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Whole body vibration exposure and its effects on heavy earthmoving machinery (HEMM) operators of opencast mines – a review

Operators of opencast heavy earthmoving machinery (HEMM), during their 8-hour shift duration, are regularly succumbed to the high level of whole body vibration (WBV) amplitudes. Due to long and continuous working in the field, the operators of HEMM may yield to adverse health effects and results in hazardous conditions if the magnitudes repeatedly exceed the permissible limits. Based on extensive literature review, the authors of the paper put forward the recognized harmful adverse health effect of short and long-term WBV exposure of HEMM operators in surface mining and also with the same view with the findings of various researchers in this field and feels that for the safety of operators, long-term understanding of WBV should be carried out instead of short term vibration monitoring.

Keywords: *Whole body vibration (WBV), heavy earth-moving machinery (HEMM), low back pain (LBP), health guidance caution zone (HGCZ), root mean square (RMS)*

1. Introduction

Opencast mines, to meet the elevated targeted production have introduced a high level of mechanization by deploying heavy-duty sophisticated machines for production and other related mining activities. Since the machines are regularly plying in unpaved and undulated surfaces the operators have succumbed to WBV. The magnitude of impact on human health depends upon the duration of operation, sitting posture, seat arrangement, and transmission characteristics of vibration to the operator's seat due to the movement of various parts of the machines concerning road conditions. Working under contentious exposure of vibration over several years may result in adverse effects on personnel physique in the form of either disease or injury to different parts of the body. The generalized ill-effect of WBV are spinal disorders in the form of lumbar scoliosis and disc, chest pain, abdominal pain, sickness, fatigue, loss of balance, headache, neck problem, tear or damage to tissues and muscles along the spinal cord, etc (Fig.1). It has also been established that either poor maintenance of HEMMs or deterioration in road conditions plays an important role in influencing the operator's health vis-à-vis poor workmanship and loss of production in the excavation world. So, to meet the high rated targeted production from the available systems, it is of paramount importance for the mining/excavation personnel to improve the haulage road conditions and machine vibration magnitudes i.e. machine health, and subsequently, reduce the hazardous exposure of operators. Cross and Walters found that WBV and vehicle jarring is a major factor and have a significant risk to mobile equipment operators' related to back pain in the mining industry [1]. Depending upon the exposure time, the operators of off-road vehicles i.e., HEMM drivers have always exposed to the hazardous environment and the magnitude depends upon haul road conditions, vehicle maintenance, status of shock absorbers, seats, and tires. The degree of harmful impact also varies with the characteristics

Fig.1 The spinal column and vibration concerns [3].

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of psychosocial stresses, a posture of sitting on the driver's seat, the contact surface area, type of work, concerning vehicle configuration, and the operator's weight [2].

The permissible duration of exposure for any operator is also influenced by the design of hydraulics of the equipment and their maintenance [4-5], the seat height with quality of suspension [6-7], tire specifications [8], the transport road conditions [9], operators' duty and aptitude and behaviour in that aspect [10] and body structure, the strength of bones, tissues and internal organs [11-12]. The influence on any physique due to WBV as stated by Rasmussenis is given in Table 1. Rasmussen in his study determined the frequency levels where different types of discomforts were observed by operators. The Table 1 indicates the discomfort frequency ranges and is observed that the frequency discomfort zone is mostly varying between 4 and 20 [13].

TABLE 1: SYMPTOMS AT DIFFERENT FREQUENCIES

Symptoms	Frequencies (H_Z)
A general feeling of discomfort	4-9
Head symptoms	13-20
Lower jaw symptoms	6-8
Influence on speech	13-20
Lump in throat	12-16
Chest pains	5-7
Abdominal pains	4-10
Urge to urinate	10-18
Increased muscle tone	13-20
Influence on breathing movements	4-8
Muscle contractions	4-9

2. Whole body vibration standards and regulations (Table 2)

TABLE 2: STANDARDS AND REGULATIONS FOR WHOLE BODY VIBRATION

ISO 2631-1:1997	Mechanical vibration and shock: Evaluation of human exposure to WBV: General requirements
BS 6841:1987	Guide to measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock
European directive 2002/44/EC	Occupational vibrations
ANSI S3.18:2002	Adoption of ISO 2631
AS 2670.1: 2001	Evaluation of human exposure to whole-body vibration (ISO 2631) Part 1: General requirements
EN 14253: 2003	Mechanical vibration – Measurement and calculation of occupational exposure to whole-body vibration with reference to health – Practical guidance
GB/T 18368: 2001	Comfort evaluation of human exposure to whole-body vibration in recumbent position.
VDI 2057-2: 2017	Human exposure to mechanical vibrations Part 1: Whole-body vibration
IS 13276 (Part 1): 2000	Adoption of ISO 2631

3. Literature review

The literature review has been carried out to summarize the present know-how on the effects of WBV on HEMM operators in opencast mines. In this regard, 33 papers were shortlisted from 352 searched and published documents. The algorithm to study the requisite papers is detailed in Fig.2. Even though there have been numerous studies in this area, only a few publications have been considered for review. The review related to discomfort has been considered that have been published in the form of scientific publications, reports, conference proceedings, dissertations, standards, guidelines, and legislation. Based on the studies, the authors want to clearly specify the problems of WBV exposure in opencast mines and how health and discomfort are related. With the help of various research articles related to field study, an extensive review related to WBV has been evaluated. Based on these, the authors of the paper want to highlight the impact of machine vibration on human health and its importance in the mining industry. Based on the comprehensive literature review and sustain an eco-friendly environment between man and machine, the authors firstly aim to improve the present knowledge of human vibration in short and long-term exposure and thereafter the precautionary measures to be adopted to improve the production and productivity in mines.

Since the last four decades, many researchers have investigated the effects of the operator's exposure on whole-body vibration due to long term operation of different types of equipment [14-19]. Though the effects are complex and have non-linear behaviour due to intricacy in the proper understanding of the complete physiological phenomena, it can be broadly concluded that the impact on human health will vary with vibration amplitude, direction, frequency, duration, and to which part of the body it is directed. It is commonly known that regular exposure to vibration magnitudes results into health problems, but the mechanics of the causes are still not properly and completely understood. Based on the problems faced during 1970's and 1980's, the International Standard ISO 2631-1 carried out some research work to develop a measurement methodology and estimate whole-body vibration exposure limits related to discomfort and other occupational diseases [19]. Based on the experimental field studies, the findings state that the effects of long term high-intensity WBV increases the health risk to the lumbar spine and affects the connected nervous system. It also recommends that the influence on human health by whole-body vibration is slow and therefore the measurement and impact on exposure period should be regularly measured to minimize the untoward health effect.

The HGCZ for evaluation of exposure risk can be explained graphically as shown in Fig.3. The maximum measured translational component of the frequency-weighted acceleration is considered for analysis and the highest weighted acceleration is considered for transient events.

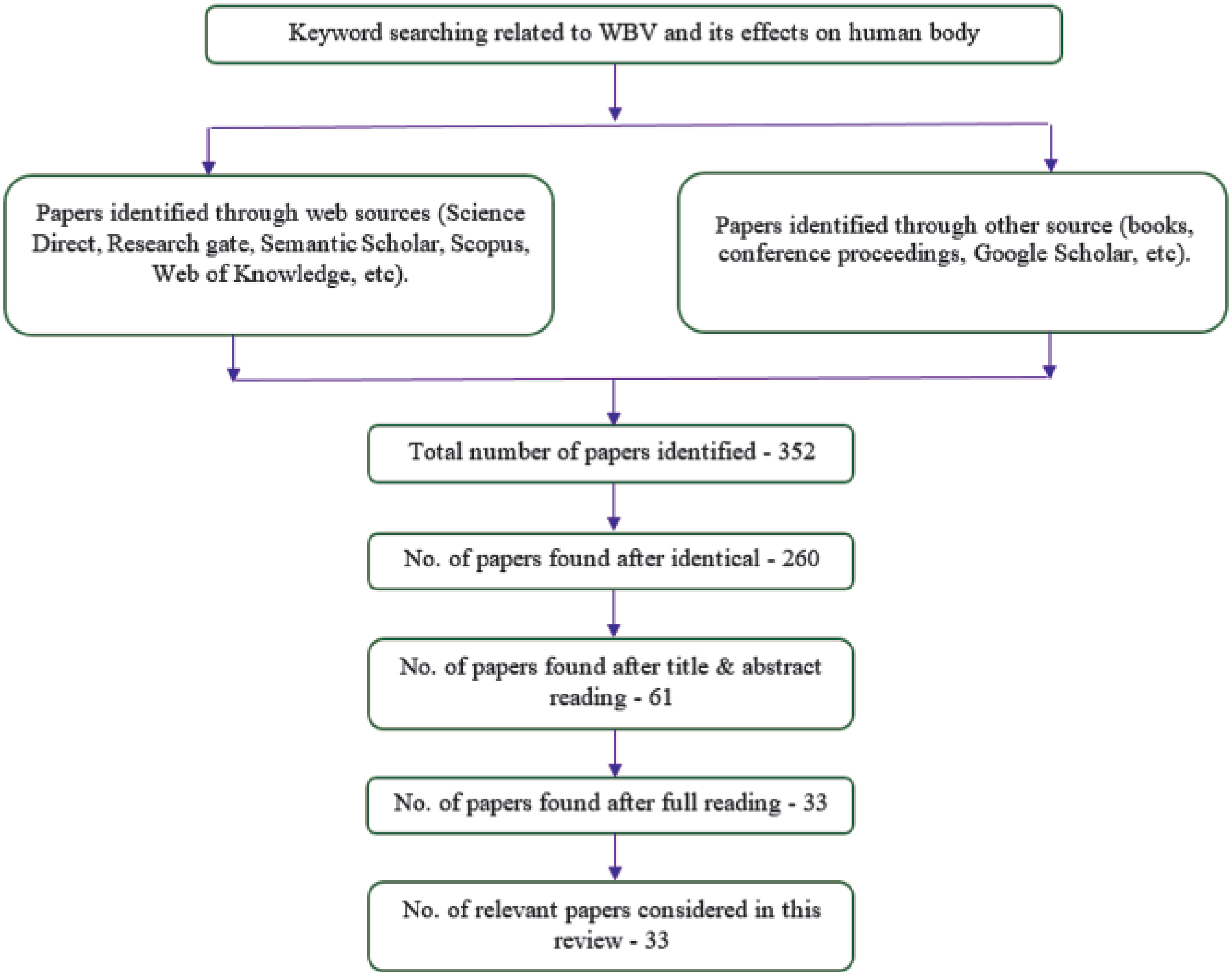

Fig.2 Search strategy and article screening process

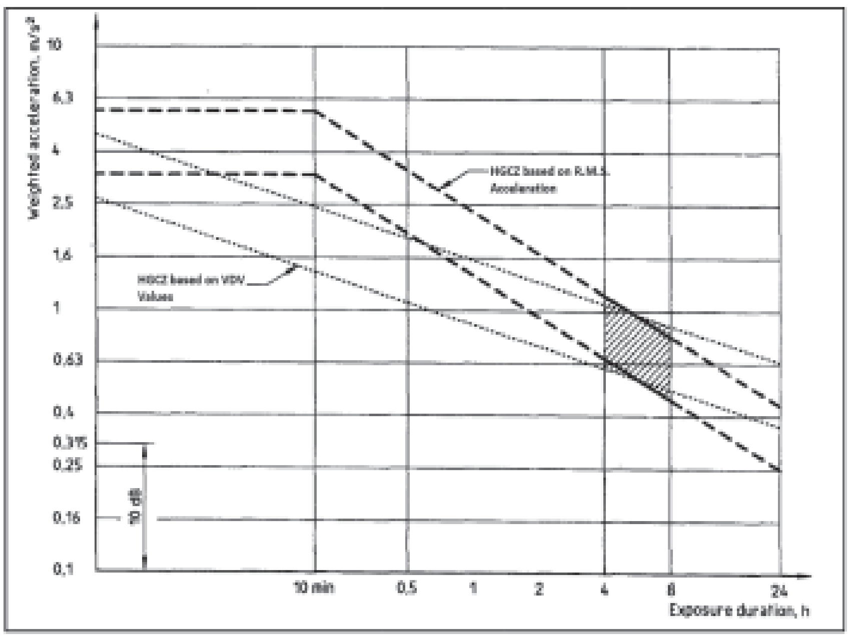

Fig.3 Health guidance caution zone (ISO 2631-1:1997)

Based on the two equations namely RMS based acceleration and vibration dose value (VDV) by putting n=2 and n=4 are plotted respectively. HGCZ is the area bounded by two sets of parallel lines plotted for the two equations. Thereafter, considering the time of exposure, the impact on health can be assessed. In the figure, the shaded area indicates a potential increase in health effects whereas above this exposure zone, health effect is expected [20].

Based on the European risk observatory report carried in France it is observed that the HEMMs operating in the excavation zone rarely crossed the limit of 1.15 ms^{-2}. Based on the study and average acceleration generated by different types of vehicles, Fig.4a, mean daily (A_8) exposure to vibration and standard deviation for off-road machines have been derived, Fig.4b [21].

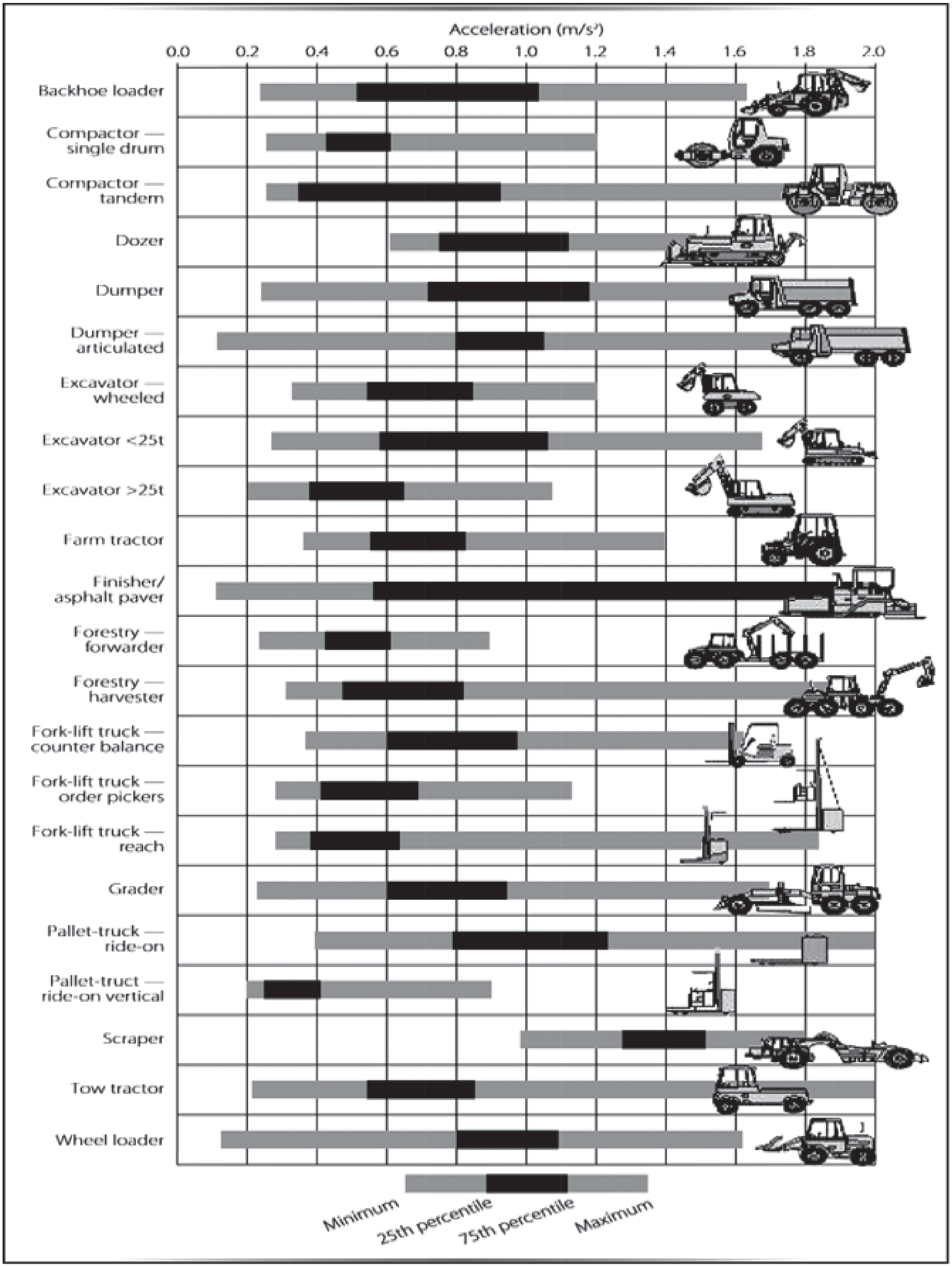

Fig.4(a) Vibration magnitudes for common mobile machines

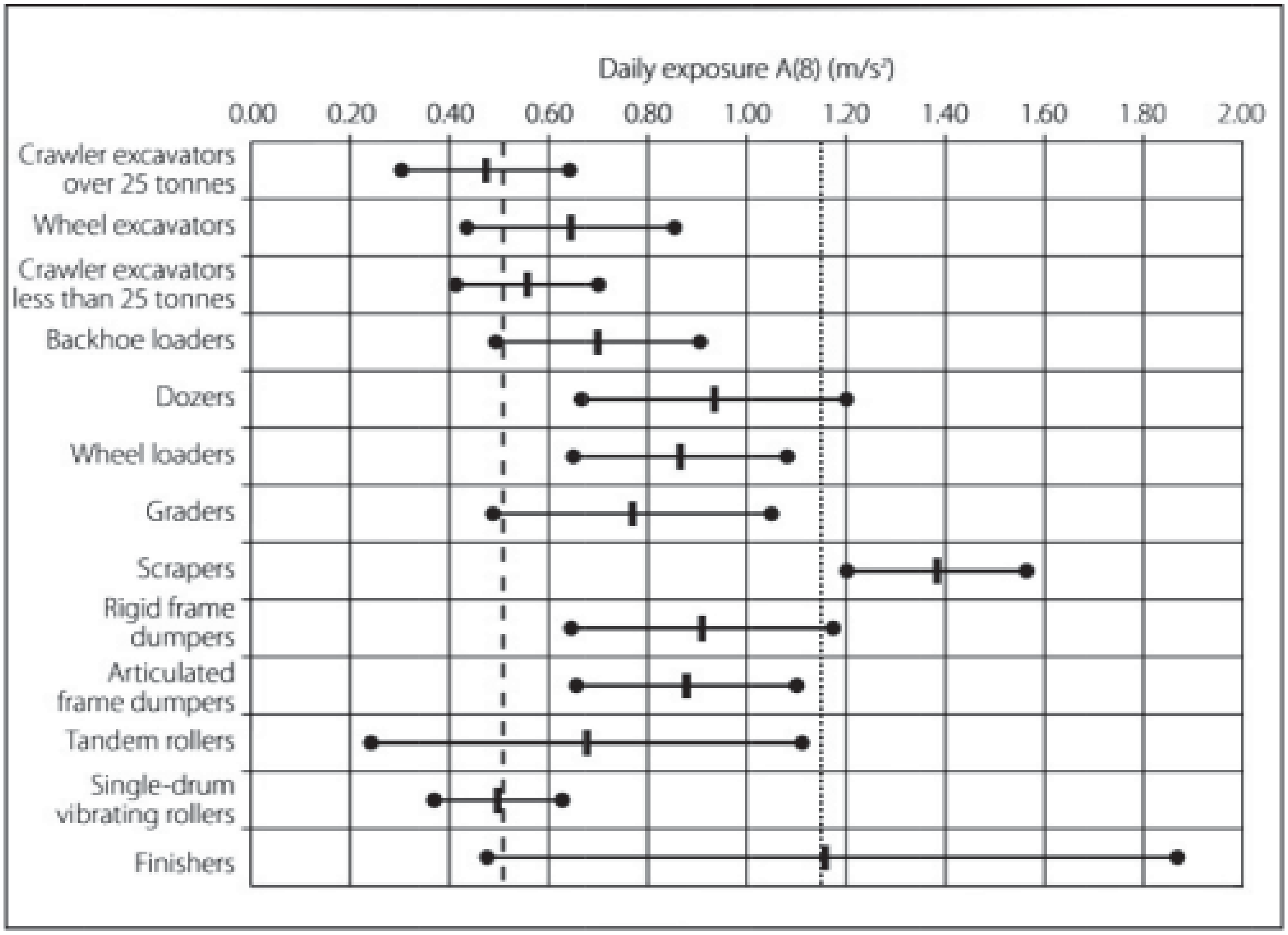

Fig.4(b) Machine wise daily exposure limits

Wolfgang and Limerical predicted the exposure of haul truck operators to WBV during their working hours in different road conditions. The different road conditions were mainly rough terrain of new production zone having moist weather, graded surface, and a combination of rough and maintained surface in a surface coal mine in New South Wales. 32 measurements made from 32 different capacities (136 t to 290 t) of haul trucks in different terrain revealed that the magnitude of acceleration for dumpers fell within the HGCZ for a work duration of 8 hours. The authors also concluded that for the same road condition, the magnitude of vibration varied with an increase in load-carrying capacity and the magnitude was higher for small-sized dumpers [22].

Kumar, carried out a study on heavy haul trucks used for the transport of overburden material. The monitoring was done to determine the vibration magnitude in orthogonal axes of the seat pan and the vibration experienced by the operators at the third lumbar and seventh cervical vertebra. The vibration data was collected during different tasks (loading, driving, dumping, and returning). The study concluded that though the magnitude of acceleration was high at the seat pan, the transmitted acceleration was low in lumbar and cervical bones and attenuated with a height of measurement in the body of the operator. But the magnitude of vibration in the vertical direction was always high causing ill effects on operators. The authors felt that multiple cushioning or padding should be implemented to reduce the transmission magnitudes to the operators. Similarly, to reduce the vibration impact on operators, the speed of plying should also be moderated during the loaded and unloaded conditions [23].

Choudhary et al., investigated the impact on operators of large blasthole drill machines and rock parameters. During the study, frequency weighted RMS acceleration (m/s^2) was monitored with respect to ISO recommendations. The machine and rock parameters that were considered are machine manufacturer, age, height, and thickness of the seat and rest height. Similarly, the rock parameters that were considered to monitor the magnitude of vibration were rock hardness, uniaxial compressive strength, and density. Authors after the study conducted for 28 operators working in different iron ore mines concluded that the magnitude of vibration increased with an increase in strength properties rock and age, height of the seat in the machine. Considering the above study the authors of the paper felt that the mechanics of vibration transmission should be properly understood and modification in the designs should be implemented to achieve lower magnitudes of vibration [24].

Smets et al., measured WBV at the seat/operator interface for eight haulage trucks of three sizes (35, 100 and 150 t) for different activities namely during loading, driving with a full load, dumping, and driving with an empty load, of normal operation. The magnitudes for equivalent daily exposure ranged between 0.44-0.82 ms^{-2} for frequency-weighted RMS and 8.7-16.4 ms^{-2} for the vibration dose value method. Most of the operators experienced musculoskeletal discomfort associated with vehicle operation. They found maximum acceleration along the z-axis (vertical) and maximum weighted RMS vibration magnitude during the loaded and unloaded travelling [25].

In addition to the above study, Mayton et al., also reviewed the Hand Arm Vibration (HAV) in addition to WBV of haul truck operators for a US surface mines/quarries. Considering HGCZ, weighted RMS accelerations, and vibration dose value (VDV) were mostly below the Exposure Action Value (EAV) for all the activities regularly carried out with dumpers. The authors, however, commented that during plying either down the slope or in wet and slippery roads, the Exposure Limit Value (ELV) was of exceptionally high percentage for VDV_x and aw_x, respectively [14].

Aye et al., measured the whole body vibration level by considering two main parameters, namely the daily exposure $A_{(8)}$ and VDV on various machines in a South African opencast mine. The study concluded that though the exposure action value exceeded for 50% of the vehicles, the exposure limit value was less for 90% of the vehicles. A similar study was also carried out by Remington et al., 1984 and concluded that about half of the operators were exposed to the vibration that exceeded the fatigue and thereby reduced the efficiency of operators. During the study, it was observed that less than 22% experienced vibration exceeding the exposure limit. The authors of the paper feel that the magnitude of vibration is directly proportional to road conditions, age, and quality of maintenance of machines and the experience and age of operators [26].

Blood et al., studied the impact of tires on WBV. Considering three types of tires and human parameters namely age, height, weight, and experience of operators, the study was conducted for three different activities i.e. driving on city-street, plowing, and scooping and dumping. The study observed that WBV was least for stock rubber-mounted tires and maximum for ladder chain mounted tires. The analysis of the data produced by the authors illustrates that the vibration magnitude on the operator's seat is the reflection of the resultant force generated during different activities with different types of tires. The magnitude of vibration with chain ladder is maximum due to the difference in surface topography on tires i.e., for ladder chain having intermittent chain lace crossing the tire width there is a frequent elevation difference during plying, resulting into an increase in vibration magnitude. However, with the basket-type chain, the tire being regularly covered the tire results into minimum contact with the floor i.e. minimum elevation difference between basket type chain, tires, and floor [27].

TABLE 3: SYMPTOMS OF VIBRATION EXPOSURE TO THE DIFFERENT ORGAN [28]

Health complaints	Symptoms of vibration exposure
The orthopedic and neurological system	• Localized or radiating pain, discomfort, numbness, tingling, loss of feeling and muscle control in spine or extremities
Gastrointestinal system	• Nausea, vomiting, indigestions
	• Flank pain (renal)
	• Hemorrhoids-related seating discomfort
Female reproductive organs	• Localized pain, discomfort, irregular periods, concern for pregnancy
Prostate	• Concern for cancer – symptoms: hematuria or prostate enlargement/PSA marker elevation
	• Peripheral veins
	• Cochlea-vestibular system – vertigo

TABLE 4: ADVERSE HEALTH EFFECTS MENTIONED BY DIFFERENT AUTHORS

Authors	Year of Publication	Findings
Seidal	1993, 2005	The harmful impact of WBV results into biochemical and biomechanical impacts on the human body resulting into LBP, spinal and neck problems, and other related problems to lead a regular healthy life[29-30].
Mandal and Srivastava	2010	Poor environmental condition, habits of miners and posture relates to physical disorder in the form of back pain[31].
Blood et al.	2010	Poor road conditions and maintenance of vehicles leads to an intermittent impact on operators in terms of spinal disorder and fatiguing of associated muscles[7].
Martin et al.	2010	Regular exposure for a high time duration to WBV will have the risk of musculoskeletal injuries by fatiguing or damaging the soft parts related to the spine and related associated muscles[25].
Kim et al.	2018	Operators of HEMM's having a long duration of operating time for excavation of mineral may enhance the biomechanical loading in the vertebra and its associated muscles[32].

4. Conclusion

Ergonomic study for HEMM operators in mining industries is presently an over riding clause to improve productivity and competitiveness in the global scenario. It will also help to build up high morale in HEMM operators throughout the workplace, decrease absenteeism, and with the decrease in workplace injuries and health problems. The literature review illustrates that exposure time to WBV is important and different diseases in addition to the LBP problem are mostly affecting the HEMM operators. It is also found that the harmful ill-effects (fatigue, insomnia, headaches, and shakiness) are mainly due to high frequency and magnitudes of vibration faced by the operators during any working shift. The authors here found that in addition to regular monitoring of WBV, attention is required for regular machine maintenance to improve the health and safety of operators. Regular monitoring of vibration and the probable cause of such magnitudes should be properly identified and rectified. Haul roads with proper road conditions and gradient should be properly maintained to reduce vibration. Implementation of hydraulic suspension, adjusting the clearance of base from the ground during driving, air/hydraulic suspension in driver's seat, and cushioning between the HEMM body and operator's seat should be properly evaluated during dumper design to reduce continuous and impulsive vibration and reduce adverse health outcomes.

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