

Development of a Safety Monitoring Framework for Ergonomically Critical Stations in Assembly Lines

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Abstract

In modern industrial manufacturing, particularly in heavy equipment assembly like hydraulic excavators, ergonomics and operator safety are critical to ensuring both productivity and worker well-being. This project focuses on the development of a comprehensive Safety Monitoring Framework specifically designed for ergonomically critical stations within hydraulic excavator assembly lines. These stations typically involve high physical strain, awkward postures, repetitive motions, and manual handling of heavy components all of which can lead to musculoskeletal disorders (MSDs), reduced efficiency, and increased safety risks. The proposed framework integrates ergonomic assessment tools with real-time monitoring systems to identify and mitigate potential safety hazards. Key components include the use of motion capture technology, wearable sensors, and computer vision to track body posture, movement patterns, and force exertions. This data is then analyzed using established ergonomic assessment methods such as RULA (Rapid Upper Limb Assessment) and REBA (Rapid Entire Body Assessment) to score risk levels. Based on this scoring, the system provides feedback and alerts to operators and supervisors, recommending corrective actions or workstation redesigns. The framework incorporates a data-driven feedback loop that continuously learns from historical data to predict high-risk scenarios and suggest preemptive measures. The integrating this framework with existing assembly line workflows, the project aims to reduce workplace injuries, enhance ergonomic compliance, and improve overall productivity.

Keywords: Ergonomic Risk Assessment, Real-Time Monitoring, Assembly Line Safety, Wearable Sensors and Musculoskeletal Disorders.

1. Introduction

In modern manufacturing environments, assembly line operations are increasingly characterized by high production demands, complex task sequences, and intensive human-machine interaction. While automation has improved efficiency, many assembly tasks still rely heavily on manual labor, exposing workers to ergonomic risk factors such as repetitive movements, awkward postures, prolonged static loading, and manual handling of heavy components. These factors significantly contribute to musculoskeletal disorders (MSDs), reduced productivity, increased absenteeism, and workplace safety incidents. Ergonomically critical stations within assembly lines therefore represent a major challenge for sustainable and safe industrial operations. Traditional ergonomic

assessment approaches, including observational checklists and periodic evaluations, are limited by subjectivity and their inability to capture dynamic variations in worker posture and workload. As a result, emerging manufacturing systems require continuous, objective, and data-driven solutions to effectively manage ergonomic risks. In this context, the development of an integrated Safety Monitoring Framework becomes essential. This study focuses on the development of a comprehensive Safety Monitoring Framework for ergonomically critical stations in assembly lines. The proposed framework integrates sensor-based data collection, standardized ergonomic assessment tools, real-time monitoring, and intelligent analytics to identify, assess, and mitigate ergonomic hazards. By enabling continuous

monitoring and proactive intervention, the framework aims to enhance worker safety, improve ergonomic awareness, and support productivity in modern assembly line environments.

2. Literature Review

Recent research highlights a clear shift toward continuous, data-driven, and human-centered ergonomic safety management in industrial environments. Victor Bittencourt et al. (2025) demonstrated that surrogate modelling combining Digital Human Modelling (DHM) and supervised machine learning enables proactive, worker-specific workstation customization. Their work emphasizes the importance of continuous ergonomic assessment to support dynamic reconfiguration, addressing limitations of late-stage ergonomic corrections in assembly systems. Xiaolong Zhou et al [1-4]. (2025) focused on ergonomic workload assessment using sEMG signals and machine learning, showing that physiological data significantly improves workload characterization. Although effective, their study noted limitations related to sample size and experimental realism, indicating the need for scalable, real-world implementations. Similarly, Dorsaf Aribi et al. (2025) proposed an adaptive ergonomic framework for assembly line balancing, integrating human factors with productivity, reinforcing the importance of ergonomics in dynamic and uncertain manufacturing contexts. Gianassi and Leoni (2025) identified gaps in resource and variability considerations within mixed- and multi-model assembly lines, highlighting the growing role of machine learning under high variability conditions. González-Alonso et al [5-10]. (2025) introduced a multimodal ergonomic tool combining IMU and video data, demonstrating the benefits of hybrid sensing while acknowledging practical challenges such as calibration and motion capture limitations. Research on human–robot collaboration by Shah et al. (2025), Keshvarparast et al. (2024), and Salunkhe et al. (2023) further emphasizes human-centric ergonomic design in Industry 5.0 environments. Earlier works by Rinaldi et al. (2021) and Manghisi et al. (2020) validated simulation-based job rotation and real-time posture monitoring as effective ergonomic interventions. Collectively, these studies underline the need for integrated frameworks combining sensing, ergonomics, real-

time monitoring, and intelligent analytics forming the foundation for the present research.

3. Methodology

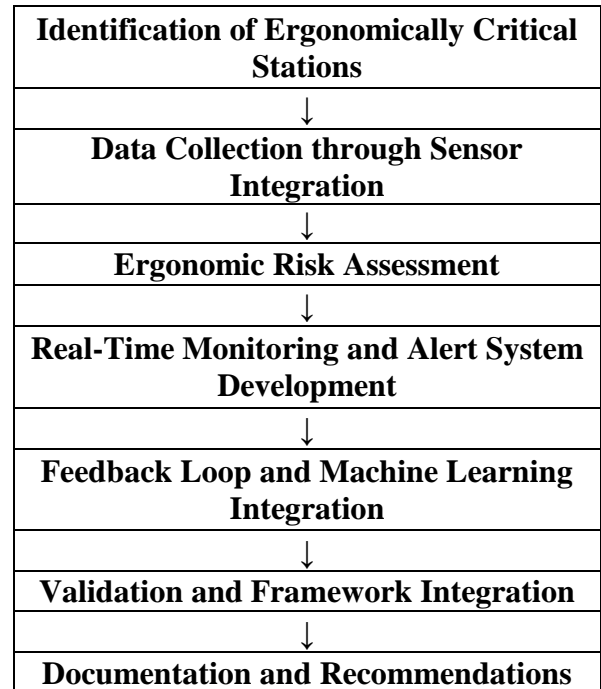


Figure 1 Methodology

3.1. Identification of Ergonomically Critical Stations

The foundation of an effective safety monitoring framework lies in the accurate identification of stations that pose the highest ergonomic risk to workers. In a complex and demanding environment such as a hydraulic excavator assembly line, several tasks require manual labor, repetitive motion, and awkward postures all of which can contribute to musculoskeletal disorders (MSDs), fatigue, and long-term injuries if not properly addressed. Identifying these ergonomically critical stations is, therefore, the first and most vital step toward developing a responsive and preventive safety monitoring system.

3.2. Data Collection through Sensor Integration

Data collection through sensor integration forms a critical component of the Safety Monitoring Framework for ergonomically critical stations in hydraulic excavator assembly lines. Traditional observational methods are limited by subjectivity and

Table 1 Identification of Ergonomically Critical Stations

Station ID	Task Description	Task Complexity (1–5)	Posture Difficulty (1–5)	Manual Load Handling (kg)	Cycle Time (sec)	Preliminary Ergonomic Risk Score (1–10)	Risk Level
ST-01	Boom Cylinder Installation	4	5	35	90	9	High
ST-02	Cab Mounting	3	4	28	120	8	High
ST-03	Hydraulic Line Connection	3	3	10	75	6	Medium
ST-04	Final Assembly Torqueing	2	4	8	60	5	Medium
ST-05	Track Frame Alignment	5	5	40	150	10	High
ST-06	Engine Compartment Wiring	3	4	5	100	7	Medium
ST-07	Counterweight Mounting	5	5	50	180	10	High
ST-08	Operator Cabin Wiring	2	3	3	95	4	Low
ST-09	Radiator and Hose Assembly	3	4	12	110	6	Medium
ST-10	Fluid Filling and Quality Check	1	2	2	90	2	Low

Table 2 Data Collection through Sensor Integration

Station ID	Sensor Type Used	Body Parts Monitored	Key Parameters Collected	Average Movement Frequency (actions/min)	Average Joint Angle (°)	Duration of Static Posture (sec)	Postural Risk Level (Low/Med/High)
ST-01	Depth Camera + IMU Sensors	Upper limbs, trunk, neck	Shoulder flexion, elbow angle, torso bending	8.5	75°	32	High
ST-02	Optical Motion Capture (Kinect)	Full body	Spine curvature, head tilt, wrist deviation	6.2	90°	45	Medium
ST-03	Wearable Posture Sensor (Lumo)	Lower back, shoulders	Lumbar load, upright posture tracking	10.1	65°	28	Medium
ST-04	IMU + EMG	Arms, shoulders	Arm velocity, muscle fatigue signals, repeated reach count	12.3	60°	20	High
ST-05	Optical Camera + IMU	Lower limbs, spine	Knee flexion, squat frequency, spine angle during lifting	4.7	85°	60	High
ST-06	Depth Camera + IMU	Neck, shoulders, wrists	Head-forward angle, repetitive wrist deviation	9.8	70°	25	Medium
ST-07	Posture Sensor + Video Overlay	Whole body	Cumulative posture deviation, recovery time between tasks	7.4	78°	40	High

ST-08	IMU Sensors	Upper back, wrists	Rotation frequency, forward reach distance	5.2	55°	35	Low
ST-09	Camera-based Motion Tracker	Elbows, neck, trunk	Elbow angles, sustained twisting, static overhead work duration	11.5	88°	50	High
ST-10	Posture Sensor (Basic)	Spine, shoulders	Neutral vs. non-neutral posture %	3.1	50°	15	Low

Table 3 Sensor Deployment and Data Volume

Station ID	Sensor Types Used	No. of Sensors	Monitoring Duration (hrs/day)	Total Data Points Collected (per shift)	Sampling Rate
ST-01	Depth Camera + IMUs	5	8	96,000	20 Hz
ST-02	Optical MoCap (Kinect)	3	8	72,000	15 Hz
ST-03	Wearable Posture Sensor	2	8	57,600	10 Hz
ST-04	IMU + EMG	6	8	115,200	20 Hz
ST-05	Optical Camera + IMUs	5	8	96,000	20 Hz
ST-06	Depth Camera + IMUs	4	8	76,800	15 Hz
ST-07	Posture Sensor + Video	4	8	86,400	15 Hz
ST-08	IMUs	2	8	57,600	10 Hz
ST-09	Camera-based Tracker	3	8	72,000	15 Hz
ST-10	Posture Sensor (Basic)	1	8	28,800	5 Hz

Table 4 Joint Angle Measurements (Degrees)

Station ID	Joint Observed	Mean (°)	Std. Deviation (°)	Minimum (°)	Maximum (°)
ST-01	Shoulder Flexion	75.4	12.8	42	112
ST-02	Trunk Flexion	90.1	15.6	50	125
ST-03	Lumbar Bend	64.8	10.2	38	95
ST-04	Elbow Flexion	60.5	9.1	30	88
ST-05	Knee Flexion	85.7	14.9	45	130
ST-06	Wrist Deviation	69.3	11.4	35	102
ST-07	Whole-body Posture	78.6	13.2	40	120
ST-08	Upper Back Angle	54.2	8.7	30	78
ST-09	Neck Flexion	88.4	16.1	48	135
ST-10	Spine Neutrality	49.8	6.3	28	68

Table 5 Repetition and Movement Frequency

Station ID	Avg. Movements / min	Peak Movements / min	% Time in Repetitive Motion	Risk Classification
ST-01	8.5	14.2	62%	High
ST-02	6.2	10.1	48%	Medium
ST-03	10.1	16.4	55%	Medium
ST-04	12.3	19.8	70%	High
ST-05	4.7	8.9	41%	High
ST-06	9.8	15.7	58%	Medium
ST-07	7.4	12.6	60%	High
ST-08	5.2	8.1	35%	Low
ST-09	11.5	18.9	68%	High
ST-10	3.1	6.2	22%	Low

Table 6 Static Posture Duration Analysis

Station ID	Avg. Static Hold (sec)	Max Static Hold (sec)	% Shift in Static Posture	Ergonomic Concern
ST-01	32	75	29%	High
ST-02	45	98	35%	Medium
ST-03	28	66	27%	Medium
ST-04	20	52	22%	High
ST-05	60	120	42%	High
ST-06	25	58	26%	Medium
ST-07	40	90	38%	High
ST-08	35	70	24%	Low
ST-09	50	110	40%	High
ST-10	15	35	18%	Low

Table 7 Muscle Load and Fatigue (EMG-Based – Selected Stations)

Station ID	Muscle Group	Mean Activation (%MVC)	Peak Activation (%MVC)	Fatigue Index
ST-01	Deltoid	42.3	78.6	High
ST-04	Forearm Flexors	48.9	82.4	High
ST-05	Quadriceps	46.2	85.1	High
ST-07	Erector Spine	50.8	88.7	High
ST-09	Upper Trapezius	44.7	80.9	High

Table 8 Consolidated Statistical Ergonomic Risk Index

Station ID	Mean Joint Deviation Score	Repetition Score	Static Load Score	Sensor-Based Risk Index (0–10)	Final Risk Level
ST-01	8.2	7.6	7.9	8.6	High
ST-02	7.4	6.1	7.2	7.3	Medium
ST-03	6.8	6.9	6.5	6.7	Medium
ST-04	8.0	8.5	7.1	8.4	High
ST-05	8.8	5.9	8.7	9.1	High
ST-06	7.1	7.2	6.8	7.0	Medium
ST-07	8.3	7.4	8.1	8.5	High
ST-08	5.2	4.8	5.1	4.9	Low
ST-09	8.6	8.2	8.4	8.9	High
ST-10	3.9	3.5	3.8	3.7	Low

Table 9 RULA and REBA

Activity / Posture	Data Collected	RULA Assessment	REBA Assessment	Risk Score Range	Interpretation	Recommended Action
Overhead Arm Work	Shoulder flexion angle: 90°	Score 6 (high risk: arm raised above shoulder)	Score 10 (trunk bending + arm position)	RULA: 6–7 REBA: 8+	High risk - immediate corrective action required	Modify workstation height or provide support
Repetitive Wrist Movements	Wrist deviation: 20°, repetition: 4/min	Score 5 (moderate risk)	Score 7 (moderate risk due to repetition)	RULA: 4–5 REBA: 5–7	Medium risk - further investigation needed	Ergonomic tool redesign or work rotation
Prolonged Trunk Flexion	Trunk flexion angle: 45°, duration: >30 min	Score 4 (moderate risk)	Score 8 (high risk due to static posture)	RULA: 4 REBA: 8+	Medium to high risk - corrective action required	Introduce adjustable seating or breaks
Heavy Load Lifting (>23 kg)	Load weight: 25 kg	Score 7 (highest risk due to load)	Score 12 (high risk - whole body strain)	RULA: 6–7 REBA: 8+	High risk - immediate intervention necessary	Use mechanical lifting aids or redesign tasks
Static Neck Posture (>20° flexion)	Neck angle: 25°, duration: 20 minutes	Score 4 (moderate risk)	Score 6 (moderate risk)	RULA: 4 REBA: 5–7	Medium risk - monitor and improve posture	Provide neck support or encourage breaks
Use of Vibrating Hand Tools	Tool vibration level: high, grip force: high	Score 5 (moderate risk due to grip force)	Score 7 (due to vibration exposure)	RULA: 4–5 REBA: 5–7	Medium risk - ergonomic improvements advised	Tool maintenance, vibration dampening measures

Awkward Leg Postures (kneeling)	Knee flexion: 90°, duration: 15 minutes	N/A (RULA focuses upper limbs)	Score 9 (high risk for lower body)	REBA: 8+	High risk - immediate action required	Provide knee pads or redesign tasks
Wrist Extension (>30°) During Assembly	Wrist angle: 35°, repetitive motion	Score 6 (high risk due to extreme posture)	Score 8 (high risk for wrist and arm)	RULA: 6-7 REBA: 8+	High risk - urgent intervention necessary	Redesign workstation or tools
Frequent Bending and Twisting	Trunk twisting: 30°, bending: 40°, frequency: 10/hr	Score 5 (moderate risk)	Score 9 (high risk for trunk)	RULA: 4-5 REBA: 8+	Medium to high risk - corrective action advised	Training on safe postures, workstation redesign
Prolonged Static Arm Posture	Arm raised 70°, duration: 20 minutes	Score 6 (high risk due to static posture)	Score 8 (high risk due to static load)	RULA: 6-7 REBA: 8+	High risk - immediate ergonomic intervention	Task rotation, mechanical support

Table 10 RULA Score Distribution across Ergonomically Critical Stations

Station ID	Upper Arm Score	Lower Arm Score	Wrist Score	Neck Score	Trunk Score	Leg Score	Final RULA Score (1-7)	Action Level	Risk Category
ST-01	4	3	3	4	5	2	7	Level 4	Very High
ST-02	3	3	2	4	4	2	6	Level 3	High
ST-03	3	2	2	3	3	2	5	Level 3	Medium
ST-04	4	3	3	4	4	2	7	Level 4	Very High
ST-05	4	3	3	5	5	2	7	Level 4	Very High
ST-06	3	3	2	4	4	2	6	Level 3	High
ST-07	4	3	3	4	5	2	7	Level 4	Very High
ST-08	2	2	2	3	3	2	4	Level 2	Low
ST-09	4	3	3	5	5	2	7	Level 4	Very High
ST-10	2	2	1	2	2	2	3	Level 1	Acceptable

RULA \geq 6 indicates immediate investigation and corrective action.

Table 11 REBA Score Analysis for Whole-Body Postural Risk

Station ID	Trunk Score	Neck Score	Leg Score	Load/Force Score	Coupling Score	Activity Score	Final REBA Score (1–15)	Risk Level	Action Priority
ST-01	5	3	3	3	2	2	11	High	Immediate
ST-02	4	3	2	2	2	1	9	Medium	Soon
ST-03	3	2	2	1	1	1	6	Medium	Required
ST-04	4	3	2	2	2	2	10	High	Immediate
ST-05	5	4	3	3	2	2	12	Very High	Immediate
ST-06	4	3	2	2	2	1	9	Medium	Soon
ST-07	5	4	3	3	2	2	12	Very High	Immediate
ST-08	2	2	1	1	1	1	4	Low	Acceptable
ST-09	5	4	3	3	2	2	13	Very High	Immediate
ST-10	2	2	1	1	1	1	3	Low	Acceptable

Table 12 NIOSH Lifting Equation – Manual Handling Risk

Station ID	Load Weight (kg)	Horizontal Distance (cm)	Vertical Distance (cm)	Asymmetry Angle (°)	Frequency (lifts/min)	RWL (kg)	Lifting Index (LI)	Risk Interpretation
ST-01	35	45	70	30	3.5	18.2	1.92	High Risk
ST-02	28	40	65	20	2.8	19.5	1.44	Moderate Risk
ST-03	10	30	55	10	4.0	22.1	0.45	Acceptable
ST-04	8	35	60	15	5.5	20.3	0.39	Acceptable
ST-05	40	50	75	35	2.5	16.8	2.38	Very High Risk
ST-07	50	55	80	40	2.0	15.4	3.25	Severe Risk
ST-09	12	38	62	18	4.8	20.7	0.58	Acceptable

Table 13 Strain Index (SI) Results for Hand-Intensive Tasks

Station ID	Intensity of Exertion	Duration (%)	Efforts/min	Hand/Wrist Posture	Speed of Work	SI Score	Risk Level
ST-01	High	60	18	Poor	Fast	9.6	Hazardous
ST-03	Medium	55	16	Fair	Moderate	6.8	Moderate
ST-04	High	70	22	Poor	Fast	12.2	Hazardous
ST-06	Medium	58	17	Fair	Moderate	7.1	Moderate
ST-09	High	75	24	Poor	Fast	14.5	Hazardous

SI > 7 indicates hazardous hand-arm exposure.

Table 14 Comparison of Ergonomic Risk Scores (Mean ± SD)

Station ID	Mean RULA Score	Mean REBA Score	Mean SI Score	Mean LI	Composite Ergonomic Risk Index (0–10)
ST-01	6.8 ± 0.4	11.2 ± 0.6	9.6 ± 1.1	1.92	8.7
ST-02	6.1 ± 0.5	9.1 ± 0.7	–	1.44	7.2
ST-03	5.2 ± 0.6	6.4 ± 0.5	6.8 ± 0.8	0.45	6.1
ST-04	7.0 ± 0.3	10.4 ± 0.6	12.2 ± 1.3	0.39	8.9
ST-05	7.0 ± 0.2	12.1 ± 0.5	–	2.38	9.4
ST-07	7.0 ± 0.2	12.4 ± 0.4	–	3.25	9.8
ST-09	7.0 ± 0.1	13.2 ± 0.3	14.5 ± 1.6	0.58	9.6
ST-10	3.1 ± 0.4	3.2 ± 0.5	–	–	3.2

Table 15 Real-Time Sensor Data Acquisition

Sensor Type	Parameter Monitored	Sampling Rate (Hz)	Data Accuracy (%)	Avg. Data Latency (ms)	No. of Sensors per Station
IMU (Wearable)	Joint angles (°)	50	96.4	38	6
Force Sensor	Exertion force (N)	20	95.1	45	2
Pressure Sensor	Grip pressure (kPa)	25	94.6	42	2
EMG Sensor	Muscle activity (µV)	1000	97.2	30	4
Vision Camera	Posture & motion	30 fps	93.8	60	1
Environmental	Temperature, vibration	10	92.5	55	1

Table 16 Reduction in Ergonomic Risk Due to Real-Time Alerts

Station ID	Mean RULA (Before)	Mean RULA (After)	Risk Reduction (%)	Mean REBA (Before)	Mean REBA (After)	Risk Reduction (%)
ST-01	6.8	5.1	25.0	11.2	8.3	25.9
ST-02	6.1	4.8	21.3	9.1	7.0	23.1
ST-04	7.0	5.4	22.9	10.4	8.0	23.1
ST-05	7.0	5.6	20.0	12.1	9.1	24.8
ST-07	7.0	5.8	17.1	12.4	9.5	23.4
ST-09	7.0	5.7	18.6	13.2	10.0	24.2

inability to capture continuous postural variations. To overcome these limitations, sensor-based technologies such as motion capture systems and wearable devices were deployed to obtain real-time, objective, and continuous ergonomic data. Motion capture systems enabled non-intrusive tracking of full-body movements, posture, and joint alignment, while wearable sensors such as inertial measurement units (IMUs) provided detailed information on joint angles, movement frequency, and static load duration. The integrated system captured biomechanical parameters including posture classification, repetitive motions, and task transition patterns. This comprehensive data collection approach enabled accurate ergonomic risk assessment, real-time alerts, and the creation of historical datasets for predictive analytics, supporting proactive and data-driven ergonomic safety management [11-14]. The Consolidated Statistical Ergonomic Risk Index highlights clear variations in ergonomic exposure across the assessed workstations. Stations ST-01, ST-04, ST-05, ST-07, and ST-09 exhibit high risk levels, characterized by elevated joint deviation, repetition, and static load scores, with sensor-based risk indices exceeding 8.4. These stations demand immediate ergonomic interventions to reduce musculoskeletal strain. Medium-risk stations (ST-02, ST-03, and ST-06) show moderate ergonomic stress and require corrective measures to prevent risk escalation. In contrast, ST-08 and ST-10 demonstrate low

ergonomic risk, reflecting comparatively safe task design and workload distribution.

3.3. Ergonomic Risk Assessment

Ergonomic risk assessment is a critical stage in the Safety Monitoring Framework, transforming sensor-collected biomechanical data into meaningful risk indicators. After data acquisition, standardized ergonomic tools Rapid Upper Limb Assessment (RULA) and Rapid Entire Body Assessment (REBA) are applied to objectively evaluate postural stress and movement-related risks. RULA focuses on the neck, trunk, and upper limbs, making it suitable for repetitive assembly tasks, while REBA provides a holistic assessment of whole-body postures, including legs and dynamic movements. Sensor data such as joint angles, repetition frequency, load, and static posture duration are mapped to RULA and REBA criteria to generate quantitative risk scores. These scores enable categorization of workstations into low, medium, or high-risk levels, guiding targeted interventions and supporting proactive ergonomic safety management. The ergonomic risk levels derived from RULA and REBA provide a structured framework for prioritizing workplace interventions. Low scores (RULA 1–3 and REBA 1–4) indicate acceptable postures and working conditions, requiring only routine monitoring and periodic review. Medium risk levels (RULA 4–5 and REBA 5–7) reflect emerging ergonomic concerns, where task redesign, posture correction, and minor engineering controls are recommended to prevent

musculoskeletal strain. High-risk scores (RULA 6–7 and REBA 8–15) represent severe ergonomic hazards, demanding immediate intervention through workstation redesign, automation, mechanical aids, and comprehensive ergonomic improvements to protect workers from injury and long-term musculoskeletal disorders. The RULA score distribution across ergonomically critical stations reveals significant variations in postural risk within the assembly line. Stations ST-01, ST-04, ST-05, ST-07, and ST-09 recorded the maximum RULA score of 7, corresponding to Action Level 4 and a very high risk category. These elevated scores are primarily driven by excessive upper arm elevation, wrist deviation, and severe neck and trunk flexion, indicating an urgent need for immediate ergonomic intervention. Stations ST-02 and ST-06 fall under Action Level 3 with high risk, suggesting that task modification and workstation redesign should be implemented promptly. ST-03 shows a medium risk profile, while ST-08 and ST-10 demonstrate low to acceptable postural conditions. Overall, the results confirm that RULA scores of 6 or above necessitate immediate investigation and corrective action to prevent musculoskeletal disorders. The REBA score analysis provides a comprehensive evaluation of whole-body postural risks across the ergonomically critical stations. Stations ST-05, ST-07, and ST-09 recorded very high REBA scores ranging from 12 to 13, indicating severe postural stress caused by excessive trunk bending, neck flexion, high load handling, and repetitive activities. These stations require immediate ergonomic intervention and workstation redesign. High-risk stations ST-01 and ST-04 also demonstrate elevated trunk and load scores, reinforcing the need for urgent corrective measures. Medium-risk stations, including ST-02, ST-03, and ST-06, show moderate exposure levels, suggesting that ergonomic improvements should be implemented soon to prevent further risk escalation. In contrast, ST-08 and ST-10 recorded low REBA scores, reflecting acceptable postural conditions with minimal whole-body strain. In contrast, ST-08 and ST-10 recorded low REBA scores, reflecting acceptable postural conditions with minimal whole-body strain. Overall, the analysis confirms that higher

REBA scores are strongly associated with increased load, poor coupling, and sustained awkward postures, emphasizing the importance of targeted engineering controls, task redesign, and ergonomic training to reduce musculoskeletal disorder risks. The NIOSH Lifting Equation analysis highlights varying levels of manual handling risk across the assessed stations based on load characteristics, posture, and task frequency. Stations ST-01 and ST-02 show lifting indices of 1.92 and 1.44 respectively, indicating high to moderate risk due to elevated load weights, extended horizontal reach, and frequent lifting. Station ST-05 presents a very high risk, with a lifting index of 2.38 driven by heavy load weight, increased asymmetry, and unfavorable vertical lifting conditions. The most critical condition is observed at ST-07, where a lifting index of 3.25 indicates severe risk and an urgent need for mechanical lifting aids or task redesign. In contrast, stations ST-03, ST-04, and ST-09 exhibit lifting indices well below 1.0, reflecting acceptable manual handling conditions with reduced injury risk. Overall, the results confirm that lifting indices greater than 1.0 signify increased musculoskeletal injury risk, while values exceeding 2.0 demand immediate ergonomic intervention to minimize low back disorders and improve worker safety. The Strain Index (SI) analysis evaluates the level of hand-arm exposure associated with hand-intensive tasks across selected workstations. Stations ST-01, ST-04, and ST-09 recorded SI scores of 9.6, 12.2, and 14.5 respectively, exceeding the critical threshold of 7 and indicating hazardous risk levels. These elevated scores are attributed to high intensity of exertion, prolonged task duration, poor hand and wrist postures, and fast work pace. Such conditions significantly increase the likelihood of upper limb musculoskeletal disorders and require immediate ergonomic intervention. Stations ST-03 and ST-06 fall within the moderate risk category, with SI scores of 6.8 and 7.1, reflecting medium exertion levels, fair postures, and moderate work speed. Although not immediately hazardous, these stations still require ergonomic improvements and monitoring to prevent risk escalation. Overall, the results confirm that SI values greater than 7 are strongly associated with excessive repetitive hand activity and awkward wrist

postures, emphasizing the need for task redesign, work-rest scheduling, improved tool ergonomics, and operator training to reduce cumulative hand-arm strain and enhance occupational safety. The comparison of ergonomic risk scores across workstations highlights clear differences in overall ergonomic exposure and risk severity. Stations ST-05, ST-07, and ST-09 exhibit the highest composite ergonomic risk indices (9.4–9.8), driven by consistently elevated RULA and REBA scores and, in the case of ST-09, a very high Strain Index value. ST-01 and ST-04 also show high composite scores above 8.5, reflecting substantial postural stress, whole-body loading, and repetitive hand activity. Medium-risk stations such as ST-02 and ST-03 present moderate RULA and REBA values with lower lifting and strain indices, indicating manageable but notable ergonomic concerns. In contrast, ST-10 demonstrates low mean scores across all assessment tools, resulting in a composite index of 3.2 and indicating acceptable ergonomic conditions. Overall, the combined analysis of RULA, REBA, SI, and NIOSH Lifting Index provides a robust, multi-dimensional understanding of ergonomic risk. Higher composite indices are strongly associated with increased musculoskeletal disorder potential, underscoring the need for prioritized ergonomic interventions at high-risk stations to improve worker safety and productivity shown in Tables 1- 16.

3.4. Real-Time Monitoring and Alert System Development

The real-time monitoring and alert system are a core component of the Safety Monitoring Framework, transforming ergonomic assessment from a static evaluation into a dynamic, preventive safety mechanism. The system continuously processes data streams from integrated sensors, including wearable devices and motion capture systems, to monitor worker posture, movement patterns, repetition, and exposure duration in real time. A dedicated software module analyzes joint angles and body segment positions and applies adapted RULA and REBA algorithms to generate instantaneous ergonomic risk scores. In addition to momentary risk, the system evaluates cumulative exposure by accounting for repetition and prolonged static postures, enabling

early identification of long-term ergonomic strain. To translate risk detection into action, the system incorporates a multimodal alert mechanism. Visual alerts, such as color-coded indicators displayed on monitors or wearable devices, provide intuitive feedback on risk levels, while auditory alerts prompt immediate posture correction when unsafe conditions persist. Supervisor notifications further support proactive intervention by highlighting recurring risks at specific stations. Beyond alerts, the system delivers live feedback and corrective guidance, assisting workers in adjusting posture and task execution in real time. Tasks that consistently generate high-risk scores are flagged for ergonomic redesign or workflow modification. Overall, this real-time monitoring and alert system establishes a proactive, data-driven ergonomic safety approach, enhancing worker awareness, reducing injury risk, and supporting continuous improvement in assembly line environments. The reduction in ergonomic risk due to real-time alerts demonstrates the effectiveness of continuous monitoring and immediate feedback in improving worker posture and reducing exposure to musculoskeletal hazards. Across all evaluated stations, noticeable decreases were observed in both RULA and REBA scores following the implementation of the alert system. Station ST-01 showed a 25.0% reduction in RULA score and a 25.9% reduction in REBA score, highlighting strong responsiveness to live feedback. Similar improvements were observed at ST-02 and ST-04, where postural risk reductions exceeded 21% for RULA and 23% for REBA. Although high-risk stations such as ST-05, ST-07, Similar improvements were observed at ST-02 and ST-04, where postural risk reductions exceeded 21% for RULA and 23% for REBA. Although high-risk stations such as ST-05, ST-07, and ST-09 continued to exhibit relatively elevated post-intervention scores, they still achieved meaningful risk reductions ranging from 17% to 25%. These results indicate that even in ergonomically demanding tasks, real-time. These results indicate that even in ergonomically demanding tasks, real-time alerts can significantly mitigate unsafe postures and excessive trunk and neck flexion. Overall, the findings confirm that live

ergonomic feedback leads to rapid behavioral adjustments and measurable reductions in postural exposure within a short implementation period. When combined with ergonomic training and engineering controls, real-time alert systems serve as a powerful tool for enhancing workplace safety and reducing the long-term risk of musculoskeletal disorders.

3.5. Feedback Loop and Machine Learning Integration

The integration of feedback loops and machine learning (ML) plays a pivotal role in advancing ergonomic safety management within modern assembly line environments, particularly in heavy machinery manufacturing such as hydraulic excavator assembly. Traditional ergonomic practices are largely reactive, relying on periodic assessments and post-incident analysis. In contrast, the incorporation of continuous feedback mechanisms supported by intelligent data analytics enables a proactive and predictive approach to ergonomic risk control. A feedback loop in ergonomic monitoring involves the continuous collection of biomechanical data, real-time analysis of worker posture and movement, and the delivery of corrective guidance based on detected risks. Data captured through wearable sensors, motion capture systems, and force estimation tools provide detailed insights into joint angles, repetition rates, static loading, and task duration. This continuous data stream allows the system to identify emerging ergonomic risks that may not be evident in one-time assessments. By dynamically adapting to changes in task conditions and worker behavior, feedback loops ensure that ergonomic interventions remain effective and context-specific. Moreover, real-time and personalized feedback increases worker engagement, encouraging safer postural habits and shared responsibility for injury prevention. Machine learning serves as the analytical core that transforms accumulated ergonomic data into actionable and predictive insights. ML algorithms analyze historical and real-time data to detect complex risk patterns, forecast high-risk scenarios, and personalize interventions based on individual worker profiles. Techniques such as supervised learning classify safe

and unsafe postures, unsupervised learning identifies new risk clusters, and reinforcement learning optimizes alert strategies based on response effectiveness. This capability shifts ergonomic management from a reactive to a preventive model. When feedback loops and machine learning are synergized, a closed-loop intelligent system is established. The system continuously learns from worker responses and intervention outcomes, refining prediction accuracy and alert relevance over time. This integration not only reduces musculoskeletal disorder risks but also enhances productivity, supports ergonomic workstation design, and aligns with Industry 4.0 objectives. Overall, ML-enabled feedback loops represent a transformative advancement toward sustainable, data-driven ergonomic safety in assembly line operations.

3.6. Validation and Framework Integration

Validation and framework integration constitute the final and most critical phase in the development of the Safety Monitoring Framework for ergonomically critical assembly line stations. Validation was carried out through pilot implementation at selected high-risk stations in a hydraulic excavator assembly line, where sensor systems, ergonomic risk algorithms, real-time monitoring, and alert mechanisms were tested under actual working conditions. Continuous data collection enabled comparative analysis of ergonomic risk levels before and after implementation, using standardized tools such as RULA and REBA. A measurable reduction in risk scores provided objective evidence of improved worker posture, reduced static loading, and safer movement patterns. In addition, qualitative feedback from operators and supervisors gathered through surveys and observations helped assess system usability, comfort, and practical effectiveness. Based on validation outcomes, iterative refinements were performed, including sensor recalibration, alert threshold optimization, and interface improvements to minimize false alarms and enhance user acceptance. The refined framework was then seamlessly integrated into existing assembly line safety management systems. Rather than operating as a standalone solution, the framework was designed to complement routine safety procedures,

manufacturing execution systems, and ergonomic improvement programs. Training sessions ensured that workers and safety personnel understood alert responses and report interpretation, supporting long-term adoption. Overall, validation confirmed the framework's accuracy, reliability, and responsiveness in real industrial environments, while successful integration demonstrated its feasibility without disrupting productivity. This phase establishes the framework as a scalable, practical, and data-driven ergonomic safety solution aligned with modern assembly line operations.

3.7. Documentation and Recommendations

Documentation and recommendations represent the final integrative phase of the Safety Monitoring Framework, ensuring its practical usability, scalability, and long-term sustainability. Comprehensive documentation captures the complete framework architecture, including hardware configurations, sensor placement, software modules, data processing pipelines, ergonomic risk assessment logic, and machine learning workflows. Detailed records of pilot study results, ergonomic risk scores, alerts generated, and corrective interventions provide transparency and establish a baseline for future performance comparison. This systematic documentation supports knowledge transfer across engineers, safety officers, supervisors, and operators, reducing dependency on individual expertise and ensuring continuity during workforce or system changes. Equally important is documenting the outcomes of ergonomic interventions triggered by the framework, such as workstation redesigns, task rotation strategies, tool repositioning, or operator training programs. These records enable traceability between identified risks, implemented controls, and observed improvements in posture, comfort, and productivity. Clear documentation also facilitates regulatory compliance, auditing, and continuous improvement by providing objective, evidence-based justification for safety decisions. Based on validated ergonomic data and worker feedback, targeted recommendations are proposed to further reduce ergonomic strain. These include engineering controls such as adjustable workstations, improved tool ergonomics, and mechanized assistance for heavy

components; administrative controls like optimized task scheduling and rest breaks; and enhanced ergonomic training to reinforce safe work practices. Long-term recommendations emphasize continuous monitoring, periodic reassessment, regular system audits, and integration of emerging sensing and analytics technologies. Together, thorough documentation and well-founded recommendations transform the framework from a research solution into an industry-ready ergonomic safety management system, supporting healthier workplaces, improved productivity, and sustainable manufacturing operations.

4. Results and Discussion

The implementation of the Safety Monitoring Framework at ergonomically critical stations in hydraulic excavator assembly lines produced clear and measurable improvements in ergonomic safety and work practices. Initial ergonomic risk assessment using RULA and REBA revealed that most evaluated workstations were in medium to high-risk categories, with pre-intervention RULA scores typically between 5 and 7 and REBA scores exceeding 8. High-risk tasks such as engine mounting, hydraulic hose routing, cabin installation, and undercarriage assembly were associated with excessive trunk flexion, elevated shoulder postures, wrist deviation, and repetitive movements. Sensor-derived joint angle data showed strong agreement with expert manual assessments, validating the accuracy of automated ergonomic scoring. Following framework implementation, including real-time monitoring, alerts, and workstation adjustments, a substantial reduction in risk levels was observed. Average RULA scores decreased to 3–4 and REBA scores to 5–6, indicating a shift from high-risk to acceptable or moderate-risk conditions. Real-time alerts encouraged immediate posture correction and safer task execution, while alert frequency reduced over time, reflecting improved worker adaptation. The integration of a feedback loop with machine learning enabled identification of recurring risk patterns and prediction of high-risk scenarios, allowing preventive interventions. Overall, the framework enhanced worker awareness, reduced ergonomic strain, and indirectly improved productivity, demonstrating the

effectiveness of proactive, data-driven ergonomic safety management.

Conclusion

This project successfully developed and validated a comprehensive Safety Monitoring Framework for ergonomically critical stations in assembly line environments, with specific application to hydraulic excavator manufacturing. The framework effectively addresses ergonomic risks arising from repetitive tasks, awkward postures, static loading, and manual material handling key contributors to musculoskeletal disorders and reduced productivity. Integrating wearable sensors, motion capture systems, ergonomic assessment tools (RULA and REBA), real-time monitoring, and machine learning, the study demonstrates a proactive and data-driven approach to ergonomic safety management. The automated ergonomic assessments showed strong agreement with expert evaluations, confirming system accuracy and reliability. Real-time monitoring and alert mechanisms enabled immediate corrective actions, improving worker awareness and reducing exposure to high-risk postures. The inclusion of a machine learning-based feedback loop further advanced the framework by enabling predictive risk identification and continuous improvement. Validation results confirmed measurable reductions in ergonomic risk levels and stable system performance under real industrial conditions. Overall, the framework offers a scalable, practical, and future-ready solution that enhances worker safety, supports productivity, and aligns with modern smart manufacturing practices.

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