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Original Article

Whole-body Vibration Exposure of Drill Operators in Iron Ore Mines and Role of Machine-Related, Individual, and Rock-Related Factors

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ABSTRACT

Background: This study aimed to assess the whole-body vibration (WBV) exposure among large blast hole drill machine operators with regard to the International Organization for Standardization (ISO) recommended threshold values and its association with machine- and rock-related factors and workers' individual characteristics.

Methods: The study population included 28 drill machine operators who had worked in four opencast iron ore mines in eastern India. The study protocol comprised the following: measurements of WBV exposure [frequency weighted root mean square (RMS) acceleration (m/s^2)], machine-related data (manufacturer of machine, age of machine, seat height, thickness, and rest height) collected from mine management offices, measurements of rock hardness, uniaxial compressive strength and density, and workers' characteristics via face-to-face interviews.

Results: More than 90% of the operators were exposed to a higher level WBV than the ISO upper limit and only 3.6% between the lower and upper limits, mainly in the vertical axis. Bivariate correlations revealed that potential predictors of total WBV exposure were: machine manufacturer ($r = 0.453$, $p = 0.015$), age of drill ($r = 0.533$, $p = 0.003$), and hardness of rock ($r = 0.561$, $p = 0.002$). The stepwise multiple regression model revealed that the potential predictors are age of operator (regression coefficient $\beta = -0.052$, standard error SE = 0.023), manufacturer ($\beta = 1.093$, SE = 0.227), rock hardness ($\beta = 0.045$, SE = 0.018), uniaxial compressive strength ($\beta = 0.027$, SE = 0.009), and density ($\beta = -1.135$, SE = 0.235).

Conclusion: Prevention should include using appropriate machines to handle rock hardness, rock uniaxial compressive strength and density, and seat improvement using ergonomic approaches such as including a suspension system.

1. Introduction

A feature of a machine is that when it oscillates due to external and internal forces, these are transmitted to workers' bodies through the part in contact with the vibrating surface, such as the handle of a machine (known as "hand–arm vibration"), surface of a piece of equipment, or seat of a mobile machine (known as "whole-body vibration", WBV). Occupational exposure to WBV has generated many health concerns and related medical and socioeconomic consequences in most industrialized countries. It is recognized as a potential risk factor for musculoskeletal disorders (MSDs) in the workplace [1,2]. Several epidemiological investigations reported the role of long-term exposure to WBV in the occurrence of low back pain and early degeneration of the lumbar spine, including intervertebral disc disorders [3–5]. Some studies indicated that lower back pain, a common disorder, is more prevalent in professional drivers than in control groups unexposed to WBV [6–8], but the authors concluded that not a single study satisfied the criterion

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to draw any conclusion about the specific health effects of WBV. Recently, studies have investigated the prevalence of MSDs among professional drivers of industrial machines and vehicles which have contributed to the understanding of the risk of back symptoms and disorders of lumbar spine [2,9–20]. A number of earlier studies have demonstrated that operators in construction stone quarry [21], locomotive [22], forklift [23], crane [24], transportation [25], and load–haul–dump (LHD) [9,26] are exposed to high levels of WBV. High levels of WBV exposure were recorded from all-terrain vehicles [27–30], farm tractors [31], professional drivers [13], heavy vehicle operators [32], and agricultural quad bikes [33].

Opencast mines are associated with high level of mechanization that includes deployment of heavy earth moving machinery for production and ancillary processes. Vibration sources in opencast iron ore mines include machines such as drills, shovels, road headers, rock breakers, bulldozers, and heavy duty dumpers. The operators of such machines are therefore expected to be subjected to high exposure to WBV. Moreover, trucks and buses operate on public roads which are paved. However, the heavy machinery in mines operate under unpaved and undulated natural surfaces with the potential of high WBV exposure. In India, the number of miners regularly exposed to WBV ranges from 1.80 lakhs to 18 lakhs and they are at risk of WBV related health consequences [34]. To date a few studies on mining industries have reported high daily WBV exposure experienced by heavy equipment operators, especially those working with load–haul–dump mining vehicles [9,26]. An earlier study involving seven LHD vehicles used in mining reported that four LHD operators experienced vibration levels within the Health Guidance Caution Zones (HGCZ) limits established in ISO 2631-1 while the remaining three operators experienced vibration levels above the HGCZ [9]. In another study it was found that 50% of the LHD operators are exposed to WBV level above the HGCZ. WBV exposure levels previously reported for LHD vehicle operators of two underground mines do suggest vibration frequencies are in a range that is harmful to human health [26]. One survey conducted in several opencast mines in India found that operators of heavy earth moving machinery were subjected to WBV exposure that exceeds the ISO 2631-1 standard and therefore the workers are at a greater health risk of WBV exposure [34]. An Australian study on 36 drivers and passengers in mining vehicles reported 80%, 75%, and 50% of workers complaining of musculoskeletal disorders, low back pain, and neck pain, respectively [35].

Many factors may influence the WBV exposure level of heavy earth moving equipment operators. This can broadly be categorized into: (1) machine related factors that include vehicle type and design, age and condition of vehicle, vehicle suspension systems, seat type and design, cab layout, position and design, vehicle or machine speed, lighting and visibility; and (2) personal factors such as drivers' age, body mass index (BMI), living style, and health status. In addition to this a job-associated factor can also be thought of which includes road condition, task design, work organization, and working condition [35–38]. Previous studies on professional drivers of forklift trucks, forestry machines, mobile cranes, trucks, tractors, subway trains, and harvesters have shown that their WBV exposure was influenced by a number of personal and physical factors including posture, workplace and vehicle characteristics (road condition, suspension systems, seat type, load, and maintenance of vehicle) as well as driving experience, driving speed, and body mass index [26,33,36–40]. The results of an earlier study on WBV exposure by the truck operators indicated that among several factors such as seat type, driver experience, road condition, truck type, and truck mileage, only the truck type and road condition are the factors that significantly influence the WBV exposure level [38]. It was suggested that the role of seat, driver experience and truck age on WBV should be explored. In the case of WBV exposure of urban taxi drivers, a study hypothesized driving speed, manufacturer, engine size, engine age, seat cushion, body weight, and age of operator as the predictive parameters [37]. It was reported that driving speed is the major parameter that influences WBV level. Engine size, wheel base, and tire width were also suggested to influence the WBV level. Notwithstanding the above studies, the research on various factors that predict the WBV exposure level is limited.

Of all the machinery in mines, the drill machines used for drilling holes for production blasts are different from others due to: (1) limited mobility; and (2) high energy operations where holes are drilled into natural strata which are very hard. In addition to machine-related and personal factors, the rock-related parameters such as hardness, uniaxial compressive strength, and density of rock significantly influences the WBV level. The drill machine is therefore a unique machine as far as WBV exposure from its operators is concerned. Depending on geo-mechanical characteristics of the strata, the operation requires high power drilling which involves a high level of vibration of machine as well as operator. However, no investigation has been carried out either on WBV exposure level of drill operators or the influence of rock-related parameters on WBV exposure in opencast mines. The present study aimed at assessing the WBV exposure (in reference to the threshold values recommended by the ISO 2631-1 (1997) [41]) and determining which factors related to machine, rock, and individual (manufacturer of machine, age of drill machine, height of seat, thickness of seat pad, height of seat rest; hardness, uniaxial compressive strength, and density of rock; operator's age, weight, height, and drilling experience) that predicted the WBV exposure levels experienced by the drill machine operators in the opencast iron ore mines in India.

2. Materials and methods

2.1. Study sites

The study was conducted during May–November 2013 in four opencast iron ore mines located in eastern India. All these mines are operated by the same company and have the same infrastructure and service facilities required for large sized and fully mechanized opencast mines. These mines supply iron ore to integrated steel plants. The method of mining is top slicing with deep hole drilling and blasting. The height of the benches is 10 m in overburden and ore with bench width more than or equal to the bench height. Down-the-hole method of drilling is being practiced with 6 inch (150 mm) diameter drills. Loading was being carried out with a combination of shovel, hydraulic excavator, and front end loaders of 2.7–4.6 m^3 capacity. Ore/waste was transported with 35–85-tonne rear discharge dumpers. Slurry explosives and nonel detonators were used for blasting. The spacing and burden in overburden/ore benches varied from 5 m to 6 m. The study mines have the same occupational, safety, and health practices.

The study protocol included: (1) face-to-face interview using a questionnaire to record personal factors including operator's age, weight, height, and drilling experience; (2) collection of drill machine-related data (manufacturer, age of drill machine, height of seat and seat rest, and thickness of seat pad) from mine office; (3) collection of rock samples from drilling sites and laboratory test for the hardness, uniaxial compressive strength, and density of rock; and (4) measurement of WBV exposure.

2.2. Participants

The study population included all 32 blast-hole drill machine operators who were working in the four mines. Among the 32 operators selected, 28 (87.5%) operators participated in this study. The four nonparticipants were not available when the study was conducted. The age of the operator was recorded from the identity card where date of the birth is mentioned. The height of the operators was measured using an anthropometer (Martin-Type anthropolometer, Takei Scientific Instruments Co. Ltd., Niigata-City, Japan [42]). The precision of the instrument for measuring height is 1 mm. The participants' weight was self-reported. Drilling experience included the time an operator has worked in the present organization, in addition to the period he has previously worked in other organizations. The machine operators work 300 days a year, 6 days a week, and 8 hours a day.

2.3. Machine features

A total of 10 drill machines from two manufacturers (Atlas Copco, Pune, India and Ingersoll Rand, Bangalore, India) were used in four mines where the study was conducted. Machines of only one model of each manufacturer (Model IDM30 of Atlas Copco and Model DM30E of Ingersoll Rand) were in use in all these mines (Fig. 1). The manufactures of the machines that were studied include two Atlas Copco machines at Mine 1, two Atlas Copco and one Ingersoll Rand machine in Mine 2, two Atlas Copco and one Ingersoll Rand machine in Mine 3, and two Ingersoll Rand machines in Mine 4.

Both the machines are multi-pass rotary drilling rig specifically designed for production blast hole drilling. The drill bit size is 127–171 mm and it can drill up to a depth of 27.4 m with a 9.1-m drill pipe change. A four-position drill pipe changer is optionally available to achieve drilling depths up to 57.7 m. The machines generate a drill bit load force of up to 133 kN. The optional angle drilling package allows the tower to be positioned up to a maximum of 20° from the vertical in increments of 5°. The machines are crawler mounted with hydraulic top-head drive arrangement. Designed for quarrying and small mining operations, it can be easily loaded onto a trawler and moved from one location to another [43].

The drill machine operator sits inside the cabin and operates it. The seats are of rigid type without any effective suspension system (Fig. 2). The age of the machine was obtained from the mechanical department of the mine.

2.4. Measurements of rock parameters

A total of 12 rock samples were collected from drilling locations at four mines. Laboratory investigations included preparation of rock core sample of NX size (diameter = 54 mm and length to diameter ratio = 2:1) and measurement of its hardness, uniaxial compressive strength, and density, the parameters that are expected to affect the WBV exposure (Fig. 3).

Hardness was measured by the Schmidt hammer rebound hardness test which consists of a hammer released by a spring that impacts against the rock surface through a plunger. The rebound distance of the hammer indicated the hardness (rebound hardness) of the rock [44]. Ten impacts were produced on different parts of the core samples and readings of impact were recorded. The average of the 10 readings was reported as the hardness of the rock. The density of the rock was calculated from the volume and the mass of rock sample. Uniaxial compressive strength measurement was performed according to standard protocols as described by the International Society for Rock Mechanics [45]. The measurement was determined by Servo controlled Universal Testing Machine of 350 ton capacity by incremental loading at a constant strain rate of 2×10^{-5}/s until failure of the NX size core sample [44]. The uniaxial compressive strength σ_c of a specimen was calculated by the following formula:

$$\sigma_c = \frac{F}{A}$$

where,

σ_c = uniaxial compressive strength of rock (mega pascal, MPa)
F = load at failure (Newton)
A = cross-sectional area of the core sample (mm^2)

2.5. WBV exposure measurement

WBV exposure were measured according to the standard procedure of the ISO 2631-1 (1997) guidelines [41]. A tri-axial seat pad accelerometer (Model no. Nor 1286) was placed on the seat of the drill machine operator with regards to direction and anatomical positioning. Vibration was measured in a three-axis coordinate system to consider the entry points of vibration in worker's body: the x-axis to measure vibration in the anterior–posterior direction, the y-axis in the medial–lateral direction, and the z-axis in the vertical direction (Fig. 4).

An accelerometer was connected to a precision vibration meter (Model no. Nor 133, ISO 8041). The time period for vibration measurement may have an influence on the measurements [46], but it is not suggested by the ISO standard. Several investigators have chosen the weighted average of three measurements made during the total cycle time as WBV exposure [46]. In this study, in order to get a representative WBV of the drill machine operators for total exposure duration of 8 hours (daily vibration exposure), the

A B

Fig. 1. Study drill machines from two manufacturers. (A) Atlas Copco (Model – IDM30). (B) Ingersoll Rand (Model – DM30E).

Fig. 2. Operator's cabin with seat structure.

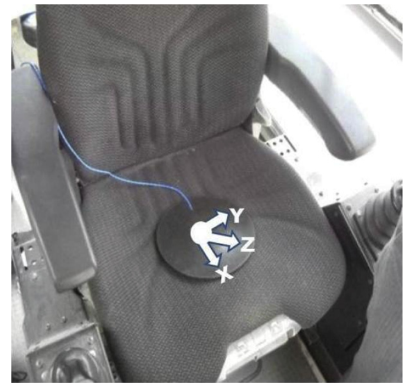

Fig. 4. Seat pad accelerometer with the measurement axes.

WBV exposure for each operator was defined as the average of three measurements made for a drilling operating cycle of average 20 minutes.

2.6. Evaluation of WBV exposure

ISO 2631-1 (1997) guidelines [41] were followed to assess the health risk from the vibration exposure. The guidelines are applicable to the vibration in the frequency range from 0.5 Hz to 80 Hz, transmitted to the body as a whole through the seat pad. The vibration evaluation procedure incorporates a method of averaging vibration level over time and over frequency band using one third octave band. The RMS acceleration of the frequency weighted vibration (a_w) over a time period provides a measure of vibration level. It is defined by the formula:

$$a_w = \sqrt{\frac{1}{T}\int_0^T a_w^2(t)dt}$$

where

$a_w(t)$ is the frequency weighted RMS acceleration at a time t (m/s^2)
T is the duration of measurement (s).

Individual RMS values of the accelerations measured by the precision vibration meter along the x, y, and z directions are represented by a_{wx}, a_{wy}, and a_{wz} respectively. As the damage risk differs along the three axes, a multiplying factor is applied to the frequency weighted vibration values. In the case of WBV, the acceleration values for the two lateral axes (x and y) are multiplied by 1.4, whereas for the vertical axis (z-axis) WBV values are multiplied by 1.0 (ISO, 1997) [41]. The total frequency weighted RMS acceleration to which a subject is exposed to during the work is obtained through the vector sum of a_{wx}, a_{wy}, and a_{wz} (ISO, 1997) [41]

$$a_{hv} = \sqrt{(1.4\alpha_{wx})^2 + (1.4\alpha_{wx})^2 + \alpha_{wz}^2}$$

where

a_{hv} is vibration total value (m/s^2)

In the present study, the exposure duration of a driller is 20 minutes. According to ISO 2631-1 [41], the upper and lower limits of the health guidance caution zone for 8 hours exposure are 0.9 m/s^2 and 0.45 m/s^2. The value of the frequency weighted RMS acceleration not exceeding ISO lower limits indicates that the worker is not at risk, between lower limit and upper limit indicates the worker is exposed to significant levels of vibration, and exceeding upper limit makes the worker vulnerable to elevated risk of health problems. These exposure levels identify the workers who deserve to benefit from specific preventive measures.

2.7. Statistical analysis

The outcome variables were the vibration exposure defined by the RMS acceleration in all three axes (a_{wx}, a_{wy}, and a_{wz}) and vibration total value (a_{hv}). The risk factors were machine-related factors (manufacturer, age of drill, height of seat, thickness of seat pad, and height of seat rest), rock-related factors (hardness, uniaxial compressive strength, and density), and operator's features (age, weight, height, and drilling experience). All variables were continuous variables except the manufacturer of machine which is a dummy variable. To determine the factors that may predict each outcome variable, we computed first the Pearson correlation

Fig. 3. NX (diameter = 54 mm, length to diameter ratio = 2:1) size of rock core samples for laboratory tests.

coefficient between each outcome variable and each risk factor. Then to determine most potential predictors we used multiple linear regression models including all factors with stepwise procedure retaining only those which were significant ($p < 0.05$) or close to significance ($p < 0.09$). All tests were two-sided with a significance level of 0.05. All statistical analyses were performed using SPSS package Version 20 (SSPS Inc., Chicago, IL, USA).

3. Results

The characteristics of the operators and their work conditions (machine and rock parameters) as well as their WBV exposures are presented in Table 1. The detailed statistics of drill machine operators, including the WBV level are given in Table 2.

3.1. Personal factors

Most of the operators were aged 50 years and older. The mean age of the participants was 52.6 years (SD = 4.5, range: 42–60 years). The average drilling experience was 16 years (SD = 7.3, range: 5–30 years) (Table 2). Years of experience in mines was not considered because of its very strong collinearity with the subject's drilling experience.

3.2. Machine related factors

The age of the drill varied from 4 years to 8.5 years (Table 2). The service age of each machine is 15–20 years. Each machine remained in operation for 8–10 hours per day. Seat height, seat pad thickness, and height of seat rest were measured in each of the drills. Seat height varied between 50 cm and 63 cm. Thickness of seat pad was either 10 m or 15 m. Height of seat rest varied from 40 cm to 50 cm (Table 2).

3.3. Rock related factors

Hardness of core samples varied from 28 to 52, suggesting wide variation of hardness of rock in the four different mines where the study was conducted. The uniaxial compressive strength (UCS) of core samples varied in the range of 9.54–53.45 MPa. Density varied from 2.2 g/cm^3 to 4.05 g/cm^3 (Table 2).

3.4. WBV exposure

Irrespective of personal, machine-, and rock-related factors, a_{wz} was higher than a_{wx} and a_{wy} for all the subjects, indicating higher WBV exposure along the vertical direction than in lateral directions (Table 1). The result is consistent with earlier studies where higher vibration exposure along vertical direction was reported [21,47,48]. Intraclass correlation coefficients of 0.77, 0.83, and 0.91 for a_{wx}, a_{wy}, and a_{wz} respectively show that the three measurements for each of the 28 operators are consistent. The distributions of vibration levels between the two machines along x-axis, y-axis, and z-axis are shown in Fig. 5. Fig. 5 reveals that the mean RMS acceleration values for Atlas Copco and Ingersoll Rand machines along x-axis are 0.64 m/s^2 (SD = 0.147) and 0.84 m/s^2 (SD = 0.36) respectively; however, the difference in mean values are not statistically significant at $p < 0.05$. Fig. 5 also reveals that the mean RMS acceleration values for Ingersoll Rand machine are higher than the Atlas Copco machine along the y-axis and z-axis, and the difference in mean values are statistically significant at $p < 0.05$.

3.5. Frequency spectrum of WBV

In addition to the higher acceleration values along the z-axis than along the x and y axis, frequency range within which the high accelerations occurs is also more in the z axis than the x axis and y axes. Specifically, the vibration spectra of a drill machine in the x, y and z axes are presented in Fig. 6.

The predominant peak frequency weighted accelerations along the z axis was 0.9 m/s^2 at 3.9 Hz. This was considerably greater than peak accelerations along x axis (0.4 m/s^2) and y axis (0.5 m/s^2) occurring at 1.4 Hz and 1.6 Hz, respectively. The high accelerations were recorded in the frequency range 1–10 Hz for z axis which is higher than the frequency ranges of 0.4–4 Hz and 0.4–6 Hz for high accelerations along x axis and y axis, respectively (Fig. 6).

The RMS accelerations were generally between the ISO recommended lower and upper limits for the x and y axes; whereas, 21.4% and 17.9% of operators had higher values than the ISO upper limit (Table 2). Along the vertical z axis, the WBV exposure level was between the ISO lower and upper limits for 3.6% of operators and higher than the ISO upper limit for 96.4% of operators. For the vector sum of the RMS values along the three orthogonal axes (vector sum a_{hv}), it was higher than the ISO upper limit for all operators indicating all workers as vulnerable to elevated health risk.

Table 3 shows the Pearson correlation coefficients between average RMS acceleration along the three axes and the vibration total value with the various factors. a_{wz} was significantly associated with manufacturer ($r = 0.492$, $p = 0.008$), age of drill ($r = 0.608$, $p < 0.001$), and rock hardness ($r = 0.649$, $p < 0.001$); its association with uniaxial compressive strength of rock ($r = 0.349$) was close to significance ($p < 0.09$). a_{wx} was significantly correlated with the age of drill ($r = 0.447$, $p = 0.017$) and hardness of rock ($r = 0.456$, $p = 0.015$); its association with uniaxial compressive strength of rock was close to significance ($p < 0.09$). a_{wy} was significantly associated with the manufacturer ($r = 0.385$, $p = 0.043$), age of drill ($r = 0.406$, $p = 0.032$), and hardness of rock ($r = 0.395$, $p = 0.037$). Vibration total value was significantly correlated with the manufacturer ($r = 0.453$, $p = 0.015$), age of drill ($r = 0.533$, $p = 0.003$), and hardness of rock ($r = 0.561$, $p = 0.002$); its association with uniaxial compressive strength of rock was close to significance ($p < 0.09$). We failed to find the associations between operator's features and WBV in all three axes; the association between operator's age and a_{wz}, and vibration total value was close to significant.

Table 4 presents the results of multiple regression models with stepwise backward procedure retaining only predictors which were significant ($p < 0.05$) or close to significant ($p < 0.09$). For vertical WBV, the models retained only manufacturer (regression coefficient β = 0.645, standard error SE = 0.152), rock hardness (β = 0.045, SE = 0.011), uniaxial compressive strength (β = 0.011, SE = 0.006), and rock density (β = −0.547, SE = 0.144). For x-axis WBV, the predictors retained were age of operator (β = −0.02, SE = 0.008), manufacturer (β = 0.318, SE = 0.083), height of seat rest (β = −0.037, SE = 0.012), hardness of rock (β = 0.013, SE = 0.007), rock uniaxial compressive strength (β_a = 0.011, SE = 0.003), and rock density (β = −0.451, SE = 0.086). For y-axis WBV, the predictors retained were age of operator (β = −0.034, SE = 0.012), manufacturer (β = 0.579, SE = 0.118), rock uniaxial compressive strength (β = 0.018, SE = 0.004) and rock density (β = −0.533, SE = 0.125). The variance explained was high for vertical WBV, x-axis WBV and y-axis WBV: R^2 was 0.714, 0.704, and 0.632, respectively.

Finally, in Table 4 for the total WBV, only six factors had significant or close to significant regression coefficients: age of operator (β = −0.052, SE = 0.032), manufacturer (β = 1.093, SE = 0.227), height of seat rest (β = −0.064, SE = 0.032), hardness of rock

Table 1
Data of individual operators ($n = 28$), machine, and rock-related factors

Operator	Individual factors				Machine-related factors					Rock-related factors			Frequency weighted RMS acceleration			
	Age (y)	Weight (kg)	Height (cm)	Drilling experience (y)	Make	Age of drill (y)	Height of seat (cm)	Thickness of seat pad (cm)	Height of seat rest (cm)	Hardness	UCS* (MPa)	Density (g/cm^3)	a_{wx}† (m/s^2)	a_{wy}† (m/s^2)	a_{wz}† (m/s^2)	a_{hv}‡ (m/s^2)
Operator 1	60	52	152	15	Atlas Copco	4.0	63	15	50	32	12.0487	2.3320	0.4792	0.5258	1.3690	1.6965
Operator 2	60	55	152	5	Atlas Copco	4.0	63	15	50	28	12.6214	2.2167	0.5563	0.4875	1.149	1.5570
Operator 3	55	67	163	15	Atlas Copco	5.3	60	15	50	28	12.6214	2.2167	0.5523	0.4754	1.1644	1.5497
Operator 4	47	60	157	5	Atlas Copco	5.3	60	15	50	50	53.4535	3.4526	0.8591	0.9026	1.9353	2.6126
Operator 5	50	62	160	15	Atlas Copco	4.0	63	15	50	32	12.0487	2.3320	0.3726	0.3905	0.8259	1.1240
Operator 6	55	70	157	30	Atlas Copco	5.1	52	10	48	38	30.1855	2.7102	0.8578	0.5634	1.1030	1.8147
Operator 7	53	74	167	27	Atlas Copco	5.1	52	10	48	38	30.1855	2.7102	0.7007	0.6163	1.0319	1.6788
Operator 8	53	55	157	15	Atlas Copco	5.1	52	10	48	38	30.1855	2.7102	1.0260	0.8655	1.6567	2.5123
Operator 9	55	85	170	30	Atlas Copco	5.1	52	10	48	32	18.4732	3.1135	0.5604	0.5995	1.1395	1.6431
Operator 10	50	70	167	20	Atlas Copco	3.5	55	10	45	32	18.4732	3.1135	0.6276	0.7714	1.2653	1.8869
Operator 11	52	50	170	18	Atlas Copco	5.1	50	10	48	36	32.6998	3.2239	0.6721	0.7871	1.4766	2.0856
Operator 12	48	70	165	20	Ingresoll Rand	8.5	58	10	45	52	33.6109	3.1113	1.6055	2.2965	3.1505	5.0333
Operator 13	60	105	187	18	Ingresoll Rand	8.5	58	10	45	36	32.6998	3.2239	0.7167	0.8490	1.6517	2.2755
Operator 14	50	62	160	20	Ingresoll Rand	8.5	58	10	45	32	18.4732	3.1135	0.9500	0.9692	1.9837	2.7640
Operator 15	45	62	170	10	Atlas Copco	8.5	60	10	50	40.75	9.5456	2.8592	0.7833	0.7507	1.6193	2.2258
Operator 16	58	65	162	20	Atlas Copco	8.5	55	10	45	42	9.5456	2.8592	0.5370	0.4693	1.3333	1.6699
Operator 17	42	65	150	20	Atlas Copco	8.5	60	10	50	52	33.6109	3.1113	0.7776	0.7390	2.0003	2.5037
Operator 18	54	55	157	23	Atlas Copco	8.5	55	10	45	50	53.4503	4.0452	0.6600	0.5985	1.5023	1.9563
Operator 19	52	47	150	5	Ingresoll Rand	8.5	53	10	50	52	33.6109	3.1113	1.1547	1.0916	2.4893	3.3398
Operator 20	53	60	157	6	Atlas Copco	8.5	60	10	50	50	53.4503	4.0452	0.6158	0.6634	1.7687	2.1762
Operator 21	48	60	162	5	Atlas Copco	8.5	55	10	45	50	53.4503	4.0452	0.7368	0.6171	1.4747	2.0035
Operator 22	55	50	157	8	Ingresoll Rand	8.5	53	10	50	52	33.6109	3.1113	1.0057	1.1963	2.7390	3.5058
Operator 23	48	55	147	21	Ingresoll Rand	5.5	55	10	50	46.2	15.3822	4.0389	0.4810	0.4180	1.5360	1.7812
Operator 24	56	65	163	18	Ingresoll Rand	6.0	55	10	40	46.2	15.3822	4.0389	0.4400	0.5242	1.7401	1.9897
Operator 25	55	50	157	20	Ingresoll Rand	6.0	55	10	40	40	19.4758	3.6178	0.7750	0.8087	1.4933	2.2043
Operator 26	50	75	157	10	Ingresoll Rand	5.5	55	10	50	40	19.4758	3.6178	0.6697	0.8880	1.9160	2.4926
Operator 27	55	70	163	10	Ingresoll Rand	5.5	55	10	50	40	19.4758	3.6178	0.4094	0.4790	1.0043	1.3382
Operator 28	55	70	168	18	Ingresoll Rand	6.0	55	10	40	46.2	15.3822	4.0389	1.0055	0.5982	1.4427	2.2023

RMS, root mean square.
* Uniaxial compressive strength.
† Frequency weighted RMS acceleration along *x*, *y* and *z* axes.
‡ Vibration total value (vector sum).

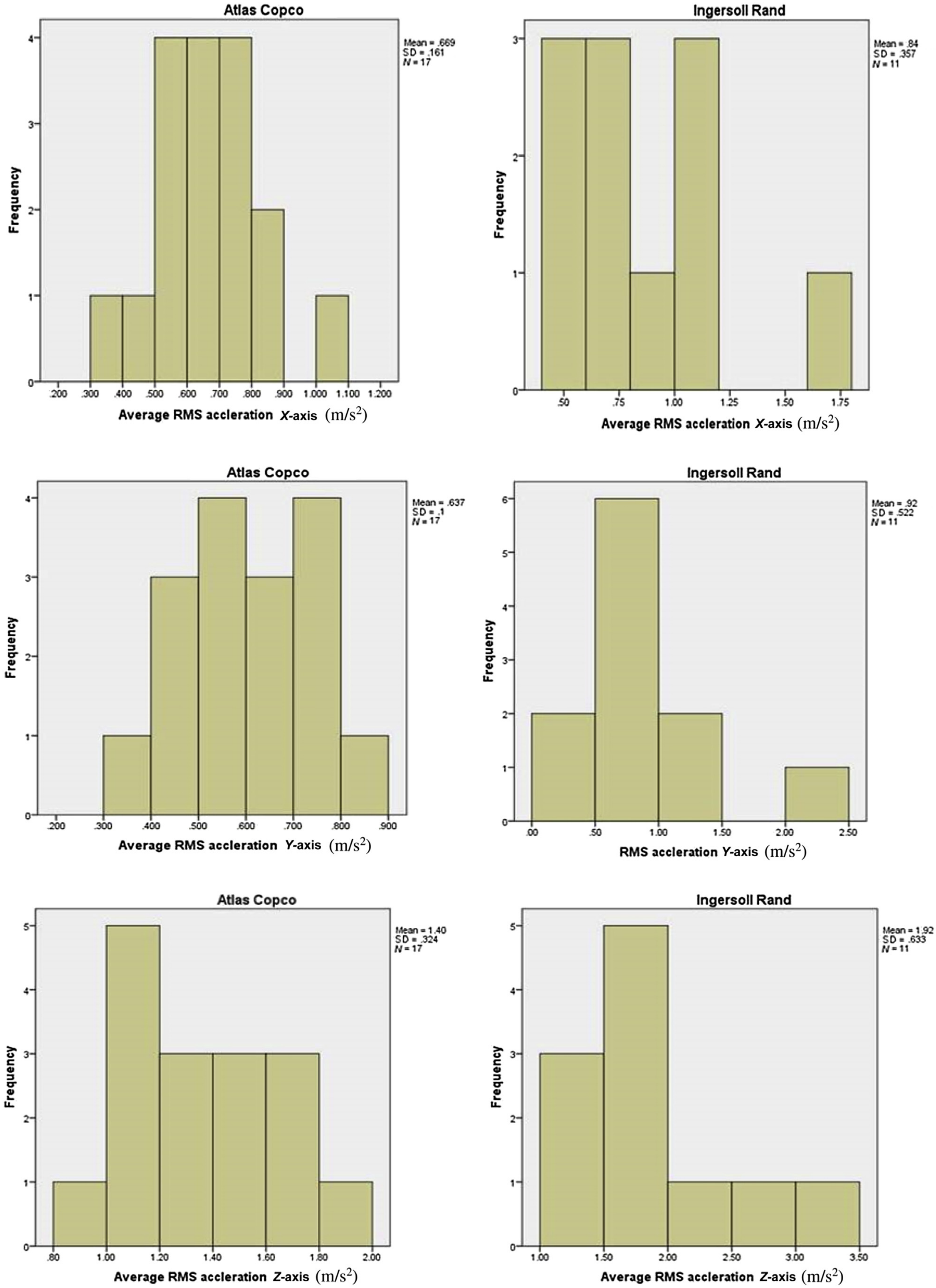

Fig. 5. Distribution of vibration levels of the drill machines along *x*, *y*, and *z*-axes. RMS, root mean square; SD, standard deviation.

Table 2
Characteristics of drill machine operators ($n = 28$)

	Mean or %	Median	SD	Skewness	Range	% of values below the ISO lower limit (0.45 m/s^2) [23]	% of values between the ISO lower and upper limits [23]	% of values above the ISO upper limit (0.9 m/s^2) [23]
Whole-body vibration (WBV): average RMS acceleration								
x-axis ($a_{wx,}$ lateral), m/s^2	0.73	0.68	0.26	1.39	0.37−1.61	10.7	67.9	21.4
y-axis ($a_{wy,}$ lateral), m/s^2	0.75	0.64	0.36	2.98	0.39−2.30	7.1	75.0	17.9
z-axis (a_{wz}, vertical WBV), per ms^2	1.60	1.49	0.53	1.26	0.83−3.15	0.0	3.6	96.4
Vibration total value (vector sum, a_{hv}), m/s^2	2.20	2.04	0.78	2.01	1.12−5.03	0.0	0.0	100.0
Operator's characteristics								
Age (y)	52.64	53	4.5	−0.32	42.0−60.0			
Weight (kg)	63.78	62	12.1	1.49	47.0−105			
Height (cm)	160.86	160	8.1	1.06	147−187			
Drilling experience (y)	15.96	18	7.3	0.03	05−30.0			
Machine-related factors								
Manufacturer*								
Atlas Copco	61							
Ingersoll Rand	39							
Drill's age (y)	06.41	5.75	1.8	0.11	03.5−08.5			
Seat height (cm)	56.32	55	3.6	0.39	50.0−63.0			
Thickness of seat pad (cm)	10.89	10	1.9	1.77	10.0−15.0			
Seat rest height (cm)	47.32	48	3.3	−1.12	40.0−50.0			
Rock-related factors								
Hardness	41.11	40	7.9	−0.02	28.0−52.0			
Uniaxial compressive strength (Mpa)	26.16	19.47	14.0	0.83	09.5−53.4			
Density (g/cm^3)	3.20	3.11	0.58	0.007	02.2−04.1			

* Binary variable coded 0 = Atlas Copco and 1 = Ingersoll Rand.
ISO, International Organization for Standardization; RMS, root mean square; SD, standard deviation.

($\beta = 0.045$, SE $= 0.018$), rock uniaxial compressive strength ($\beta = 0.027$, SE $= 0.009$), and rock density ($\beta_a = -1.135$, SE $= 0.235$).

4. Discussion

The present study demonstrates that all drill operators in iron ore mines in eastern India were exposed to a very high total vibration magnitude which is mostly due to the exposure in vertical axis. The exposure level exceeded the ISO upper limit. All the workers in these mines were thus highly vulnerable to an elevated health risk. The exposure along *x* and *y* axes was much lower. Such a greater vibration exposure along the *z* axis than along the *x* and *y* axes has also been reported in other studies on WBV exposure on various areas: railroad locomotives in United States [47], vehicles on test track in Canada [48], and haulage trucks in an aggregate stone quarry operation in United States [21]. Our work is an original study which investigated the WBV exposure of drill machine operators in mines. It is the first in this research area despite an expected high WBV exposure of drill operators and its consequences on health. Our findings may be an additional piece to the literature about the WBV exposure in mining industry that may help when designing prevention to limit the WBV exposure and its consequences on health.

We failed to find an influence of all operators' features considered (weight, height, and drilling experience), except operator's age for WBV *x* and *y*-axes as well as total WBV. These results were somewhat expected as all study operators were highly exposed to WBV and, in addition, the operator's age interval was reduced (42–60 years) while the operators appeared to be rather aged and thus with a decline in physical and mental capabilities as observed in the general population [49]. It should be noted that this was in agreement with the high prevalence of low and upper back pain (64.3%), pain in lower and upper limbs, and elbows (shoulders, forearm, elbows, wrist, hand and fingers, knees, legs, and feet; 67.9%),

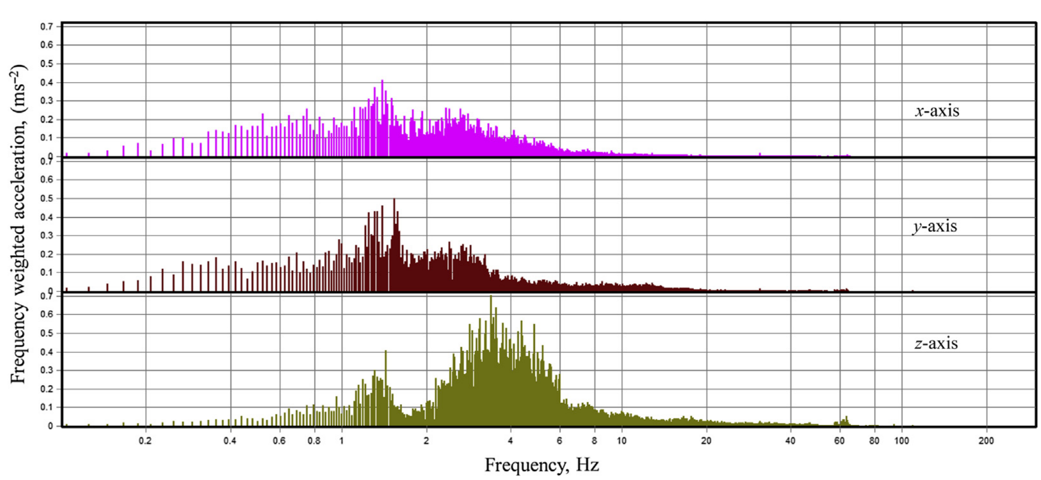

Fig. 6. Frequency distribution of vibration levels of the drill machines along *x*, *y*, and *z*-axes.

Table 3
Bivariate correlations between average RMS acceleration along three axes (a_{wx}, a_{wy}, a_{wz}) and vibration total value (a_{hv}) with various factors ($n = 28$)

	($a_{wx,}$ lateral WBV), m/s^2		($a_{wy,}$ lateral WBV), m/s^2		(a_{wz}, vertical WBV), m/s^2		(a_{hv}, vibration total value), (m/s^2)	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Operator's characteristics								
Age (y)	−0.288	0.138	−0.287	0.139	−0.322	0.095	−0.319	0.098
Weight (kg)	−0.080	0.685	0.008	0.966	−0.185	0.346	−0.104	0.599
Height (cm)	0.014	0.944	0.099	0.618	−0.155	0.431	−0.042	0.833
Drilling experience (y)	−0.040	0.839	−0.075	0.705	−0.280	0.149	−0.160	0.416
Machine-related factors								
Manufacturer[§]	0.318	0.099	0.385*	0.043	0.492[†]	0.008	0.453*	0.015
Age of drill	0.447*	0.017	0.406*	0.032	0.608[‡]	< 0.001	0.533[†]	0.003
Height of seat	−0.203	0.301	−0.080	0.687	−0.048	0.810	−0.103	0.602
Thickness of seat pad	−0.309	0.110	−0.249	0.202	−0.285	0.141	−0.302	0.119
Height of seat rest	−0.164	0.403	−0.090	0.648	−0.020	0.919	−0.091	0.644
Rock-related Factors								
Hardness	0.456*	0.015	0.395*	0.037	0.649[‡]	<0.001	0.561[†]	0.002
Uniaxial compressive strength	0.331	0.085	0.282	0.146	0.349	0.069	0.336	0.081
Density	0.026	0.897	0.021	0.917	0.217	0.268	0.129	0.512

Correlation coefficient was significantly different from zero with: *$p < 0.05$, [†]$p < 0.01$, [‡]$p < 0.001$.
[§] Binary variable coded 0 = Atlas Copco and 1 = Ingersoll Rand.
r, Pearson correlation coefficient; WBV, whole-body vibration.

presence of a disease (50%), and regular alcohol consumption (64.3%) which were revealed by a supplementary analysis on the study operators. The finding in our study that body weight was not a significant predictor for WBV is in agreement with the result of a study among rural workers driving quad bikes [39]. It is in contrast to the result of a study in urban taxi drivers which reported a relationship between a driver's body weight and WBV exposure [37]. This is due the fact that the effect of the body weight is observed for an effective seat suspension system while in our study the seat had no effective suspension system. Similar to a survey on 90 highway truck drivers [38], drilling experience was not a significant predictor of WBV exposure here. The association found between operator's age and WBV was also observed in a study previously stated in urban taxi drivers [37]. Our findings may also be partly attributed to a lack of power for statistical test due to a relatively small number of participants like in other studies in the literature [48,50–52]. Our findings suggest that prevention is needed to evaluate and monitor the WBV exposure and associated health problems for all drill operators.

This study shows that the age of drills is not a significant risk factor for WBV while manufacturer is an important predictor. One study on highway transport truck operators also found an influence of manufacturers of trucks on WBV exposure [38]. It may be noted that when both manufacturers and age of drill were considered in regression models, only the manufacturer was found to be associated with WBV exposure. Manufacturing of a machine had thus a higher potential role than its age. These results highlight that it is important to choose appropriate drill machines which are well designed and constructed by a manufacturer that uses good materials and carries out better assemblage. Our study further reveals that seat height, thickness of seat pad, and seat rest height do not predict vertical WBV exposure. Several studies observed a reduction in vibration magnitude for drivers by using correct seat suspension in various vehicles such as tractors and trucks [53]. It may be noted that in our study the drilling machines had no seat suspension systems. Prevention to limit the WBV exposure should consider the quality of drill machines and assure that they have a correct seat suspension system.

Finally, we found that rock density and uniaxial compressive strength were potential predictors of WBV. A compact packing of minerals in rock mass makes the rock mass dense and allows smoother drilling. Thus WBV level decreases with increase of density of rock. It was therefore expected that multivariate analysis retained rock density as a potential factor negatively related with

Table 4
Multivariate regression analyses[†] for average root mean square acceleration of drill machine operators in the three axes *x*, *y*, *z* (a_{wx}, a_{wy}, a_{wz}) and vibration total value in terms of various predictors ($n = 28$)

	$a_{wx,}$ lateral WBV, m/s^2		$a_{wy,}$ lateral WBV, m/s^2		$a_{wz,}$ lateral WBV, m/s^2		a_{hv}, vibration total value, m/s^2	
	β (SE)	*p*	β (SE)	*p*	β (SE)	*p*	β (SE)	*p*
Operator's features								
Age (y)	−0.02 (0.008)*	0.024	−0.034 (0.012)[‖]	0.007	–	–	−0.052 (0.023)*	0.032
Machine-related factors								
Manufacturer[‡]	0.318 (0.083)[¶]	0.001	0.579 (0.118)[¶]	<0.001	0.645 (0.152)[¶]	<0.001	1.093 (0.227)[¶]	<0.001
Height of seat rest	−0.037 (0.012)[‖]	0.004	−0.036 (0.018)[§]	0.053	–	–	−0.064 (0.032)[§]	0.058
Rock-related factors								
Hardness	0.013 (0.007)[§]	0.071	–	–	0.045 (0.011)[¶]	<0.001	0.045 (0.018)*	0.022
Uniaxial compressive strength	0.011 (0.003)[‖]	0.004	0.018 (0.004)[¶]	<0.001	0.011 (0.006)[§]	0.089	0.027 (0.009)[‖]	0.009
Density	−0.451 (0.086)[¶]	<0.001	−0.533 (0.125)[¶]	<0.001	−0.547 (0.144)[¶]	<0.001	−1.135 (0.235)[¶]	<0.001
R^2 (explained variance)	0.704		0.632		0.714		0.746	

* $p < 0.05$.
[†] With stepwise procedure retaining predictors significant ($p < 0.05$) or close to significance ($p < 0.09$) only.
[‡] Binary variable coded 0 = Atlas Copco and 1 = Ingersoll Rand.
[§] Close to significance ($p < 0.09$).
[‖] $p < 0.01$.
[¶] $p < 0.001$.
β, regression coefficient; RMS, root mean square; SE, standard error; WBV, whole-body vibration.

WBV. It is a fact that the stronger the rock material, the more energy is required for drilling. This is reflected in our finding that the compressive strength is a potential predictor positively related to WBV. Rock hardness was also a potential predictor for WBV exposure in x and z axes and for vibration total value (except for WBV in y axis). It is well known that when the drill bit encounters the hard grains in the rock mass, it experiences a shifting form in its path and this results in vibration of the drill bit and drill rod. Therefore, rock hardness was positively related to WBV. Our study reveals all three rock related factors as potential predictors of WBV because their variation in magnitude was high, particularly for hardness and compressive strength.

The present study had some limitations and strengths. It measured WBV level experienced through summer to spring and did not encompass all seasons of the year. However, we think that the seasonal variations of WBV exposure are small. As in other studies [48,50–52], the study population was relatively small which may lead to a lack of power for statistical tests. The role of machine-related factors such as feed pressure and rotary pressure which may have influence on WBV, could not be assessed in this study. The study mines belong to the same company and were from the same geographical location which has facilitated the study. All the drill machine operators participated in this study.

In conclusion, the present study demonstrates that all drill operators in iron ore mines in India are highly exposed to WBV exposure and consequently to an increased risk of health problems as suggested by the ISO 2631-1 (1997) guidelines [41]. The WBV exposure is associated with the drill manufacturer and the nature of the rock (uniaxial compressive strength and density) and not to the operator's stature and nor to his age and drilling experience. The company and the workers may be informed about these risks in order to find remedial measures. The operators should be aware of the risk and the consequences of WBV on health (back disorders, low back pain, intra-spinal forces, Raynaud's phenomenon of fingers and toes, myocardial infarction, etc.) [6,18,50,54–56]. As the nature of the rock cannot be changed, WBV prevention should be explored by the following ways: using the most suitable and recent machines with proper design in mines which can handle higher rock uniaxial compressive strength and density; improvement of the seat including an appropriate suspension system; and ergonomic and participative approaches development to limit prolonged sitting and improve cab design [35]. However, these possible interventions should be monitored and evaluated.

Conflicts of interest

All authors have no conflicts of interest to declare.

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