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Biomechanical Modelling of Musculoskeletal Loading During Operation of Engine-Powered Stationary Grain Threshers in Nigeria

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ABSTRACT: *Locally fabricated stationary grain threshers are widely used by smallholder farmers in Nigeria; however, the internal biomechanical loading imposed on operators during machine feeding tasks has received limited quantitative investigation. This study developed a biomechanical strain model linking lifting parameters, joint kinematics, and operational productivity to internal spinal loading during operation of two engine-powered stationary threshers. Thirteen experienced operators performed standardized threshing tasks using Machine 1 (M1: feed height 92 cm; capacity 3000 kg·h⁻¹) and Machine 2 (M2: feed height 161.5 cm; capacity 6500 kg·h⁻¹). Anthropometric characteristics, lifting frequency, load mass per lift, and trunk and upper-limb joint angles were recorded. Postural and lifting risks were evaluated using the NIOSH Revised Lifting Equation (RNLE), Rapid Entire Body Assessment (REBA), and Rapid Upper Limb Assessment (RULA). Multiple linear regression modelling quantified the relationship between lifting parameters and threshing productivity. M2 required significantly greater lifting frequency (10 ± 1.81 lifts·min⁻¹) and load mass per lift (2.06 ± 0.22 kg) compared with M1 (7 ± 1.59 lifts·min⁻¹; 1.75 ± 0.44 kg). Peak trunk flexion exceeded 100° during lift initiation for both machines, indicating substantial deviation from neutral posture. REBA scores ranged from 8–11, indicating high postural risk, while RULA scores ranged from 6–7, suggesting that ergonomic modifications are required. The NIOSH Lifting Index exceeded unity for both machines, indicating elevated probability of low-back injury under repetitive exposure. Regression modelling produced a statistically significant productivity model, F (2,10) = 425.987, p < .001, with R² = 0.974, demonstrating that lifting frequency and load magnitude explained 97.4% of the variance in threshing output. The findings indicate that although locally fabricated threshers increase processing efficiency, productivity gains occur alongside increased cumulative biomechanical loading, particularly at the lumbosacral and shoulder regions. Ergonomic redesign focused on optimizing feed height and reducing load moment arms is therefore recommended to mitigate musculoskeletal risk while maintaining operational efficiency.*

Keywords: *biomechanical modelling, NIOSH lifting equation, REBA, RULA, agricultural ergonomics, musculoskeletal disorders, grain threshers, Nigeria*

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I. INTRODUCTION

Agricultural mechanization in Sub-Saharan Africa has expanded rapidly in response to labour constraints and post-harvest losses. However, most interventions emphasize productivity gains with limited quantitative evaluation of operator biomechanical exposure [1, 3, 4]. In Nigeria, locally fabricated stationary grain threshers have largely replaced manual threshing and remain dominant among smallholder farmers due to affordability and local manufacturability. Although these systems increase processing capacity, they require repetitive manual feeding at fixed inlet heights, often under flexed and asymmetric postures. The musculoskeletal consequences of these loading patterns remain insufficiently quantified.

From a biomechanical standpoint, grain feeding constitutes a repetitive asymmetric lifting task involving trunk flexion, shoulder abduction, and lower-limb stabilization. The task generates an external flexion moment about the lumbosacral joint (L5–S1) that must be counterbalanced by trunk extensor muscle forces. Static moment equilibrium about L5–S1 can be expressed as:

$$M_{ext} = (W_L * d_L) + (W_T * d_T)$$

$$M_{muscle} = F_m * d_m$$

where (W_L) is the lifted load, (d_L) its horizontal moment arm, (W_T) the upper-body weight, (d_T) its moment arm, (F_m) trunk extensor muscle force, and (d_m) its moment arm. Because d_m is substantially smaller than d_L, modest external loads can produce disproportionately large internal muscle forces [2, 9]. Resultant spinal compression (F_C) and anterior shear (F_s) at L5–S1 may be approximated as:

$$F_C = F_m \cos\theta + W_L + W_T$$
$$F_s = F_m \sin\theta$$

where (θ) denotes trunk inclination. Increased flexion angle and horizontal reach therefore amplify compressive and shear loading.

Cumulative exposure to repetitive lifting in non-neutral postures is strongly associated with work-related musculoskeletal disorders (WRMSDs), particularly affecting the lumbar spine and shoulder complex [7, 10]. Evidence from African agricultural settings indicate high prevalence of low-back and upper-limb symptoms among operators of manually fed equipment [6, 11]), suggesting that mechanization without ergonomic optimization may shift rather than eliminate physical risk.

Several validated ergonomic assessment frameworks support structured risk quantification. The NIOSH Revised Lifting Equation (RNLE) estimates a Recommended Weight Limit and corresponding Lifting Index based on task multipliers [12]. Rapid Entire Body Assessment (REBA) and Rapid Upper Limb Assessment (RULA) offer validated observational tools for whole-body and upper-limb postural risk [5, 8]. Despite their extensive industrial application, integration of biomechanical modelling with standardized risk assessment remains limited in evaluations of locally fabricated agricultural machinery in Sub-Saharan Africa.

Accordingly, this study aimed to develop a biomechanical strain model linking lifting parameters to threshing productivity; quantify postural and lifting risk using RNLE, REBA, and RULA; compare biomechanical exposure between two commonly used engine-powered stationary threshers; and provide modelling-based recommendations for ergonomic redesign to reduce cumulative lumbosacral loading while maintaining productivity.

II. MATERIAL AND METHODS

This study adopted an integrated experimental and analytical approach to quantify biomechanical loading during the operation of locally fabricated engine-powered stationary grain threshers. The methodological framework combined anthropometric measurements, task observation, kinematic analysis, ergonomic risk assessment, and biomechanical modelling to examine the relationship between lifting parameters and musculoskeletal loading during threshing operations. Two commonly used threshers with different structural configurations and operational capacities were evaluated to determine how machine design influences operator posture, lifting dynamics, and productivity.

Field measurements were conducted under controlled operating conditions using experienced operators performing typical grain-feeding tasks. Anthropometric characteristics were recorded to support biomechanical calculations and contextualize observed postures relative to operator body dimensions. Key task variables—including lifting frequency, load mass per lift, and joint postures—were measured to quantify manual handling demands.

Ergonomic risk was evaluated using established assessment tools, including the NIOSH Revised Lifting Equation, Rapid Entire Body Assessment, and Rapid Upper Limb Assessment, while a biomechanical model of the lumbosacral joint was applied to estimate spinal compression and shear forces during feeding tasks. Finally, multiple regression analysis was used to determine the influence of lifting frequency and load mass on threshing productivity, enabling the development of a predictive model linking operational performance with biomechanical exposure. Collectively, these methods provide a comprehensive framework for evaluating human–machine interaction and identifying ergonomic improvements for safer and more efficient small-scale agricultural mechanization.

2.1 Participants

Thirteen physically active volunteers (11 males, 2 females; age: 24.8 ± 3.2 years; height: 173.91 ± 5.96 cm; body mass: 63.38 ± 7.86 kg) participated. Inclusion criteria required absence of self-reported musculoskeletal disorders, neurological impairment, or recent head injury. All participants provided informed consent. Anthropometric variables relevant to lifting biomechanics (stature and segment dimensions) were measured using standard procedures and are summarized in Table 1.

2.2 Apparatus

Threshing was performed using the selected locally fabricated stationary grain thresher. Grain mass was measured with a calibrated mechanical weigh balance (ISO 9001 certified; 120 kg capacity; 1 kg resolution). Sagittal-plane kinematics were recorded using a Samsung SL102 digital camera (10.2 MP; 3× optical zoom), positioned perpendicular to the movement plane to minimize parallax error. Images were analyzed in AutoCAD

2007 (Autodesk Inc., USA). Body temperature was recorded pre- and post-trial using a digital thermometer to estimate acute thermal strain.

2.3Experimental Procedure

Each participant completed three standardized threshing trials, each lasting 1 minute. Participants repetitively lifted grain from ground level to the machine inlet, representing lift initiation and termination phases. Initial grain mass was recorded before each trial; the quantity lifted was determined by subtracting post-trial residual mass from the initial mass. Lifting frequency (lifts·min^{-1}), load per lift (kg), and displacement distances were documented.

Still images corresponding to lift initiation and completion were extracted for angular analysis. The following joint angles were quantified: knee (thigh–lower leg), ankle (lower leg–foot), elbow (upper arm–forearm), wrist (forearm–hand), neck (head–trunk), shoulder flexion/abduction, and lumbosacral flexion (trunk relative to vertical). Participants completed a structured discomfort questionnaire after testing, supplemented by brief oral interviews to capture perceived exertion.

2.4Justification for Two-Dimensional Analysis

The task involved predominantly sagittal-plane trunk flexion and vertical load displacement; therefore, 2D sagittal analysis captures the primary determinants of L5–S1 loading (Chaffin *et al*., 2006). Camera alignment perpendicular to the motion plane reduced projection error. This approach provides a valid and field-appropriate method for occupational lifting assessment in low-resource contexts.

2.5Reliability

To assess intra-rater reliability, 20% of randomly selected images were reanalyzed after two weeks. Intraclass correlation coefficients (ICC, two-way mixed, absolute agreement) were calculated. Standard error of measurement (SEM) was computed as:

$$SEM = SD\sqrt{1 - ICC} \qquad 1$$

$ICC \geq 0.80$ was considered acceptable.

2.6Biomechanical Modelling Framework

To quantify musculoskeletal loading during threshing, three complementary ergonomic models were applied: the NIOSH Revised Lifting Equation (RNLE), Rapid Entire Body Assessment (REBA), and Rapid Upper Limb Assessment (RULA). These tools integrate task geometry, repetition, load magnitude, and posture into a structured biomechanical risk evaluation and are conceptually linked to the L5–S1 moment equilibrium described in the Introduction.

2.6.1 Linkage to L5–S1 Biomechanics

The threshing task generates an external flexion moment about L5–S1:

$$M_{ext} = (W_L * d_L) + (W_T * d_T) \qquad 2$$

Muscle equilibrium requires:

$$M_{muscle} = F_m * d_m \qquad 3$$

Because $d_m \ll d_L$, small increases in horizontal reach or trunk flexion substantially increase internal muscle force. Resultant compression and shear are approximated as:

$$F_C = F_m \cos\theta + W_L + W_T \qquad 4$$

$$F_s = F_m \sin\theta \qquad 5$$

RNLE quantifies acceptable external load relative to geometry and frequency (affecting $W_L$and d_L), while REBA and RULA capture postural deviations influencing θ, thereby modifying internal compression and shear.

2.6.2 NIOSH Revised Lifting Equation (RNLE)

The Recommended Weight Limit (RWL) was computed as:

$$RWL = LC * HM * VM * DM * AM * FM * CM \quad 6$$

where:

$\boldsymbol{LC}$= Load Constant (23 kg)
HM = Horizontal Multiplier
VM = Vertical Multiplier
DM = Distance Multiplier
AM = Asymmetric Multiplier
FM = Frequency Multiplier
CM = Coupling Multiplier

The Lifting Index (LI) was calculated:

$$LI = \frac{Load\ Weight}{RWL} \quad 7$$

$LI \leq 1$ indicates nominal risk; $1 < LI < 3$ indicates increased risk; $LI \geq 3$ indicates high risk requiring redesign.

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2.6.3 Rapid Entire Body Assessment (REBA)

REBA scores were derived from measured trunk, neck, leg, and load parameters. Segment scores (Group A: trunk/neck/legs; Group B: upper limbs) were combined with activity modifiers to generate a final score (1–15).

Risk interpretation:

i. 1: Negligible
ii. 2–3: Low
iii. 4–7: Medium
iv. 8–10: High
v. ≥11: Very high

REBA primarily reflects whole-body posture contributing to increased trunk inclination angle (θ) in Equations 4 and 5.

2.6.4 Rapid Upper Limb Assessment (RULA)

RULA assessed shoulder, elbow, wrist, and neck postures, including repetition and static loading. Final action levels (1–7) indicate urgency of intervention:

i. 1–2: Acceptable
ii. 3–4: Further investigation
iii. 5–6: Change required soon
iv. 7: Immediate action

RULA captures upper-limb positioning that may indirectly alter trunk compensation patterns and horizontal reach distance (d_L).

2.6.5 Integrated Interpretation

RNLE quantifies load acceptability relative to task geometry; REBA and RULA evaluate postural determinants of trunk moment generation. Together, these models operationalize the biomechanical pathway from external task demands to internal L5–S1 compression and shear, enabling comparison between machines and integration into regression-based productivity modelling.

2.7 Data Analysis

Descriptive statistics (mean ± SD) were computed for all variables. Differences between machines were evaluated using repeated-measures ANOVA. Significant effects were followed by Bonferroni-adjusted pairwise comparisons. Effect sizes were reported as partial eta squared ($\eta^2 p$), with $\alpha = 0.05$.

Regression Modelling

Multiple linear regression examined the relationship between lifting parameters (frequency, load per lift, trunk flexion) and productivity:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \in \qquad 8$$

where Y represents productivity, X_1 lifting frequency, X_2 load magnitude, and X_3 trunk flexion angle. Model fit was evaluated using R^2 and adjusted R^2. Statistical significance was assessed using the F-statistic.

Assumption Testing

Model assumptions were verified using Shapiro–Wilk tests and Q–Q plots (normality), residuals vs fitted plots (homoscedasticity), Durbin–Watson statistics (independence), variance inflation factors (VIF < 5), and Cook's distance (influence). All analyses were performed using standard statistical software, with significance set at $p < 0.05$.

Power Analysis

An a priori power analysis was conducted using G*Power 3.1 for linear multiple regression (fixed model, R^2 deviation from zero) with two predictors. Assuming $\alpha = 0.05$, power $(1-\beta) = 0.80$, and a medium-to-large effect size ($f^2 = 0.35$) consistent with biomechanical productivity modelling, the required minimum sample size was N = 12.

III. RESULTS

This section presents the findings from the anthropometric measurements, task performance analysis, ergonomic risk assessment, and biomechanical modelling conducted during the operation of the stationary grain threshers. The results describe the characteristics of the study participants, operational parameters of the threshing tasks, and the associated postural and lifting risks. Outcomes from the NIOSH Revised Lifting Equation, Rapid Entire Body Assessment, and Rapid Upper Limb Assessment are presented alongside regression analysis examining the relationship between lifting parameters and threshing productivity. Together, these results provide quantitative insight into the interaction between operational efficiency and biomechanical loading experienced by operators during grain feeding tasks.

Anthropometric Parameters of the Participants

Mature tree, old growth, dry and moist savanna, dense foliage cover, gardens, low stream, upstream, annual and perennial canals are among constant threat of **Habitat Fragmentation** ($(TIC_t^1)_1^1$: 52.56), **Human Intervention** ($(TIC_t^1)_1^1$: 66.09) and **Over Exploitation** ($(TIC_t^1)_1^1$: 43.61) with significant level of risk impact. Sand dunes, saplings, mid dense foliage cover, river bank and seasonal canal, lake and ponds and marshes are under pressure.

Table 1: Participant Anthropometric Characteristics (N = 13)

Variable	Mean	SD	Min	Max
Age (years)	24.8	3.2	20	35
Height (cm)	173.91	5.96	165	186
Weight (kg)	63.38	7.86	53	78
Arm Reach (cm)	77.04	4.14	69.5	83.5
Shoulder Height (cm)	142.0	12.9	106	159.5

Table 1 summarizes the anthropometric characteristics of the 13 participants involved in the threshing task. The participants had a mean age of 24.8 ± 3.2 years, indicating a relatively young and physically active sample. This age range is generally associated with higher musculoskeletal capacity and lower prevalence of degenerative disorders; therefore, the biomechanical loads observed in the study may represent conservative estimates compared with those experienced by older agricultural workers. The mean stature of 173.91 ± 5.96 cm suggests moderate homogeneity in body size among participants. Body height influences working posture during manual loading tasks, particularly when machine feeding heights are fixed. When equipment height does not correspond to operator stature, workers may adopt increased trunk flexion or shoulder elevation, which increases the moment arm between the load and the lumbosacral joint and consequently elevates spinal compression forces.

Participants had a mean body mass of 63.38 ± 7.86 kg, which contributes to the gravitational moment generated by the upper body during forward bending tasks. Variations in body mass therefore influence internal muscular effort required to stabilize the spine during lifting. Mean arm reach (77.04 ± 4.14 cm) and shoulder height (142.0 ± 12.9 cm) are particularly relevant for threshing machine operation because they determine horizontal reach distance and optimal feeding height. Larger reach distances increase horizontal load displacement, thereby increasing lumbar moments, while variability in shoulder height suggests that a fixed machine configuration may impose non-neutral postures for some operators. Collectively, these anthropometric characteristics highlight the importance of anthropometrically compatible machine design to minimize biomechanical loading during repetitive threshing tasks (Table 1).

Operational Activities on the Selected Threshers

Table 2: Lifting and Productivity Variables

Parameter	M1	M2
Frequency (lifts·min^{-1})	7 ± 1.59	10 ± 1.81
Load per lift (kg)	1.75 ± 0.44	2.06 ± 0.22
Output (kg·min^{-1})	12.59 ± 2.41	20.38 ± 3.84

Table 2 presents the lifting characteristics and productivity outcomes for the two stationary threshers evaluated in the study. The results show that Machine 2 (M2) required a higher lifting frequency (10 ± 1.81 lifts·min^{-1}) compared with Machine 1 (M1) (7 ± 1.59 lifts·min^{-1}). This indicates that operators feeding M2 performed approximately 43% more lifting cycles per minute, thereby increasing the rate of repetitive manual handling. High lifting frequency is a key factor influencing cumulative biomechanical loading, as repetitive movements reduce recovery time for musculoskeletal tissues and increase fatigue risk.

Similarly, in Table 2, the load per lift was slightly higher for M2 (2.06 ± 0.22 kg) than for M1 (1.75 ± 0.44 kg). Although the absolute difference in load magnitude appears modest, even small increases in lifted mass can significantly elevate lumbar moment and spinal compression forces, particularly when combined with non-neutral trunk postures and repetitive lifting patterns. The combined effects of higher lifting frequency and load magnitude resulted in substantially greater processing output for M2 (20.38 ± 3.84 kg·min^{-1}) compared with M1 (12.59 ± 2.41 kg·min^{-1}), representing approximately a 62% productivity increase. While this demonstrates the operational efficiency of the larger machine, the productivity gain is achieved through increased physical workload on the operator.

Postural Risk Assessment

Table 3: Assessment Tools Results as Related to Working with Selected Machines

Assessment Tool	M1	M2	Risk Interpretation
NIOSH LI	> 1	> 1	Increased risk
REBA	8–10	9–11	High risk
RULA	6	7	Action required

Table 3 summarizes the ergonomic risk associated with operating the two stationary grain threshers using three established assessment tools: the NIOSH Revised Lifting Equation, Rapid Entire Body Assessment, and Rapid Upper Limb Assessment. Collectively, the results indicate that both machines expose operators to elevated biomechanical risk, with slightly greater risk observed for Machine 2 (M2).

The Lifting Index (LI) derived from the RNLE exceeded unity (LI > 1) for both machines, indicating that the lifting demands surpass recommended safety limits for a considerable portion of the working population. Such values are commonly associated with increased risk of work-related musculoskeletal disorders, particularly under repetitive lifting and trunk flexion conditions typical of threshing operations.

Postural evaluation using REBA classified the tasks as high risk, with scores ranging from 8–10 for M1 and 9–11 for M2, indicating that ergonomic intervention is required. The slightly higher scores for M2 likely reflect increased lifting frequency and greater trunk and shoulder elevation during hopper loading. Similarly, RULA scores of 6 for M1 and 7 for M2 indicate that the upper limb postures adopted during feeding are ergonomically unfavorable and warrant corrective action. These elevated scores suggest substantial loading on the shoulder and upper back musculature during repetitive lifting.

Overall, the combined RNLE, REBA, and RULA assessments consistently indicate high biomechanical exposure during threshing operations. The slightly higher risk associated with M2 corresponds with its higher throughput, highlighting a productivity–risk trade-off in which increased machine output is accompanied by greater musculoskeletal loading. These findings emphasize the need for ergonomic design improvements—such as optimized hopper height and assisted feeding mechanisms—to reduce operator strain while maintaining productivity.

Regression Model

Table 4: Regression Model Predicting Output

Predictor	B	SE	β	t	p
Constant	-15.986	1.16	—	-3.784	<0.001
Frequency	1.956	0.082	0.811	23.95	<0.001
Load	8.141	0.456	0.604	17.845	<0.001

F (2,10) = 425.987, $p < 0.001$; $R^2 = 0.974$; Adjusted $R^2 \approx 0.969$

Table 4 presents the results of the multiple regression analysis examining the influence of lifting parameters on threshing productivity. Lifting frequency (lifts·min^{-1}) and load mass per lift (kg) were included as predictors of grain output (kg·min^{-1}). The regression model was highly significant (F (2,10) = 425.987, $p < 0.001$), indicating that the predictors collectively explain a substantial proportion of the variation in machine productivity. The model demonstrated a very high coefficient of determination ($R^2 = 0.974$), showing that approximately 97.4% of the variance in threshing output is explained by lifting frequency and load mass. The adjusted R^2 (≈ 0.969) remained similarly high, confirming the robustness of the model despite the limited sample size.

Both predictors were statistically significant ($p < 0.001$). Lifting frequency exhibited the strongest standardized effect ($\beta = 0.811$, $t = 23.95$), indicating that increases in the number of lifts per minute substantially enhance output. The unstandardized coefficient ($B = 1.956$) implies that each additional lift per minute increases productivity by approximately 1.96 kg·min^{-1}, assuming load mass remains constant. Load mass per lift was also a significant positive predictor ($\beta = 0.604$, $t = 17.845$), with its coefficient ($B = 8.141$) indicating that increasing the mass handled per lift markedly improves machine throughput.

The resulting regression model for predicting threshing productivity is:

$$Output = -15.986 + 1.956F + 8.141L;$$

where: F represents lifting frequency (lifts·min^{-1}) and L represents load mass (kg).

Power Analysis Justification

An a priori power analysis was conducted for multiple regression with two predictors (frequency and load per lift). The following assumptions were made:

i. $\alpha = 0.05$
ii. Power $(1-\beta) = 0.80$
iii. Medium-to-large effect size ($f^2 = 0.35–0.50$) typical in biomechanical productivity modelling

Using Cohen's formula:

$$f^2 = R^2 / (1 - R^2)$$

Given observed $R^2 = 0.974$:

$f^2 = 0.974 / (1 - 0.974) \approx 37.46$ (extremely large effect)

For medium effect ($f^2 = 0.35$), required sample ≈ 12–15 participants.

Therefore, N = 13 achieves adequate statistical power (>0.80) for detecting large effects, though generalizability remains limited by sample size. The observed effect size ($R^2 = 0.974$; $f^2 = 37.46$) indicates an extremely large effect, confirming that the study was sufficiently powered to detect significant predictor effects.

Biomechanical Posture Model During Grain Loading Task

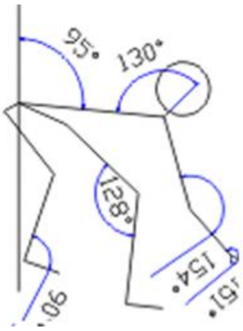

Fig. 1 A: Origin of Lift (Stooped Posture)

Figure 1A presents biomechanical posture during manual lifting while feeding grain into the thresher. Joint angles at the trunk, neck, elbow, hip, and knee were measured from video posture analysis. Blue arcs indicate measured joint angles used for ergonomic risk assessment. The diagram exemplifies significant lumbar moment arm increase and elevated spinal compression forces due to horizontal load displacement.

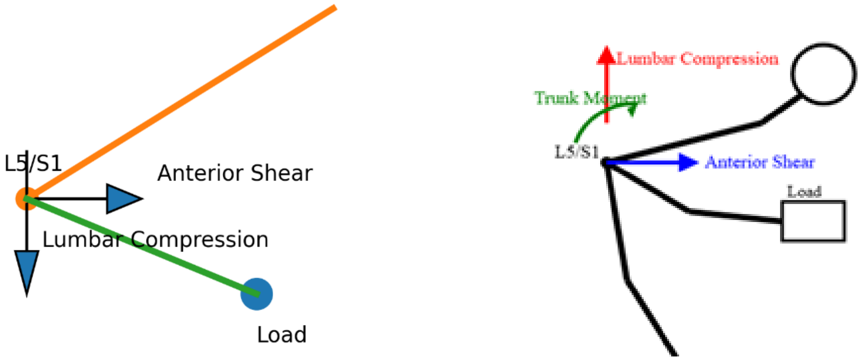

Fig. 1B: Free Body Diagram and Biomechanical Loading of Lumbar during Lifting

In Figure 1B, the free body diagram illustrates the biomechanical forces acting on the lumbar spine, specifically at the L5/S1 joint, during a forward-bending lifting task such as feeding grain into a thresher hopper. This joint acts as the primary pivot point of the trunk and is commonly used in occupational biomechanics to evaluate spinal loading during manual material handling. The diagram shows the external load force, represented by the mass being lifted and positioned anterior to the body. Because the load is located at a horizontal distance from the L5/S1 joint, it generates a forward bending moment about the lumbar spine. To maintain equilibrium, the spinal extensor muscles must generate counteracting forces, which leads to significant lumbar compression along the spinal axis. This compressive force is represented by the downward vector and reflects the combined effects of body weight, lifted load, and muscle force required to stabilize the trunk (Figure 1B).

In addition to compression, Figure 1B highlights the presence of anterior shear force, shown as the horizontal vector acting at the L5/S1 joint. Anterior shear occurs when forward trunk flexion causes part of the gravitational force from the trunk and the lifted load to act parallel to the intervertebral disc plane. Elevated anterior shear forces are particularly important because they increase stress on spinal ligaments and intervertebral discs, potentially contributing to low back disorders during repetitive lifting tasks. The angled vector representing the load indicates the moment arm between the lifted object and the lumbar joint, which is a critical determinant of spinal loading. As this horizontal distance increases, such as when the worker bends forward or reaches farther from the body, the resulting moment about the lumbar spine increases substantially. Consequently, both lumbar compression and anterior shear forces rise proportionally (Figure 1B).

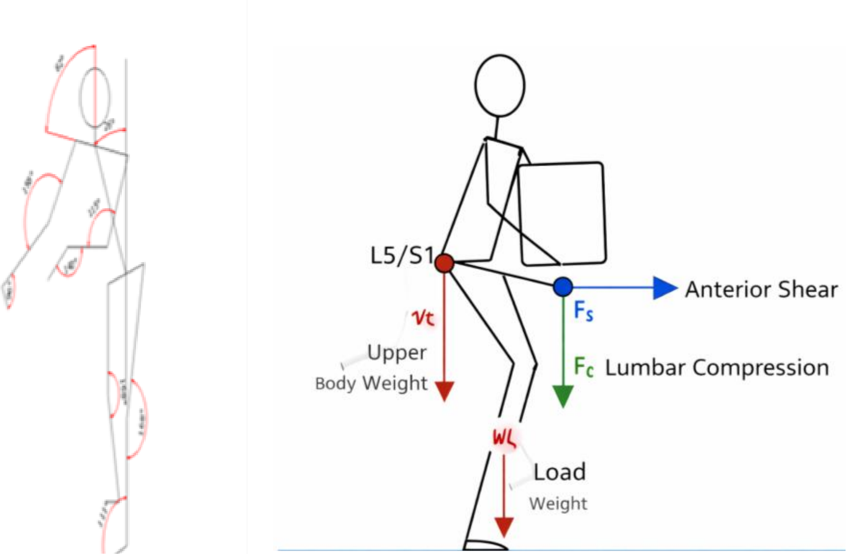

Fig. 2A: End of Lift (Semi-Upright) Fig. 2B: Free Body Diagram and Biomechanical Loading at the End of Lift

The semi-upright posture observed at the end of the lifting phase reduces spinal loading relative to the initial lifting posture due to a decrease in the horizontal distance between the lifted load and the L5–S1 joint (Figure 2A). As the trunk approaches vertical alignment, the lumbar bending moment declines, resulting in lower compressive and shear forces acting on the intervertebral discs. However, significant biomechanical loading persists because the operator must maintain the load in an elevated position during hopper feeding. Figure 2B shows the free body analysis indicates that lumbar compression is primarily influenced by the load magnitude and the residual trunk flexion angle, while anterior shear forces arise from gravitational components acting parallel to the spinal axis. Consequently, even semi-upright feeding postures may contribute to cumulative spinal loading during repetitive threshing tasks. Ergonomic interventions that allow the load to be positioned closer to the body or reduce hopper height could further decrease lumbar moments and associated musculoskeletal strain.

Established Biomechanical Models from the Findings

To quantify the relationship between operational productivity and biomechanical loading during threshing, a combined productivity–spinal load model was developed. The modelling framework integrates empirical regression analysis with biomechanical equilibrium equations describing spinal loading at the L5–S1 joint.

1. Productivity Model

Threshing productivity was empirically modelled using multiple linear regression:

$$P = \beta_0 + \beta_1 f + \beta_2 l$$

where:

P = Threshing output (kg·min^{-1})
f = Lifting frequency (lifts·min^{-1})
l = Load mass per lift (kg)

From the experimental data, the regression model was:

$$P = -15.986 + 1.956f + 8.141l$$

This relationship indicates that increases in lifting frequency and load magnitude directly increase machine throughput.

2. Lumbar Moment Model

The external bending moment acting about the lumbosacral joint during lifting is given by:

$$M_{L5/S1} = (l * g * d_L) + (W_T * g * d_T)$$

where:

$M_{L5/S1}$ = Lumbar moment (Nm)
W_T = Upper body mass (kg)
g = Gravitational acceleration (9.81 m·s⁻²)
d_L = Horizontal distance from load to L5/S1 (m)
d_T= Horizontal distance from trunk center of mass to L5/S1 (m)

3. Lumbar Compression Force

The compressive force acting along the spinal axis is approximated as:

$$F_c = \frac{M_{L5/S1}}{r_m} + (l + W_T)g$$

where:

F_c= Lumbar compression force (N)
r_m= Moment arm of spinal extensor muscles (~0.05 m)

4. Cumulative Spinal Load

Because threshing is a repetitive task, cumulative spinal loading over time can be expressed as:

$$CL = F_c * f * t$$

where:

CL = Cumulative lumbar load (N·min)
t = task duration (min)

5. Integrated Biomechanical Productivity Model

Substituting the lumbar compression expression into the cumulative loading equation yields:

$$CL = \left[\frac{lgd_L + W_T g d_T}{r_m} + (l + W_T)g\right] ft$$

Thus, productivity and spinal loading can be expressed as coupled relationships:

$$P = f(l)$$
$$CL = f(l, W_T, t, d_L)$$

This formulation demonstrates that increasing productivity through higher lifting frequency or load mass inevitably increases cumulative spinal loading, highlighting the productivity–ergonomic trade-off inherent in manually fed threshing systems.

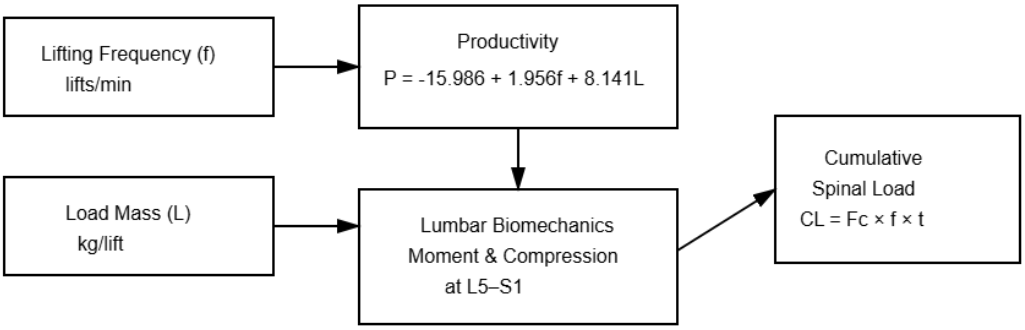

Fig.3: Vector Diagram Representing Integrated Biomechanical Productivity Model

Figure 3 presents an integrated biomechanical–productivity framework explaining how operational parameters of grain threshing influence both output performance and musculoskeletal loading on operators. The conceptual model links task variables, productivity outcomes, and biomechanical consequences, providing a systems-level explanation of the productivity–ergonomic trade-off observed in mechanized threshing operations.

An integrated biomechanical productivity model was developed to relate manual feeding parameters to both threshing output and spinal loading. Productivity increased as a function of lifting frequency and load mass, expressed as $P = -15.986 + 1.956f + 8.141l$. However, these same parameters also increased lumbar compression forces due to greater bending moments at the L5–S1 joint. When combined with the spinal moment equilibrium model, the results demonstrate that cumulative lumbar loading increases proportionally with lifting frequency, load mass, and horizontal load distance. The model therefore highlights a productivity–risk trade-off in manual threshing operations and indicates that ergonomic redesign strategies should focus on reducing the load moment arm through improved hopper height, feed chute design, and mechanical loading assistance.

This relationship explains why operators of elevated threshers often experience high musculoskeletal strain despite relatively moderate load masses.

IV. DISCUSSION AND CONCLUSION

The present study provides quantitative evidence that productivity improvements achieved through the use of locally fabricated stationary grain threshers are associated with increased biomechanical loading on machine operators. The regression analysis demonstrated that lifting frequency and load mass per lift explain a substantial proportion of the variability in threshing output ($R^2 = 0.974$), indicating that machine throughput in manually fed systems is largely determined by the rate and magnitude of manual material handling performed by the operator. Similar productivity relationships have been reported in agricultural and industrial manual handling tasks, where task output is strongly influenced by handling frequency and load magnitude.

However, increases in lifting frequency and load mass also elevate musculoskeletal loading. Biomechanical modelling conducted in this study indicates that repetitive feeding of grain into threshers generates substantial bending moments about the lumbosacral joint (L5–S1). These moments arise from the combined effects of trunk flexion and horizontal load displacement during feeding operations. Previous occupational biomechanics research has shown that even moderate loads can generate high spinal compression forces because trunk extensor muscles operate with a relatively small moment arm relative to the external load moment. Consequently, internal muscle forces must increase significantly to maintain postural equilibrium.

The postural risk assessment results further support these findings. REBA scores ranging from 8 to 11 and RULA scores between 6 and 7 indicate that the observed working postures fall within high-risk categories requiring ergonomic intervention. Similar postural risk levels have been reported in agricultural tasks such as crop harvesting, manual loading, and traditional threshing operations, where workers frequently adopt non-neutral trunk and shoulder postures. The trunk flexion angles observed in the present study exceeded 100° during lift initiation, indicating substantial deviation from neutral posture and increased spinal loading.

In addition to lumbar loading, the feeding process required considerable shoulder abduction and flexion as operators raised grain toward the hopper opening. Sustained shoulder elevation increases muscular demand on the deltoid and rotator cuff muscles and has been associated with increased risk of upper limb musculoskeletal disorders in repetitive manual handling tasks. When combined with high repetition rates, these biomechanical demands may lead to cumulative trauma over extended threshing periods.

The ergonomic risk evaluation using the NIOSH Revised Lifting Equation further confirms the hazardous nature of the task. Lifting Index values greater than one indicate that the lifting demands exceed recommended limits for a substantial portion of the working population. This finding suggests that prolonged exposure to the observed threshing tasks may increase the likelihood of developing work-related low back disorders.

A key contribution of this study is the integration of productivity modelling with biomechanical loading analysis. While previous agricultural ergonomics studies have often focused on observational risk assessment methods, the present work quantitatively links operational productivity to internal spinal loading. This integrated approach provides a more comprehensive framework for evaluating human–machine interaction in small-scale agricultural mechanization systems.

Overall, the results reveal a clear productivity–biomechanical exposure trade-off in smallholder mechanized threshing systems. Although locally fabricated threshers substantially improve grain processing efficiency compared with manual threshing, their present configuration requires repetitive lifting under non-neutral postures. Ergonomic redesign, such as optimizing hopper height, reducing horizontal reach distance, and incorporating gravity-assisted feeding mechanisms could significantly reduce cumulative spinal loading while maintaining or improving productivity. Integrating biomechanical modelling with ergonomic risk assessment therefore provides an effective framework for designing safer and more sustainable small-scale agricultural technologies.

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