, this strategic view aligns with broader Industry 5.0 trends, focused on human-centricity, sustainability, and resilience (European Commission, 2021). By framing cobot implementation in this way, manufacturers can move beyond seeing automation only as a cost-saving tool and instead treat it as a key part of a safer, more flexible, and more competitive production system.

Besides mentioned benefits, several limitations should be acknowledged. First, this study involved a single participant, which limits generalizability. However, the main focus was on postural analysis rather than statistical generalization. Second, the experiment was conducted in laboratory rather than real industrial conditions, which may not fully capture workplace complex nature and other relevant risks (e.g., hazards, organizational factors, cognitive ergonomics).

Future research should include a larger number of participants to allow for more reliable general conclusions and to better understand individual differences. It should also examine whether the improvements in ergonomics and performance remain stable over time and how operator workload changes as users become more familiar with the system. Additionally, integrating artificial intelligence for dynamic task allocation and adaptive HMI design represents a promising direction for further improving human-robot collaboration.

6. CONCLUSION

In the context of rapid technological changes, companies seeking to maintain competitiveness and ensure sustainable competitive advantage must be ready to adapt to new industrial trends and invest in advanced, human-centric manufacturing solutions. This shift reflects the growing humanization of production, where the worker is placed at the center of the process, with a stronger focus on health, safety, and overall well-being. Companies are increasingly directing more resources and strategic initiatives toward their employees, recognizing them as a key driver of performance and innovation. Ergonomic solutions powered by new technologies can significantly reduce the risk of WMSDs. An ergonomic approach to workplace design with collaborative robotics represents a key factor in the continuous improvement of industrial systems and an important step toward a future of manufacturing based on human–machine collaboration.

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