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Original article

Whole-Body Vibration Exposure vis-à-vis Musculoskeletal Health Risk of Dumper Operators Compared to a Control Group in Coal Mines

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ABSTRACT

Background: Whole-body vibration (WBV) exposure of coal mine dumper operators poses numerous health hazards. The case-control study was aimed at assessing the relative musculoskeletal health risk of dumper operators' exposure to WBV with reference to the nonexposed group.
Methods: Measurements of WBV exposure were taken at the operator–seat interface using a human vibration analyzer for 110 dumper operators in three coal mines. This vibration measurement was supplemented by a questionnaire survey of 110 dumper operators exposed to WBV and an equal number of workers not exposed to WBV. The relative risk of musculoskeletal disorders (MSDs) has been assessed through the case-control study design.
Results: ISO guidelines were used to compare the health risk. It was observed that the prevalence of pain in the lower back was 2.52 times more in the case group compared to the control group. The case group of Mine-2 was 2.0 times more prone to vibration hazards as compared to Mine-3.
Conclusion: The case group is more vulnerable to MSDs than the control group. The on-site measurement as well as the response of the dumper operators during the questionnaire survey corroborates this finding.
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1. Introduction

A high level of mechanization, in terms of deployment of heavy earthmoving machinery (HEMM), is a step forward toward meeting out the staggering demand for minerals in this hitherto unforeseen industrial era. However, the use of large scale HEMMs has induced severe complications on the health and safety of the operators—especially in terms of whole-body vibration (WBV) leading to musculoskeletal disorders (MSDs). Dumper is an improved version of equipment, which plays a major role in coal handling in the mining process. The magnitude of WBV in dumper operations is higher because they travel on undulated and uneven paths encountered in coal mines.

Vibration, in general, is recognized as a mechanical movement that oscillates about a reference point. WBV is a head-to-toe exposure, when vibration is transmitted to the equipment operators in mines through the seat-pad. Human vibration at the workplaces, especially the exposure to WBV, is responsible for MSDs in the frequency range of 0.5 to 80 Hz [1]. It can be observed that MSDs are one of the largest work-related problems in the United States [2]. On the other hand, vibration shock is a sudden vibration acceleration applied to a system rather than the exposure to a steady vibration. The potential of vibration shock to cause health hazards is manyfold more than exposure to a steady vibration. The presence of transient vibration, also called shock, is evaluated by calculating the crest factor. The crest factor is the ratio between the maximum peak value and the root-mean-square (r.m.s.) value for the measurement period. The more impulsive a vibration, the higher is its crest factor. Impulsive vibrations are considered to be more hazardous than nonimpulsive ones. Thus, the crest factor is a good indicator of the level of harmfulness of the vibration. Vibration dose value (VDV) is considered for the assessment of health hazards whenever the value of the crest factor exceeds 9.0 [1].

Rather than the vibration magnitude, epidemiological evidence suggests that WBV may act in combination with other occupational, nonoccupational, and individual risk factors and play a role in the development and the recurrence of MSDs [3,4]. HEMM operators, on average, are exposed to significantly greater vibration and vibration shock than other categories of workers in mines, such as fitter,

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welder, electrician, mechanic, and supervisor. Many studies address the role of contributing factors along with WBV on the causation of MSDs [5–9]. For dumper operators, the relationships between vibration magnitude, age of the operators, and their years of exposure to lower back pain, blood pressure, and diabetes are established in the literature [5]. In a comparative assessment, it is observed that dumper operators in mines are more vulnerable to vibration hazards than the shovel and drill machine operators [6]. Therefore, in this study, dumper operators have been considered for assessing their vibration exposure level. To further extend this analysis, a case-control study has been conducted for dumper operators with an equal number of workers in the mines not exposed to vibration.

In a case-control study, the groups are generally defined on the basis of exposure or nonexposure to a physical hazard, or on the basis of the presence or the absence of a given disease in epidemiological investigations. It is a tool to analyze whether an exposure bears a special impact on the case or the control group.

There are plenty of instances of case-control studies outside the mining industry. A review of 370 case-control studies on cancer patients revealed that response rates from case-control studies have declined over the years, and nonparticipation of the subjects is reported in some of the studies [10]. In a study on vaccine effectiveness, it is emphasized that case-control studies should rely on the confidence interval of estimates rather than the point estimate [11]. The application of the case-control studies is also extended either to diagnose hypertension of people exposed to noise [12] or to study elevated blood lead levels because of people exposed to lead [13]. The case-control study on human vibration exposure is analyzed to understand the effect of WBV on pregnancy [14] or to correlate the hand-arm vibration syndromes [15].

It can be observed that the case-control studies on WBV in the mining industry are rarely reported where most of the operators operate heavy vehicles and are regularly exposed to WBV as a part of their occupation. Therefore, the present paper explains an epidemiological approach of a case-control study that focuses on musculoskeletal pains as the response parameter. The relative risk of musculoskeletal pain of professional dumper operators exposed to WBV in coal mines was considered as the case group, and various workers, who were not exposed to HEMM vibration such as the fitter, welder, electrician, mechanic, and mining supervisor, were considered as the control group.

2. Study methodology

2.1. Brief description of the study area

The case-control study was carried out on a group of dumper operators and control group workers of three opencast coal mines. The concerned mines, located in northern India, are highly mechanized and belong to the same owner. A shovel-dumper combination is deployed for coal extraction. The bench height for both coal and overburden benches was 10 m and the bench width was more than height. The spacing and burden in both coal and overburden benches varied between 5 and 6 m. The coal or overburden was picked and loaded by a shovel mainly of 11 m^3 bucket capacity. The shovel loaded coal and overburden on rear discharge dumpers. The available dumpers belonged to two manufacturers: Caterpillar and Bharat Earth Movers Limited (BEML). Model No. 777D of 100-ton capacity and 777C of 85-ton capacity were of Caterpillar make, and BH100T of 100-ton and BH85T of 85-ton capacity were of BEML make. Dumpers were deployed for transportation of coal to the coal handling plant or overburden to the dumping yard. The coal/overburden of dumpers was discharged from the rear end using the hydraulic system.

Table 1
Distribution of data collection for the case-control study

Mine	Case group	Control group
Mine-1	34	24
Mine-2	43	38
Mine-3	33	48
Total	110	110

2.2. Case and control groups

A cross-sectional study has been carried out on a sufficiently large number of population (henceforth called 'subjects'). Out of a total of 220 subjects, 110 were dumper operators exposed to vibration, and 110 were different types of workers who were not exposed to machine vibration but were working in the mining premises. The distribution of collected data of case and control groups from the coal mines is presented in Table 1. Simultaneously, a questionnaire survey of all the 220 subjects was also conducted. All the subjects were selected on a random basis.

Before conducting the survey work, the subjects were apprised about the study and the importance of their cooperation in its success. The vibration measurement and questionnaire assessment were conducted in three phases—October 2017, June 2018, and September 2018. Through the questionnaire, the personal information of the subjects was collected, which includes age, experience, weight, and height. The questionnaire also contained whether the subjects had developed any musculoskeletal pain over the past six months, if so, in which region(s) of the body. Various body parts for musculoskeletal symptoms were already mentioned in the questionnaire. A standardized and well-defined questionnaire was used to conduct a face-to-face interview of the case and control groups which minimizes the interviewer's bias. Face-to-face interview is often a preferred method with individuals who are illiterate or of low educational level as observed in mining equipment operators and workers. Moreover, the interviewers were well trained to conduct the interview using the standard questionnaire, thus limiting the potential interviewers' bias during the assessment.

For the calculation of discomfort/pain, 11 body points were considered. These body points were grouped into five body regions: (i) Neck and shoulder were grouped as the neck region; (ii) forearm, elbow, wrist, and fingers as the hand region; (iii) upper back region; (iv) lower back region; and (v) knees, legs, and feet as the leg region. The scorings of the body points were collected through the questionnaire. The scores were represented as ordinal scales ranging from 1 to 5. The subjective quantification scales for discomfort were rated as *never* = 1, *rarely* = 2, *occasional* = 3, *often* = 4, and *always* = 5.

2.3. Limitations and scope of the study

The scope of the present paper is limited to investigating the association between contributing parameters of WBV of dumper operators and MSDs. It can be noted that while evaluating the MSDs, family histories of operators or workers were not considered as a part of the present questionnaire. Except for MSDs, other possible health effects of WBV on cardiopulmonary function, cognition, deep vein thrombosis, fertility, gastrointestinal disorders, hearing loss, diabetes, hypertension, and peripheral neuropathy were not a part of this investigation. The questionnaire assessment did not consider the amount of smoking or alcohol consumption, because while conducting the preliminary investigation to know the status of consumption and its frequency, the operators/workers were reluctant to disclose these figures. The data related to lifestyle were also collected. However, it is not considered as a variable in the case-control analysis.

2.4. *WBV instrumentation and measurement procedure for the case group*

The instrument, a human vibration analyzer (type 4447), used in the study is a handy and easily portable one. It is a versatile instrument to measure WBV. It incorporates a triaxial accelerometer that receives input signals along three axes simultaneously. The recommended sensitivity is 10.0 mV/(m/s^2) for WBV. Fig. 1 depicts a typical snapshot of the arrangement for WBV measurement of a dumper operator, including proper placement of the accelerometer during field condition.

With the help of the human vibration analyzer, measurement of WBV exposure for dumper operators was carried out, according to Standard No. ISO 2631-1:1997 [1]. The accelerometer was placed on the seat of the operator. Vibration exposure was measured along three basi-centric directions of the sitting posture of the operator, namely, fore-and-aft (x), lateral (y), and vertical (z) axes. WBV measurements of dumper operators were taken from the starting of the loading activity till its return to the loading site.

According to the guidelines of ISO 2631-1:1997 [1], appropriate scaling factors were applied to the axes, e.g., $K_x = K_y = 1.4$ and $K_z = 1$. The presence of shock was evaluated through the crest factor. Using the raw vibrational data, equivalent frequency-weighted r.m.s. acceleration for the 8-hour duration, A (8), and daily vibration dose value for the 8-hour duration, *VDV*(8), were estimated. These values were used for predicting health as per the Health Guidance Caution Zone (HGCZ).

2.5. *Statistical analysis*

For the analysis of the case-control study, both the case group and control group workers were coded. Logistic regression analysis was carried out for identifying the significant factors inducing musculoskeletal health risk to the dumper operators with respect to the control group subjects. The generated field data were analyzed using the statistical package IBM-SPSS version 23 [16] for drawing statistical inferences to calculate the relative risks faced by the WBV-exposed dumper operators.

In general, regression has been limited to those situations in which the dependent variable is continuous. In health-related research, the use of the relationship between independent variables and a dependent variable is mainly discrete. In the circumstances where the outcome variable is dichotomous, assuming only one of two mutually exclusive values, logistic regression models can be used [17]. The dichotomous dependent variables are usually coded as '1' for the presence of a disease or exposure to a physical hazard and '0' for the absence of a disease or nonexposure to physical hazard. For calculation of the relative risk for the 11 independent variables considered in this paper, a generalized form of a logistic regression model is presented in Eq. (1).

$$\ln\left[\frac{z}{1-z}\right] = \beta_0 + \beta_0 x_1 + \beta_2 x_2 + \ldots + \beta_{11} x_{11} \qquad (1)$$

where β_0 is the constant; $\beta_1, \beta_2, \ldots, \beta_{11}$ are the coefficients associated with independent variables $x_1, x_2, \ldots, x_{11}$ respectively; and z is the probability of exposure to vibration.

Table 2
Descriptive statistics of personal factors of the case and control groups

Personal factor	Case group			Control group		
	Mean	SD	Range	Mean	SD	Range
Age (year)	50.3	8.6	25.0–60.0	48.7	9.0	31.0–60.0
Weight (kg)	71.9	11.9	45.9–105	70.2	10.5	35.5–111
Height (m)	1.7	0.1	1.5–1.8	1.7	0.1	1.4–1.9
Experience (year)	26.7	9.3	0.2–38	24.7	10.7	2.0–41.0
Body mass index (kg/m^2)	25.7	4.0	16.3–36.3	25.4	3.2	16.2–34.5

Note: SD = standard deviation.

3. Results

3.1. *Outcome of the questionnaire survey*

Statistical analysis of personal factors for the case and control groups is summarized in Table 2.

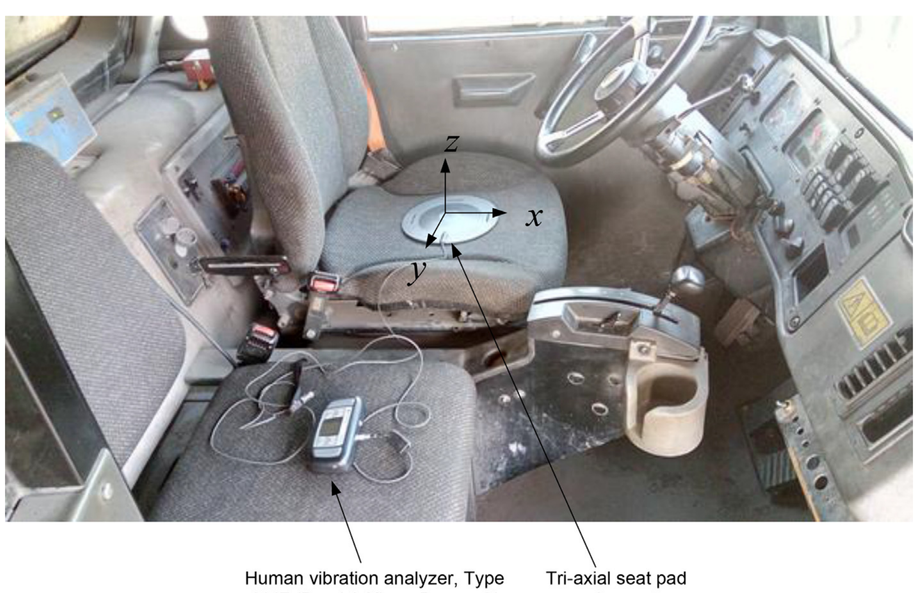

Fig. 1. Vibration measurement instrumentation placed on the dumper seat.

Table 3
Variables of the case and control group subjects and their classification

Variable	Category	Code		Case group (%)	Control group (%)
Age	<45 years	0		28 (25.5%)	35 (31.8%)
	≥45 years	1		82 (74.5%)	75 (68.2%)
Experience	<13 years	0		18 (16.4%)	26 (23.6%)
	≥13 years	1		92 (83.6%)	84 (76.4%)
Smoking	No	0		69 (62.7%)	80 (72.7%)
	Yes	1		41 (37.3%)	30 (27.3%)
Alcoholic	No	0		68 (61.8%)	77 (70.0%)
	Yes	1		42 (38.2%)	33 (30.0%)
Body mass index	<25	0		56 (50.9%)	49 (44.5%)
	≥25	1		54 (49.1%)	61 (55.5%)
Neck region	No (≤2)	0		98 (89.1%)	99 (90.0%)
	Yes (>2)	1		12 (10.9%)	11 (10.0%)
Hand region	No (≤4)	0		95 (86.4%)	96 (87.3%)
	Yes (>4)	1		15 (13.6%)	14 (12.7%)
Upper back region	No	0		78 (70.9%)	87 (79.1%)
	Yes	1		32 (29.1%)	23 (20.9%)
Lower back region	No	0		70 (63.6%)	89 (80.9%)
	Yes	1		40 (36.4%)	21 (19.1%)
Leg region	No (≤3)	0		97 (88.2%)	102 (92.7%)
	Yes(>3)	1		13 (11.8%)	8 (7.3%)
Mine	Mine-1	1	0	34 (30.9%)	24 (21.8%)
	Mine-2	0	1	43 (39.1%)	38 (34.5%)
	Mine-3	0	0	33 (30.0%)	48 (43.6%)

Table 3 illustrates the categorization of the variables in the study. The code used for different categories of variables is also illustrated. Code “0” is used for the reference category and code “1” for the remaining categories. Personal habits like smoking tobacco products and alcohol use were incorporated as one of the variables in the study. The subjects who are not smokers or occasional smokers were considered as ‘nonsmokers’ and coded as “0”. Those who smoked more than one cigarette per day were considered as ‘smokers’ and are coded as “1”. Similarly, the subjects who don’t drink or rarely drink were considered as ‘nonalcoholic’ and remaining were considered as ‘alcoholic’. Only male subjects were considered in this study. The number of subjects and their percentage (shown in bracket) for both the case and the control groups are also given in Table 3.

3.2. Characteristics of WBV exposure of the case group and evaluation of MSD risks

From the raw data obtained through the accelerometer, the A (8) along three basi-centric axes, the VDV (8), and the crest factor have been calculated. Table 4 presents the raw data of the vibration parameters as well as all the calculated values of A (8), VDV (8), and the crest factor using them. From Table 4, it is seen that the mean value of $A(8)$ is 0.87 m/s^2 and that of $VDV(8)$ is 24.49 $m/s^{1.75}$ and the crest factor is 9.39 for the case group of operators exposed to vibration.

According to ISO 2631:1997, the lower and upper limits of HGCZ are 0.45 m/s^2 and 0.90 m/s^2 respectively for A (8) and 8.5 $m/s^{1.75}$ and 17 $m/s^{1.75}$ respectively for VDV (8). When the vibration measurement results are compared with HGCZ Standards [1], it is observed that 38.2% of operators are exposed to likely health risks, whereas 61.8% of them fall in a potential risk zone. It is striking to note that if VDV (8) is considered as the criterion, more number of operators would fall in the likely risk zone compared to the A (8) criterion. On the basis of VDV (8), daily vibration dose value, a staggering 93.6% of operators would fall under likely risk—only a meager 6.4% would come under the potential risk zone.

3.3. Statistical analysis for the case and control study

For statistical analysis using the binary logistic regression model, 11 variables were considered. Only three variables were found to be statistically significant in the logistic model.

Results of the regression model are presented in Table 5 in terms of $Exp(\beta)$ representing odds ratio, p-value, and 95% confidence interval (CI) for all the variables under study.

Using the regression coefficient (β), the relative risk is calculated for each independent variable. On examination of the odds ratios, it is revealed that the case group is vulnerable to lower back pain by 2.52 times (95% CI [1.19, 5.31]) as compared to the control group. Such pain is attributable to the nature of work by the case group. The case group of Mine-2 is 2.0 times (95% CI [0.98, 4.08]) more prone to vibration hazards as compared to the reference mine (Mine-3).

4. Discussion

The health risks of WBV reported in most of the research works are referred to as MSDs. This paper attempts to identify the relative risks the dumper operators (i.e., the case group) are facing in comparison with the mineworkers who are not exposed to HEMM vibration (i.e., the control group). Dumper operators are exposed to WBV as a part of their nature of duty, and when these exposures are evaluated against the control group, it is revealed that the prevalence of lower back pain in the case group is 2.52 times more than that in the control group. In the literature, lower back pain is predominantly reported as the major health impact of vibration on HEMM operators [18–20]. The relatively high risk of dumper operators indicates that exposure to vibration is more likely to inflict MSDs on them. Ergonomically designed seats and work postures coupled with a reduction of vehicle operation period are expected to reduce the risk of lower back pain in dumper operators [20].

Most of the dumper operators of the three coal mines under study are facing the symptoms of MSDs, which is apparent from the magnitude of vibration as discussed earlier. The measurements of

Table 4
Summary of whole-body vibration exposure of the case group

Parameter	Frequency-weighted r.m.s. acceleration values, m/s^2				Crest factor values			Vibration dose value, $m/s^{1.75}$			
	a_{wx}	a_{wy}	a_{wz}	A (8)	CF_x	CF_y	CF_z	VDV_x	VDV_y	VDV_z	VDV (8)
Mean	0.43	0.37	0.87	0.87	7.89	7.46	9.39	3.00	2.53	6.06	24.49
Median	0.40	0.35	0.85	0.85	7.54	7.19	8.69	2.95	2.53	6.01	23.70
SD	0.10	0.08	0.20	0.19	1.65	1.58	2.64	0.67	0.56	1.41	5.05
Minimum	0.22	0.22	0.42	0.45	5.10	4.61	5.94	1.58	1.44	2.93	14.23
Maximum	0.67	0.72	1.37	1.37	15.91	15.12	21.13	5.69	4.74	9.35	36.75

Note: a_{wx}, a_{wy}, a_{wz} = frequency-weighted r.m.s. acceleration values in x, y, z axes respectively; VDV_x, VDV_y, VDV_z = vibration dose values in x, y, z axes respectively, $A(8)$ = daily frequency-weighted r.m.s. acceleration; $VDV(8)$ = daily vibration dose value.

Table 5
Statistical estimates for the contributing variables to develop MSD pain among the case and control groups

Variable	β	Wald	Significance	$Exp(\beta)$	95% CI for $Exp(\beta)$	
					Lower	Upper
Age	-0.037	0.008	0.930	0.96	0.43	2.18
Experience	0.389	0.674	0.411	1.48	0.58	3.74
Smoking	0.315	0.893	0.345	1.37	0.71	2.63
Alcohol	0.289	0.82	0.365	1.34	0.71	2.50
Neck group	-0.195	0.15	0.699	0.82	0.31	2.21
Upper back	0.112	0.084	0.772	1.12	0.53	2.38
Lower back	0.923	5.889	0.015*	2.52	1.19	5.31
Leg	0.506	0.868	0.352	1.66	0.57	4.82
Hand group	-0.681	1.683	0.194	0.51	0.18	1.42
BMI	-0.239	0.679	0.41	0.79	0.45	1.39
Mine-1	0.543	2.639	0.104	1.72	0.89	3.32
Mine-2	0.691	3.589	0.058**	2.00	0.98	4.08
Mine-3#		4.33	0.115			
Constant	-0.961	4.864	0.027*	0.38		

reference mine, *significant at $p < 0.05$; **significant at $p < 0.10$.

exposure to vibration revealed that they fall in the zone of likely health risk to potential health risk, as suggested in the HGCZ of ISO 2631-1:1997. Through a critical review, Bovenzi [19] has proved that lower back pain is predominantly high in occupations having high exposure to WBV. As the lower back pain is more prominent in the case group (dumper operators) than its counterpart, suitable precautionary measures should be taken by the mine management to protect the dumper operators from the hazardous impacts of vibration.

5. Conclusions

The study shows that the case group is exposed to high levels of vibration whose magnitude is maximum on the z axis. For evaluation of vibration and assessment of risk, Standard No. ISO 2631-1:1997 was followed. The case group subjects (dumper operators) are regularly exposed to vibration and vibrating shocks as a part of their occupation. In contrast to this, the control group subjects (including the fitter, welder, electrician, mechanic, and mining supervisor) were not exposed to any vibration or their exposure to vibration was naturally very low. Health issues of the case and control groups were observed through a questionnaire as well as personal interviews. Lower back pain was a common symptom in dumper operators, as revealed from the questionnaire response. This is likely due to their prolonged exposure to vibration while operating the machine.

The present study considered 220 subjects consisting of 110 each in the case and control groups in three coal mines. The case-control study concludes that the vulnerability to vibration hazards is higher in the case group than in the control group. This result is corroborated by both the vibration measurement and the questionnaire response. It is also evident from the vibration magnitude as well as from the symptoms of lower back pain. Studies related to the health consequences of occupational exposure to WBV are very limited in Indian mines—though the level of mechanization is staggeringly on the rise. The present study will provide very useful findings to the mine management to outline the policies for guarding the regular dumper operators against WBV syndrome reflected as lower back pain.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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