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Individual Determinants of Musculoskeletal Disorder Risk Among Dumper Operators in Coal and Iron Ore Mines: A Cross- Sectional Study

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Abstract

Musculoskeletal Disorders (MSD) associated with exposure to Whole-Body Vibration (WBV) are a widespread occupational health problem among dumper operators in mining operations worldwide. WBV is a well-recognised workplace hazard that contributes to chronic pain and long-term health complications. This study assessed WBV exposure among dumper operators working under different mining conditions and examined its association with factors that have received limited attention in earlier studies. In addition to vibration exposure, the influence of seat design, machine age, load tonnage, and dumper operating speed on WBV levels was investigated. Data were collected using the Nordic Musculoskeletal Questionnaire (NMQ) and through face-to-face interviews. A total of 112 dumper operators from coal and iron ore mines participated in the study. The results showed that operators in coal mines were exposed to higher vibration levels than those in iron ore mines. The mean vertical Root Mean Square (RMS) acceleration was 0.65m s^{-2} in coal mines compared to 0.48m s^{-2} in iron ore mines, while the mean daily exposure A(8) was 0.63m s^{-2} and 0.48m s^{-2}, respectively. Musculoskeletal pain was reported by 43% of coal mine operators and 46% of iron ore mine operators, with lower back pain being the most prevalent complaint in both groups. Increasing age (>45 years) was significantly associated with MSD in both coal (adjusted OR = 3.09) and iron ore mines (adjusted OR = 2.54). High WBV exposure (>0.9 m s^{-2}) showed a significant association with MSD in iron ore mines (adjusted OR = 4.68), whereas obesity (Body Mass Index, BMI >25 kg m^{-2}) was a significant risk factor in coal mines (adjusted OR = 6.19). Poor seat compatibility significantly increased the odds of MSD in iron ore mines (adjusted OR = 2.64). Anthropometric assessment revealed notable mismatches between seat dimensions and operator body measurements in both mining environments. This study highlighted that higher WBV exposure among coal mine operators and a high prevalence of lower back pain in both mining environments. Furthermore, MSDs were significantly related to age, WBV exposure level, body mass index, and seat compatibility, underscoring the importance of ergonomic interventions and vibration control in surface mining operations. Regular evaluation and reduction of both MSD and WBV exposure are essential.

Keywords: *Ergonomics, Health Hazard, Musculoskeletal Disorders, Surface Mining, WBV Exposure*

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1. Introduction

A substantial proportion of the global workforce is routinely exposed to WBV in the course of their occupational activities[1]. In the United States alone, nearly four million workers—approximately 2.7% of the total workforce—experience daily WBV exposure[2-5]. A large body of epidemiological evidence has established a strong relationship between WBV exposure and the occurrence of MSD. National injury statistics further indicate that MSD account for roughly one-third of all reported work-related injuries and illnesses in a given year[1]. Early manifestations of WBV exposure, such as discomfort or pain in the lower back, are frequently overlooked, which can progressively result in more severe and chronic health conditions[6-10]. These problems

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are particularly common among workers who perform their duties in a seated posture for prolonged periods. In addition to musculoskeletal effects, WBV exposure has also been linked to adverse respiratory, digestive, and reproductive health outcomes[6-7]. Since WBV does not target a single organ system, it is often underestimated as an occupational hazard, despite its well-documented negative impact on worker health and performance.

Mining remains a critical driver of industrial and economic development worldwide. However, it places considerable physical demands on the workforce. The increasing mechanisation of mining operations has led to widespread use of heavy equipment such as drills, shovels, dozers, and haulage dumpers. Among these, dumpers play a central role in material transportation and are operated for extended durations, resulting in continuous WBV exposure for operators. Several investigations have quantified WBV levels in haul trucks of varying capacities and operating conditions. While some studies have reported vibration magnitudes within the limits prescribed by ISO 2631-1:1997/Amd-2010, others have documented exposure levels that exceed recommended thresholds, particularly in the vertical direction. The findings across studies reveal substantial variations in WBV exposure, influenced by equipment type, operating conditions, and site characteristics. Importantly, elevated WBV levels have been associated with a higher prevalence of lower back pain and other MSD among haul truck operators, emphasising the occupational health risks faced by this group[11-20].

Although the adverse health effects of prolonged WBV exposure are well recognised, limited research has systematically examined the contributing factors that govern WBV exposure in mining environments. At present, evidence remains insufficient to conclusively determine whether dumpers operating under different surface mining conditions consistently expose operators to hazardous vibration levels. Consequently, a detailed assessment of the determinants of WBV exposure is required before effective control strategies and preventive measures can be developed. Large-scale studies conducted across multiple mining sites are particularly important, as they can capture exposure patterns and health risks that may vary with mining conditions and operational practices[11-20].

Previous studies have mostly examined WBV exposure in relation to equipment and work practices, often based on limited mine locations or small sample sizes. The influence of individual factors, such as age, work experience, and personal health, on MSD risk among dumper operators has been less explored. This study addresses this gap by assessing MSD prevalence and analysing how these individual factors contribute to risk across both coal and iron ore mines, providing a broader and more comparative understanding than previous research. To overcome this gap, the present study examines WBV exposure and MSD prevalence among dumper operators working in two distinct mining contexts—coal mines and iron ore mines. The objectives of this study were to determine the prevalence of musculoskeletal disorders among dumper operators working in coal and iron ore mines, to identify key individual determinants associated with musculoskeletal disorder risk, and to compare the influence of these determinants between operators employed in coal and iron ore mining. The analysis is based on direct WBV measurements and musculoskeletal health data obtained using the standardised NMQ.

2. Methods

2.1 Study Site

The investigation was conducted in selected coal and iron ore mining operations situated in the eastern region of India. Participants were randomly recruited from the workforce and included only if they were employed as full-time dumper operators with at least one year of operational driving experience.

Data acquisition was performed during routine work shifts without altering normal operational practices, thereby ensuring that the recorded WBV exposures represented actual field conditions. All operators provided written informed consent before participation. The study design and procedures were reviewed and approved by the Indian Institute of Technology Kharagpur, in compliance with ethical standards for research involving human participants.

Dumper operators typically worked approximately 300 days per year and were allotted a uniform rest break of 45 minutes during each shift. Work schedules, rest

periods, and exposure durations were consistent across all participants. Furthermore, all operators were assigned to operate the same category of heavy-duty dumpers, which minimised variability arising from differences in equipment type or operational conditions. This standardisation in machinery and work routine facilitated a controlled assessment of WBV exposure and associated risk factors.

In the present study, the coal mining operations primarily supplied fuel to integrated thermal power stations, whereas the iron ore mines served as raw material sources for integrated steel production facilities.

2.2 Data Collection

The dumper operators in both mining environments were instructed to carry out their routine job activities under normal working conditions. Each operator remained seated in the dumper for approximately eight hours per shift, excluding a scheduled rest break of 30 minutes. Their primary task involved transporting coal, iron ore, and overburden material from the loading area to designated dumping locations within the mine for subsequent processing. Ethical clearance for the study was obtained from the institutional ethics committee. Before participation, all operators received a clear explanation of the study objectives and procedures and provided informed consent.

The study included a total of 112 dumper operators, comprising 47 operators from coal mines and 65 from iron ore mines. Operators' dates of birth were verified using official identity documents, whereas body weight and height were measured, and work experience was recorded from the office logbook. Work experience was defined as the duration for which an operator had been engaged in dumper operation in their current role. Static anthropometric measurements—including standing height, erect sitting height, buttock–popliteal length, popliteal height, and buttock width—were recorded using a Martin-type anthropometer following standard anthropometric measurement procedures.

Information on MSD prevalence was collected using the NMQ, which captures self-reported discomfort across specific body regions. In addition to MSD-related data, the questionnaire gathered demographic information and job-related characteristics. Investigators assisted participants during questionnaire administration to ensure clarity and accurate responses, thereby minimising potential misunderstanding.

During the field investigation, seat dimensions were measured and compared with the operators' anthropometric characteristics to assess ergonomic compatibility. Operators' sitting heights were measured using an anthropometer, while seat backrest heights were measured using a measuring tape. Seat compatibility was evaluated by comparing the seated height of operators with the corresponding backrest height of the dumper seats. Seats were identified as incompatible when the operator's sitting height exceeded the backrest height. Additionally, on-site observations revealed that the dumper seats were fitted with inadequate suspension systems, lacked vertical adjustment mechanisms, and had firm or damaged cushioning. Seats exhibiting inappropriate height, insufficient suspension, absence of adjustment features, and rigid or worn cushions were collectively categorised as poorly designed.

In the present investigation, vibration exposure was assessed for 18 dumpers operated by 47 drivers in coal mines and 17 dumpers operated by 65 drivers in iron ore mines. These dumpers were engaged in multiple haulage operations, including the transportation of extracted minerals, overburden, and waste material across different mining zones. To ensure uniformity, all dumpers included in the study were of identical load capacity and shared the same seat design specifications. During operations, all operators consistently used seat belts. The seating system consisted of foam-based seat cushions with a uniform thickness of 10cm.

In coal mines, dumpers were primarily used to transport overburden to both internal and external dumping sites, while coal was unloaded at in-pit bunkers. For in-pit dumping and coal unloading operations, the hauling distance was relatively short, generally not exceeding 500m. In contrast, the haul distance for external dumping operations ranged from approximately 1.1 to 2.0km. In iron ore mines, dumpers transported ore to the crusher plant, and overburden material was deposited at designated subgrade waste dump sites. Information regarding the manufacturer, operational age, and usage history of the dumpers was obtained from the mine's mechanical department.



Figure 1. Norsonic vibration meter.

WBV exposure was measured using an instrumented hard rubber disc fitted with piezoelectric accelerometers having a sensitivity of 100 mV/g (Figure 1). The disc was placed at the interface between the operator and the seat, specifically between the top surface of the seat cushion and the operator's buttocks. Vibration data were recorded on 8 GB flash memory cards and analysed using NorVibraTest software. Data acquisition was performed at a sampling frequency of 2500Hz with a 16-bit resolution. The vibration analyser provided numerical outputs, which were extracted for subsequent processing and comparison with the health guidance values specified in ISO 2631-1:1997/Amd. 1:2010 standards[21-22].

2.3 Statistical Analysis

Statistical analysis was carried out to describe WBV exposure, operator characteristics, ergonomic factors, and their association with MSD among dumper operators in coal and iron ore mines. Descriptive statistics were used to summarise WBV exposure parameters, including frequency-weighted RMS acceleration, 8-hour daily exposure, A(8), Vibration Dose Values (VDV), and crest factors, and are presented as mean and standard deviation. Categorical variables such as age group, BMI category, seat compatibility, experience level, and MSD prevalence were expressed as frequencies and percentages. Comparisons between coal and iron ore mine operators for categorical variables were performed using the chi-square test, and statistical significance was assessed at a p-value < 0.05. Ergonomic compatibility between seat dimensions and operator anthropometry was evaluated by comparing measured seat parameters with anthropometric percentiles to identify potential mismatches. To examine factors associated with MSDs, binary logistic regression analysis was conducted separately for coal and iron ore mine operators. Crude Odds Ratios (COR) with 95% Confidence Intervals (CIs) were first estimated for age, WBV exposure level, BMI, and seat compatibility. Adjusted Odds Ratios (AOR) were then calculated by including relevant covariates in multivariable models to control for potential confounding effects. The strength and direction of associations were interpreted based on odds ratios and corresponding confidence intervals. All statistical tests were two-sided with a significance level of $p < 0.05$. The 95% CI was chosen. The statistical analyses were carried out using the Statistical Package for Social Sciences (SPSS) software package, version 25.0.

3. Results

Table 1 presents the descriptive statistics of WBV exposure among dumper operators in coal and iron ore mines. Operators in coal mines experienced consistently higher frequency-weighted RMS acceleration across all axes compared to those in iron ore mines (Figure 2). The mean vertical vibration (a_{wz}) was notably higher in coal mines (0.65m s^{-2}) than in iron ore mines (0.48m s^{-2}). A similar trend was observed for daily RMS exposure, A(8), with coal mine operators recording a higher mean value (0.63m s^{-2}) than iron ore mine operators (0.48m s^{-2}). It is about 20.6% more than the prescribed EAV of 0.5m s^{-2} as per the new Coal Mine Regulation 2026. Vibration Dose Values (VDV) also indicated greater operator exposure in coal mines. The mean daily VDV(8) was 13.85 m $s^{-1.75}$ for coal mine operators compared to 10.98m $s^{-1.75}$ for iron ore mine operators. Crest Factor (CF) values exceeded 9 in all axes for both mining environments, with iron ore mines showing higher crest factors, particularly along the vertical axis (CF_z = 15.09), suggesting a greater contribution of impulsive shocks.

The individual characteristics of dumper operators are summarised in Table 2. Musculoskeletal pain was reported by 43% of coal mine operators and 46% of iron ore mine operators, with no statistically significant difference between the groups (p = 0.427). The age distribution was comparable across mining types, although a higher

Table 1. Comparisons of whole-body vibration exposure levels of dumper operators in coal and iron ore mines

Parameters	Coal Mines (n=47)					Iron Ore Mines (n=65)				
	Mean	Median	SD	Skewness	Kurtosis	Mean	Median	SD	Skewness	Kurtosis
Frequency-weighted RMS acceleration ($m\ s^{-2}$)										
x-axis (a_{wx})	0.40	0.39	0.08	0.07	-0.59	0.21	0.20	0.032	0.44	0.21
y-axis (a_{wy})	0.35	0.36	0.05	-0.09	-0.66	0.21	0.21	0.026	0.09	-0.72
z-axis (a_{wz})	0.65	0.64	0.12	0.14	-0.21	0.48	0.47	0.10	0.81	0.97
Daily RMS Exposure, A(8)	0.63	0.63	0.12	0.14	-0.21	0.48	0.47	0.10	0.81	0.97
Vibration Dose Value ($m\ s^{-1.75}$)										
x-axis (VDV_x)	3.26	3.26	0.60	0.66	0.17	2.37	2.36	0.37	0.33	0.06
y-axis (VDV_y)	2.81	2.70	0.50	1.32	2.78	2.34	2.37	0.29	-0.12	-0.53
z-axis (VDV_z),	5.48	5.39	1.03	0.62	-0.24	5.24	5.14	1.22	1.07	1.83
Daily VDV Value, VDV(8)	13.85	14.54	2.89	0.24	-0.21	10.98	10.56	2.25	1.11	1.33
Crest Factor										
CF_x	8.99	8.75	2.01	0.69	0.59	11.11	10.60	1.89	1.17	2.60
CF_y	8.12	7.53	2.35	2.39	0.35	10.46	10.47	1.57	-0.18	-0.10
CF_z	11.31	11.14	1.93	0.79	0.61	15.09	14.16	4.80	1.08	0.78

Abbreviations: n = number of subjects; SD = standard deviation

proportion of coal mine operators belonged to the older age group (>45 years). Seat incompatibility was more prevalent among iron ore mine operators (57%) than coal mine operators (47%), though the difference was not statistically significant (p = 0.193). Experience levels and BMI categories were similarly distributed between the two groups, with nearly half of the operators in both mines having more than 15 years of experience.

Table 3 compares seat dimensions with anthropometric measurements of dumper operators. Several mismatches were observed between seat dimensions and operator anthropometry in both mining environments. In particular, the seat pan length and width did not adequately accommodate operators at the lower and upper percentiles of buttock–popliteal length and buttock width. Seat height also showed variability, with minimum and maximum values extending beyond the recommended anthropometric range, indicating potential ergonomic inadequacies in seat design.

The prevalence and frequency of MSD are presented in Table 4. Lower back pain was the most commonly reported MSD in both iron ore (50.7%) and coal mines (55%). Upper back and knee discomfort were also frequently reported, particularly among iron ore

Table 2. Characteristics of dumper operators in coal and iron ore mines

Individual Factors	Coal Mines (n=47) %	Iron Ore Mines (n=65) %	p-value
Musculoskeletal Pain			0.427
Yes	43	46	
No	57	54	
Age (yr)			0.258
<35	38	29	
35-45	21	35	
>45	41	36	
50-60	43.1	24.5	
Seat Compatibility			0.193
Proper	53	43	
Improper	47	57	
Experience (yr)			0.769
< 5	28	34	
5-15	23	20	
> 15	49	46	
BMI (body mass index kg/m^2)			0.432
Normal (18-22 kg/m^2)	49	43	
Overweight (22-25 kg/m^2)	25	37	
Obese (> 25 kg/m^2)	26	20	

Abbreviations: n, number of subjects

Based on the Nordic Musculoskeletal Questionnaire (NMQ).

mine operators. Coal mine operators reported a higher prevalence of shoulder, leg, and hand/finger discomfort. Most MSDs were reported as occurring "sometimes" or "often," indicating recurrent symptoms rather than occasional discomfort.

Table 5 summarises the crude and adjusted odds ratios for MSD among operators in coal (n = 47) and iron ore mines (n = 65). Increasing age was associated with a higher prevalence of MSD in both mining sectors. In crude analysis, workers aged over 45 years showed significantly higher odds of MSD compared with those younger than 35 years in coal mines (cOR = 5.86; 95% CI: 1.42–24.1) and iron ore mines (cOR = 5.26; 95% CI: 1.42–19.4). After adjustment for covariates, this association remained statistically significant in both coal mines (aOR = 3.09; 95% CI: 1.30–62.6) and iron ore mines (aOR = 2.54; 95% CI: 1.07–39.8). WBV exposure demonstrated elevated odds of MSD with increasing exposure level for both coal and iron ore mines. In iron ore mines, high WBV exposure (>0.9m s^{-2}) was significantly associated with MSD in both crude (cOR = 3.32; 95% CI: 1.30–14.2) and adjusted analyses (aOR = 4.68; 95% CI: 1.36–17.43).

Table 3. Dimensions of the seat and anthropometric measurements of dumper operators (sample size=112)

Seat Components	Associated Anthropometry	Coal Mines (n=47)				Iron Ore Mines (n=65)			
		Seat, cm		Anthropometry, cm		Seat, cm		Anthropometry, cm	
		Min	max	5th percentile	95th percentile	min	max	5th percentile	95th percentile
Height of Backrest	Sitting Height (normal)	NA	79	71.00	85.00	NA	68	75.56	86.06
Length of the seat pan	Buttock Popliteal Length	47	51	40.24	49.26	NA	49	38.60	49.32
Width of the seat pan	Buttock Width	NA	51	31.60	45.50	NA	52	29.84	39.90
Height of Seat	Popliteal Height	27	50	37.88	46.52	37	45	40.34	46.96

NA-Not Available

Table 4. Musculoskeletal disorders among dumper operators in coal and iron ore mines

MSD	Coal Mines (n=47)						Iron Ore Mines (n=65)					
	Cases	% total	Frequency of Occurrence				Cases	% total	Frequency of Occurrence			
			Rarely	Some-times	Often	Always			Rarely	Some-times	Often	Always
Neck	7	17.5	3	3	1	0	5	7.7	0	4	1	0
Shoulder	8	20	4	3	1	0	8	12.3	1	5	2	0
Forearm	4	10	3	0	1	0	5	7.7	0	2	3	0
Elbow	1	1	1	0	0	0	3	4.6	0	2	1	0
Wrist	2	2	2	0	0	0	3	4.6	0	3	0	0
Hand and Finger	5	12.5	5	0	0	0	2	3.1	1	1	0	0
Upper back	6	15	3	2	1	0	19	29.2	0	12	6	1
Lower back	22	55	2	13	5	2	33	50.7	1	21	8	2
Knees	10	10	1	9	0	0	13	20	0	10	3	0
Legs	8	20	3	3	1	1	5	7.7	0	4	1	0
Feet	3	7.5	3	0	0	0	4	6.1	0	2	2	0

Abbreviations: n, number of subjects

Based on the Nordic Musculoskeletal Questionnaire (NMQ).

Table 5. Associations between musculoskeletal disorders[a] and other individual factors of dumper operators: Odds Ratio (OR) and 95% Confidence Interval (95% CI)

		Musculoskeletal Disorders[b]		
	Coal Mines (n=47)		**Iron Ore mines (n=65)**	
	Crude odds ratio (cOR) and 95% CI			
	OR	**95% CI**	**OR**	**95% CI**
Age (ref: <35 years)				
35–45 years	3.20	(0.57 to 17.7)	2.83	(0.81 to 9.89)
>45 years	**5.86****	(1.42 to 24.1)	**5.26***	(1.42 to 19.4)
WBV Exposure (ref: Low <0.45 m s^{-2})				
Moderate (0.45-0.9 m s^{-2})	1.23	(0.11 to 14.0)	1.02	(0.16 to 6.62)
High (>0.9 m s^{-2})	5.14	(0.44 to 59.4)	**3.32***	(1.30 to 14.2)
BMI (ref: Normal kg/m^2)				
Overweight (23-25 kg/m^2)	2.02	(0.46 to 8.86)	1.10	(0.36 to 3.35)
Obese (>25 kg/m^2)	**2.51***	(1.70 to 42.3)	**3.47***	(1.01 to 14.1)
Seat Compatibility (ref: Proper)				
Improper Seats	1.87	(0.58 to 6.06)	**4.58****	(2.92 to 31.4)
	Adjusted odds ratio (aOR) and 95% CI			
Age (ref: <35 years)				
35–45 years	2.69	(0.31 to 23.2)	4.29	(0.73 to 25.1)
>45 years	**3.09****	(1.30 to 62.6)	**2.54***	(1.07 to 39.8)
WBV Exposure (ref: Low 0.45 m s^{-2})				
Moderate (0.45-0.9 m s^{-2})	0.47	(0.02 to 9.34)	3.65	(0.30 to 43.4)
High (>0.9 m s^{-2})	2.98	(0.18 to 48.8)	**4.68***	(1.36 to 17.43)
BMI (ref: Normal kg/m^2)				
Overweight (23-25 kg/m^2)	0.97	(0.14 to 6.39)	0.96	(0.17 to 5.16)
Obese (>25 kg/m^2)	**6.19***	(1.10 to 43.1)	1.51	(0.20 to 11.2)
Seat Compatibility (ref: Proper)				
Improper Seats	2.10	(0.35 to 12.29)	**2.64****	(2.10 to 15.53)

Bold types: significant OR: **p<0.01; *p<0.05.

Based on the Nordic Musculoskeletal Questionnaire (NMQ)

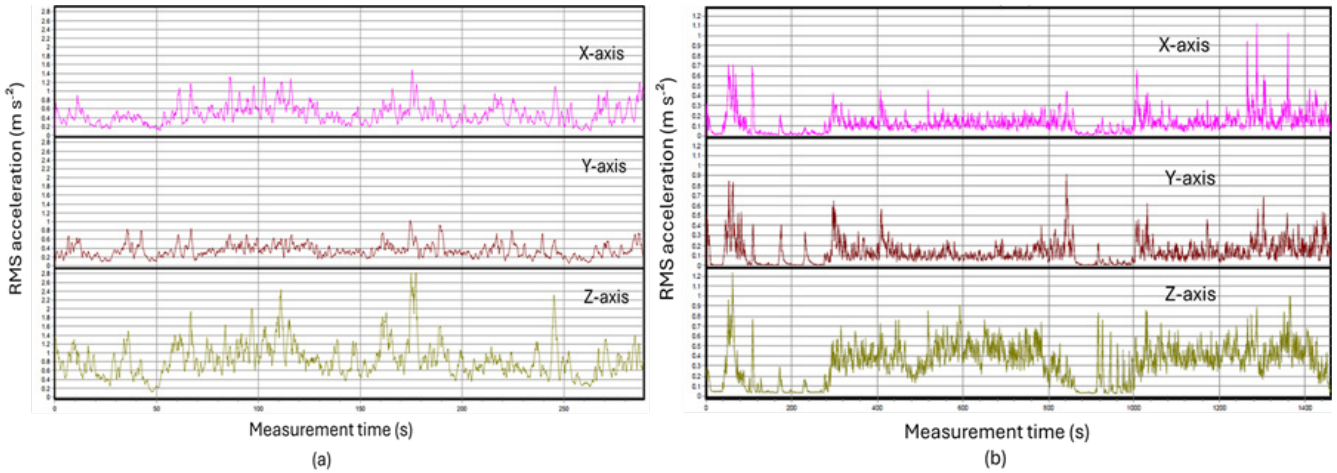


Figure 2. Snapshot of a frequency-weighted RMS acceleration for a dumper operator: **(a)** coal mines; **(b)** iron ore mines.

In coal mines, although higher odds were observed for moderate and high WBV exposure, these associations did not reach statistical significance after adjustment. BMI showed differing patterns between the two mining sectors. Obesity (>25 kg m^{-2}) was significantly associated with MSD in coal mines in both crude (cOR = 2.51; 95% CI: 1.70–42.3) and adjusted models (aOR = 6.19; 95% CI: 1.10–43.1). In iron ore mines, BMI categories were not significantly associated with MSD after adjustment. Seat compatibility was an important ergonomic factor influencing MSD occurrence. In iron ore mines, improper seating was significantly associated with higher odds of MSD in crude (cOR = 4.58; 95% CI: 2.92–31.4) as well as adjusted analysis (aOR = 2.64; 95% CI: 2.10–15.53). In coal mines, although increased odds of improper seating were observed, the associations were not statistically significant in the adjusted model.

4. Discussion

This study provides an integrated evaluation of WBV exposure, operator characteristics, seat–anthropometry compatibility, and MSD among dumper operators in coal and iron ore mines. By combining objective vibration measurements with ergonomic and epidemiological analyses, the findings offer insight into the multifactorial determinants of MSD risk in surface mining operations.

4.1 WBV Exposure Between Coal and Iron Ore Mines

The WBV exposure results indicate that dumper operators in coal mines are subjected to higher frequency-weighted RMS accelerations across all three axes compared with their counterparts in iron ore mines. The dominance of vertical vibration (z-axis) in both mining environments is consistent with the nature of dumper operations, where uneven haul roads, loading impacts, and vehicle suspension characteristics primarily transmit vibration along the vertical direction. These findings align somewhat with previous studies on WBV exposure, which have similarly reported higher vibration levels along the z-axis compared to the x- and y-axes in various vehicular contexts, such as track locomotives in the United States, trucks on test tracks in Canada, and haul trucks in aggregate stone mines in the United States[23-25]. Some of the other past studies conducted specifically on haul truck operators have also reported higher vibration magnitude in the z-axis[12,26]. The higher daily RMS exposure, A(8), observed in coal mines suggests sustained vibration exposure over the work shift, potentially reflecting longer operating hours, poorer haul road maintenance, or more frequent loading–unloading cycles. In contrast, although iron ore mines exhibited comparatively lower RMS acceleration values, higher crest factors, particularly along the vertical axis, were observed. Elevated crest factors indicate the presence of transient shocks and impulsive vibration, which

are inadequately captured by RMS metrics alone. The relatively high VDV values in both mining environments further confirm the contribution of shocks and peaks to overall vibration exposure. These findings emphasise the importance of using complementary WBV metrics, such as VDV and crest factor, in accordance with ISO 2631 recommendations, to better characterise exposure in heavy mining equipment operations.

4.2 Prevalence and Patterns of Musculoskeletal Disorders

The comparison of individual characteristics revealed broadly similar demographic and occupational profiles between coal and iron ore mine operators, with no statistically significant differences across most variables. The high prevalence of self-reported musculoskeletal pain in both groups highlights MSD as a common occupational health issue among dumper operators, regardless of mining type. Age distribution indicates that a substantial proportion of operators belonged to older age groups, particularly in coal mines. This is relevant given the cumulative nature of WBV exposure and its long-term effects on the musculoskeletal system. Similarly, nearly half of the operators in both mining environments had more than 15 years of work experience, suggesting prolonged exposure to vibration and constrained postures. Although seat incompatibility was more frequently reported in iron ore mines, the absence of statistical significance suggests that ergonomic deficiencies in seating systems are widespread across both sectors.

4.3 Influence of Individual and Ergonomic Factors

The BMI distribution showed a considerable proportion of overweight and obese operators, which may exacerbate biomechanical loading and influence vibration transmission. These findings indicate that dumper operators are exposed to multiple interacting risk factors: demographic, ergonomic, and occupational, which may contribute to MSD development.

The assessment of seat dimensions relative to operator anthropometry revealed notable mismatches across several seat components. In both coal and iron ore mines, seat pan length and width did not consistently accommodate the 5th to 95th percentile range of buttock–popliteal length and buttock width. Such mismatches may lead to inadequate thigh support, increased pressure concentration, and compromised sitting posture. Similarly, variability in seat height relative to popliteal height suggests that some operators may experience excessive knee flexion or insufficient foot support, which can increase discomfort and musculoskeletal strain during prolonged sitting. The absence of adjustable features or standardised ergonomic criteria in seat design further limits the ability to accommodate operator diversity. These ergonomic shortcomings may also reduce the effectiveness of seat suspension systems in attenuating WBV, thereby amplifying vibration transmission to the spine.

Lower back pain was the most prevalent MSD among dumper operators in both coal and iron ore mines, underscoring the vulnerability of the lumbar spine to WBV exposure. The high occurrence of upper back, knee, shoulder, and leg discomfort suggests that WBV exposure interacts with static and awkward postures, repetitive control movements, and prolonged sitting. The frequency distribution indicates that most MSD were reported as occurring "sometimes" or "often," suggesting chronic or recurrent symptoms rather than sporadic pain. Coal mine operators reported higher prevalence in certain body regions, such as shoulders and lower limbs, which may be associated with higher RMS vibration exposure and longer cumulative exposure duration. These patterns align with previous evidence linking WBV exposure, particularly in the vertical axis, to spinal degeneration and lower back disorders. Our results align with several previous studies. In Denmark, Netterstrom and Juel (1989) found that 57% of drivers suffered from recurring upper and lower back disorders[27]. In another study, it has been observed that back pain (56.8%) and knee and leg pain (29.5%) were prevalent among tractor drivers in Zahedan, attributing this to WBV exposure[28]. These findings are consistent with other research on drivers and office workers, highlighting the widespread issue of musculoskeletal pain related to WBV in the mining and other industries[29-30].

The present findings highlight the multifactorial nature of MSD among mining equipment operators, with age, WBV exposure, BMI, Body Surface Area (BSA) and

seat compatibility emerging as key contributing factors. The persistence of age as a significant predictor of MSD in both coal and iron ore mines after adjustment indicates the cumulative impact of prolonged occupational exposure and age-related musculoskeletal degeneration. This observation is consistent with earlier studies reporting higher MSD prevalence among older operators due to reduced tissue resilience and longer exposure histories to mechanical stressors and vibration. WBV exposure demonstrated a sector-specific influence on MSD risk, with a stronger and statistically significant association observed in iron ore mines. High WBV exposure remained a significant predictor of MSD in iron ore operations even after adjustment, suggesting that vibration magnitude and exposure characteristics in these mines may exceed ergonomic tolerance thresholds more frequently than in coal mines. Differences in equipment type, haul road conditions, haul road distance, operational speeds, and maintenance practices may contribute to this contrast. The lack of statistical significance in coal mines, despite elevated odds, may also reflect limited sample size and resultant uncertainty rather than the absence of effect. BMI showed a pronounced effect in coal mines, where obesity significantly increased the adjusted odds of MSD. Excess body weight may amplify biomechanical loading and increase spinal compression, thereby intensifying the adverse effects of vibration exposure. The absence of a similar association in iron ore mines suggests that occupational exposure factors may dominate MSD risk in that setting, potentially masking individual-level anthropometric effects. Seat compatibility emerged as a critical ergonomic determinant, particularly in iron ore mines, where improper seating significantly increased the likelihood of MSD even after adjustment. Inadequate seat design and poor vibration isolation can increase vibration transmissibility and promote sustained awkward postures, thereby accelerating musculoskeletal strain. These findings reinforce the importance of ergonomic seat design and regular maintenance as practical intervention measures for MSD risk reduction. The observed differences between coal and iron ore mines underscore the need for sector-specific ergonomic and risk management strategies. While exposure reduction and equipment-based interventions appear especially relevant for iron ore mining, worker health management and ergonomic optimisation may yield greater benefits in coal mining operations. The results emphasise that effective MSD prevention requires an integrated approach combining engineering controls, ergonomic improvements, and individual-level risk mitigation measures.

5. Study Limitations

Despite the robust methodology and comprehensive data collection, this study has certain limitations. First, the sample was limited to two types of mines: coal and iron ore, which may not reflect conditions in other mining environments, such as bauxite, limestone, or underground mines. Second, although efforts were made to capture authentic operator behaviour by encouraging normal working routines, the presence of measurement equipment could have influenced driving behaviour, introducing potential observation bias. Additionally, environmental and road quality variables, which are known to influence WBV exposure, were not explicitly measured or controlled. Finally, the cross-sectional design limits the ability to infer causality between WBV exposure and musculoskeletal disorders. Future studies incorporating longitudinal designs and broader mine types, while including road condition assessments, are recommended for more generalisable conclusions.

6. Conclusions

This study provides a comparative assessment of WBV exposure and associated MSD risks among dumper operators working in iron ore and coal mining environments. The findings indicate that operators in coal mines are exposed to higher frequency-weighted RMS accelerations and daily vibration doses compared to those in iron ore mines, particularly along the vertical (z) axis, which is known to be critical for spinal disorders. Lower back pain emerged as the most prevalent MSD among operators in both mining sectors, underscoring the combined influence of prolonged WBV exposure and suboptimal seat design. Although individual characteristics such as age, body mass index, and work experience were broadly comparable between the two groups, regression analyses revealed that higher WBV exposure levels, increasing age, obesity, and improper seat compatibility significantly elevated the risk of MSDs.

Notably, improper seat design showed a strong and consistent association with MSD prevalence, especially in iron ore mines. Further studies involving larger and more diverse samples across various mining setups are recommended to generalise the findings and inform national-level safety policies. The study further highlights the need for a comprehensive WBV database for Indian mines and adds valuable insights into WBV exposure in the mining industry. Future research should develop effective WBV management strategies and explore long-term health outcomes to enhance the occupational health and safety of mining personnel.

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Author Contribution

Rahul Upadhyay: Conceptualization, methodology development, data collection, formal analysis, interpretation of results, manuscript writing, and preparation of the original draft. Ashis Bhattacherjee: Supervision, conceptual guidance, review of methodology, critical revision of the manuscript, and overall academic oversight. Aditya Kumar Patra: Methodology support, data interpretation, validation of findings, and manuscript review and editing. Suprakash Gupta: Data analysis support, interpretation of results, manuscript review, and technical inputs. All authors reviewed and approved the final version of the manuscript.