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Human Postural Analysis for Reducing Biomechanical Stress in Construction Equipment Assembly

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Abstract – *The ergonomics of construction equipment assembly lines are pivotal in enhancing worker safety and operational efficiency. This project focuses on designing and implementing manufacturing aids, such as workbenches and lifting tackles, to mitigate biomechanical fatigue identified through the replication of worker postures during product assembly. Utilizing advanced software, a comprehensive biomechanical analysis is conducted, evaluating parameters such as Flexion-Extension compression, L4-L5 compression, moment, and joint shear. The analysis ensures that the compression ratio adheres to the National Institute for Occupational Safety and Health (NIOSH) the standard limit of 3433 Nm. Based on method studies and the principle of easy accessibility, customized manufacturing aids are designed to optimize worker posture and reduce biomechanical strain. Post-implementation, a subsequent analysis is performed to assess the effectiveness of these aids in alleviating biomechanical stress and improving worker posture. The results demonstrate a significant reduction in biomechanical fatigue, validating the efficacy of the designed aids in promoting a safer and more efficient assembly line environment. This study underscores the importance of ergonomic interventions in industrial settings, offering a structured approach to enhancing worker well-being and productivity.*

Key Words: Ergonomics, Biomechanical analysis, Manufacturing aids, Posture Optimization, Worker Accessibility.

1.INTRODUCTION

The construction equipment manufacturing industry is characterized by Inherently complicated assembly tasks tending to make workers take up physically stressful positions are typical of the construction equipment industry. These tasks enhance the risk of musculoskeletal disorders (MSDs) and biomechanical loading. In order to improve worker comfort, safety, and productivity, ergonomics is vital in solving such issues. One of the main causes of work-related MSDs, especially in manufacturing industries, is awkward postures and improper lifting, according to NIOSH (NIOSH, 2021) [18]. Repetitive work, heavy lifting, and sustained awkward postures on assembly lines cause high biomechanical stress, especially on joints, muscles, and the lower back (L4-L5). These problems not only compromise workers' health but also affect productivity and general operation efficiency [17].

This project aims to address these concerns through the creation and application of ergonomic production equipment, like workbenches and lifting tackles, to specifically suit assembly lines for construction equipment. Utilizing sophisticated software, a detailed biomechanical analysis is conducted by simulating the workers' accurate positions when performing assembly tasks. For effective compliance with the NIOSH standard threshold of 3433 Nm (NIOSH, 1981), this assessment considers essential parameters such as joint shear, moment, compression of L4-L5, and flexion-extension compression [18]. For biomechanical protection and enhancing posture, the results inform the creation of manufacturing assistance that considers principles of method study and worker access [7].

In order to measure the efficiency of the suggested aids in reducing biomechanical stress and improving the posture of workers, a follow-up study is conducted after installation. This constant practice guarantees that the interventions improve general assembly line productivity while ensuring they meet ergonomic requirements. The goal of this program is to design manufacturing aids that are safer, more productive, and more comfortable for workers through the application of ergonomic concepts to their construction. This will ultimately improve the welfare of workers and the sustainability of the construction equipment manufacturing sector.

The main goals of this research are threefold. Firstly, the research will analyse worker postures during assembly operations and determine biomechanical risks using advanced ergonomics software. This includes simulating the exact worker postures in a virtual setup and performing an elaborate biomechanical analysis to assess parameters like L4-L5 compression, joint shear, and flexion-extension moments [4]. These parameters are contrasted with standard ergonomic criteria, such as the NIOSH lifting equation [19], to determine high-risk postures and tasks. Second, based on the results of the biomechanical analysis, the research seeks to design and implement customized manufacturing aids, such as adjustable workbenches, lifting aids, and better tool positions, to mitigate the risks identified in Table.4. These aids are customized to facilitate better accessibility for workers and minimize uncomfortable postures. Lastly, the research aims to assess the efficacy of the implemented aids using a post-intervention biomechanical analysis. The assessment measures the decrease in biomechanical strain and examines improvements in worker posture to ensure that the designed aids are ergonomic and enhance worker safety and efficiency. All of these goals are part of an integrated strategy to reduce biomechanical risks and ensure a safer and more productive work place in construction equipment assembly lines.

2.PROCEDURE TO GENERATE BIOMECHANICAL REPORT

The biomechanical analysis was conducted using digital human modeling software to evaluate worker postures and assess ergonomic risks in the assembly process. The following methodology was adopted:

- *Posture Replication* – The exact postures of workers during assembly were replicated in the digital environment based on observational data (see Fig – 1) and video recordings. Key joint angles, body positioning, and task constraints were carefully adjusted to ensure accuracy [17].
- *Anthropometric Parameter Definition* – The human model was configured using anthropometric data relevant to the worker population, including stature, weight, and limb dimensions, to ensure realistic simulation outcomes.
- *Task and Environment Setup* – The assembly environment was recreated, incorporating workstations, tools, and components [17]. The worker's interactions with objects, reach zones, and material handling activities were simulated to reflect real working conditions.
- *Biomechanical Analysis Execution* – The software's analytical tools were utilized to calculate key biomechanical parameters, including:
  - Flexion-extension compression
  - L4-L5 spinal compression
  - Joint shear and moment forces
  - Abdominal pressure and overall body load

These parameters were compared against recommended ergonomic thresholds to identify high-risk postures.

- *Risk Evaluation and Interpretation* – The results were evaluated against established ergonomic guidelines by following Table.3, such as permissible spinal compression limits. Postures exceeding safe limits were classified as high-risk, warranting intervention.
- *Intervention Design and Validation* – Based on the findings, ergonomic solutions such as workbenches and lifting aids were designed Fig. 3 to minimize strain [7]. A comparative analysis was performed by reassessing the modified postures with the proposed interventions to quantify improvements in biomechanical stress.
- *Final Assessment and Documentation* – The effectiveness of the intervention was statistically validated, and a detailed report was generated, summarizing the improvements in ergonomic conditions Table.4 [19]. The results were documented for further refinement and implementation in the assembly process.

3.DATA COLLECTION

To evaluate ergonomic risks in the construction equipment assembly line, a structured data collection approach was followed based on the Table. 1. Initially, photographs were taken to capture actual worker postures, which were essential for REBA (Rapid Entire Body Assessment) calculations and for accurate digital replication. These postures were then replicated in specialized software to enable precise biomechanical analysis.

This helped identify high-risk tasks and postures, which were prioritized for ergonomic intervention. Based on this analysis, custom manufacturing aids were designed and implemented to reduce ergonomic stress. Updated postures were analysed again in the software to validate the effectiveness of these solutions. Finally, a comparison of biomechanical analysis values was made using the NIOSH recommended limit of 3433Nm to confirm improvements.

Table-1: Data Collection steps

Step	Outcome
Photographs	Captured real-world postures for REBA calculation and for accurate replication.
Replicating in Software	Created digital models for precise biomechanical analysis.
Biomechanical Data Collection	Identified high-risk tasks and postures.
Identifying Risk Areas	Prioritized tasks requiring ergonomic intervention.
Solution Development	Designed and implemented manufacturing aids tailored to worker needs.
Updated Posture Analysis	Validated the effectiveness of the solutions through software analysis.
Comparison between before and after improvements	Comparing values of biomechanical analysis based on the NIOSH standard value 3433Nm

4.METHODOLOGY

This study follows a structured approach to identify ergonomic risks, analyse worker postures, and develop solutions to improve safety and efficiency in construction equipment assembly. The methodology consists of the following steps:

Step 1: Problem Identification and Data Collection

Identifying ergonomic problems related to manual material handling in the assembly process is the initial step. Observations, time studies, and employee feedback are used to document posture, force exertion, and task duration. This data serves as the foundation for further investigation.

Step 2: Biomechanical Analysis and Risk Assessment

A digital human modelling tool is used to replicate actual worker postures and assess ergonomic risks. The following key parameters are analysed:

- L4-L5 Spinal Compression – To determine lower back strain levels.
- Moment and Joint Shear Forces – To evaluate stress distribution on joints.
- RULA and REBA Analysis – To quantify postural risks.
- NIOSH Lifting Equation Calculations – To assess safe lifting conditions.

Step 3: Identification of High-Risk Postures and Solution Development

Postures with high ergonomic risk scores are identified Table 2. The root causes of these risks, such as poor workstation design or excessive bending, are analysed. Based on these insights, ergonomic interventions such as workbenches and lifting aids are designed Fig. 3 to optimize worker posture and reduce biomechanical stress [7].

Step 4: Virtual Simulation and Comparative Analysis

The solutions are subsequently evaluated in virtual simulations to measure their efficiency. The improved postures are compared with the baseline conditions to evaluate reductions in spinal compression, joint shear forces, and overall ergonomic risk.

Step 5: Conclusion and Documentation

The final step is summarizing the findings and stating the impact of the proposed solutions. The study concludes with recommendations for the improvement of ergonomics in construction equipment assembly to enhance the safety and efficiency of the workers.

This stepwise methodology ensures a systematic approach to identifying, analyzing, and mitigating ergonomic risks noted in Table.4. in industrial settings.

5. PROBLEM DEFINITION

A posture evaluation needs to be done at every workstation along the assembly line of construction equipment in order to identify which workstation most exposes workers to MSDs with the most hazardous work posture that needs to be corrected immediately. Previous reviews reported that the workers are exposed to high compression and strain in the lumbar region related to flexion.

Additional research and redesign of the work system, especially of manual material handling tasks such as the loader arm subassembly, is necessary. Work posture analysis of assembly line workers identified that some activities have medium to high ergonomic risk. On the basis of analysis of the REBA score and duration of work, these activities fall under the category of high-risk that needs to be corrected immediately in ergonomics.

TABLE-2: Reba Scores and Task Duration for High-Risk Task

Stage Name	Task Description	REBA Value	Task duration Time (Mins)
Loader arm subassembly	Loader arm Retaping	10	45
Engine Assembly	Coolant metal pipe connection	9	10
Engine Assembly	Backhoe valve hose Assembly	12	24
Electrical Assembly	Hose connection between cabin and engine Transmission	10	25
Electrical Assembly	Front axle and cabin hose connection	10	15
Bonnet Main assembly	Bonnet Main assembly	9	40
Cabin Subassembly	Cabin Harness routing	8	29

Therefore, in the subassembly process of the loader arm for backhoe loader machines, workers are required to adopt a prolonged forward-bending posture while performing pneumatic fastening tasks. This posture, maintained for approximately 45 minutes across six machines and REBA value of 10 detailed in Table 2, places significant strain on the lower back and upper limbs [8], increasing the risk of musculoskeletal disorders (MSDs). The repetitive nature of the task, combined with constrained workspace conditions, further exacerbates ergonomic concerns. Addressing these ergonomic challenges is crucial to improving worker safety, reducing fatigue, and enhancing overall assembly line efficiency.

6. CURRENT POSTURAL ANALYSIS

To quantify the ergonomic effect of the task being measured, the postural angles measured were employed to reconstruct the correct posture using ergonomic analysis software. The L4-L5 moment, compressive loads, and biomechanical loads on each body region were determined from a 25th percentile human manikin. The overall result is presented below:

6.1 Postural Angle Replication

Each angle of the joint recorded during the task observation was entered into the ergonomic software to guarantee accurate replication of posture [17]. The analysis of posture is depicted in Fig. 1.

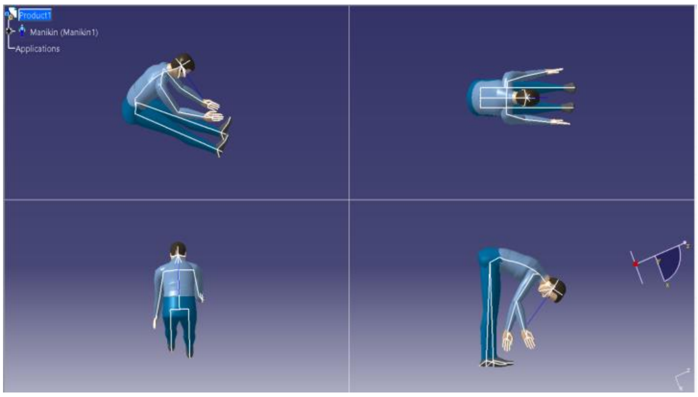

Fig – 1: Perspective views, postural analysis of the worker.

6.2 L4-L5 Biomechanical Load Analysis

The examination of the lumbar spine (L4-L5) area encompassed the calculation of the parameters specified in Table 3:

Table 3: Biomechanical Analysis for the Working Posture

Summary Data Tab	
Analysis	**Value**
L4-L5 Moment [N-m]	178
L4-L5 Compression [N]	3246
Body Load Compression [N]	282
Axial Twist Compression [N]	0
Flex/Ext Compression [N]	2964
L4-L5 Joint Shear [N]	42 Anterior
Abdominal Force [N]	97
Abdominal Pressure [N_m2]	3

These values were compared against Fig. 2 NIOSH standard value [19] to assess the risk of lower back strain [10].

6.3 Segmental Load Distribution

Forces and moments in various regions of the body, i.e., upper body, lower body, and torso, were computed. The body load compression came out to be 282 N and there was no compression due to axial twist.

Table - 4: Risk Identified

Parameter	Risk Identified
L4-L5 Compression	High compression load on the spine
Joint Shear Force	Anterior shear force on L4-L5 joint
Abdominal Pressure	Increased intra-abdominal pressure
Repetitive Motion	Frequent heavy lifting (12+ times daily)
Sustained Posture	Prolonged posture (15 min - 1 hr)
Workstation Design	Lack of ergonomic lifting aids

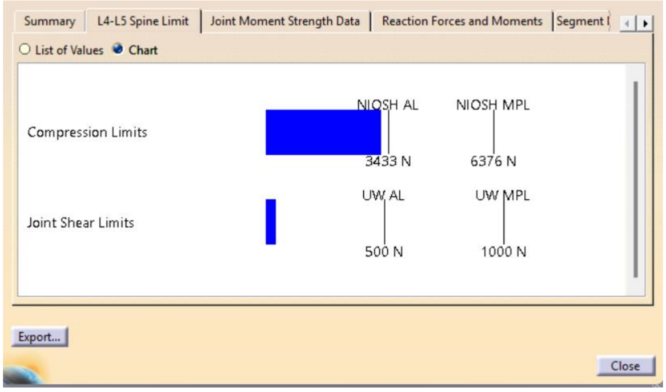

Fig - 2: Comparison between L4-L5 Compression [N] with NIOSH AL

6.4 Ergonomic Risk Assessment

The results show significant flexion/extension compression (2964 N) and lumbar compression (3246 N), suggesting a significant risk of lower back pain. Table 4 lists the identified ergonomic risks [15]. These findings suggest that in order to lower musculoskeletal risks, ergonomic solutions such as workstation redesign, tool adaptations, or posture adjustments may be required.

The following sections provide a comprehensive examination of these results and their significance for reducing manual material handling tasks on the manufacturing line for construction equipment. Table 3 presents a summary of the computed values.

6.5 Biomechanical Analysis of L4-L5 Compression and Moment Calculation

To assess the risk of lumbar injuries, the biomechanical examination focused on determining the segmental inputs to the overall force at the L4-L5 spinal segment. According to the following equation [2], the total force at L4-L5 (FL4-L5) is the sum of the forces from body weight, external load, flexion/extension, and axial rotation:

FL4-L5 = F Body Load + F External Load + F Flexion/ Extension + F Axial Twist (1)

Where:

- Body Load Compression (282 N): Represents the force exerted by the upper body weight on the L4-L5 segment (NIOSH, 1981) [19].
- Flexion/Extension Compression (2964 N): Results from bending forward or backward during the task ;9'.
- Axial Twist Compression (0 N): In this case, no significant compression was observed due to twisting.
- External Load Contribution: If the worker was holding an external load, its weight would be added to the total force [18].

For this analysis, the total L4-L5 compression force was calculated as followed by Equation (1).

FL4-L5 = 282 N + 2964 N + 0 N = 3246 N

Thus, the total L4-L5 compression force was determined to be 3246 N, which is below the NIOSH recommended limit of 3433 N (NIOSH, 1981) [19] but still indicates a significant biomechanical load.

6.6 L4-L5 Moment Calculation

When a force is applied at a distance from a pivot point, a moment (torque) is created. The subsequent equation is utilized to calculate the L4-L5 moment, which is affected by position and upper body weight [10]:

ΣML4-L5 = Σ (Fi × di) (2)

Where:

- Fi = Force acting on each body segment.
- di = Perpendicular distance from L4-L5 to the force application point.

From the analysis, the L4-L5 moment was computed by the Equation no (2):

ML4-L5 = 178 Nm

This moment represents the torque exerted on the lumbar spine due to the worker's posture and task dynamics.

6.7 Abdominal Force and Pressure

The ability of the abdominal muscles to withstand spinal loads is crucial. The following equation was used to calculate the abdominal force (Fabdominal) [9]:

$$\text{Fabdominal} = \text{ML4-L5} / \text{dab} \qquad (3)$$

Where dab is the moment arm of the abdominal muscles. The analysis yielded an abdominal force of Equation (3):

$$\text{Fabdominal} = 97 \text{ N}$$

The abdominal pressure (Pabd) was then calculated using the cross-sectional area of the abdomen (Aabd):

$$\text{Pabd} = \text{Fabdominal} / \text{Aabd} \qquad (4)$$

The resulting abdominal pressure was from the Equation no (4):

$$\text{Pabd} = 3 \text{ N/m}^2$$

The lumbar spine could be the main area of biomechanical stress, as indicated by the minimal abdominal pressure, which demonstrates minimal exertion from the abdominal muscles during the activity [10].

7.SOLUTION DEVELOPMENT

A solution was developed to minimize the risks identified through the ergonomic risk assessment. A workbench designed for the loader arm subassembly Fig. 3 is the proposed solution, which seeks to decrease labor-intensive manual material handling [13].

7.1 Design Considerations

The workbench was designed with the following ergonomic principles in mind:

- Optimal working height: To reduce excessive bending and flexion at the lumbar spine.
- Adjustable fixtures: To accommodate different assembly requirements with minimal worker exertion.
- Accessibility improvements: Ensuring that tools and components are within reach, reducing awkward postures.

7.2 Expected Impact on Ergonomic Risks

Implementing the workbench is expected to:

- Reduce L4-L5 compression forces by minimizing excessive bending.
- Lower the risk of flexion/extension compression by supporting a more neutral posture.
- Improve overall work efficiency and worker comfort

Significant risks associated with the current manual material handling process were found by the ergonomic evaluation, particularly with regard to lumbar compression and strain from bending.

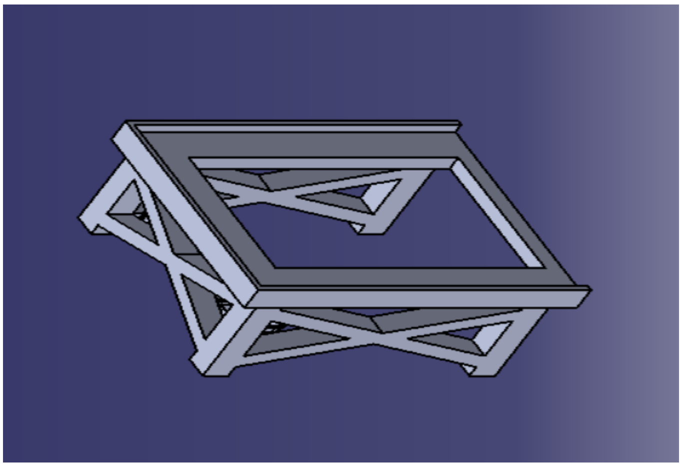

Fig -3: Proposed Workbench for Loader Arm Subassembly

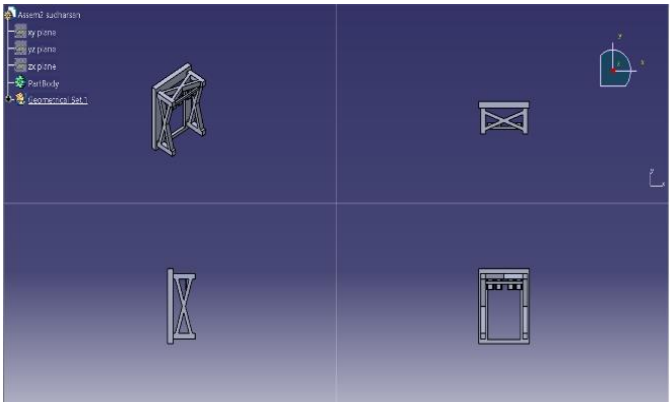

Fig – 4: Perspective views of Proposed Workbench for Loader Arm Subassembly

8.POSTURE IMPROVEMENT RECOMMENDATIONS

A fresh ergonomic analysis was conducted to evaluate improvements in worker posture following the establishment of the recommended workbench for the loader arm subassembly [13]. Ergonomic analysis software Fig. 5 was used to model the changed posture, indicating that the revised working conditions met optimal ergonomic requirements [19].

8.1 Key Observations:

- Reduced Lumbar Compression: The workbench minimizes excessive bending, significantly lowering L4-L5 compression forces.
- Improved Working Posture: Workers maintain a more neutral spinal alignment, reducing the risk of flexion-related strain.
- Decreased Upper Limb Load: The optimized work surface height ensures that arms remain in a comfortable working zone, reducing muscle fatigue.

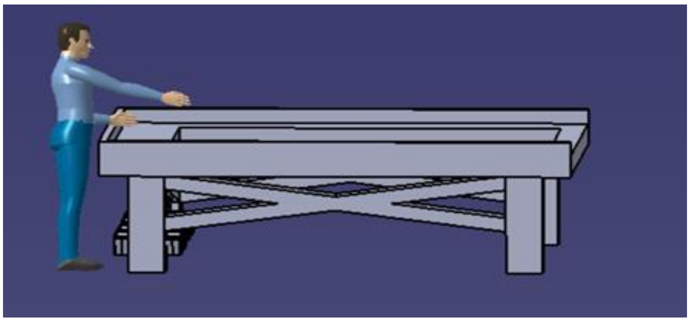

Fig- 5: Simulation Posture After Improvements

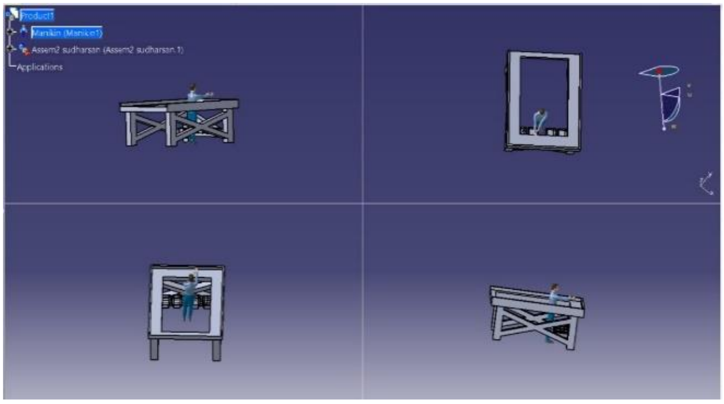

Fig – 6: Perspective views of Simulation Posture After Improvements

8.2 Validation:

Significant ergonomic improvements were demonstrated when comparing the postures before and after implementation. The adjusted working posture with the workbench is illustrated in Fig. 5, highlighting the reduced biomechanical requirements.

9.RECOMMENDED POSTURAL ANALYSIS

Following the execution of the suggested workbench, a subsequent biomechanical load analysis at L4-L5 was performed to evaluate enhancements in worker posture analysis value listed in Table 5. then reductions in lumbar load compared with NIOSH AL Standard was show in Fig. 7. The revised posture was examined with ergonomic software, and the outcomes indicated a notable reduction in compression forces at L4-L5 and strain associated with flexion.

9.1 Impact of the Workbench Implementation:

- Reduced Lumbar Compression: The L4-L5 compression force was reduced by approximately 43.6%, indicating lower strain on the lower back Table.4.
- Lower Flexion/Extension Load: The Flex/Ext compression reduced by 60.4%, suggesting improved posture with reduced forward bending.
- Minimized Joint Shear and Abdominal Stress: The anterior shear force dropped significantly, while abdominal forces and pressure were eliminated, reducing musculoskeletal risks.

Table – 5: Biomechanical Analysis After simulation posture improvements.

Summary Data Tab	
Analysis	**Value**
L4-L5 Moment [N-m]	70
L4-L5 Compression [N]	1828
Body Load Compression [N]	354
Axial Twist Compression [N]	35
Flex/Ext Compression [N]	1173
L4-L5 Joint Shear [N]	7 Anterior
Abdominal Force [N]	0
Abdominal Pressure [N_m2]	0

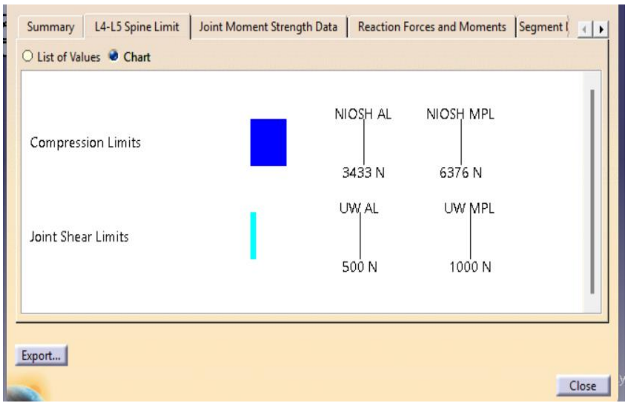

Fig – 7: Compression load after simulation posture

These results imply that the workstation intervention significantly improved ergonomics. By reducing the biomechanical pressure on the lumbar spine, the better posture helped to reduce ergonomic risks and enhance worker safety.

10.CONCLUSIONS

The ergonomic improvements implemented have led to significant reductions in biomechanical stresses on the lower back and abdominal region. The L4-L5 moment was reduced from 178 N·m to 70 N·m, representing a 60.7% reduction. Similarly, the overall L4-L5 compression force dropped from 3246 N to 1828 N, a reduction of 43.7%. Within this, the flexion/extension compression showed a notable 60.4% decrease, falling from 2964 N to 1173 N. However, body load compression increased from 282 N to 354 N (an increase of 25.5%), and axial twist compression, which was previously absent, appeared at 35 N. This suggests a redistribution of load, possibly due to changes in posture and task dynamics.

Further improvements were observed in the L4-L5 joint's shear force, which decreased from 42 N to 7 N anterior, marking an 83.3% reduction. Abdominal loading was completely eliminated, with both abdominal force and pressure dropping from 97 N and 3 N/m^2 to zero, respectively, representing a 100% reduction. These results clearly indicate that the implemented changes has significantly enhanced ergonomic safety by minimizing spinal loading and completely removing abdominal strain.

11.Future Improvements

Future advancements will focus on simplifying assembly processes, reducing manual handling requirements, and improving ergonomic standards to greatly boost productivity and worker safety in the construction equipment assembly line. Better posture, reduced physical strain, and enhanced productivity can be realized by implementing advanced assembly methods, optimizing workflow arrangements, and refining workstation layouts.

Furthermore, enhancements in assembly consistency, methods for handling materials, and tools will help reduce assembly duration and variability in task performance. Sustained improvements in employee comfort and productivity will be guaranteed by implementing best practices and continuously evaluating ergonomic issues.

To further optimize operations and raise total assembly efficiency, future research can look into innovative approaches to workstation automation, digital work instructions, and lean manufacturing techniques.

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