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ORIGINAL PAPER

Ergonomic evaluation of workstation design using taguchi experimental approach: a case of an automotive industry

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Abstract

Manual operations are still playing a pivotal role in the performance of product-based industries due to the operator's ability to flexible learning. The operators are doing various repetitive tasks in awkward postures. This causes upper body Musculoskeletal Disorders (MSDs), which critically affect the operator's upper limb and lower back. So, this study is conducted to address the ergonomic aspects of manual operations to reduce the risk of upper body MSDs. Rapid upper limb assessment (RULA) and lower back analysis (LBA) are performed in JACK software to analyze the upper working posture and measure the forces acting on the L4/L5 spinal segment. The Taguchi experimental design approach was applied to optimize the workstation of an assembly line in the automotive industry to diminish forces and ANOVA to find the significance of design factors. Analysis of means (ANOM) and S/N ratios are conducted along with surface and contour plots. The results reveal that the upper working posture and forces acting are critical for the operator and roots upper body MSDs and thrilling fatigue. The outcomes recommend amending the design of the workstation. The Taguchi approach suggested optimum design, improving compression and Anterio-Posterior (AP) shear forces of 2.21 and 4.83%, respectively. The conveyor height has the most astonishing effect on compression and AP shear forces acting on the L4/L5 spinal segment with a contribution of 90.63 and 93.57%, respectively. The findings of this study make it easier for the industrial and managerial staff to perform an ergonomics evaluation for estimating the risk of MSDs. Further, the work can be extended to the dynamic posture analysis and to define exposure towards MSDs.

Keywords Lower Back Analysis · Musculoskeletal Disorders · Rapid Upper Limb Assessment · Spinal segment · Taguchi approach

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1 Introduction

From the last decades, automation in manufacturing industries has been increased to improve productivity. Manual operations are still crucial in product-based sectors due to an increase in demand for customized products. The operators' performance plays an essential role in improving productivity and quality in product-based industries [1]. The operators have to make more efforts to achieve the required productivity while performing repetitive and precise assembly operations. It provides attention to the growth of efficient manual operations [2]. The operators are maintaining the most awkward postures while working on the assembly lines in a standing position. These awkward postures could cause a risk of Musculoskeletal Disorders (MSDs) if postures are kept for long intervals. The MSDs mainly affect the operator's upper extremity and lower back, which results in excessive fatigue. The manual operations have a higher probability of incurring MSDs. The operators faced many challenges to maintain their postures while working in standardized routines and limited space. This causes lower back pain. The severe lower back pain is a risk factor of sickness absence among the employees [3]. The prolonged lower back pain act as a symptom of MSDs. This indicates that an ergonomic workspace evaluation must examine the various design factors responsible for the MSDs. The operator experiences more compression and shear forces on the lower back while pushing and pulling operations [4]. The limits of tolerance suggested that the compression forces are initially depending on epidemiological and biomechanical research. The two lowest vertebras of the lumbar spine are L4 and L5, which are attached with a disc, joints, nerves and soft tissues. The L4 and L5 spinal segment supports and allows the body to move in multiple directions. Several forces acting on L4/L5 spinal segment are causing lower back pain for the operator. The presence of lower back pain for a long time increases the possibility of MSDs. The forces acting on the L4/L5 spinal segment be calculated by performing LBA. Ergonomics is focused on creating a better working environment with proper safety and performance levels [5].

Ergonomic aspects have a strong influence on the quality of products; an inadequate ergonomic approach is related to the product quality in terms of errors and failures [6]. A service-learning project was introduced to aware the students about the real ergonomic situations. The students worked with employees of the organization to develop ergonomic solutions for establishing a comfortable and safe working environment. This leads to enhancing the productivity of an organization [7]. Ergonomic evaluation of workspace and manual operations plays a pivotal role to improve efficiency, comfort and safety. The presence of awkward postures and lower back for a long time increases the risk of MSDs. Therefore, the ergonomic evaluation, including RULA and LBA, helps to identify the risk of MSDs. RULA was performed to evaluate the upper working posture of the operator [8]. RULA is an observational method, and the RULA score is calculated to estimate the risk [9]. The automotive electrical production line simulation results in a 36% physical overload reduction, lowered sick leave by 51.6% and enhanced production rate [10].

The lower back pain may be depending on spinal curvature and pressure on the disc. This can be evaluated in various conditions by using computer-aided ergonomic design systems [11]. The design of a radio assembly line was optimized to minimize the risks of MSDs and improve the performance of assembly lines [12]. An alternative ergonomic approach can tackle some problematic aspects of man–machine interaction in assembly lines [13]. JACK software was used to generate body typologies from Italian anthropometric data. The results were compared with a global manikin to identify appropriate anthropometric data for ergonomic evaluation [14]. The integration of virtual reality and simulation tools was used for real-time sensing to develop a synergic system. The virtual reality device provides an input to create an immersive environment while simulation tools continuously monitor the body posture of a working operator [15]. JACK software simulated a bus chassis assembly line to improve working conditions and efficiency by considering ergonomic aspects [16]. The simulated assembly operations were used as an input for the digital humanities to provide the working postures and cycle time for performing various operations [17]. A methodology was described for the ergonomic evaluation of a workstation in the manufacturing industry to provide some ergonomic improvements in the existing workstation design in terms of energy expenditure and cycle time [18]. The CAD model of an original workspace can be imported to a digital human modelling (DHM) and simulation software for replication and ergonomic evaluation of the various assembly operations [19]. Spine training was provided to nurses and other medical professionals to significantly decrease lower back pain and improve their working postures, including ergonomic, awareness and active therapy [20]. The virtual manufacturing simulation system can create a valuable workbench to evaluate assembly operations [21]. The data of operator activities was collected via traditional ethnographic methods and automatics non-optical techniques for digital modelling, and qualitative analysis is performed for a richer interpretation of major explanatory factors [22]. The operator can be replaced by a digital human named manikin in JACK's environment to perform ergonomic analysis for various working postures [23]. The sitting to lying movements associated with an upper limb of the passenger was analyzed in the JACK to optimize the design of the train's sleeping berth [24]. Gait analysis is the study of human movements using instrumentation for the measurement of various body movements. It can be utilized in the customized design of ankle–foot orthosis for drop foot patients [25]. Ankle–foot orthoses are assistive devices prescribed for several physical and neurological disorders affecting the mobility of the lower limbs [26]. The ankle–foot orthosis enhances human gait in children with cerebral palsy to avoid depression or traumatize muscle contractures [27]. The work process and workplace simulated by DHM Jack software for a material handling operation and best design selected by genetic algorithm results in enhanced productivity [28]. Three DHM software Jack, Santos and ViveLab compared based on ergonomic risk valuation proficiencies and Jack stances out in ecological ergonomics [29]. The DHM was utilized to evaluate the viability of using a head-mounted display with a motion capture scheme to simulate real-world work-related responsibilities. The Siemens Jack and Oculus Rift can be used to posture-based ergonomic evaluations for practice with simulated realism job [30]. The DHM Jack utilized to judge spinal loads during pushing, pulling and lifting in paramedic equipment bags [31]. Virtual manufacturing software utilized to enhance the ergonomic performance of manual workstation in the semiconductor industry by conducting RULA and method time measurement [32]. Jack was used to generating virtual manufacturing simulations to design assembly lines in amenability with plant ergonomics [33]. Jack software was also utilized to improve human-centred workplace design [34]. The body movement of dentist evaluated with system developed based on Kinect v2 and study conducted on ten dentists [35]. Jack software offers human-centred design tools for accomplishment ergonomic scrutiny of simulated products and virtual work environments.

The design appraisal development of innovative products is time-intensive, and it requires the alliance and harmonization of activities completed by several experts with different competencies and roles. Now, performed using different interactive simulation tools and diverse product illustrations [36]. An interactive simulation methodology is proposed to improve ergonomic and optimization of product design and consists of a productive real-time solver, a haptic interface with force feedback, and executed in a virtual reality situation [37]. A prototyping tool, M-Integrator, was presented for supporting building interactive kinetic artefacts, and it prototypes an entire framework from the early stage of the production procedure. It showed an amalgamation of virtual and physical mechanisms which supported the interactive simulation through the session [38]. A systematic approach is used while considering path-planning progressions for manipulation tasks such as assembly, maintenance or disassembly in a virtual reality simulation. It is divided into coarse and fine planning [39]. An interactive simulation in virtual reality is frequently used to assess or optimize nonlinear mechanical systems subjected to large deformations [40]. Industrial process plants are progressively fetching multifaceted structures with a high level of automation. However, the final plant productivity and overall equipment efficiency depend on an interactive simulation, optimized engineering design, installation practice, and supervision of human operators. In minimising cost and increasing productivity, interactive simulation engineering plays a significant role [41].

Taguchi experimental design and group decision-making technique were combined to realize the optimum user experience design [42]. Taguchi approach is widely used in various industrial sectors to minimize the experimental requirements to design an optimum workstation [43]. The Taguchi tactic was used for optimization and improvement in the performance of production companies that supply energy concerning health, safety and ergonomic aspects [44, 45]. This approach helped the company officials better to understand the benefits in terms of health and safety. The Taguchi approach is a beneficial statistical tool to increase the effectiveness and quality of the product [46]. It also has significant applications in ergonomics and biomechanical when factors of the issues are at a discrete level. The ergonomics design factors can be statistically analyzed using the Taguchi approach to observe the significant effects on ergonomic parameters [47]. A study was conducted to guide the foundry industrialists in analyzing the mismatch between the workers' job profiles and redesigning the workstation layouts to minimise the risk severity associated with the tasks carried out by staff [48]. The data was acquired from 120 Indian male motorcyclists using a static simulator test-rig to identify the comfortable riding posture and optimum riding position for improving motorcycle design for a better riding experience. The best possible optimum riding position among the nine test conditions was estimated using Taguchi DOE [49]. So, a literature review suggests that the Jack, DHM software, interactive simulation and Taguchi approach has been applied successfully for the optimization of ergonomic performance and design.

1.1 Problem formulation: present work

This study has been conducted on the workstation of an assembly line in the automotive industry in Minda Corporation Limited, Noida, India. The assembly of the product consists of many lightweights and heavy metal components. Therefore, precise assembly work has been performed by the operators to get the final product. The operators are working on the workstation in a standing position to perform various manual, repetitive tasks for an extended period. As a result, the operators continuously maintain the most awkward postures while performing the assigned manual tasks. As a result, working operators feel excessive fatigue and chronic pain due to repetitive tasks. This causes MSDs in the upper body of the working operators. The upper body MSDs mainly affect the

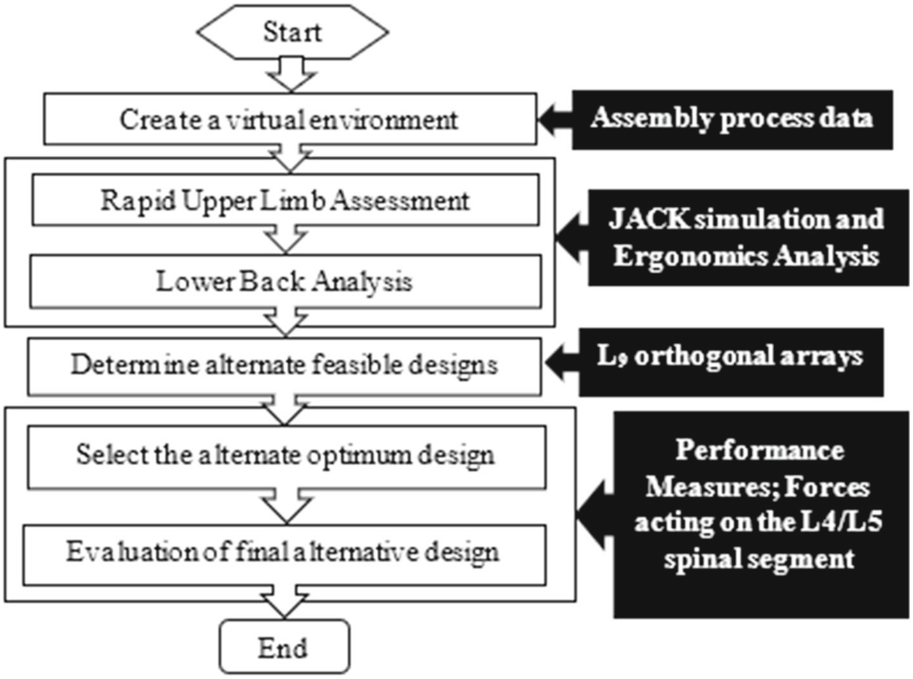


Fig. 1 Methodology for ergonomic evaluation and design optimization of a workstation

shoulders, arm, wrist, neck and lower back of the operator, which causes excessive fatigue. Moreover, the existing techniques consume a lot of time and manually effort in which some mistakes can occur due to much paperwork. Accordingly, there is a need to optimize the design of the workstation to minimize the risk of the MSDs using a semi-automatic ergonomic approach which requires less time. The objectives of the current work are as follows:

- To analyze the various awkward postures of working operators by considering different human factors and ergonomic aspects.
- To find the optimum design of workstation with consideration of human factor and ergonomic aspects.

The ergonomic evaluation has been performed to analyze the awkward postures of the operator while performing the assigned operations. The operator is continuously working for 9 h in the same standing posture. The upper limb of the working operator is exposed to the risk of MSDs. The operator repetitively performed the same operation during working hours. Therefore, the compression and shear forces act on the operator's L4/L5 spinal segment repetitively. The repetitive application of these forces also exposes the lower back of the operator to the risk of MSDs. Therefore, RULA and LBA methods are selected for the ergonomic evaluation of the working operator to minimize the risk of MSDs. RULA has been performed to evaluate the upper working posture for the operator to estimate the risk of MSDs. LBA has been applied to assess the forces acting on the lower back's L4/L5 spinal segment. The working postures and the forces acting on the L4/L5 spinal segment are evaluated to examine the risk of MSDs. The RULA and LBA are performed in the virtual environment of DHM software (Jack software by Siemens). The workstation of the assembly line is simulated in the virtual environment of JACK for the ergonomic evaluation of the working operator. The Taguchi tactic is used to observe the effect of various design factors on lower back forces.

2 Material and methods

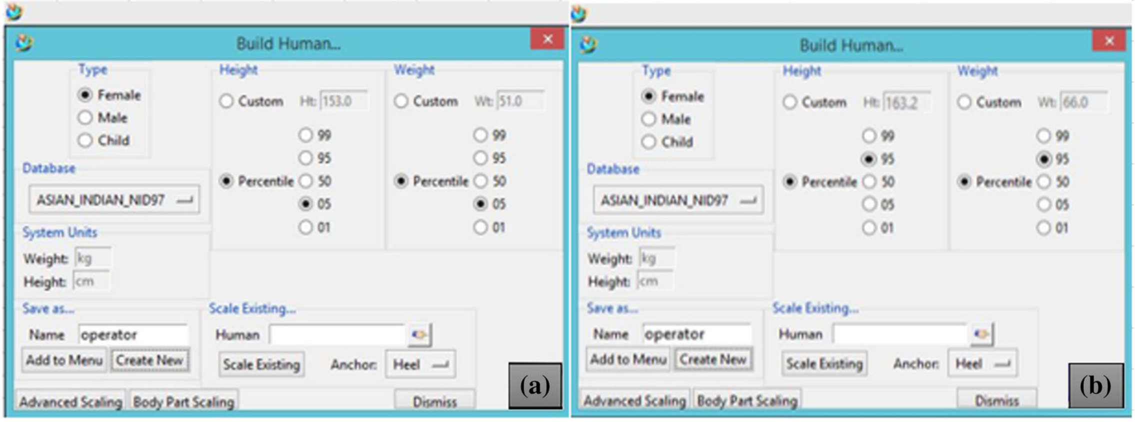
The methodology of this study includes analysis of a workstation, RULA and LBA of the working operator. The methods used for ergonomic evaluation and design optimization of the workstation is described in Fig. 1.

The Taguchi experimental design approach was applied to find an alternative optimum workstation design with minimum compression and shear forces acting on the L4/L5 spinal segment. In addition, the Minitab-18 software was utilized.

2.1 Ergonomic Evaluation Methods

2.1.1 Rapid Upper Limb Analysis (RULA)

The RULA was introduced to determine the exposure of the individual operator to ergonomic risk aspects associated with upper extremity MSDs. The RULA analyses the working posture of the operator by considering the repetitiveness of operations, loads and muscle use. The RULA provides a grand score that indicates the required changes for min-



(a)
Type: ● Female ○ Male ○ Child
Height: ○ Custom Ht: 153.0 ● Percentile ○ 99 ○ 95 ○ 50 ● 05 ○ 01
Weight: ○ Custom Wt: 51.0 ● Percentile ○ 99 ○ 95 ○ 50 ● 05 ○ 01
Database: ASIAN_INDIAN_NID97
System Units: Weight: kg Height: cm
Save as... Name: operator
Scale Existing... Human: Anchor: Heel

(b)
Type: ● Female ○ Male ○ Child
Height: ○ Custom Ht: 163.2 ● Percentile ○ 99 ● 95 ○ 50 ○ 05 ○ 01
Weight: ○ Custom Wt: 66.0 ● Percentile ○ 99 ● 95 ○ 50 ○ 05 ○ 01
Database: ASIAN_INDIAN_NID97
System Units: Weight: kg Height: cm
Save as... Name: operator
Scale Existing... Human: Anchor: Heel

Fig. 2 **a** Build human tab containing 5th percentile of anthropometric data to create a manikin; **b** 95th percentile of anthropometric data to create a manikin

imizing the risk of upper limb MSDs. The grand score of RULA also helps to design or redesign the manual operations by showing the immediate requirement of ergonomic improvement. The manual process can be simulated in the virtual environment of JACK (by Siemens PLM software). The inputs are entered manually, such as load, arms supported or not, and the frequency of the operations. The JACK considers the operator's most awkward posture and divides the posture into two groups; body group A posture and body group B posture. The body group A stance includes the upper arm, lower arm, wrist and wrist twist of the operator, whereas body group B posture has the neck and trunk of the operator. JACK considers all provided inputs and generates RULA grand score according to joint angles and twisting of the wrist, arms, legs and trunk. The grand score generated by the JACK recommends the ergonomic modifications required to reduce the risk of upper limb MSDs of the operator:

- Grand score 1–2 indicates that posture is acceptable if not maintained or repeated for long periods.
- Grand score 3–4 indicates that further investigation is needed, and changes may be required.
- A grand score of 5–6 indicates that investigation and changes are required soon.
- Grand score 7 indicates that investigation and changes are required immediately.

2.1.2 Lower Back Analysis (LBA)

LBA is performed to estimate the forces acting on the lower back of the manikin. The manikin can be working in various postures and different loading conditions. This analysis uses a complex biomechanical low-back model based on the anatomical and physiological data from the scientific literature. This analysis can determine the compression, Anterio-Posterior shear and lateral shear forces acting on the L4/L5 spinal segment. LBA can be performed in the JACK software to evaluate the risk of MSDs, including lower back pain for the working operator. Accordingly, the workspace can be redesigned or modified to minimize the risk of MSDs.

2.2 Creation of Virtual Environment

A virtual environment is created in JACK's workspace. Here, a female operator is replaced by a virtual human named manikin. The manikin has been created with proper anthropometry data and customized according to race, physical model, vision parameters and appearance in JACK software. For example, the 5th and 95th percentile anthropometry data of Asian Indian females are used to create manikins to build the JACK software's human tab.

The JACK tab contains an anthropometry database following the gender, race and population research of the region. The build human tab for creating a manikin with the 5th percentile and 95th anthropometry data of Asian Indian females is shown in Fig. 2. The workstation of the assembly line is prepared in Solid-works and imported into the workspace of JACK software. The reach zones are defined to find the reachability of manikin in 3-dimensional space. The reach zone represents all possible positions that manikins can reach by using their arms. The optimal working region for the selected manikins is considered an ideal zone, as shown in Fig. 3.

2.3 Simulation of the Workstation for RULA and LBA of the Operator

The workstation of the assembly line has been simulated for the ergonomic evaluation of working operators. The actual workstation is shown in Fig. 4a and replaced by a virtual workstation of ergonomic assessment, as shown in Fig. 4b. The operator is continuously working for 9 h in the same standing posture.

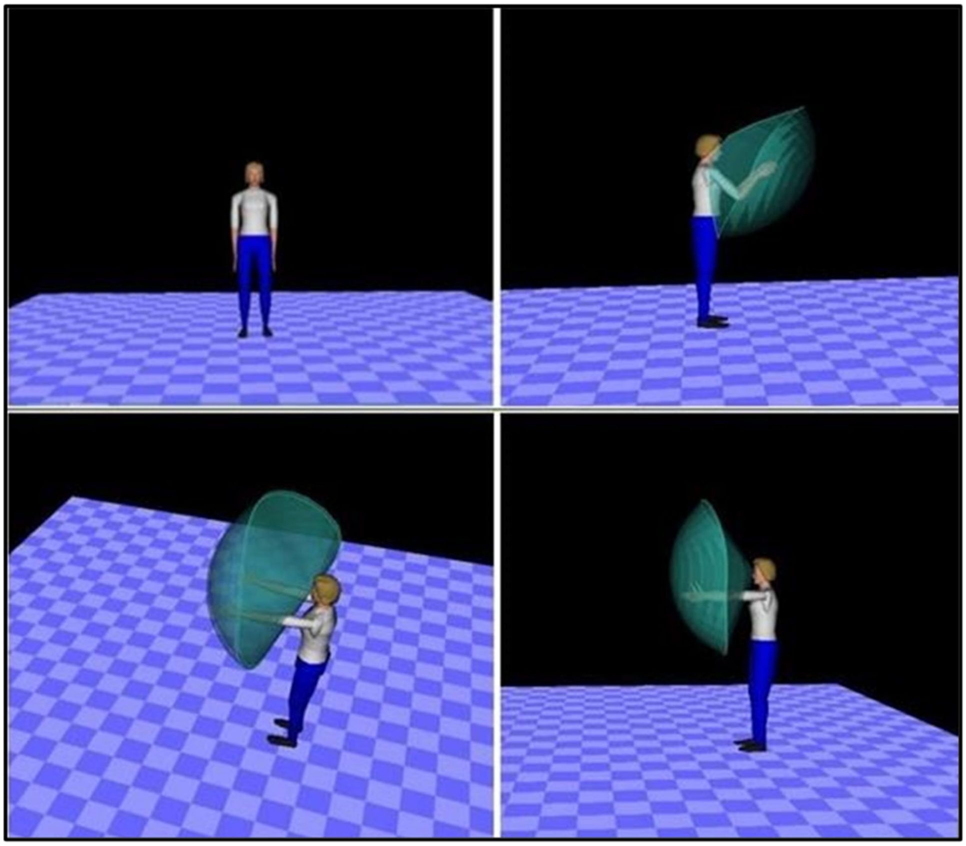


Fig. 3 An ideal reach zone represents an optimal working region for a manikin

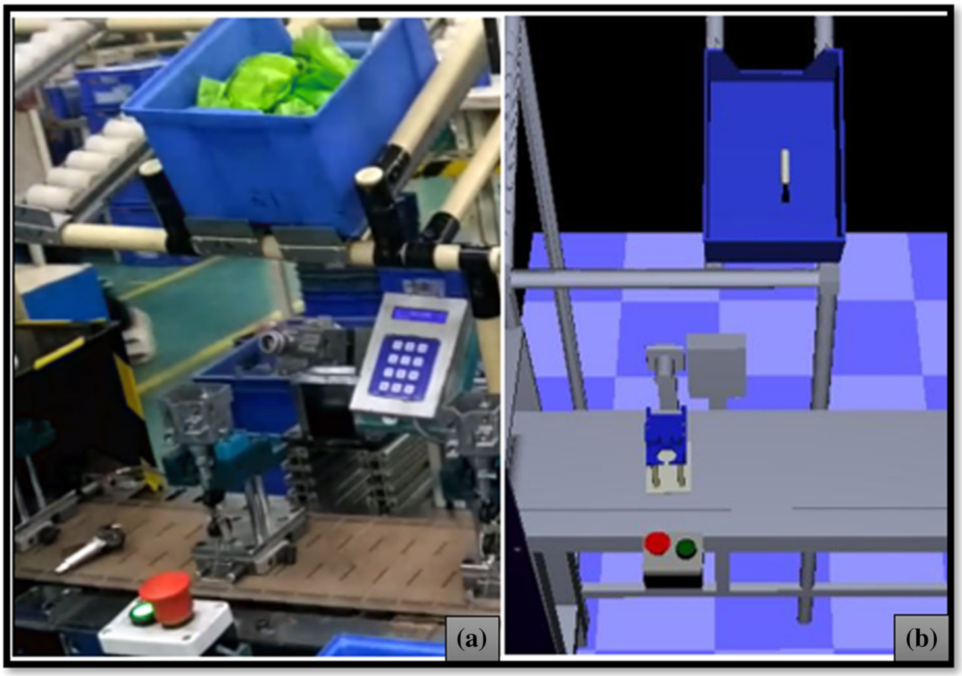


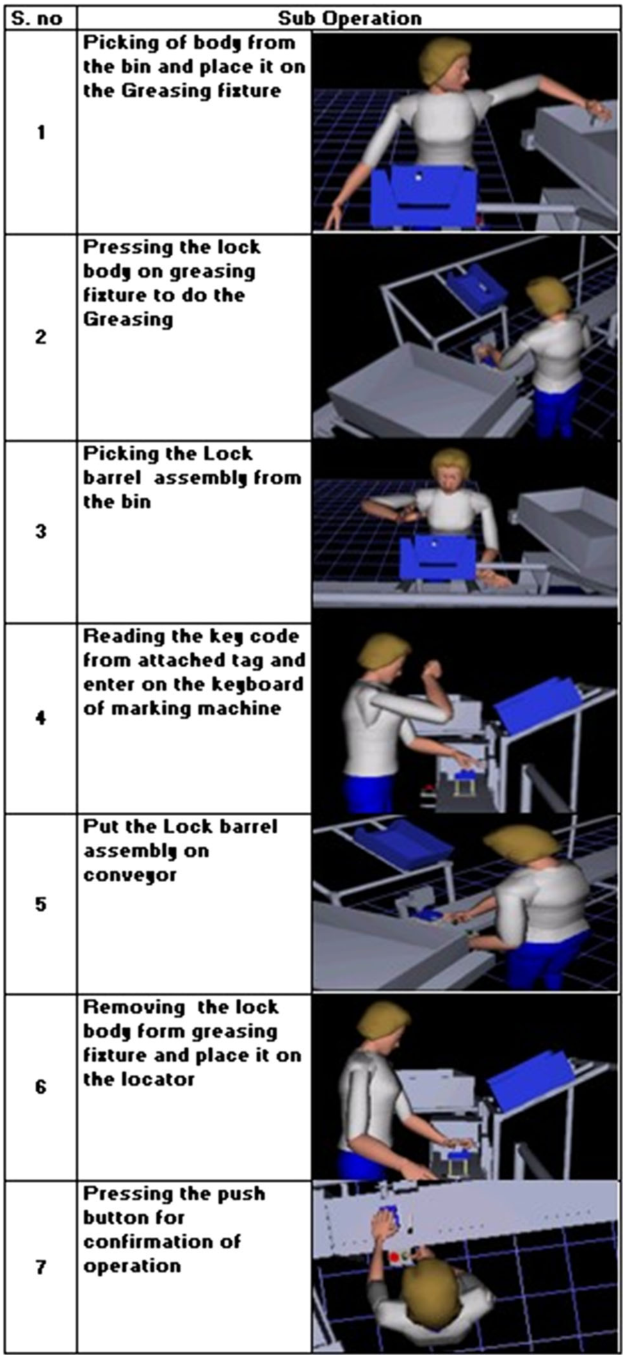
Fig. 4 **a** Overview of the actual workstation of an assembly line; **b** Virtual workstation designed in JACK software

Therefore, the upper limb and lower back of the operator is exposed to the risk of MSDs. The operational activities of the operator working on the workstation are captured in a video camera. The captured data is further analyzed manually. The operation performed by the operator on the workstation is breakdown into seven sub-operations to make better analysis and simulation. This captured data is used as an input to instruct the manikin. The virtual workstation is designed in the environment of JACK software. Each sub-operation is manually fed into JACK's tab to create a simulated environment following the captured data. The manikin is performing seven sub-operations on the workstation of an assembly line, as shown in Fig. 5. JACK access the most awkward postures maintained by manikin while performing the various sub-operations. The upper working postures of the manikin are analyzed by performing RULA. The compression and shear forces acting on the L4/L5 spinal segment has been evaluated by performing LBA. Further, this article focused on optimising workstation design with minimum forces acting on the L4/L5 spinal segment.

3 Taguchi experimental approach for optimum workstation design

Taguchi experimental design approach was introduced to investigate the influence of various parameters on the mean and variance of the process performance characteristics. The Taguchi experimental design approach includes using orthogonal arrays to organize the parameters affecting the process aspects with a minimum number of experiments. Thus, it can save time and resources [50]. Furthermore, the Taguchi design approach lies in the consistency of experimental design, analysis, lesser duration of experiments, and performance robustness while removing noise factors [51, 52]. The S/N (signal to noise) ratio and orthogonal array are two of the most often utilized techniques [53, 54]. The primary quality aspects are "the nominal-the-better," "the larger-the-better," and "the smaller-the-better." Because the compression and AP shear forces should be kept as minimal as possible, the "smaller-is-better" category of the S/N ratio was used in this study. The S/N ratios may be calculated using the Minitab software.

The primary design factors are the height of body bin stand (HS), working width (WW), and height of conveyor (HC) in mm, which are affecting the performance of an operator. These major design factors on an assembly line are shown in Fig. 6. Level 1 of each factor is obtained by measuring quantities in an actual workspace of the assembly line. Further, the level 2 and 3 factors are decided according to the hypothesis that the operator's effort and fatigue are minimal. The primary design factors and their levels are shown in Table 1. Small values vary the primary design factors. The slight variations in the workstation design result in various changes in joint angles of the working operators, which further results in awkward postures. The operators are working for 9 h per day by maintaining these awkward postures. It increases the presence of MSDs. Further, two response parameters are selected for the statistical analysis. These responses are compression forces and AP shear forces acting on the L4/L5 spinal segment.



S. no	Sub Operation
1	Picking of body from the bin and place it on the Greasing fixture
2	Pressing the lock body on greasing fixture to do the Greasing
3	Picking the Lock barrel assembly from the bin
4	Reading the key code from attached tag and enter on the keyboard of marking machine
5	Put the Lock barrel assembly on conveyor
6	Removing the lock body form greasing fixture and place it on the locator
7	Pressing the push button for confirmation of operation

Fig. 5 Manikin is performing various sub-operations on a workstation of an assembly line

To design an optimum workspace and determine the contribution of individual design factor on the lower back forces, the experiments based on the Taguchi L_9 orthogonal array are carried out. The orthogonal array indicates the combination of factor defining in each experiment and allows the simultaneous determination of several variables with a minimum number of experiments. The L_9 orthogonal array is shown in Table 2.

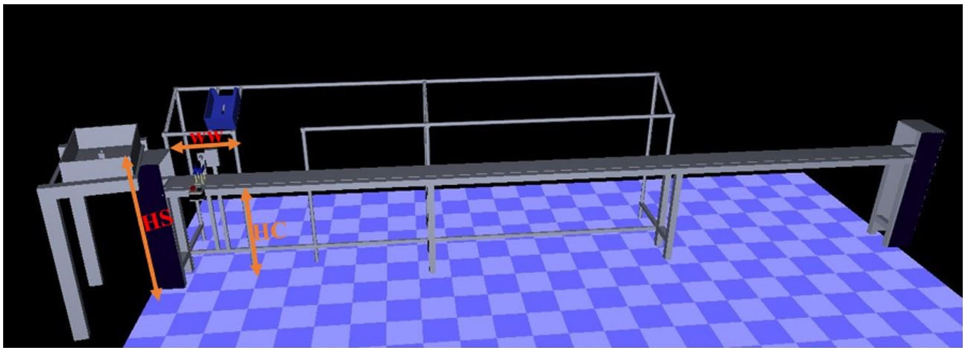


Fig. 6 An assembly line with major design factors affecting the performance of the operator

Table 1 Major design factors and their levels

Symbol	Factors	Levels		
		1	2	3
A	Height of body bin stand (HS) in mm	1450	1500	1550
B	Working width (WW) in mm	284	282	280
C	Height of conveyor (HC) in mm	858	850	840

Table 2 Standard L_9 orthogonal array

Exp. No.	Levels of factors		
	Factor A (HS)	Factor B (WW)	F ctor C (HC)
1	1450	284	858
2	1450	282	850
3	1450	280	840
4	1500	284	850
5	1500	282	840
6	1500	280	858
7	1550	284	840
8	1550	282	858
9	1550	280	850

The forces acting on the working operator's L4/L5 spinal segment are evaluated as the essential criteria to determine each design alternative and validate the final optimum design. The combinations of various design factors significantly affect the compression and shear forces acting on the working operator's L4/L5 spinal segment. These effects are considered to select the best combination of factors for the optimum design of the workspace. This optimum design will ensure the minimum values of forces acting on the L4/L5 spinal segment. The results are analyzed using the Analysis of Means (ANOM), analysis of S/N ratios and Analysis of Variance (ANOVA). The "smaller is the best" is considered for means to get optimum design factors with minimum values of acting forces, and the S/N ratio is always considered "larger the better".

4 Results and discussion

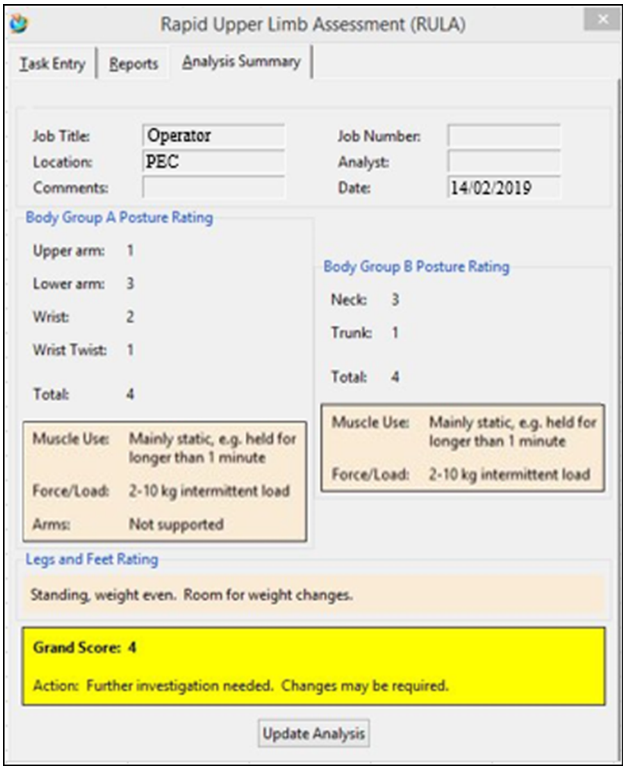
4.1 RULA: grand scores for the manikin working on the workstation

The workstation is simulated in the virtual environment of JACK for ergonomic evaluation of the manual operations of the operator. RULA is performed to evaluate the risk of the upper limb MSDs of the operator. JACK analyze the working postures of the manikin and generate RULA grand score for the most awkward posture.

The grand score for the most awkward working posture of the 5th percentile manikin is found to be 4, as shown in Fig. 7. This grand score indicated that the operational posture of the manikin is acceptable if not maintained for a prolonged period. On the other hand, the grand score for the most awkward working posture of the 95th percentile manikin is found to be 6, as shown in Fig. 8. This grand score indicates that the operational posture of the 95th percentile manikin is not acceptable. The current grand score also points out that further investigation and changes are required soon in the existing assembly process.

4.2 LBA: compression and shear forces acting on the L4/L5 spinal segment of the manikin

The workstation has been simulated in the virtual environment of JACK to perform the LBA. The LBA is performed to evaluate the compression and shear forces acting on the L4/L5 spinal segment of the lower back of the operator. The LBA considers the compression, AP shear and lateral shear forces acting on the L4/L5 spinal segment of 5th percentile manikin, as shown in Table 3. The sub-operation number 3 has the highest compression and AP shear force value, which becomes risky for healthy operators working in the same posture for long time intervals. There is no appearance of lateral shear forces except sub-operation number 1. The total compression and AP shear forces for the complete operation are 2577.09 N and 323.05 N, respectively. The LBA evaluates the compression, Anterio-Posterior and lateral shear forces act-



Job Title: Operator
Location: PEC
Comments:
Job Number:
Analyst:
Date: 14/02/2019

Body Group A Posture Rating
Upper arm: 1
Lower arm: 3
Wrist: 2
Wrist Twist: 1
Total: 4

Muscle Use: Mainly static, e.g. held for longer than 1 minute
Force/Load: 2-10 kg intermittent load
Arms: Not supported

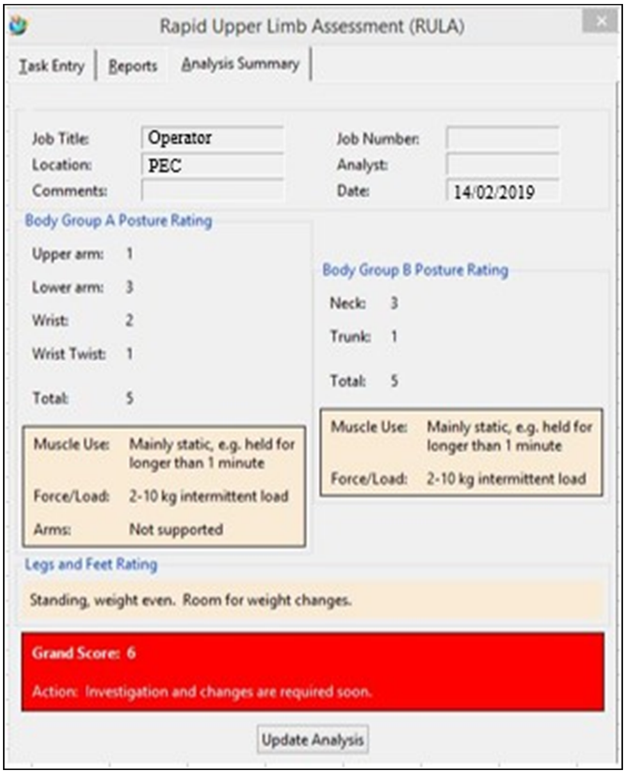
Body Group B Posture Rating
Neck: 3
Trunk: 1
Total: 4

Muscle Use: Mainly static, e.g. held for longer than 1 minute
Force/Load: 2-10 kg intermittent load

Legs and Feet Rating
Standing, weight even. Room for weight changes.

Grand Score: 4
Action: Further investigation needed. Changes may be required.

Fig. 7 RULA grand score for 5th percentile manikin, generated by JACK for most awkward posture



Job Title: Operator
Location: PEC
Comments:
Job Number:
Analyst:
Date: 14/02/2019

Body Group A Posture Rating
Upper arm: 1
Lower arm: 3
Wrist: 2
Wrist Twist: 1
Total: 5

Muscle Use: Mainly static, e.g. held for longer than 1 minute
Force/Load: 2-10 kg intermittent load
Arms: Not supported

Body Group B Posture Rating
Neck: 3
Trunk: 1
Total: 5

Muscle Use: Mainly static, e.g. held for longer than 1 minute
Force/Load: 2-10 kg intermittent load

Legs and Feet Rating
Standing, weight even. Room for weight changes.

Grand Score: 6
Action: Investigation and changes are required soon.

Fig. 8 RULA grand score for 95th percentile manikin, generated by JACK for most awkward posture

ing on the L4/L5 spinal segment of 95th percentile manikin, as shown in Table 4. The sub-operation number 3 has the highest value of compression and AP shear force. This may cause critical issues for healthy operators if the same posture is maintained for a prolonged period. There is no appearance of lateral shear forces except sub-operation number 1. The total compression and AP shear forces for the complete operation are 3221.37 N and 430.82 N, respectively.

The grand RULA scores of the 5th percentile manikin are low compared to the manikin created with the 95th percentile. Similarly, the forces acting on the L4/L5 spinal segment of the 5th percentile manikin are also small compared to the manikin created with the 95th percentile. Therefore, the working range of the existing working station is convenient for the working of the manikin created with the 5th percentile. However, the manikin created with the 95th percentile experienced excessive fatigue and body movement compared to the 5th percentile manikin while performing the same operation. This results in more risk of upper body MSDs for the manikin created with 95th percentile.

Therefore, it has become adequate to optimize the design following the manikin created by 95th percentile anthropometry data. The RULA scores for manikin with the 95th percentile are found to be critical. This indicates that further ergonomic investigation and immediate modifications are required in the existing assembly process. The compression and AP shear for manikin with 95th percentile are still low but can cause serious health issues for the healthy operators as working in the same posture for a prolonged period. The compression and AP shear forces for the complete operation are 3221.37 and 430.82 N, respectively. The operator takes 9.9 s to perform the current process and continuously working for 9 h in the same standing posture.

The operator repetitively performed the same process during working hours. Therefore, the compression and shear forces act on the operator's L4/L5 spinal segment repetitively. The repetitive application of these forces may cause excessive fatigue and critically affect the healthy operator's lower back. This causes upper body MSDs for the operator. Therefore, there is a need to modify the existing workstation design to reduce the compression and shear forces on the L4/L5 spinal segment. The compression and shear forces can be reduced to less than these values to minimize the operator's fatigue and risk of upper body MSDs. The compression and shear forces are minimized for optimizing the workstation design by using Taguchi experimental design approach.

Table 3 Lower back analysis for the manikin created with 5th percentile

Operation	Sub-operation		L4/L5 Forces (N)		
			Compression	AP Shear	Lateral Shear
Body greasing and keycode feeding	1	Picking the body from the bin and place it on the greasing fixture	284.58	24.02	1.47
	2	Pressing the lock body on the greasing fixture to do the greasing	329.28	27.68	0.00
	3	Picking the lock barrel assembly from the bin	**462.73**	**85.39**	0.00
	4	Reading the key code from the attached tag and enter it on the keyboard of the marking machine	420.02	68.86	0.00
	5	Put the lock barrel assembly on a conveyor	359.04	37.48	0.00
	6	Removing the lock body from the greasing fixture and place it on the locator	399.18	55.34	0.00
	7	Pressing the push-button for confirmation of operation	322.26	24.28	0.00

AP shear = Anterio-Posterior shear

Table 4 Lower back analysis for the manikin created with 95th percentile

Operation	Sub-operation		L4/L5 Forces (N)		
			Compression	AP Shear	Lateral Shear
Body greasing and keycode feeding	1	Picking the body from the bin and place it on the Greasing fixture	355.73	30.02	1.84
	2	Pressing the lock body on greasing fixture to do the Greasing	411.60	34.61	0.00
	3	Picking the Lock barrel assembly from the bin	**578.41**	**106.74**	0.00
	4	Reading the key code from the attached tag and enter on the keyboard of the marking machine	525.02	86.08	0.00
	5	Put the Lock barrel assembly on a conveyor	448.80	46.85	0.00
	6	Removing the lock body from the greasing fixture and place it on the locator	498.98	69.17	0.00
	7	Pressing the push-button for confirmation of operation	402.83	30.35	0.00

AP shear = Anterio-Posterior shear

4.3 Influence of major design factors on the compression and AP shear forces

Taguchi experimental design approach is performed to evaluate the influence of major design factors on the compression and AP shear forces acting on the operator's L4/L5 spinal segment. The operation performed on the workstation is analyzed to evaluate the influence of significant design factors and find the optimum design accordingly. The experiments have been performed with nine different workstations designs and noted compression and AP shear forces in each trail. The various designs of the workstation are analyzed in a virtual environment of JACK software to measure compression and AP shear forces. Table 5 represents the Taguchi experimental design for the L_9 orthogonal array with variations in responses viz. compression and AP shear forces.

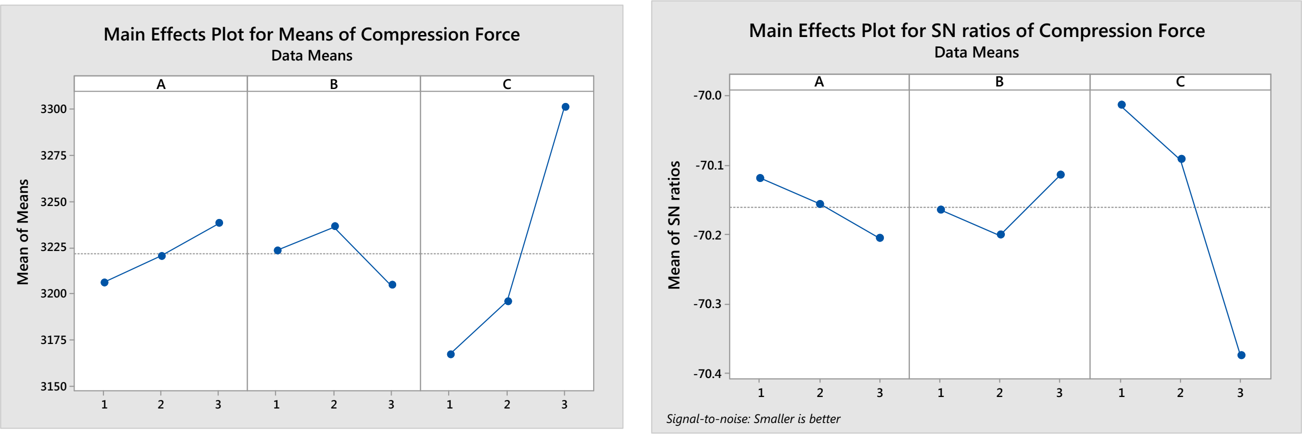
Analysis of means (ANOM) and S/N ratios plot for each response factor viz. compression and AP shear forces are shown in Figs. 9a and b, respectively. The plots are graphically describing the average of each level of the design factors. Therefore, the levels of the design factors representing minimum compression and AP Shear forces can be quickly evaluated. From the ANOM plots, with the increase in the height of the bin stand, both compression and AP shear forces are increasing.

With the rise in working width, compression force first increases, and with further advancement, it decreases, but AP shear force follows a constant path. With an increase in the height of the conveyor, both the compression and AP shear forces are falling. The effect of factors viz. height of bin stand A, working width B and height of the conveyor c on total compression force and total AP shear force also

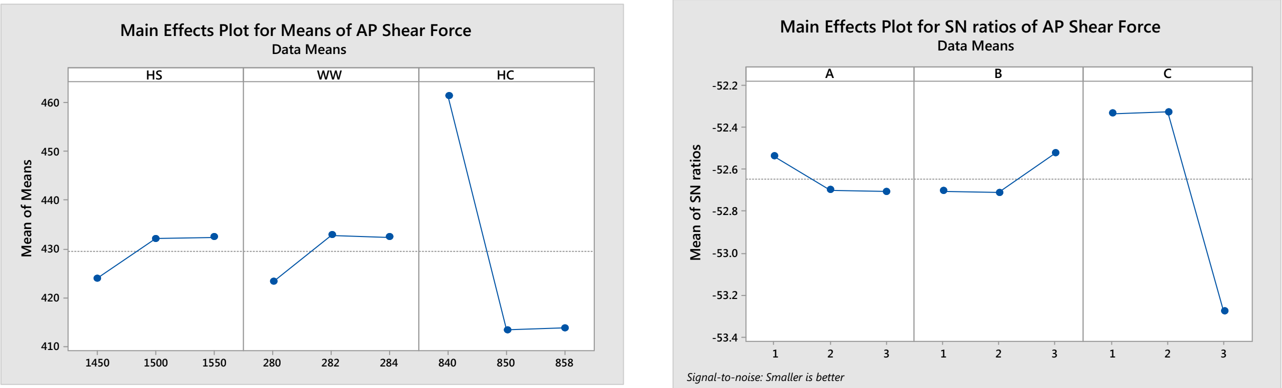
Table 5 Taguchi experimental design for L_9 orthogonal array with responses

Exp. No	Levels of factors			L4/L5 Forces (N)		S/N Ratios	
	Factor 1 (HS)	Factor 2 (HS)	Factor 3 (HC)	Compression Force	AP Shear Force	Compression Force	AP Shear Force
1	1450	284	858	3153.51	411.19	– 69.976	– 52.281
2	1450	282	850	3196.22	410.98	– 70.093	– 52.276
3	1450	280	840	3268.72	449.71	– 70.288	– 53.059
4	1500	284	850	3196.39	419.07	– 70.093	– 52.446
5	1500	282	840	3315.16	467.34	– 70.410	– 53.393
6	1500	280	858	3150.02	410.01	– 69.966	– 52.256
7	1550	284	840	3320.9	467.12	– 70.425	– 53.389
8	1550	282	858	3198.51	420.11	– 70.099	– 52.467
9	1550	280	850	3195.52	410.21	– 70.091	– 52.260

HS = Height of bin stand, *WW* = working width, *HC* = Height of conveyor, *AP shear* = Anterio-Posterior shear



(a) Main effect plot of means and S/N ratios; the impact of various design factors on compression forces



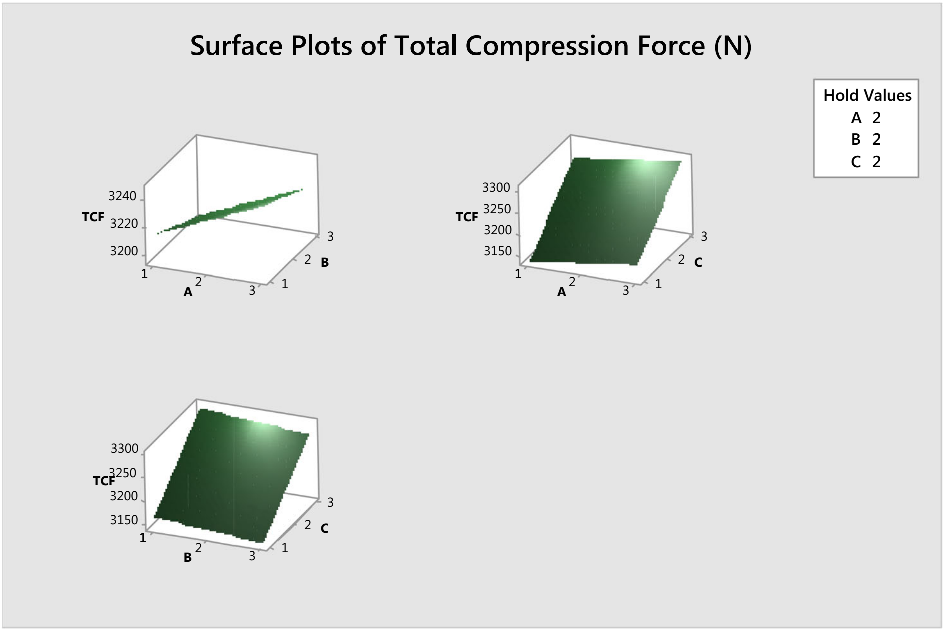
(b) Main effect plot pf means and S/N ratios; the impact of various design factors on AP shear forces

Fig. 9 **a** Main effect plot of means and S/N ratios; the impact of various design factors on compression forces **b** Main effect plot pf means and S/N ratios; the impact of various design factors on AP shear forces

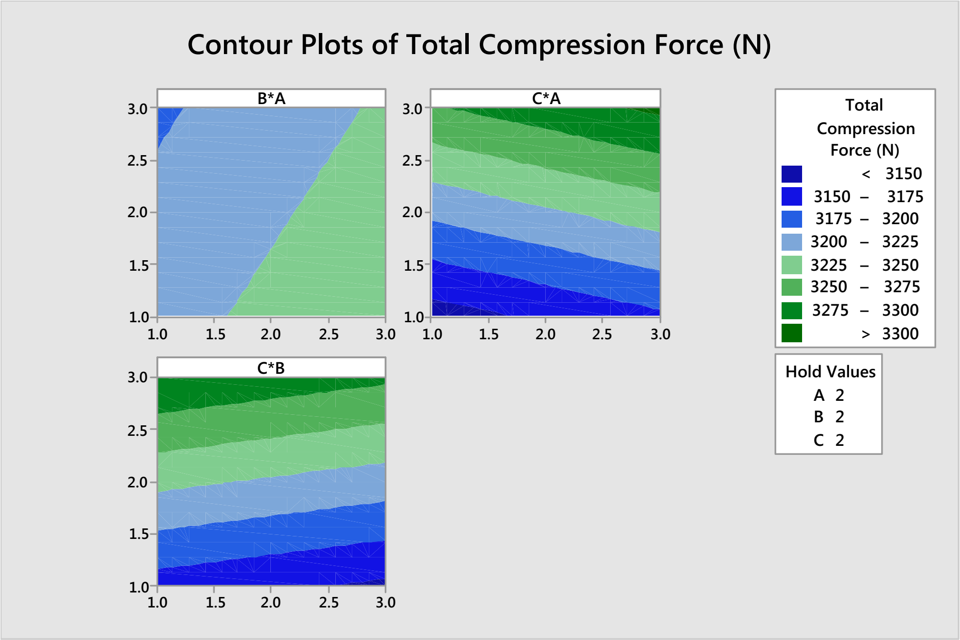
shown with surface and contour plots in Figs. 10a, b and 11a, b, respectively.

The main effect's plots noted the optimum design factors with minimum compression and AP shear forces. The minimum compression force value is at a lower level of HS, the middle level of WW and a higher level of HC, refer to Fig. 9a and similar results for S/N ratios.

Fig. 10 **a** Surface Plots for Total Compression Force **b** Contour Plots for Total Compression Force



(a) Surface Plots for Total Compression Force



(b) Contour Plots for Total Compression Force

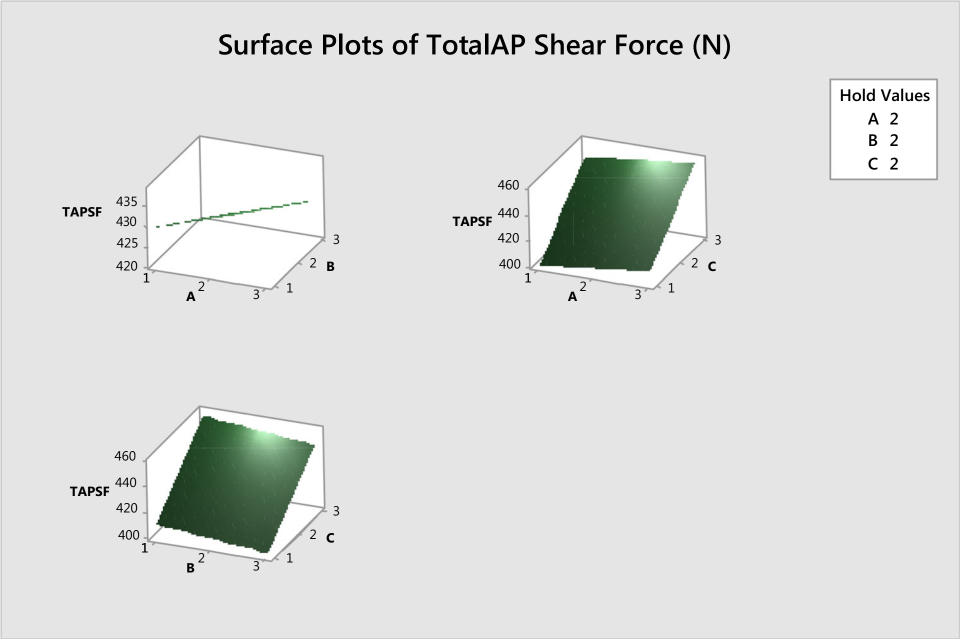
Similarly, the optimum value of AP shear force exists at a lower level of HS and WW and a higher level of HC, refer to Fig. 9b and similar results for S/N ratios. From Table 5, trial number 6 corresponds to the optimum factor level combination, both for compression force and AP shear force. The optimum design factors/level are HS-2, WW-3 and HC-1**.**

The range analysis is carried out to examine the influence of each design factor on both responses, viz. compression force and AP shear force for means. The results of the range analysis are presented in Table 6 for compression forces and in Table 7 for AP shear forces. Table 6 indicates the significance of design factors on the compression forces, whereas Table 7 suggests the importance of design factors on the AP shear forces.

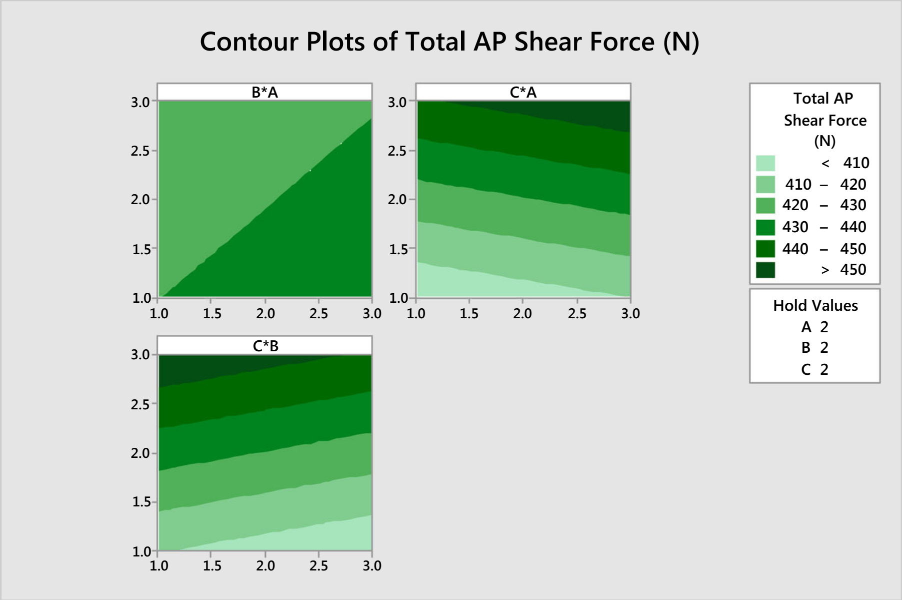
The order of significance of design factors on compression force as per delta rank is;

HC > HS > WW.

Fig. 11 **a** Surface Plots for Total AP Shear Force **b** Contour Plots for Total AP Shear Force



(a) Surface Plots for Total AP Shear Force



(b) Contour Plots for Total AP Shear Force

Table 6 Range analysis of compression forces acting on the L4/L5 spinal segment for means

Level	HS	WW	HC
1	3206	3205	**3302**
2	3221	**3237**	3196
3	**3238**	3224	3167
Delta	32	32	134
Rank	2	3	1

HS = Height of bin stand, *WW* = working width, *HC* = Height of conveyor

Table 7 Range analysis of AP shear forces acting on the L4/L5 spinal segment for means

Level	HS	WW	HC
1	424.0	423.3	**461.4**
2	432.1	**432.8**	413.4
3	**432.5**	432.5	413.8
Delta	8.5	9.5	48.0
Rank	3	2	1

HS = Height of bin stand, *WW* = working width, *HC* = Height of conveyor

The order of significance of design factors on AP shear force as per delta rank is;

HC > WW > HS.

The height of the conveyor is found to be the most significant factor, both for compression force and AP shear force, followed by the height of the body bin stand for compression force and working width for AP shear force.

4.4 Analysis of variance (ANOVA)

ANOVA is a statistical technique that predicts the influence and contribution of design factors based on the analysis of experimental results. The contribution has been calculated by dividing the sum of the squares of a factor by the total sum of squares [44, 55–57]. Thus, computed F-ratio is used for finding the significance of design factors. The results of ANOVA for the compression and AP shear forces acting on the lower back of an operator are tabulated in Tables 8 and 9, respectively. The ANOVA has been performed at a 95% confidence level, where a factor is considered to have a significant impact on forces if the p-value of the factor is < 0.05.

The design factors of the workstation are found to be significant as the P-value of each factor is less than 0.05 for compression and AP shear forces. Table 8 represents that the height of the conveyor has the most significant impact on the compression force with 90.63% of the contribution, followed by the height of bin stand and working width with 4.71 and 4.66% contributions, respectively. Similar results can also be seen for S/N ratios from Table 8.

Similarly, Table 9 describes ANOVA for means of AP shear force. Again, the height of the conveyor has the most substantial influence on the AP shear with 93.57% of the contribution, followed by the height of bin stand and working width with 2.86 and 3.57% contributions, respectively. Again, the error contribution of almost zero per cent indicates that any significant factor was not omitted from the experimental design. Similar results can also be seen for S/N ratios from Table 9.

4.5 Comparative assessment of forces

The results of optimum levels of factors achieved with the Taguchi experimental design approach contrast with current developments. The compression and AP shear forces are acting on the lower back of the operator. The optimum values achieved with the Taguchi method of compression and AP shear forces 3150.02 and 401.01 N, found in trail 6, as shown in Table 5.

These forces are less than the acting forces in the existing workstation design of the assembly line, as shown in Fig. 12. Case-1 refers to total forces per the LBA evaluations, i.e., the forces acting on the L4/L5 spinal segment of 95th percentile manikin. Case-2 refers to total forces obtained with the Taguchi design approach. It confirms that the final workstation design with the least values of compression force and AP shear is an optimum alternative. According to LBA analysis, the compression force reduced by 71.35 N and AP shear force diminished by 20.81 N on L4/L5 spinal segment. So, there is an improvement in compression force and AP shear 2.21 and 4.83%, respectively. The optimum factor levels achieved with minimum forces acting on L4/L5 spinal segment are shown in Table 10. The optimum design of the workstation has a height of bin stand at 1500 mm, working width at 280 mm, and the conveyor height at 858 mm. The optimum factor levels with minimum forces acting on L4/L5 spinal segment are HS-2, WW-3, and HC-1.

This study focused on analyzing the various awkward postures of working operators and finding the optimum workstation design considering human factors and ergonomic aspects. The study revealed the feasibility of JACK software to perform the RULA and LBA. The present RULA grand score indicates that the working postures of the operators are not acceptable. The current grand score also suggests a further investigation and change in the existing assembly operation. Further, LBA states that the forces acting on the lower back of the operator is still low but can cause lower back pain of the operators if maintaining the same posture for a long time. Accordingly, RULA and LBA prove the possibility of MSDs in the operators' body while working on the existing workstation. Therefore, the Taguchi experimental design approach was used to find the optimum design of the workstation. The optimum design of the workstation reduces the possibility of MSDs for the working operators.

Moreover, ANOVA and range analysis prove that the height of the conveyor has the most significant impact on the forces acting on the L4/L5 spinal segment of the operators. Therefore, a minor variation in the height of the conveyor may cause a more remarkable change in the forces acting on the L4/L5 spinal segment of the operators.

4.6 Implications for research and practice

The study's findings make it easier for the industrial and managerial staff to perform an ergonomics evaluation to estimate the risk of Musculoskeletal disorders. This approach saves a lot more time than the manual observation method, with easy rectifying any mistake in JACK. This eliminates the many usages of plain papers to conduct the RULA and LBA, so the JACK's accuracy is better than the manually observational approach. Further, using DHM software, JACK performs RULA and LBA consumes less time than the manual observation method. This eliminates the many usages of plain papers to conduct the RULA and LBA. Moreover, the accuracy of the JACK is better than the manually observational approach.

Table 8 Analysis of variance of the mean and S/N ratio for compression forces

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution (%)
Means							
A	2	1557.200	1557.200	778.600	654.360	0.002	4.71
B	2	1541.100	1541.100	770.500	647.590	0.002	4.66
C	2	29,986.500	29,986.500	14,993.200	12,600.650	0.000	90.63
Residual Error	2	2.400	2.400	1.200			0.007
Total	8	33,087.200					100
S/N ratios							
A	2	0.011	0.011	0.006	1241.200	0.001	4.71
B	2	0.011	0.011	0.006	1230.480	0.001	4.67
C	2	0.216	0.216	0.108	23,874.340	0.000	90.62
Residual Error	2	0.000	0.000	0.000			0.003
Total	8	0.238					100

HS = Height of bin stand, *WW* = working width, *HC* = Height of conveyor, *DF* = Degree of freedom, *SS* = Sum of squares, *MS* = Mean squares

Table 9 Analysis of variance of the means and S/N ratios for AP shear forces

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution (%)
Means							
A	2	139.620	139.620	69.810	1222.580	0.001	2.859
B	2	174.100	174.100	87.050	1524.470	0.001	3.566
C	2	4568.910	4568.910	2284.450	40,007.950	0.000	93.573
Residual Error	2	0.110	0.110	0.060			0.002
Total	8	4882.740					100
S/N ratio							
A	2	0.053	0.053	0.027	114.530	0.009	2.771
B	2	0.068	0.068	0.034	145.290	0.007	3.515
C	2	1.801	1.801	0.900	3872.880	0.000	93.691
Residual Error	2	0.000	0.000	0.000			0.024
Total	8	1.922					100

HS = Height of bin stand, *WW* = working width, *HC* = Height of conveyor, *DF* = Degree of freedom, *SS* = Sum of squares, *MS* = Mean squares

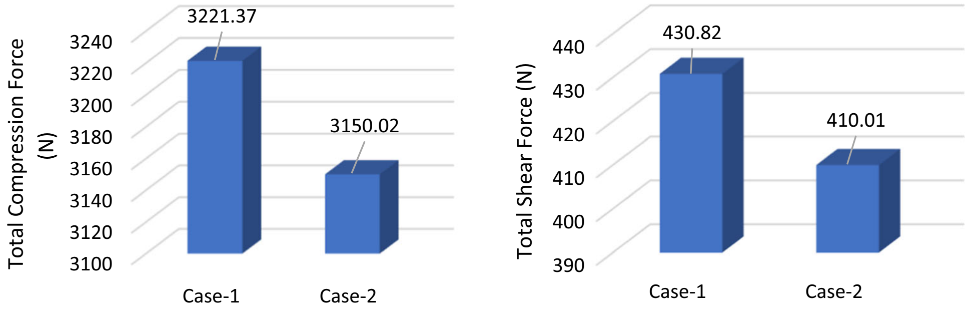


Fig. 12 Comparative Assessment of Forces

5 Conclusions

With the Taguchi experimental design approach, this study focuses on optimising workstation design to minimize compression and shear forces acting on the L4/L5 spinal segment. Herein, Taguchi experimental design approach is used to ergonomically optimize the workstation design, which contributes a lot to the advancement of Ergonomic research. Furthermore, the DHM software JACK was applied to evaluate the upper working posture and forces acting on the operator's L4/L5 spinal segment. The study results in the following conclusions:

Table 10 Optimum design factors and their levels

S. No	Factor	Level	Value (mm)
1	Height of body bin stand	2	1500
2	Working width	3	280
3	Height of conveyor	1	858

1. The upper working posture and forces acting on the L4/L5 spinal segment are critical for the operator while performing the assigned task on the workstation. Unfortunately, this causes upper body MSDs and extreme fatigue. Accordingly, the study endorses modifying the workstation design to provide better working conditions for the operator.
2. The optimum work station design suggested by the Taguchi method is at the height of bin stand 1500 mm, working width of 280 mm and height of conveyor 858 mm. This approach is a useful tool for evaluating the quantitative effects of various design factors on ergonomic aspects. As a result, the compression force was reduced by 71.35 N and AP shear force diminished by 20.81 N on L4/L5 spinal segment as per LBA analysis.
3. ANOVA results indicate that all design factors significantly impact the responses, including compression and AP shear forces. However, the conveyor height has the most extraordinary influence on compression and AP shear forces acting on the L4/L5 spinal segment with a contribution of 90.63 and 93.57%, respectively. The ANOM analysis also results in similar outcomes.
4. This study can be extended to the dynamic posture analysis using motion sensing devices such as Kinect and Mocap and define exposure towards MSDs by considering the magnitude and direction of the forces and duty cycle.

Further, Taguchi experimental design approach can also be implemented with another ergonomic method such as Ovako Working Analysis System (OWAS) and Rapid Entire Body Assessment (REBA) to optimize the workspace design of different industries. Thus, MSDs can be evaluated in the entire body of the operator.

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