Original Article

Assessment of Relative Health Risks of Vibration-Exposed Equipment Operators in Coal Mines

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Abstract

Objective: The present study aims at evaluating the influence of whole-body vibration (WBV) exposure and its contributing factors on musculoskeletal disorders (MSDs) of equipment operators in coal mines. **Methodology:** In this paper, WBV measurement was conducted for 100 equipment operators exposed to vibration, followed by a questionnaire survey. This questionnaire survey was also extended to 104 workers with limited exposure to vibration. **Results:** The daily average frequency-weighted acceleration A(8), when compared with health guidance caution zone (HGCZ) of ISO 2631-1, reveals that 15% operators are exposed to likely health risk and 82% to potential health risk. The relative risk of MSDs of vibration-exposed operators was 2.63 times more than the control group. Moreover, when mines were compared, Mine B showed a 3.27 times higher likelihood of vibration hazards compared to Mine A. **Conclusion:** Equipment operators in mines are exposed to vibration as a part of their occupation. The company management may take preventive measures through design of workplace and work environment for minimizing vibration exposure on operators to reduce MSDs.

Keywords: Coal mines, equipment operators, musculoskeletal disorders, relative risk, whole-body vibration

Introduction

Vibration is a significant occupational hazard in opencast mining operations. Equipment operators are continuously exposed to vibration, which can result in whole-body vibration (WBV). Opencast mining consists of several operations, e.g., drilling, blasting, loading, and transportation of mineral/overburden. In each operation/activity, the majority of the work is accomplished with the deployment of the heavy earth-moving machinery (HEMM).[1] During operation, these HEMM generate a lot of vibration, which is primarily transferred to operators as WBV mainly through the human–seat interface, resulting in exposing the operator to multiple shocks and continuous exposure to WBV.

Exposure to WBV can lead to musculoskeletal disorders (MSDs). Various factors, such as personal factors (age, experience, and body mass index (BMI), machine-related factors (seat suspension, vehicle suspension, vehicle maintenance, and condition), and work-environmental factors (haul roads conditions), affect the occurrence of MSDs.[2] A report published in 2005 on Ontario Mining Industry, by the Canadian accident statistics, revealed that traumatic injuries occurred due to haul truck operations are about 16%.[3] The elevated exposure to WBV among heavy vehicle operators in the mining industry may contribute to the disproportionately high prevalence of MSDs. Among two distinct components of WBV: A continuous oscillatory component from general operating conditions, and a transient shock component from travelling over rough terrain, impulsive WBV exposures are more prominent in mining vehicles compared with on-road vehicles.[3-5] Exposure to these transient shocks is known to contribute to the degeneration of lumbar spine more than the continuous oscillatory component.[6]

Research works indicate that exposure to WBV poses a significant impact on occupational health risk, potentially leading to various types of MSDs, such as lower back pain,[7-13] upper back issues,[14-16] shoulder pain,[17,18] neck problems,[19,20]

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and knee ailments.[21] In the UK alone, it is estimated that exposure to WBV contributed to approximately 444,000 cases of lower back pain among males and 95,000 among females during 1997–1998.[22] Additionally, the U.S. Bureau of Labour Statistics reported in 2014 that MSDs comprised 32% of all injury and illness cases among full-time workers.[23]

Epidemiological studies indicate a direct relationship between prolonged exposure to WBV and MSDs.[24] Increasing epidemiological evidence also suggests that occupational WBV exposure can lead to various health complications, some of which may be irreversible.[25] Epidemiological research indicates that WBV, combined with occupational, nonoccupational, and individual risk factors, can contribute to the onset and recurrence of MSDs. HEMM operators experience significantly higher vibration exposure compared to other mine workers, such as fitters, mechanics, welders, foremen, and supervisors, despite working in similar geographical conditions. Therefore, this study focuses on assessing the vibration exposure levels of HEMM operators. To extend the analysis, a case–control study was conducted, comparing HEMM operators exposed to vibration (case group) with workers not exposed to vibration (control group). Numerous studies have been reported on the personal factors of HEMM operators, such as age, experience, BMI, and type of operation. However, there is rarely any study which considered these personal factors in association with MSD as a case–control study.

Researchers have reported that various confounding factors, coupled with exposure to WBV, may influence the occurrence of MSDs.[2] Some studies indicate a positive correlation between WBV exposure and the age[12] and experience[26,27] of operators. Moreover, certain studies have established associations between vibration magnitude, operator age, and experience in relation to MSDs affecting the lower back, upper back, and other regions among HEMM operators.[18,28]

In light of these findings, this paper evaluates HEMM operators to assess their relative risk of vibration exposure compared to a control group having limited exposure to vibration. Despite the prevalence of WBV exposure among HEMM operators in the mining sector, documented case–control studies on this topic are scarce. Hence, this study aims to ascertain the impact of WBV exposure and its personal factors on MSDs among equipment operators.

Study Methodology

A research team contacted the mine management to discuss their possible participation in the study and visited the mine with prior approval for data collection during December 2021 and November 2022. The study protocol includes: (i) Description of the study site and the study sample, (ii) Measurement of WBV using a B & K type 4447 human vibration analyzer, (iii) A standardized workers' response device questionnaire, which collects participants' biographical information and details of musculoskeletal discomfort experienced over the past 12 months. (iv) Conduct a logistic regression analysis to examine the relationship between the MSDs as the dependent variable and age, experience, case–control groups, and individual mine as independent variables.

Study site and study sample

This research was focused on HEMM operators in three opencast coal mines in India. The same company owns all three mines and is heavily automated. Coal extraction involves deep hole drilling, blasting, and using a shovel and dumper combination. Minimum bench height was 10 m for both coal and overburden. The bench's width equals or exceeds its height. The shovel feeds coal/overburden onto rear discharge dumpers. The HEMM used for this study consists of 56 dumpers, 39 Hyva trucks, two water tankers, one shovel, one dozer, and one grader. Operators were selected randomly at the site and were explained about the study process. Dumpers/Hyva trucks were deployed either for coal transport, that is, from the face to the coal handling plant or coal yard, or for overburden transport from the face to the dumping yard. The loaded coal/OB on dumpers was discharged from the rear end using the hydraulic system.

In the literature, most of the WBV-related studies have adopted cross-sectional epidemiological research to identify underlying mechanisms of injuries/disorders. This cross-sectional study involved 204 participants, comprising 100 operators (38 from Mine A, 32 from Mine B, and 30 from Mine C) classified as the case group, who were HEMM operators exposed to vibration. The remaining 104 participants (44 from Mine A, 30 from Mine B, and 30 from Mine C) constituted the control group. The control group consisted of individuals working in similar mining environments, such as fitters, welders, supervisors, and office staff, who were not exposed to vibration. This study has obtained ethical approval from the institutional ethics committee. Operators and workers were informed about the study, and their consent was obtained. The confidentiality of their personal and medical information was maintained. Field-based questionnaire surveys were conducted for both groups, with participants randomly selected and briefed about the research upon their arrival at the mining site. It is noteworthy that the subjects considered in all three coal mines are exclusively male workers and operators. Additionally, the majority of the selected subjects came from low-income families and had received inadequate education.

Measurement of the WBV exposure

The WBV exposure is measured following the ISO 2631-1:1997 guidelines using a B & K type 4447 human vibration analyzer. A seat pad accelerometer is placed on the operator–seat interface, and measurements are recorded for at least 20 min. The raw data includes root mean square (RMS), maximum transient vibration value, total RMS, peak value, and total vibration dose value (VDV) for X, Y, Z axes. These values are then used to calculate the frequency-weighted average RMS acceleration A(8) and cumulative transient VDV(8). Finally, A(8) and VDV(8) are compared with the HGCZ specified in the ISO 2631-1 standard, as illustrated in Figure 1.[29]

As shown in Figure 1, if A(8) is below 0.45 m/s^2, health risks are unlikely. When A(8) ranges between 0.45 and

0.90 m/s^2, there is a potential health risk, while values exceeding 0.90 m/s^2 indicate a likely health risk. Similarly, for VDV (8), values below 8.5 m/s$^{1.75}$ suggest a lower likelihood of health risk. A range of 8.5–17 m/s$^{1.75}$ indicates a potential health risk, and values exceeding 17 m/s$^{1.75}$ signal a likely health risk.

Questionnaire survey

A predefined questionnaire was administered for the 204 subjects, including equipment operators and workers, and their responses are recorded. This questionnaire included personal factors, such as age, education, number of dependent family members, work experience, and smoking and drinking habits. It also assessed musculoskeletal pain experienced over the past 12 months, covering areas, such as the shoulders, arms, wrists, upper back, lower back, knees, and legs. Scores for MSDs and certain personal variables were recorded using an ordinal scale ranging from 1 to 5, classified as never = 1, seldom = 2, occasional = 3, often = 4, and always = 5. For a few cases, the scale ranged from 1 to 3, and it was rated as no = 1, cannot say = 2, and yes = 3.

Relative risk estimation for MSDs in case–control group subjects

As mentioned earlier, the case group comprised professional HEMM operators exposed to WBV, whereas the control group consisted of various workers working in the similar environmental conditions, who were either not exposed to HEMM vibration, or having a limited exposure to vibration, namely mining supervisor, fitter, electrician, welder, and mechanic. In this study, the MSDs are considered as dependent variable. The relative risks of both group subjects are estimated using a logistic regression model using the software package IBM SPSS v. 23.[30] The logistic regression is a statistical approach preferred for modelling the categorical dependent variable with one or more predictor variables. It is typically used when the desired outcome is dichotomous.

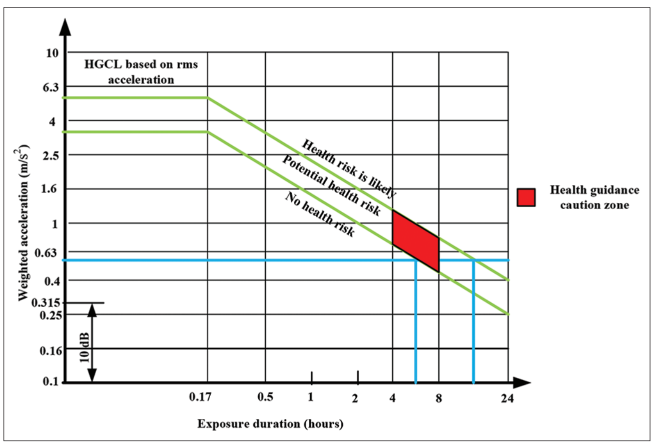

Figure 1: Health guidance caution zone defined by ISO 2631-1:1997[29]

The variable coding for logistic regression analysis for MSDs as the dependent variable, and contributing factors as independent variables are presented in Table 1. The dichotomous dependent variable (MSDs) is coded as "0" for low MSDs score with less potential for MSDs and "1" for high MSDs score having more potential to diseases. Similarly, all the other contributing factors (independent variables) are coded as "0" and "1." The percentage of subjects in each category are also presented in Table 1.

An individual, aged 45 years or younger, is classified as young, while those above 45 years are considered old.[31] The body mass index of a person is categorized as "not overweight" for values up to 25, and above 25 it is classified as overweight/obese.[32]

Results

The raw WBV data of 100 operators was obtained from the human vibration analyzer B & K type 4447.[2] The raw data is used to calculate A(8) and VDV(8) along the three basic-centric axes. It is observed that mean value of A (8) is 0.73 ± 0.19 m/s^2, with a range of 0.23–1.54 m/s^2, while mean value of VDV(8) is 16.76 ± 4.07 m/s$^{1.75}$, with a range of 5.22–28.20 m/s$^{1.75}$. It can be revealed from A(8) that 3% operators are less likely to health risk, whereas 82% operators are exposed to a potential health risk, and 15% face likely health risk. Similarly, based

Table 1: Classification and coding of variables for the logistic regression model

Variable	Category explanation	Category		Code		Case group (%)	Control group (%)
MSDs score	Low score	≤23†		0		43 (43%)	80 (77%)
	High score	>23		1		57 (57%)	24 (23%)
Age (year)	Young	≤45†		0		55 (55%)	51 (49%)
	Old	>45		1		45 (45%)	53 (51%)
Experience in mines (year)	Less	≤15†		0		37 (37%)	44 (42.4%)
	More	>15		1		63 (63%)	60 (57.6%)
Body mass index (kg/m^2)	Normal	<25†		0		67 (67%)	71 (68.2%)
	Obese	≥25		1		33 (33%)	33 (31.8%)
Case and control	Exposure to vibration	Case		1		100 (100%)	0 (0%)
	Non-exposure to vibration	Control†		0		0 (0%)	104 (100%)
Mine	Mine A	Mine A†	1	0	0	38 (38%)	44 (42.4%)
	Mine B	Mine B	0	1	0	32 (32%)	30 (28.8%)
	Mine C	Mine C	0	0	1	30 (30%)	30 (28.8%)

†reference category, MSDs=Musculoskeletal disorders

on VDV (8), 1% of the operators have less likely to health risk, whereas 58% are exposed to a potential health risk, and 41% are at a likely health risk.

The data pertaining to musculoskeletal disorders (MSDs), including symptoms such as pain in the shoulder, wrists, arms, lower back, upper back, knees, and legs, was collected through a questionnaire survey. Descriptive statistics for MSDs among the case group and control group are presented in Table 2. The questionnaire survey is conducted to assess MSDs and the responses of both case group and control group according to their perception are recorded, on an ordinal scale of 1 to 5 for pain in shoulder, forearm, elbows, wrist, fingers, upper back, lower back, knees, legs, ankles, and feet. Their total responses are summed up to make a grand total of MSDs score out of 55. The mean MSDs score for case group is 24.09 ± 6.99 with range between 11 and 44, whereas for control group, mean MSDs score is 17.00 ± 6.24 with range between 11 and 34.

The mean scores for pain in the lower back, upper back, knees, and shoulders are notably higher compared to other body parts among both equipment operators and workers [Table 2]. To examine the relationship between MSDs and various independent variables, a case–control study was conducted. In the binary logistic regression analysis, only two out of the five variables considered were found to be significant in the model. Table 3 presents the corresponding odds ratios, *P* values, and 95% confidence intervals for the analyzed factors.

Table 2: Musculoskeletal disorders of the case group and control group

Musculoskeletal disorders	Case group		Control group	
	Mean	SD	Mean	SD
Shoulder	2.85	1.31	1.33	0.73
Forearm	1.55	1.03	1.44	0.89
Elbow	1.63	1.08	1.4	0.71
Wrist	1.55	1.02	1.36	0.84
Palm and finger	1.34	0.86	1.56	1.01
Upper back pain	2.57	1.42	2	1.26
Lower back pain	3.78	0.90	1.78	1.26
Knee	3.32	1.11	1.56	1
Legs	2.37	1.41	1.38	0.9
Ankles	1.56	1.06	1.53	1
Feet	1.57	1.10	1.57	1.1

SD=Standard deviation

Table 3 presents the regression coefficients (β) obtained from the model. The sign of β (positive or negative) indicates direction of the relationship between dependent and independent variables. The exponential β (Exp(β)) represents the odds ratio for each independent variable. In logistic regression analysis, the odds ratios revealed that operators exposed to vibration have 2.63 times (95% CI [1.42, 4.84]) more risk of MSDs compared to the workers having limited or no exposure to vibration. Similarly, operators in Mine B are 3.27 times (95% CI [1.52, 7.03]) more prone to vibration hazards as compared to those in Mine A.

Discussions

MSDs are among the leading causes of chronic illness, affecting millions of people worldwide. However, since MSDs are not perceived as life-threatening hazards, because of which they often receive less attention, resources, and ergonomic planning. Allocating adequate resources could help reduce morbidity, ultimately lowering both the incidence and prevalence of these health risks or disorders. In this paper, 97% operators are exposed to a potential health risk to likely health risk when A (8) is considered, and 99% operators are potential health risk to likely health risk in case of VDV (8) when compared with the HGCZ of ISO 2631-1. It is corroborated with the results published in previous studies, stating that the majority of the operators are exposed to a potential health risk to likely health risk of HGCZ.[18,28,33-35] Therefore, these hazardous WBV levels require attention to minimize the vibration exposure or the associated hazards.

Subsequently, various studies suggest that acute exposure to WBV alone may not directly result in significant skeletal or muscular damage; however, several contributing factors can influence its severity. The link between WBV and lower back

Table 3: Relative risk of operators' musculoskeletal pain

Variable	Category	β	Exp (β)	Significance	95% CI
Age (year)	Young	-	(1)	-	-
	Old	-0.026	0.97	0.94	[0.43, 2.16]
Experience in mines (year)	Less exposure	-	(1)	-	-
	More exposure	-0.024	0.97	0.95	[0.41, 2.28]
Body mass index (kg/m^2)	Normal	-	(1)	-	-
	Obese	-0.07	0.93	0.83	[0.47, 1.84]
Case–control	Case	0.96	2.63*	0.002	[1.42, 4.84]
	Control†	-	(1)	-	-
Mine	Mine A†	-	(1)	0.003	-
	Mine B	1.18	3.27*	0.002	[1.52, 7.03]
	Mine C	0.21	1.23	0.668	[0.46, 3.25]
Constant	Constant	-1.48	0.23*	0.003	-

†reference category. *results are significant at P<0.05 level; CI=Confidence interval

pain has primarily been established through cohort studies, which often do not quantify the specific vibration inputs responsible for symptoms. In a comparison between two groups of workers, findings from the present cross-sectional study indicate that equipment operators exposed to WBV are 2.63 times more likely to be affected by MSDs than the control group with lower vibration exposure. Similar findings are reported in an earlier study on case group and control group, stating that dumper operators' prevalence of lower back pain is 2.52 times more compared to the control group.[28] Another study on 65 dumper operators reported that the case group has 5.37 times much higher risk of upper back pain than the control group.[36] The absence of acute effects on clinical markers aligns with previous research, suggesting that MSDs develop due to prolonged WBV exposure rather than short-term exposure to physical risk factors.[37] Therefore, cross-sectional WBV studies have their own significance in identifying the relative risks.

In the logistic regression model, while estimating the relative risk, the statistical relationship between experience in mines categories and MSDs categories of the case and control group was not statistically significant. An attempt was made to understand whether there is a linear relationship that exists between MSDs and experience in mines [see Figure 2a and b], as it is believed that the prevalence of MSDs increases with experience. The graphs indicate a poor linear relationship that exists between MSDs and experience in mines, with the coefficient of determination (R^2) of less than 0.1 in both cases. Therefore, in the generated database, work experience and prevalence of MSDs are not linearly dependent. These results are corroborated with the results published in earlier studies, showing that WBV exposure is not affected by the age of the operators[26,33,38] and experience in mines.[38]

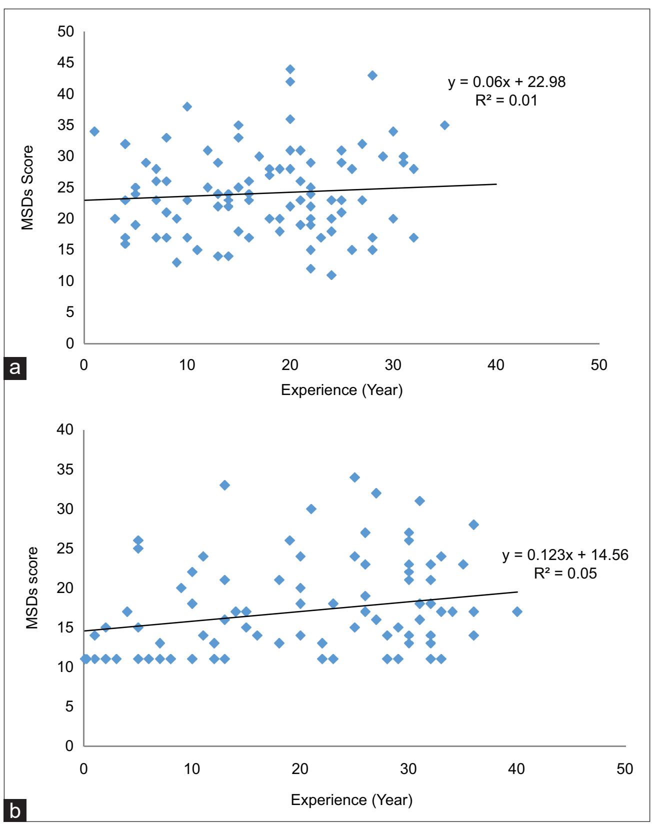

Figure 2: (a) Relationship between experience in mines and MSDs in the case group. (b). Relationship between experience in mines and MSDs in the control group

Results revealed that Mine B is more prone to vibration hazards than Mine A. To understand this impact, the questionnaire assessment results related to aging of HEMM and haul road conditions were also analyzed. It may be noted that the mean age of HEMM recorded in Mines A, B, and C is 3.77 ± 2.93, 2.06 ± 0.24, and 1.70 ± 0.91 years, respectively. Moreover, the questionnaire survey is also carried out for haul road conditions and the responses of operators according to their perception are noted down on an ordinal scale of 1 to 5 for steepness, width of haul road, undulation, roughness, turning, and sight distance (i.e., how far an operator can see haul road condition from the cabin) of haul road. Their total responses are summed up to make a grand total of haul road conditions 30. The mean score of haul road conditions for Mine A (20.68 ± 2.49), Mine B (21.59 ± 2.21), and Mine C (21.03 ± 2.61) reveals that the perception of operators about haul road conditions for all the mines is similar. Therefore, the age of the HEMM and the perception of operators about the haul road conditions do not vary between the case study mines, and the effect of poor condition of haulage roads and aging of HEMMs on WBV is the study limitation. However, the causation of MSDs depends on multiple contributing factors and further assessment is required to understand the effect of HEMM maintenance, suspension system, ergonomic design of the seat, and posture of operators as well as haul road conditions.

Conclusion

Exposure to WBV has been recognized as a major contributor to pose musculoskeletal risks among heavy equipment operators. An assessment of WBV measurements using the HGCZ criteria of ISO 2631-1:1997 indicated that most operators are exposed to potential health risks based on their daily frequency-weighted RMS acceleration. Findings of the cross-sectional study revealed that equipment operators exposed to vibration were 2.63 times more likely to develop MSDs compared to their nonexposed counterparts. It is recommended that mine management can consider implementing suitable ergonomic design strategies to reduce musculoskeletal risks faced by equipment operators. Adopting such proactive measures can improve workplace safety and promote the overall well-being of operators exposed to vibration.

Ethical clearance

Ethical approval for this study has been obtained from the institutional ethics committee, Institute of Medical Sciences, Banaras Hindu University, Varanasi-221005, India.

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Conflicts of interest

There are no conflicts of interest.

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