

## Occupational Health Implications of High-frequency Whole-body Vibration Exposure in Mine Workers

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### ABSTRACT

Whole-body vibration (WBV) exposure is a significant occupational hazard in mining and heavy machinery operations, which can lead to long-term musculoskeletal and physiological disorders. This study investigates the magnitude of vibration exposure experienced by mine equipment operators under actual field conditions. Vibration measurements were conducted using a tri-axial accelerometer integrated with a customised data acquisition system. The signals were processed using appropriate filtering and frequency weighting techniques according to ISO 2631-1 standards. Key parameters such as root mean square (RMS) acceleration, daily exposure value A(8), and vibration dose value (VDV) were evaluated and compared with the Health Guidance Caution Zone (HGCZ) limits. The results show that the operators of dumpers and wheel loaders are exposed to vibration levels exceeding recommended threshold limits, particularly along the vertical (Z) axis,

thereby increasing the risk of musculoskeletal disorders. The findings highlight the need for effective vibration mitigation strategies, including ergonomic interventions, improved seat suspension systems, and optimised work schedules. This research offers useful guidance on how to evaluate and control whole-body vibration (WBV) exposure in mining settings.

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## INTRODUCTION

Whole-body vibration (WBV) is a significant occupational hazard in mining and heavy machinery operations for workers who are exposed to prolonged vibration during equipment operation. Continuous exposure to WBV has been associated with a wide range of health issues like musculoskeletal disorders (MSDs), lower back pain, cardiovascular disturbances, gastrointestinal complications, and neurological impairments (Chaudhary et al., 2022). Out of these issues, lower back disorders are the most frequently reported, especially among dumpers and heavy vehicle operators, due to sustained exposure to vertical vibration components during long working hours (Upadhyay et al., 2022a, 2022b). These health conditions affect worker well-being and lead to reduced productivity with increased occupational health burden in mining industries (Upadhyay et al., 2024).

The vibration frequencies in the range of 4-8 Hz coincide with the natural frequency of the human spine, leading to resonance effects that amplify biomechanical stress. Prolonged exposure to such frequencies can result in significant physiological changes like degeneration of spinal discs, impaired nerve function, and reduced peripheral blood circulation. Vibration-induced reduction in oxygen supply can adversely affect vital organs such as the brain, heart, kidneys, and muscles, leading to long-term health complications (Zhukova et al., 2022). These findings highlight the importance of understanding vibration exposure from a mechanical and biomedical view (Singh et al., 2018; Singh et al., 2019).

Many field-based and analytical studies have investigated WBV exposure in mining environments. For instance, case-control studies conducted on dumper operators have demonstrated a higher prevalence of musculoskeletal disorders compared to non-exposed groups, emphasising the direct relationship between WBV exposure and occupational health risks (Kumar et al., 2022). Similarly, large-scale investigations in Indian mining sectors have utilised questionnaire-based approaches such as the Nordic Musculoskeletal Questionnaire (NMQ), along with vibration measurements, to record discomfort and health impacts among operators (Mandal et al., 2013; Upadhyay et al., 2022a). These studies underline the necessity for regular monitoring, early diagnosis, and preventive strategies to mitigate the adverse effects of WBV exposure.

Advanced analytical techniques have been employed to enhance the understanding of WBV-related risks. Bayesian network models have been used to identify critical risk factors and predict the chance of developing musculoskeletal disorders among dumper operators (Atal et al., 2022). Experimental studies have focused on evaluating the transmissibility characteristics of vehicle seats using Seat Effective Amplitude Transmissibility (SEAT) analysis, which plays a key role in reducing vibration transmission to the human body (Sharma & Mandal, 2021). These investigations demonstrate that machine design and operational conditions significantly influence vibration exposure levels.

Studies in the agricultural and transport sectors provide valuable insights into vibration behaviour under various operating conditions. Experimental investigations using techniques such as Fast Fourier Transform (FFT) analysis have identified dominant vibration frequencies typically in the range of 0.8-4 Hz, which overlap with the natural frequencies of different parts of the human body (Singh et al., 2022). Parameters such as vehicle speed, load, terrain condition, and operator posture have been found to significantly affect vibration magnitude and exposure duration. These findings point out the importance of both time-domain and frequency-domain analysis in assessing WBV exposure (Harsha et al., 2014; Hildebrand et al., 2008; Liang & Chiang, 2008; Tiemessen et al., 2008).

Occupational safety initiatives have focused on incorporating Industry 4.0 technologies and machine learning for effective management of Whole-Body Vibration (WBV). For instance, Sakinala et al. (2024) successfully utilised machine learning techniques to predict WBV risk for heavy equipment operators in underground mining, while Vikram et al. (2024) demonstrated how varying operational parameters and rock types significantly influence exposure levels. The contemporary frameworks now leverage digital monitoring and decision-support systems to transition from reactive compliance to proactive ergonomic risk mitigation (Misita et al., 2024; Ullah et al., 2025). Cross-sectional evidence also confirms a high correlation between prolonged exposure to heavy machinery and chronic musculoskeletal disorders, which calls for these updated monitoring strategies (Mpendu et al., 2026).

Despite having extensive literature, most studies are conducted either under controlled laboratory environments or involve large datasets with complex modelling approaches (Basri & Griffin, 2013; Beard & Griffin, 2016; Bovenzi, 2015). There is a lack of field-based investigations that capture real-time vibration exposure under actual mining conditions using compact and customised data acquisition systems. Limited attention has been given to directly correlating measured vibration parameters with ISO 2631-1 Health Guidance Caution Zone (HGCZ) limits for practical and immediate risk assessment. This gap is particularly relevant in developing regions, where site-specific conditions and operational practices may significantly influence vibration exposure levels (Bandyopadhyay et al., 2012; Charles et al., 2018; Combs et al., 2018; Du et al., 2018).

Whole-body vibration (WBV) research (Nyarubeli et al. 2026) has focused on improving measurement accuracy and real-time exposure assessment using wearable sensor technologies and smart data acquisition systems. Studies published after 2022 have highlighted the use of wireless sensing devices and integrated monitoring frameworks for capturing field-level vibration data with higher reliability. Data-driven approaches, including machine learning-based risk classification and predictive modelling, are being used to assess occupational exposure and associated health risks (Darabont et al. 2025). Studies also emphasise the importance of combining experimental measurements with

ergonomic assessment to develop mitigation strategies in mining and heavy machinery environments (Kumar et al., 2001; Sorainen et al., 1998). These developments indicate a more precise, real-time, and application-oriented WBV assessment methodology, particularly under practical field conditions.

The present study aims to experimentally evaluate whole-body vibration exposure among mine equipment operators under real working conditions. The specific objectives of this study are to (i) measure vibration levels using a tri-axial accelerometer integrated with a customized data acquisition system, (ii) analyse vibration exposure in terms of root mean square (RMS) acceleration, daily exposure value A(8), and vibration dose value (VDV), and (iii) assess the associated health risks by comparing the measured values with ISO 2631-1 standards. The study provides practical insights into vibration exposure characteristics across different types of mining equipment and highlights the need for mitigation strategies, ergonomic improvements and exposure management practices.

## **EXPERIMENTAL METHODOLOGY**

The experimental methodology adopted to quantify whole-body vibration (WBV) exposure in mine equipment operators under real working conditions. The methodology covers the overall measurement plan (selection of operators and machines, sensor locations, and measurement duration), the instrumentation and calibration procedures, and the data acquisition settings used to capture tri-axial acceleration signals. The recorded vibration signals were then processed using ISO-recommended frequency-weighting and filtering to obtain exposure metrics such as RMS acceleration, daily exposure value A(8), vibration dose value (VDV), and crest factor. These parameters were compared with relevant ISO guideline limits to enable a consistent assessment of occupational health risk across different equipment categories.

### **Measurement Strategy**

Whole-body vibration (WBV) measurements were conducted under actual mining operating conditions to evaluate the vibration exposure experienced by equipment operators. Physical measurements were obtained from three critical locations: two seating interfaces (seat-operator contact on the back and buttocks) and the arm positions. These locations were selected to capture both whole-body and hand-arm vibration components during machine operation.

### **Instrumentation and Data Acquisition**

The vibration measurements were carried out using a tri-axial accelerometer integrated with a human vibration measurement system (Larson Davis HVM200). The device

is compliant with ISO 8041 standards and can measure whole-body and hand-arm vibration in accordance with ISO 2631 and ISO 5349 guidelines. The accelerometer has a measurement range suitable for low-frequency vibration (typically 0.5–80 Hz) and a sensitivity appropriate for human vibration analysis. The system supports three-channel simultaneous data acquisition along orthogonal axes (X, Y, and Z). The data acquisition was performed, ensuring adequate resolution for capturing both low-frequency WBV and transient vibration peaks. The acquired signals were stored and processed using the manufacturer-supported software interface.

### **Calibration Procedure**

Before data collection, the vibration measurement system was calibrated using standard calibration procedures to ensure measurement accuracy and reliability. The calibration was performed in accordance with manufacturer guidelines, and sensor alignment was verified to match the human body coordinate system specified in ISO 2631-1. This ensures that the measured vibration components accurately represent the directional exposure experienced by the operator.

### **Data Collection Procedure**

Vibration data were recorded under normal working conditions of mining equipment. The measurements were conducted continuously for a specific duration while the operators performed their routine tasks. Appropriate care was taken to ensure that sensor placement did not interfere with the operator's activity or machine operation. Each measurement was conducted for a duration of 20 minutes, and the data were recorded continuously with an averaging interval of 5 seconds to capture variations in vibration levels during operation. The recorded signals represent acceleration as a function of time for each axis. These time-domain signals were further processed to evaluate vibration exposure parameters.

### **Signal Processing and Analysis**

The acquired vibration signals were processed using standard procedures recommended in ISO 2631-1. The raw acceleration signals were filtered and frequency-weighted to account for human sensitivity to different vibration frequencies. The processed signals were then used to compute key vibration exposure parameters. A band-limited frequency weighting filter was applied to the raw acceleration signals to account for human sensitivity to vibration across different frequency ranges. The processed signals were used to compute RMS acceleration,  $A(8)$  and VDV values.

## Evaluation Parameters

### Root Mean Square (RMS) Acceleration

The values of acceleration as a function of time are obtained from the vibration measurements conducted in the field. Subsequently, the computations are executed utilising the subsequent formulas, Equation 1. RMS value of the acceleration can be calculated by:

$$\text{rms}_{\text{ws}} = \left[ \frac{1}{T} \int_0^T a_w^2(t) dt \right]^{1/2} \quad [1]$$

### Daily Exposure Value A(8)

In general, A (8) Equation 2 is the daily exposure value for 8 hours of work. The Daily Exposure Action Value (EAV) is a measure used to evaluate the magnitude of whole-body vibration (WBV) exposure that a person undergoes throughout a typical workday, usually lasting 8 hours. It acts as a limit that determines when special measures should be implemented to reduce the impact of vibration. EAV is quantified using the root mean square (RMS) acceleration, often denoted in units of metres per second squared (m/s<sup>2</sup>).

$$A(8)_S = k_S \text{rms}_{\text{ws}} \sqrt{\frac{T_{\text{exp}}}{T_0}} \quad [2]$$

where ‘s’ represents the axis along which the measurement is carried out, rmsws-weighted RMS acceleration, T - signal duration, a<sub>w</sub> - weighted acceleration, A(8)<sub>S</sub> - Daily exposure value, k<sub>S</sub> - weighted factor, T<sub>exp</sub> = Time of exposure, T<sub>0</sub> = 8 hours. And can be represented by another relationship as mentioned in Equation 3,

$$A(8)_S = a_w \sqrt{\frac{T_{\text{exp}}}{T_{\text{ref}}}} \quad [3]$$

Where, a<sub>w</sub> is the RMS acceleration value (in m/s<sup>2</sup>) of the vibration. T<sub>exp</sub> is the total exposure duration during the workday. T<sub>ref</sub> is the reference duration (8 hours or 28,800 seconds).

### Vibration Dose Value (VDV)

The vibration dose value can be calculated as per Equation 4.

$$\text{VDV}_{\text{ws}} = \left[ \int_0^T a_w^4(t) dt \right]^{1/4} \quad [4]$$

where ‘s’ represents the axis along which the measurement is carried out,  $VDV_{ws}$  – weighted vibrational dose value,  $T$  – signal duration,  $a_w$  – weighted acceleration.

$$VDV_s = k_s VDV_{ws} \sqrt{\frac{T_{exp}}{T_{meas}}} \quad [5]$$

(or)

$$VDV_s = k_s rms_{ws} T^{0.25} \quad [6]$$

where ‘s’ represents the axis along which the measurement is carried out,  $rms_{ws}$  – weighted RMS acceleration,  $T$  – signal duration,  $VDV_s$  - Vibration dose value as per Equations 5 and 6,  $k_s$  - weighted factor,  $T_{exp}$  - daily duration of vibration exposure,  $T_{meas}$  - duration of measurement taken.

### Crest Factor

Crest factor can be calculated as per Equation 7,

$$\text{Crest factor} = \frac{\text{Peak value}}{\text{RMS value}} \quad [7]$$

If the crest factor  $> 9$ , then the VDV value must also be considered along with the A(8) to conclude vibration exposure.

### Assessment Based on ISO Standards

The calculated vibration parameters were evaluated in accordance with ISO 2631-1 guidelines. The obtained values of A(8) and VDV were compared with the Health Guidance Caution Zone (HGCZ) limits to determine the level of risk associated with vibration exposure.

### Equipment Configuration and Sensors Placement

Whole-body vibration (WBV) measurements were carried out using a seat pad sensor integrated with a tri-axial accelerometer. The sensor was mounted on a rubber adapter and placed at the seat–operator interface to capture vibration transmitted to the human body during machine operation. The operator was seated directly on the sensor pad to ensure accurate transmission of vibration signals.

In addition to WBV measurements, hand-arm vibration was recorded using accelerometers mounted on specialised adapters positioned on the operator’s hand interface

(handle or grip surface). Care was taken to ensure that sensor placement did not interfere with normal machine operation while maintaining firm contact for reliable data acquisition.

The sensors were aligned according to the standard human body coordinate system, where the vertical direction (Z-axis) corresponds to the spinal axis of the operator. Proper alignment ensures that vibration components are accurately captured in all three orthogonal directions (X, Y, and Z), as illustrated in Figure 1.

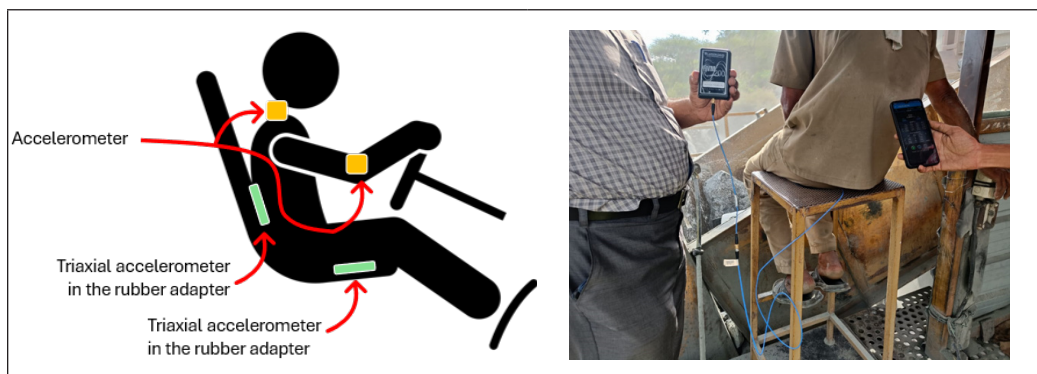


Figure 1. Freebody diagram of the measuring system and placement of sensors, (b) WBV measurement setup for the crusher operator

## Instrument Description

The vibration measurements were performed using the Larson Davis HVM200 Human Vibration Meter, a portable and robust device designed for evaluating human exposure to vibration. The instrument is a three-channel system compliant with ISO 8041:2005 standards and supports measurements in accordance with ISO 2631 (whole-body vibration) and ISO 5349 (hand-arm vibration).

The device is equipped with integrated Wi-Fi capability for real-time data transmission and monitoring. It incorporates built-in frequency weighting filters and signal processing capabilities required for accurate assessment of human vibration exposure. The system is also compatible with standard occupational health guidelines, including the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs) and European Directive 2002/44/EC.

## Applicable Standards

The evaluation of vibration exposure in this study is based on the guidelines provided by ISO 2631-1, which defines methods for quantifying and assessing whole-body vibration in occupational environments. The standard considers key parameters such as vibration magnitude, frequency, and exposure duration to establish acceptable exposure limits.

According to ISO 2631-1, the human body is particularly sensitive to vertical vibration in the frequency range of 4-8 Hz, which coincides with the natural frequency of the spine. Prolonged exposure within this range can lead to resonance effects and increased health risks.

The ISO standards also provide frequency weighting factors for different axes of vibration, enabling a more accurate assessment of human response to vibration. These weighting factors are used in the calculation of RMS acceleration,  $A(8)$ , and VDV values, as presented in Table 1.

### **Human Body Coordinate System**

The measurement of vibration exposure requires proper alignment of sensors according to standardised coordinate systems. For whole-body vibration, the ISO 2631 coordinate system is used, where the X-axis represents the fore-and-aft direction, the Y-axis represents the lateral direction, and the Z-axis represents the vertical direction aligned with the spine.

Sensors for WBV measurements are typically placed at the seat interface for seated operators, while additional placements such as the backrest or foot platform may be used depending on the application. For hand-arm vibration measurements, ISO 5349 guidelines are followed, where sensors are positioned on the hand, wrist, or tool interface to capture transmitted vibration.

Proper sensor placement is essential to ensure consistency, accuracy, and comparability of vibration measurements across different studies. The coordinate system used in this study is illustrated in Figure 2.

### **Standard Operating Procedure for Vibration Measurement**

Along with accurate measurement of vibration magnitude, precise estimation of exposure duration is essential for reliable assessment of human vibration exposure. In this study, a structured standard operating procedure (SOP) was adopted to ensure consistency in data acquisition and analysis.

### **Measurement Approaches**

Two standard approaches are generally followed for evaluating vibration exposure:

#### **Task-Based Measurement Approach**

Vibration measurements are recorded only during periods when the operator is actively exposed to vibration. Each measurement corresponds to a specific machine operation or working condition. The total exposure duration is calculated by summing only the active vibration periods. This approach provides an accurate characterisation of vibration levels for individual tasks; however, it requires detailed observation and time tracking of work activities.

Table 1  
 ISO standard guidance on values of the Caution Zone for a human

Whole Body Vibration (WBV)	ISO 2631 – 1	
	Daily Exposure Value (m/s <sup>2</sup> )	Vibration Dose Value (m/s <sup>1.75</sup> )
Exposure Action Value	0.43	8.5
Exposure Limit Value	0.86	17
Hand-arm vibration (HAV)	ISO 5349 – 1	
Exposure Action Value	2.5	0.4
Exposure Limit Value	5	0.8

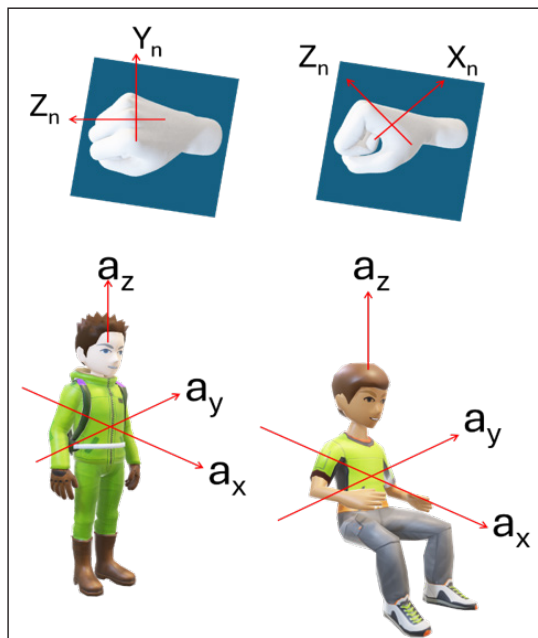


Figure 2. Coordinate system of the hand and whole body according to ISO standards for the placement of the sensor

### Full-shift Measurement Approach

A continuous measurement is carried out over an extended duration covering multiple operating conditions, including machine operation, idle periods, and breaks. The resulting data represents an average exposure over the entire work cycle. While this method simplifies data collection, it may not capture variations associated with specific tasks or operating conditions.

In the present study, an appropriate combination of these approaches was adopted to ensure both accuracy and practical feasibility of measurements.

### Measurement and Signal Processing Procedure

The vibration magnitude was primarily quantified in terms of acceleration, as it is the most widely accepted parameter for evaluating human vibration exposure. The accelerometer provides a signal proportional to acceleration, which is further processed to obtain meaningful exposure parameters.

The acquired signals were subjected to digital filtering to remove noise and isolate the frequency range relevant to human vibration exposure. Frequency weighting was applied separately for each axis (X, Y, and Z) to account for the directional sensitivity of the human body to vibration, as specified in ISO standards.

The processed signals were then used to compute vibration parameters such as RMS acceleration, A(8), and VDV, which provide measures of continuous and transient vibration exposure.

### Data Acquisition and Software Tools

Data acquisition and processing were carried out using the Larson Davis HVM200 system along with its dedicated software tools. The G4 LD Utility software was used for post-processing and analysis of recorded vibration data in a desktop environment. The LD Atlas mobile application was used for real-time monitoring and data acquisition during field measurements.

These tools enabled efficient data collection, storage, and analysis, ensuring accuracy and reliability of the vibration exposure assessment, which supports the research workflow illustrated in Figure 3.

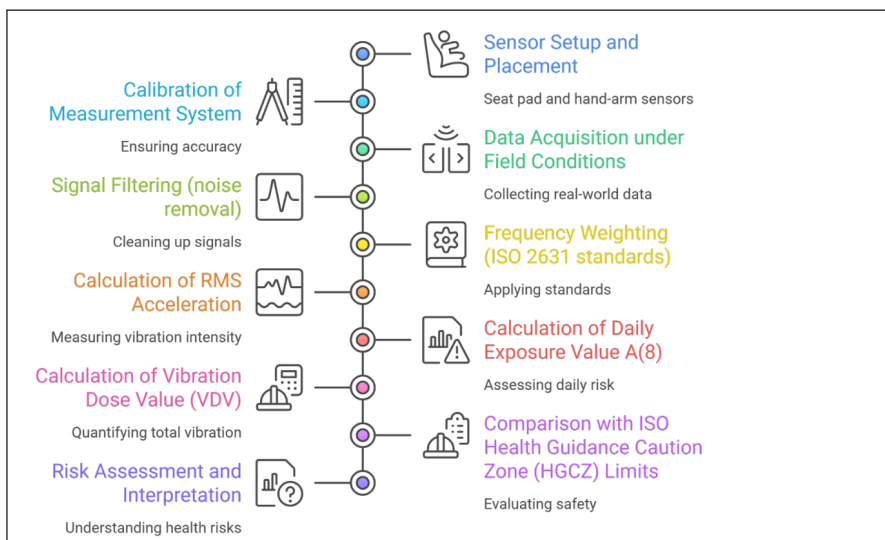


Figure 3. Workflow

## RESULTS AND DISCUSSION

### Measurement Overview and Data Organisation

Whole-body vibration (WBV) measurements were carried out on four operators handling different categories of mining equipment, namely crushers, dumpers, and wheel loaders. The data acquisition system was configured with a storage interval of 1 second and an averaging interval of 5 seconds to capture both steady-state and transient vibration behaviour. Each measurement was carried out for a duration of 20 minutes under normal working conditions to ensure consistency across all observations.

A structured questionnaire was used to collect operator-specific details, including age, height, weight, body mass index (BMI), years of experience, and daily working hours. These parameters were considered important in understanding the influence of individual characteristics on vibration exposure and associated health risks. The collected data were systematically organised and presented in tabular form, categorised based on the type of equipment operated and the operator profile. Table 2 presents the details of the operators, while Table 3 summarises the measured vibration parameters used for further analysis.

The experiment involved four operators: Operator 1 and Operator 2 (crusher operators), Operator 3 (dumper operator), and Operator 4 (wheel loader operator). This categorisation enabled comparison of vibration exposure across different types of mining equipment and operational conditions.

Owing to the exploratory nature of the study and the limited number of operators available under actual field conditions, the analysis was primarily descriptive. Comparative evaluation was performed using RMS acceleration, A(8), VDV, and crest factor values across equipment categories. The observed differences were interpreted with reference to ISO 2631-1 Health Guidance Caution Zone limits.

### Vibration Magnitude Analysis

The measured vibration data across the three orthogonal axes (X, Y, and Z) provide important insights into the exposure levels experienced by different operators. It is observed that the vertical (Z-axis) component of vibration is dominant in most cases, which aligns with the typical transmission of vibration through the seat operator interface during machine operation.

Operators 1 and 2, associated with crusher operations, exhibit relatively low vibration levels across all axes. The root mean square (RMS) acceleration values are below  $0.1 \text{ m/s}^2$ , and the corresponding A(8) values remain within safe limits. Similarly, the vibration dose values (VDV) for these operators are below  $0.5 \text{ m/s}^{1.75}$ , indicating minimal exposure and low health risk under current operating conditions. These findings can be attributed to the relatively stationary nature of crusher operations and shorter exposure durations.

Table 2  
Physical and technical information about the studied human

Personal Factor	Operator 1	Operator 2	Operator 3	Operator 4
Machine	Crusher	Crusher	Dumper	Wheel loader
Age (year)	53	55	31	29
Weight (kg)	55	65	60	75
Height (m)	1.8	1.65	1.7	1.65
Experience (year)	25	32	8	12
Body Mass Index (kg/m <sup>2</sup> )	16.97	23.87	20.76	27.55
Working hours/day (hour)	4	4	6	8

Table 3  
Various data were measured for different operators in Mines

Indicators	X- axis				Y- axis				Z- axis			
	1	2	3	4	1	2	3	4	1	2	3	4
$a_{rms}$ (m/s <sup>2</sup> )	0.0623	0.0406	0.7092	0.1241	0.0806	0.0615	1.0035	0.1461	0.7884	0.6642	1.5146	1.2773
$a_{peak}$ (m/s <sup>2</sup> )	0.4445	0.2536	3.6708	0.7437	0.5829	0.3697	5.7151	0.8960	6.7202	5.7254	8.5772	8.3764
Crest factor	7.1347	6.2473	5.1760	5.9928	7.2325	6.0123	5.6952	6.1326	8.5239	8.6200	5.6630	6.6057
A(8) (m/s <sup>2</sup> )	0.0617	0.0402	0.8599	0.1737	0.0798	0.0609	1.2167	0.2045	0.5575	0.4697	1.3317	1.2773
VDV(m/s <sup>1.75</sup> )	0.2593	0.1689	5.7288	1.5653	0.3271	0.2496	8.1371	1.8380	2.2376	1.8852	8.8005	11.211

Operators 3 and 4, associated with dumper and wheel loader operations, exhibit significantly higher vibration exposure. Operator 3 recorded the highest RMS acceleration along the Z-axis ( $1.5146 \text{ m/s}^2$ ), with an A(8) value of  $1.3317 \text{ m/s}^2$  and a VDV of  $8.8005 \text{ m/s}^{1.75}$ . Similarly, Operator 4 exhibited an A(8) value of  $1.2773 \text{ m/s}^2$  and a VDV of  $11.2108 \text{ m/s}^{1.75}$ , indicating severe vibration exposure. These elevated values are primarily due to continuous machine movement, uneven terrain, and longer operating durations.

### **Comparison with ISO Standards**

The measured vibration parameters were evaluated based on the ISO 2631-1 Health Guidance Caution Zone (HGCZ). As summarised in Table 1, the whole-body vibration exposure action value is  $0.43 \text{ m/s}^2$  for an 8-hour working period; exceeding this threshold necessitates the implementation of control measures to reduce vibration exposure.

The results indicate that crusher operators (Operators 1 and 2) operate well below the EAV, suggesting a low risk of immediate health effects. However, dumper and wheel loader operators (Operators 3 and 4) significantly exceed this threshold, placing them within or above the upper limit of the HGCZ. This indicates a high probability of developing vibration-related health disorders if exposure continues over extended periods.

### **Crest Factor and Transient Effects**

The crest factor values for all operators were found to be greater than 6, indicating the presence of transient shocks or peak accelerations during machine operation. Although the crest factor values are below the critical limit of 9, the repeated occurrence of such transient loads can contribute to cumulative stress on the musculoskeletal system.

In such scenarios, reliance solely on RMS-based metrics may underestimate the severity of exposure. Therefore, the inclusion of VDV provides a more comprehensive evaluation of vibration exposure, particularly for conditions involving intermittent shocks and uneven operating surfaces.

### **Health Risk Assessment**

The quantitative analysis of vibration data highlights significant differences in occupational exposure and associated health risks among the operators. Operators 3 and 4 are subjected to high levels of vibration, particularly along the vertical axis, which is closely associated with spinal loading. Prolonged exposure to A(8) values exceeding  $1.2 \text{ m/s}^2$  can lead to serious health issues such as lower back pain, spinal disc degeneration, and circulatory disturbances in the lumbar and pelvic regions.

The elevated VDV values further indicate cumulative exposure to vibration energy, increasing the likelihood of soft tissue damage and long-term musculoskeletal disorders.

Factors such as operator posture, machine design, terrain conditions, and individual characteristics such as BMI and age may amplify these effects.

Although the vibration levels for Operators 1 and 2 are within acceptable limits, long-term exposure, even at moderate levels, may contribute to cumulative health risks. Therefore, continuous monitoring and preventive measures are recommended for all operators regardless of current exposure levels.

### **Implications and Mitigation Strategies**

The findings of this study emphasise the need for effective vibration mitigation strategies in mining environments. Engineering controls, such as improved seat suspension systems, vibration isolation mechanisms, and optimised vehicle design, can significantly reduce vibration transmission to the operator.

Administrative measures, including job rotation, reduced exposure duration, and scheduled rest periods, can further minimise the risk of vibration-related health issues. Periodic medical examinations and ergonomic training programs are essential for early detection and prevention of musculoskeletal disorders.

The integration of advanced monitoring systems, wearable health monitoring technologies, including real-time vibration tracking and data-driven exposure analysis, can enhance occupational safety and support informed decision-making. Without timely intervention, prolonged exposure to high vibration levels may lead to chronic health conditions, reduced productivity, and increased occupational health burden.

### **CONCLUSION**

This study investigated the significance of whole-body vibration (WBV) exposure on the health of mine workers operating different categories of heavy machinery. Experimental measurements conducted under real field conditions provided valuable insights into the variation of vibration exposure across different types of equipment and operators. The analysis revealed clear differences in vibration magnitude and associated risk levels depending on both operational conditions and individual characteristics.

The results indicate that crusher operators (Operators 1 and 2) experience vibration levels within the acceptable limits specified by ISO 2631-1, suggesting low immediate health risks. However, prolonged exposure over several years may still contribute to cumulative musculoskeletal effects, highlighting the need for continuous monitoring and preventive health assessment. In contrast, dumper and wheel loader operators (Operators 3 and 4) were exposed to significantly higher vibration levels, particularly along the vertical (Z) axis. The recorded A(8) and VDV values exceed the Health Guidance Caution Zone (HGCZ), indicating a high probability of developing vibration-induced disorders such as lower back pain, spinal degeneration, and associated physiological complications.

These findings emphasise the urgent need for implementing vibration mitigation strategies in mining environments. Engineering interventions such as improved seat suspension systems, vibration isolation mechanisms, and optimised vehicle design can significantly reduce vibration transmission. Administrative measures, including reduced exposure duration, job rotation, and structured work-rest cycles, are essential to minimise occupational risk. Periodic medical examinations and ergonomic awareness programs should also be incorporated to identify early symptoms and prevent long-term health deterioration.

The integration of advanced technologies such as real-time vibration monitoring, artificial intelligence-based exposure tracking, and predictive analytics can enhance early risk detection and support data-driven decision-making for occupational safety. Overall, this study highlights that without appropriate preventive measures, operators exposed to high-magnitude vibrations are at a significant risk of developing chronic musculoskeletal and neurological disorders. Therefore, long-term vibration control strategies and health-focused interventions are critical for ensuring sustainable and safe mining operations.

A limitation of the present study is the relatively small number of operators and equipment categories investigated. Future studies involving larger operator populations and additional mining equipment are recommended to improve the generalisability of the findings.

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