

A Research Methodology for Assessment of Whole-Body Vibration Exposure of HEMM Operators in Mines — An Approach

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The main objective of this paper is to provide an approach to assess the exposure of Whole-Body Vibration (WBV) on the Heavy Earth moving Machinery (HEMM) operators and its impacts on Musculoskeletal Disorders (MSDs) taking into consideration of various contributing factors. The WBV is measured using a human vibration analyzer. Anthropometric measurements along with postural assessment are carried out simultaneously. Data related to physical and physiological factors are evaluated using a questionnaire survey on personal, machine, work environment, and health parameters. After data collection, modelling, and analysis are done using a suitable machine learning tool to get a better knowledge of the occurrence of MSDs at workplaces. Various models are used in the literature for the assessment of risks faced by the operators exposed to WBV hazards. This modelling would help in identifying the role of contributing factors of WBV to inflict MSDs on the workers, with a view to either eliminate or minimize its detrimental effects. Adoption of this research methodology will help researchers to measure WBV, collect data on contributing factors, and to establish correlations with any type of MSDs using a suitable machine learning tool.

Keywords: Equipment operators, Human vibration, Musculoskeletal disorders (MSDs), Rapid upper limb assessment (RULA), WBV contributing factors

Introduction

Vibration is an oscillatory motion usually perceived as a to-and-fro motion of a body about a fixed axis. The human body responds to vibration depending on its mode of entry, that is either Hand-Arm Vibration (HAV), or Whole-Body Vibration (WBV). The HAV refers to vibration that enters the body through hands and arms, typically transmitted through hand-held powered tools like drill machines. In contrast, WBV enters the body through an intermediate supporting surface, while the person is standing, sitting, or resting back on a vibrating object. The WBV is commonly encountered in seated vibrating machinery.^{1,2} It can also be experienced by the general public in daily life, like travelling in or riding a bus/train/car/motorcycle. It occurs due to continuous contact with the vibrating surface. Vibration at low frequencies is recognized as a hazard, affecting people at work in a variety of industries, *inter alia*, agriculture, construction, mining, manufacturing, and transportation.

Mining industry is considered as one of the high-risk occupations from vibration hazards point of view.

Various unit operations of mining, such as drilling, loading, and transportation generate vibration that can affect the workers exposed to WBV. These processes are carried out using Heavy Earth Moving Machinery (HEMM) that includes dumper, shovel, drill machine, scraper, and loader. The HEMM produces machine vibrations or shocks which are transmitted in the human body via HAV or WBV. The WBV responds to vibration in the frequency range of 0.5 to 80 Hz. When WBV is transmitted to the human body as a whole or any individual part of the body at the natural vibration frequency of the body, it results in resonance. Under such condition, the whole body or individual part will vibrate at a higher magnitude of frequency than that of the applied force itself. As a result, it manifests as muscle contraction in a voluntary way and causes fatigue or lower performance of the muscle; consequently leading to a number of health hazards.³

In the United States alone, over four million individuals are exposed to WBV every day, out of which more than half a million individuals operate HEMM that causes a high exposure of WBV.⁴ Many researchers have reported that long-term exposure to WBV as well as adoption of awkward posture can lead to Musculoskeletal Disorders (MSDs). As per World Health Organization (WHO) report 2021,

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approximately 1.71 billion individuals worldwide suffer from MSDs. Lower Back Pain (LBP) is the most common symptom of MSDs caused to professional drivers, or persons continuously exposed to higher level of vibration.^{2,5-8} According to many epidemiological researchers, long-term exposure to WBV has been linked to pain in lower back⁵ as well as upper back^{2,7,9}, early lumbar spine degeneration^{10,11}, and intervertebral disc disorder.^{12,13}

The MSDs are the primary contributor to disability across the globe. The LBP is the single largest cause of disability in many countries. In Canada, prevalence of MSDs, in general, is high. Overall prevalence has increased from 23.01% in 1990 to 27.8% in 2017.⁽¹⁴⁾ Many research works have been conducted for the measurement of WBV and understanding the role of its contributing factors. However, it has not been fully explored how the contributing factors affect the man-machine interface, leading to MSDs.

Therefore, this paper discusses the influences of multidisciplinary factors of WBV in causation of MSDs at the workplaces. This paper provides a comprehensive methodology on vibration measurement, questionnaire formulation and its validation, human anthropometric factors, and statistical machine learning algorithm to understand and analyze how various contributing factors are correlated to the MSDs.

Work Process Flow

The work process flow (Fig. 1) outlines the systematic steps to be adopted for measuring WBV, collecting data on contributing factors, and correlating them with MSDs using a suitable machine learning tool.

WBV and Its Measurement

Whole-Body Vibration

As mentioned earlier, WBV is generally caused by the vehicles and working machinery.¹ Higher level of WBV can lead to health risks, which becomes more important when exposure period is long, its magnitude is high, and the vibration also includes frequent impacts or shocks.¹⁵ Therefore, in order to ensure a safe and healthy work environment, the International Organization for Standardization (ISO) has established specific guidelines with demarcation of the limits.

The ISO has issued guidelines like ISO 2631-1:1997 (Mechanical vibration and shock – evaluation of human exposure to whole-body vibrations)¹, and ISO 2631-5:2004 (Mechanical vibration and shock – evaluation of human exposure to WBVs containing multiple shocks)¹⁶, for measurement and evaluation of WBV exposure. According to ISO 2631-1:1997, vibrations shall be measured at the point(s) from which vibration enters the body. There are three contact points in the human-machine interface through which WBV is transmitted to human being from the vibrating machine. The contact points are back, ischial tuberosity (i.e., bottom of the pelvis), and feet. Most of the vibration measurements are conducted using an accelerometer, placing it at ischial tuberosity. The illustration in Fig. 2 shows the basic axes of the human coordinate system, which is used for the measurement of WBV as per ISO 2631-1:1997 guidelines.

According to the ISO 2631-1:1997, magnitude of human vibration is measured either by frequency-

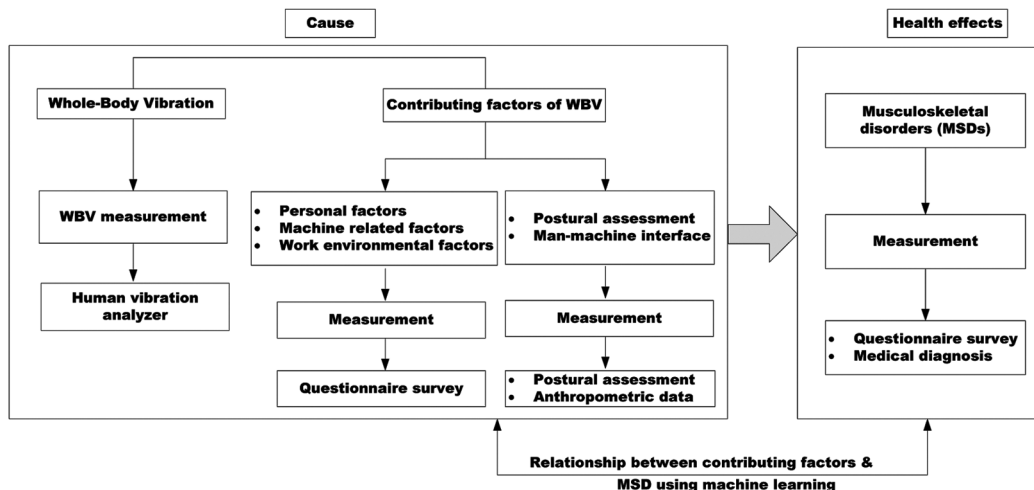


Fig. 1 — Work process flow

weighted ‘Root Mean Square’ (RMS) acceleration or by ‘Vibration Dose Value’ (VDV) for eight hours, generally expressed as A(8) for RMS and VDV(8) for VDV. These are considered as the principal methods of defining the frequency-weighted acceleration amplitudes for WBV measurement and assessment.¹⁷ For the 8-hour exposure, ISO 2631-1:1997⁽¹⁾ defines the boundary of the Health Guidance Caution Zone (HGCZ), as depicted in Fig. 3.

It can be observed from Fig. 3 that if the A(8) is less than 0.45 m/s², the vibration has no health risk. If it lies between 0.45–0.90 m/s², it can pose potential health risk. And, health risk is likely to be caused if it is greater than 0.90 m/s². On the other hand, in case of VDV(8), the value less than 8.5 m/s^{1.75} denotes less likely health risk, in between 8.5–17 m/s^{1.75} indicates potential health risk, and more than 17 m/s^{1.75} gives the signal for likely health risk.

Similarly, ‘Static Compression Dose’ (*S_{ed}*) and ‘factor *R*’ are measured following ISO 2631-5:2004 guidelines.¹⁶ The *S_{ed}* represents the cumulative

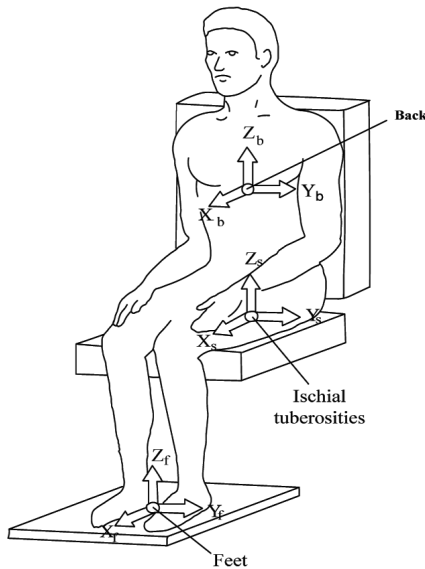


Fig. 2 — Baso-centric axes of the human for WBV measurement

exposure of the human body or a mechanical system to static compressive force over time. It demonstrates a linear relationship between the components of the compressive stress caused by input shocks and the peak acceleration response in the spine, achieved by normalizing the acceleration dose for average daily exposure. An *S_{ed}* below 0.5 indicates a low probability of adverse health effects, while an *S_{ed}* value above 1.2 bears a high probability of health risk.

Moreover, factor *R* is a measure to assess the risk of injury on the lumbar spine induced by WBV exposure and repetitive shocks. It estimates the cumulative effect of WBV over time, considering amplitude, duration and frequency of vibration. It is calculated considering the age of the worker, as exposure time increases with age. The factor *R* below 0.8 suggests a low probability of adverse health effects, whereas factor *R* above 1.2 indicates a high probability of health risk.¹⁸ It may be noted that with increasing age of the operator, the strength of the lumbar spine decreases.

A few human vibration analyzers are given in Table 1.

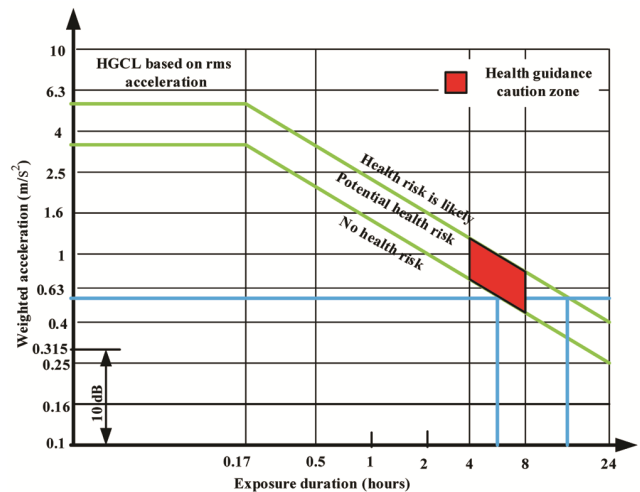


Fig. 3 — Health guidance caution zone of ISO 2631-1:1997⁽¹⁾

Table 1 — A few WBV measuring instruments

| Make ^{Ref} | Model | Frequency range |
|------------------------------------|-------------------------------------|---|
| Brüel & Kjaer ^{6,8,19,20} | Human vibration analyzer type 4447 | 8–1000 Hz (HAV) 0.5–80 Hz (WBV) |
| SVANTEK ^{21,22} | SV human vibration meter & analyzer | 0.5–2 kHz for 1/1 octave band 0.40–2.50 kHz for 1/3 octave band |
| Larson Davis ^{12,18} | Larson Davis HVM 100 | HVM 100 bandwidth depends on the type and model of accelerometer. |
| | Larson Davis HVM 200 | HVM 200: 0.5–2 kHz for 1/1 octave band, 0.40–2.50 kHz for 1/3 octave band |
| Norsonic ²³ | Nor No. 113, 1286 | 0.6–65 Hz (WBV) |

WBV Measurement Procedure

For WBV measurement, the seat pad accelerometer is positioned on the HEMM operators’ seat, as depicted in Fig. 4. Measurements are carried out at the operator–seat interface using a tri-axial seat pad accelerometer, along with a control panel that records the vibrational exposure as signals, known as a human vibration analyzer. The complete WBV measurement procedure and assessment using vibration analyzer is shown in Fig. 5.

During measurement, the accelerometer is mounted on the operator’s seat at the ischial tuberosities, where the operator sits while operating the HEMM. To minimize measurement errors caused by nominal displacement due to inadvertent movements of equipment operators, a temporary adhesive tape is used to securely fix the seat pad accelerometer in place. The accelerometer measures vibration in three translational axes based on human basi-centric axes, namely fore-and-aft (*x*-axis), lateral (*y*-axis), and vertical (*z*-axis) axes. During measurement, appropriate frequency-weighting curves are applied for each axis: W_d for *x*-axis, W_d for *y*-axis, and W_k for *z*-axis. The accelerometer is placed in the ischial tuberosities position such that the *z*-axis is always along the direction of the spinal column (Fig. 4).

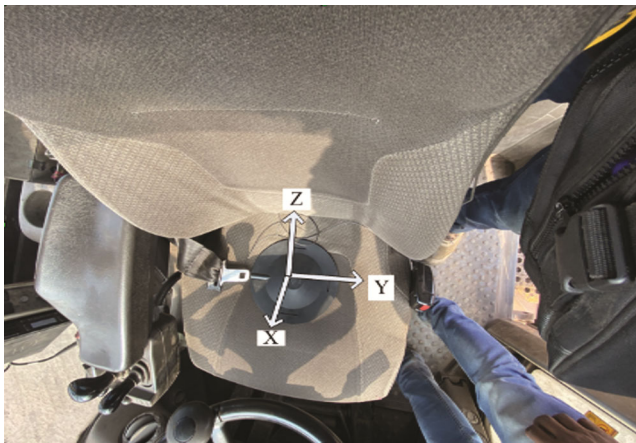


Fig. 4 — Positioning of seat pad accelerometer on dumper operator’s seat

Once the setup is made, the accelerometer is connected to the human vibration analyzer. Then the HEMM operator is asked to perform his daily routine work. The ISO 2631-1:1997 recommends a minimum duration of 20 min for WBV assessment. In certain cases, a complete cycle or multiple cycles of the activity are recommended depending on the mine layout, specific activity, and equipment capacity. Signal data is temporarily stored in the human vibration analyzer itself, which is later transferred to a Laptop/PC through a data cable (Fig. 5). Subsequently, the data is processed to estimate the daily exposure dosage. The daily exposure A(8) and VDV(8) are then compared against HGCZ of ISO 2631-1: 1997 (Fig. 3) to know the vibration risk level.

WBV & its Contributing Factors

The WBV, in combination with various contributing factors, leads to MSDs amongst the operators of vibrating equipment. These contributing factors can be broadly divided into four categories: (i) personal, (ii) machine related, (iii) work environment, and (iv) human physical as well as man–machine interface factors.

Personal Factors

The personal factors of the operators such as age, experience, Body Mass Index (BMI), anthropometric characteristics, health status, and biodynamic response are the leading contributing factors of WBV exposure. Many studies have been carried out to find a relationship between the age of the operator and WBV exposure for causation of MSDs. As the operator gets old and exposed for long duration, the lumbar spine (L1 to L5) starts degrading resulting from the high impact of vibration exposure. Some studies found a linear relationship between age and WBV exposure.²⁴ It seems that age and experience (number of years exposed to WBV) are also most critical factors that can affect the operator’s health due to vibration exposure. In general, young workers are less affected by WBV as their exposure to WBV

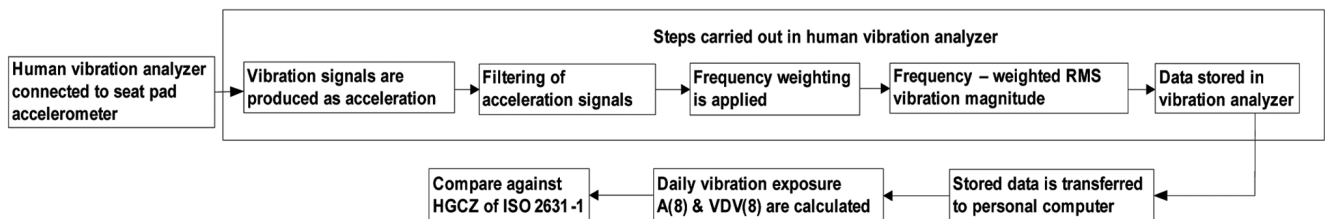


Fig. 5 — Process of WBV measurement data acquisition & health hazard assessment

is low. On the other hand, old workers having several years of experience suffered from serious health issues.²⁵ Another study showed that the peak of the WBV magnitude is linearly correlated with BMI.²⁶

Machine Related Factors

Opencast mines are highly dependent on HEMM for both production and ancillary processes.^{27,28} Major sources of vibration in opencast mines are, *inter alia*, dumpers, bulldozers, scrapers, draglines and excavators. Operators of such heavy machines are commonly exposed to a high level of WBV. Machine-related factors that can influence the WBV exposure in operators include seat suspension, subjective discomfort, biomechanical loading, type of load and activity, vehicle design parameters, and maintenance of the machine.^{22,29,30}

It may not be possible to completely eliminate the machine vibrations at workplaces. Therefore, reducing the WBV to the extent possible and thereby minimizing the health hazards should be the top priority. Transmission of machine-related vibration can be reduced to some extent through effective seat suspension and seat design.³¹ As the age of the machine/equipment increases, the effectiveness of the suspension system decreases, resulting in an increased level of vibration.^{32–34} Vehicles with over 40,000 km usage provide a noticeable rougher ride experience compared to new vehicles in terms of VDV.²⁹ Moreover, factors like machine/vehicle maintenance, its operating speed, and loaded and unloaded conditions influence the machine vibration directly or indirectly.^{13,35,36} A thorough understanding of machine parameters would help in further reducing the vibration levels.

Work Environmental Factors

The most important work environmental factor is the haul road condition, which increases the likelihood of causing MSDs. Other factors include geo-mechanical characteristics of strata, job rotation, working duration, illumination at the workplaces, and the task design.^{22,37} Haul road conditions are defined by factors such as road roughness, inclination, undulation, surface condition, and maintenance. The roughness of the road is usually encountered in the new areas of exploitation. Road roughness increases the amplitude of machine vibration. In turn, this leads to higher amplitude of WBV as well – especially along the z-axis of acceleration.^{3,15,38}

Geo-mechanical characteristics of the strata, such as hardness, density, and uniaxial compressive

strength of the rock, are also liable to influence the WBV level significantly in some cases. For harder rock, a large drill machine with high power consumption is deployed, which causes higher WBV.²⁷

Human Physical and Man–Machine Interface Factors

Human anthropometric parameters as well as postural parameters come under this category.

Postural Parameters

Posture is the position in which one holds the body, upright or bent, while performing a task. It is mainly expressed as the alignment of the musculoskeletal system in a certain systematic sequence to perform a required range of motion at each joint.³⁹ By maintaining a good posture, stress can be eventually distributed to the intended ligaments and muscles. Good posture helps in maintaining all the vital organs in a good shape, and facilitating the nervous system to function properly. Various factors affect the posture, including anatomical and physical parameters, such as age, physical, occupational, recreational, emotional, environmental, social, and cultural factors.⁴⁰ Adoption of awkward posture accelerates the development of MSDs.

Posture assessment refers to the systematic study of the posture data applying a set of principles. During this process, the overall body is examined and checked.⁴¹ The main objective of performing posture assessment is to assess the likelihood of risk associated with the posture. Though there are various approaches for postural assessment, four commonly used methods are visual observation, plumb line, photography & radiography.⁴²

Visual observation is the most commonly used method for assessing the posture. Main advantage of this method is that it doesn't require any kind of special equipment. In this method, the subject is made to wear bare necessary clothes, maintaining social decorum. Observations are made from the anterior, posterior and lateral views, and then compared with the predefined guidelines. However, visual observation has a limitation that it cannot detect any minor alterations in the posture. Plumb line posture is analyzed in the form of an ideal plumb line alignment for both side view and back view. In this method, the subject stands in front of a posture grid and is asked to walk a few steps to reach a pre-determined spot and then stop.⁴³

In contrast, photographic or filming method allows the observer to identify the postural changes with

respect to time, and it can interrelate various parts through measurements using specific software. This method is less capital intensive, quick, and easy to process. But it requires a set of methodological processes involving various steps such as the environmental condition, resolution of the camera, duration of the observation, camera position, framing and stability of the camera.⁴⁴ Once the photographs are obtained, they are studied by using some specific software. One of the limitations associated with this method is the parallax error in the measurements caused by the camera lens.⁴⁵ Since the photographs are taken as two-dimensional (2-D) images, the area facing the front is only focused. Even in the software, the image is available in 2D. Several cameras at a time are to be used to capture images of a single object from different directions. Out of the 2-D images, a 3-D image is reconstructed for analysis purposes.⁴⁴ The radiography method is the latest technology and often referred to as the ‘gold standard method.’ This method is costly. It also involves high risk since the subject is exposed to harmful radiation. Hence its application is very limited – only for research purposes.

During underground mining activities, the worker frequently requires to change his position & posture depending on the machinery location, roof height, and a few other work environmental factors.⁴⁶ In such a situation, the worker needs to adopt various kinds of awkward posture, forceful lifting, and movement that lead to MSDs.^{47,48}

Rapid Upper Limb Assessment (RULA) for Posture Analysis

Rapid upper limb assessment is used to identify and eliminate the awkward posture adopted by the operator. The specific aim of the development of RULA was to evaluate workers’ exposure to ergonomic risk factors associated with the upper extremities of the body inflicted by MSDs.⁴⁹ It provides a record of the individual operator’s regular posture concerning neck, trunk, and upper limbs. It is used to examine the risk factors correlated with the body’s posture, muscle use and load present to determine the posture score. A single-page worksheet is used to assess body posture, repetition, and load. The RULA worksheet is divided into two groups. Group A is for Arm and Wrist analysis, while Group B is for Neck, Trunk, and Legs. Based on these groups, evaluation is done and scores obtained from each body part are noted down in the worksheet.⁵⁰⁻⁵² Once scoring is completed, tables on the RULA

| Score | Level of MSDs risk | Actions to be taken |
|-------|--------------------|---|
| 1–2 | Acceptable | No action required |
| 3–4 | Low risk | Change may be needed, investigate further |
| 5–6 | Medium risk | Change soon, further investigation |
| 7 | Very high risk | Implement the change now |

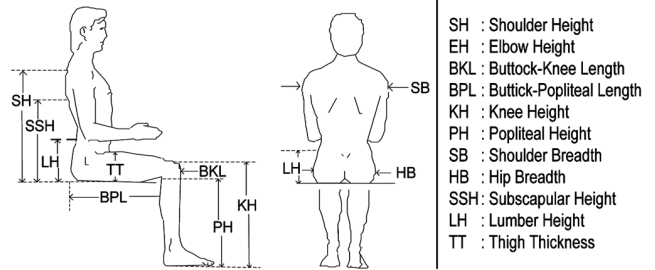


Fig. 6 — Measurements of anthropometric elements

worksheet are used to compile the risk factors to generate a score that represents the level of MSDs risk, as presented in Table 2⁽⁵⁰⁾.

Steps to carry out RULA:

- i. Monitor the working operator several times and determine the work cycle time.
- ii. Determine every position from both the left and right side that needs evaluation.
- iii. Score is determined using the RULA worksheet.
- iv. Calculate the final score to figure out the risk.
- v. Verify the final scores from Table 2 and determine whether changes are necessary in the posture.
- vi. If any changes are made in the posture, then repeat the above steps until the score is reduced to 4 or below.

Anthropometric Parameters

Anthropometry is the study and technique of measuring human body parts, concerning to the dimension of the bones, muscles, and tissues to assess the composition of the body. These measurements provide vital information about a person’s physical health, growth, and development. The measurements of anthropometric elements of the body are shown in Fig. 6.

The anthropometric data is collected using an anthropometer, weighing machine, and tape to measure recumbent length. Using these tools, height, weight, BMI, knee length, buttock knee length, and popliteal length of an operator can be measured easily.^{53,54}

Anthropometric Measurement

The anthropometric data is collected with the help of an anthropometer. The data measured using the anthropometer are standing height, sitting height (erect condition and working condition), knee length, buttock knee length, and buttock-popliteal length as shown in Fig. 6. The measured anthropometric data are then compared to the seat dimension to the match/mismatch of the seat dimension vs. anthropometric data. The matching of anthropometry with seat dimension has been carried out by researchers in driving industry^{55,56} and educational institution.⁵⁷ This method can also be used in ergonomic designing of workstation and seat.

Development of Questionnaire

A pre-defined set of questionnaires is given to the subjects during the anthropometric measurement. The questionnaire contains personal factors (age, BMI, working experience, smoking and drinking habits), machine related factors (age of the machine, kilometers driven, vehicle maintenance, load capacity), work environmental factors (haul road conditions, lighting, visibility, and temperature) and occurrence of MSDs (shoulder, arms, wrist, upper back, lower back, knees and legs). In case of assessing MSDs and some personal factors, the scores are represented as ordinal scales ranging from 1 to 5 (rated as never = 1, rarely = 2, occasional = 3, often = 4, always = 5). Similarly, suitable scale of 1 to 5 is made in an optional opinion type questionnaire for the machine-related and work environmental parameters. Researchers generally prefer to use a 5-point based Nordic scale.³⁶ However, a 10-point scale is also used for the assessment of MSDs in WBV studies.⁵

Health Effects of Vibration on Human Body

This section deals with the most common health effects of vibration, namely MSDs and its assessment.

Musculoskeletal Disorders (MSDs)

When the HEMM operators in mines are exposed to WBV over a long period as a part of their occupation, it results in various kinds of injuries in the form of work-related MSDs.⁵⁸ The musculoskeletal system consists of two components: muscular system and skeletal system. The muscular system consists of soft tissues like tendons, ligaments, joint capsule, and synovial membranes. The skeletal system consists of hard tissues of bones and cartilages. The injuries or disorders that affect the musculoskeletal system are

termed as MSDs. The MSDs risks resulting from the work environment are known as work-related MSDs.⁵⁹ Work-related MSDs cause pains at LBP, shoulder, neck, lumbar spine, upper back, knees, and disorders of joints and spine muscles.^{19,60,61}

By far, LBP is the most prominent and unfavorable health hazard of work-related MSDs. Almost 15% of the adults, in general, suffer from the LBP that may last for more than two weeks even if they take rest.^{62,63} The National Institute for Occupational Safety and Health (NIOSH), in 15 out of 19 studies, found strong evidence of linear correlation between WBV and LBP.⁶⁴ It has been suggested that LBP is directly related to both frequency and magnitude of the WBV, and exposure duration.⁶⁵ The occurrence of LBP and the early degradation of lumbar spine, including inter-vertebral disc disorder, is greater in case of heavy vehicle drivers than those who are not exposed to WBV.^{10,20,47,62} Many hypotheses have been put forward relating the LBP and the BMI. One such proposed hypothesis is that high body mass enhances LBP, since the spine has to support a greater amount of weight, increasing pressure on the lumbar disc or other structures.⁶⁶ Therefore, measurement and assessment of MSDs at the workplaces have been carried out in many research works.

Assessment of MSDs

The MSDs, in general, are assessed through a standard questionnaire or a medical diagnosis.

Assessment of MSDs through Questionnaire Survey

A set of predefined questions is asked to the operators regarding their various health issues on MSDs (e.g., LBP, pain in upper & lower limb, sensory disorder). They are also asked about their other problems like digestive disorder, respiratory & circulatory issues. The response data are then used to correlate with WBV exposure to see whether a significant relationship exists.

Assessment of MSDs through Medical Diagnosis

Through medical diagnosis, it can be known whether an operator is suffering from any kind of MSDs. A physician often diagnoses the MSDs based on the results and history of a physical examination. Laboratory tests, imaging tests, or other diagnostic procedures are necessary to assist the physician in confirming the diagnosis.⁶⁷ Various kinds of medical diagnosis those are performed by the physicians include X-ray plate, computed tomography (CT) scan, magnetic resonance imaging (MRI), and ultrasonography (USG).⁶⁷

Machine Learning Algorithm (MLA): A Tool for Assessment of WBV Impacts

The measurement of WBV, role of its contributing factors, and its associated health effects have been discussed so far. For researchers, understanding the relationship between the causes and effects of WBV is often essential. For instance, one might aim to identify specific relationships between contributing factors and their role in the development of MSDs or its symptoms in particular regions of the body. To achieve such a relationship, use of ‘machine learning algorithm (MLA)’ is highly recommended. These tools can help uncover patterns and establish connections between variables, offering a deeper understanding of the causation mechanisms.

The MLA is a computational approach that allows a computer to learn patterns, insights, and rules from data without distinct programming for a specific task. These algorithms are the foundation of machine learning and can be used to evaluate data, forecast outcomes, or make choices directly without any human interaction. When a dataset is fed into these algorithms, it identifies patterns, structure, or relationship in the data through training. Then it creates a mathematical model to represent the learned patterns. Once trained, the model itself can make decisions or predictions on new data sets. The MLA can play an important role in analysis because of its automating decision-making process and adaptability to improve its algorithm over time as it processes more and more data. The MLA can be classified into three main groups based on the nature of the learning process and the type of data. These groups

are supervised learning (support vector machine, fuzzy logic, artificial neural network, logistic regression, and Bayesian network), unsupervised learning (K-means clustering algorithm, hierarchical clustering, principal component analysis), and semi-supervised learning algorithm.⁶⁸ It can be suggested because of various advantages over traditional analysis due to its adaptability, scalability, non-linear problem solving, which increases human efficiency in real-time applications.

In the present research methodology, MLA can be used to evaluate, analyze, and monitor various contributing factors affecting the impact of WBV exposure resulting in MSDs. The overview of the cause & effect relationship between WBV exposure and MSDs is shown in Fig. 7. It shows some of the identified factors and parameters which can mediate the impact of WBV exposure, as discussed earlier.

From Fig. 7, it can be seen that there are various factors which may affect the risk of MSDs. Each of the factors has many parameters, which may be the root cause to impact the MSDs. It is seen from Fig. 7 that the relationship between WBV and MSDs is a complex network. Therefore, solution of this network through traditional methods will be a tedious and time-consuming task. But using MLA, the solution can be obtained in a very short time. This would help in understanding and identifying the contributing parameters to eliminate or minimize their effects on WBV exposure leading to MSDs.

The developed model will aid in identifying the role of contributing parameters along with WBV to

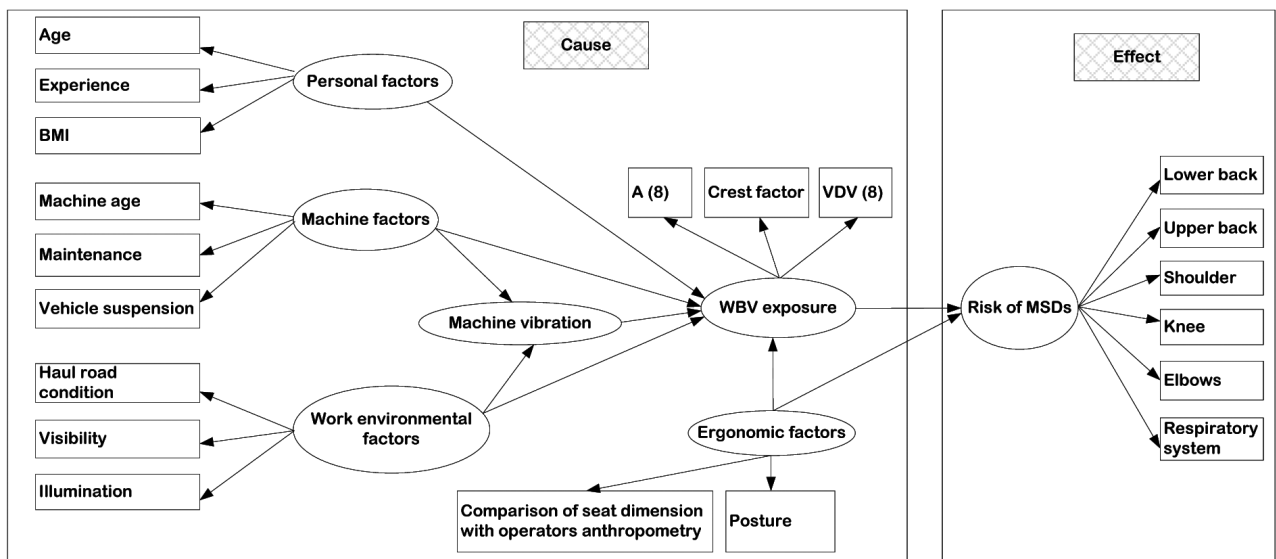


Fig. 7 — Cause & effect relationships between confounding factors of WBV, WBV exposure and MSDs

cause MSDs, so that efforts can be made to either eliminate or minimize its effects. Several studies have adopted linear regression to identify a significant linear relationship between the absorbed vibration power and the anthropometric seat shape and sitting positions.⁶⁹ In another WBV study in agriculture, multiple linear regression analysis was employed to test relationships between the WBV magnitudes as the response variable, and the personal factors of the operators, machine-related factors of the quadbike, and the dairy farm type as independent variables.¹⁷

Subsequently, researchers applied logistic regression models to identify important factors causing musculoskeletal health risks in dumper operators against a control group of respondents who are not exposed to vibration.⁶ These models incorporated daily WBV exposure as an input variable to estimate the relative risk, providing insights into the likelihood of musculoskeletal complaints in the spine.^{19,20}

With the advancement of computational tools, Bayesian Network was also used to forecast the causal contributing risk factors of WBV of dumper operators in the development of MSDs to prioritise the variables for human health risk.⁸ A Structural Equation Modelling (SEM) was also proposed to understand the complex causal relationships between the work-related MSDs with respect to exposure to WBV, as well as personal, habitual, and work-related factors, among dumper operators of Indian surface iron ore mines.⁷⁰ Research on WBV should go beyond the monitoring and data generation, and should be directed towards deriving complex relationships for thorough understanding of MSD causation through supervised learning models, including Artificial Neural Network (ANN), genetic algorithm, and Bayesian Network.

Conclusions

Although occurrence of the MSDs is a prime concern linked to WBV, the role of contributing factors in its causation is yet to be explored critically. This approach paper has the potential to assess MSDs issues among the HEMM operators exposed to WBV vis-à-vis its contributing factors. Application of multivariate statistical analysis and machine learning tools is expected to bring valuable insights into the prevalence of MSDs at workplaces. Furthermore, equipment manufacturers can play a vital role by incorporating ergonomic designs in HEMM, such as improved seat suspension systems and seat designs to optimize the transfer of vibration at the human-

machine interface. In addition, adoption of proper condition-based preventive maintenance can also reduce vibration generation at source.

Although ergonomic design of workplace and equipment plays a paramount role for combatting MSDs, training of HEMM operators and organizing awareness programs on vibration hazards can initiate preventive measures to get rid of its ill effects. Though the methods to control or reduce vibrations are reported in many investigations, there is still a need for further investigation to explore the role of various contributing factors on causation of MSDs using machine learning techniques.

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Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical Statement

Ethical approval for this study has been obtained from the institutional ethics committee, Institute of Medical Sciences, BHU, Varanasi, India (Reference number: No. Dean/2024/EC/7108).

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