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Original Research

WHOLE-BODY VIBRATION MEASUREMENT AT THE MINING MACHINERY OPERATOR'S WORKPLACE IN SMES

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Abstract: Increased mechanization in mining results in a larger number of workers being exposed to longer durations of whole-body vibration (WBV). Occupational exposure to vibration is associated with an increased risk of musculoskeletal pain in the back, neck, hands, shoulders, and hips; the development of peripheral and cardiovascular disorders and gastrointestinal problems; and it may even increase the risk of developing certain cancers. In that aim, in this survey, whole-body vibration exposure levels were measured during the shift at 22 mining machinery operators' workplaces in 3 surface mining. A triaxial accelerometer V31 was used to measure vibration exposure. Measurements were conducted in accordance with the procedures described in applicable standards in the field. The results indicate that the observed workplaces exceeded the action limit values according to the EU Directive 2002/44/EC, as well as the lower limit values of health risks according to the ISO 2631 standard. The lower limit value of health risk according to the ISO 2631 standard was exceeded at 50% of machines. The action value of WBV according to the EU Directive 2002/44/EC was exceeded in 36% of machines. The dominant vibrations were indicated along the X and Y axes. Operators on bulldozers and loaders are most often exposed to the harmful influence of WB vibrations. Research indicates that there is a risk of harmful impact of WBV that needs to be prevented and highlights the need for further research to identify the most critical risk factors and develop effective prevention and protection strategies for mining machinery operators' workplace risks caused by vibrations.

Keywords: Whole-body vibration, mining machinery, operator, SME.

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1. INTRODUCTION

As one of the most important sources of raw materials to the global industry, the mining sector is expanding progressively each year, but it should not be neglected that it is also one of the most hazardous, due to the high accident rate, significant health hazards, and possible property damages (Bugarić et al., 2024; Spasojević et al., 2024). In the mining sector, 47% of all fatalities are caused by accidents involving mining machinery, but there are hardly any studies that take ergonomic and/or contextual aspects into account regarding the mining industry (Misita et al., 2024). According to Brocal et al. (2019), there is a substantial correlation between industrial and occupational risks, with the human component serving as the primary link between the two.

Vibration exposure at work has been linked to a higher incidence of musculoskeletal pain in the hands, shoulders, hips, back, and neck (Charles et al., 2018; Issever et al., 2003; Li et al., 2015). Additionally, it might play a role in the development of cardiovascular, peripheral, digestive, and even immunity disorders (Krajnak, 2018; Robbins et al., 2014; Song et al., 2019). Furthermore, more recent research indicates that vibration exposure at work may raise the risk of getting several types of cancer (Kia et al., 2020; Krajnak, 2018).

The small- and medium-sized enterprises (SMEs) sector is one of the primary areas of entrepreneurial activity in Western Balkan countries, with tremendous potential for growth (Rehman et al., 2019). Additionally, it is thought that SMEs boost the economy by transferring new technologies, boosting employment, and expanding production, among other things (Rehman et al., 2019). Because their business operations are carried out with limited resources, SMEs have specific management processes, such as those in Serbia (Ćoćkalo et al., 2011). The social effects of mining have been more prevalent in social-scientific mining studies over the past ten years (Sydd et al., 2022), so SMEs with scarce resources deserve special attention. There are obstacles to implementing the circular economy in Serbia's mining industry, such as the requirement for technology investment and legal restrictions (Vujović et al., 2025), and that fact stresses the actuality of the topic by surveying Serbian SMEs in the mining sector.

Evidently, vibration at work has not been sufficiently examined till now, especially in Serbian SMEs in the mining sector. Accordingly, the aim of this paper is to assess whole body vibration (WBV) at the mining machinery operator's workplace in SMEs. Its structure is as follows: after the introduction, the previous research is examined in the second part; in the third part, measurement methodology and its results are presented, while in the last part, conclusions are presented.

2. PREVIOUS RESEARCH

The Society of Occupational Medicine (2023), in their study, provides an overview of the impact of WBV and hand-arm vibration syndrome on worker health, with a particular focus on risk assessment and worker protection guidelines. The results indicate an association of WBV with lower back pain, degenerative changes in the spinal vertebrae, decreased bone density, and increased risk of muscle wasting. The document also highlights that although there are standardized methods for measuring WBV, epidemiological evidence of its long-term health effects is limited. Similarly, a guide by Safe Work Australia (2016) draws on an analysis of previous research, health standards, and regulatory requirements to identify key factors influencing WBV and indicates musculoskeletal disorders, particularly in the lower back, as well as increasing the risk of fatigue, reduced concentration, and other health problems, and offers recommendations to reduce the risk, including technical measures (e.g., improving seating and suspension systems), administrative measures (e.g., limiting the duration of exposure), and training workers to recognize and mitigate the effects of WBV. Both documents include different occupations and industry types, including mining machinery operators.

Besides recommendations given in publications such as the above-mentioned, the results of Sharma et al. (2020) recently show that heavy machinery operators are regularly exposed to high levels of vibration during eight-hour shifts, often exceeding the recommended limits of the ISO 2631/1-1997 standard. Sharma et al. (2020) also note that the effects of WBV are complex and exhibit non-linear behavior, and that due to the complexity, there are problems in properly understanding the entire physiological phenomenon.

Certain authors use triaxial accelerometers for WBV measurements, a few of them in the mining industry, as below.

Akinnuli et al. (2018) investigated the impact of WBV on a sample of 30 earthmoving machine operators in the construction industry, and the results indicated that WBV often exceeded recommended limits, with the daily vibration values of most subjects exceeding the permissible threshold of 0.5 m/s², with maximum recorded values of up to 1.15 m/s², which is twice the recommended limits. Authors of this study conducted WBV measurements using a GCDC X16-4 triaxial accelerometer on a bulldozer, excavator, grader, loader, vibratory roller, and backhoe. The results indicated that all values of vertical vibrations (Z axis) were within the Health Guidance Caution Zone (HGCZ), while horizontal vibrations (X and Y axes) were lower. However, in certain machines, such as backhoes and excavators, the WBV exceeded the exponential exposure limit (ELV), indicating the need for technical and ergonomic improvements. Furthermore, the Crest Factor (CF) was in most cases greater than 9, which indicates the presence of multiple impact shocks during operation. Chaudhary et al. (2019), in their study of 39 drill operators, examine the association between WBV exposure and various occupational and personal factors in Indian iron ore mines. The results showed that 70% of the operators were exposed to vibrations exceeding the recommended limits of the ISO 2631/1-1997 standard, with the dominant vibrations observed along the vertical (z) axis. Multivariate regression analyses showed that operator age, drill model, rock hardness, and material density were significant predictors of vibration exposure. Tekin (2022) evaluates the WBV exposure levels of mining machine operators in three different surface coal mines in western Turkey and compares them with ISO 2631/1-1997 standards and EU Directive 2002/44/EC (2022). The research sample included 41 different models and brands of mining machines, and factors such as machine type, duration of exposure, and dominant vibration axis were analyzed. The results showed that all operators were exposed to WBV below the limit value of 1.15 m/s², but 44% of operators were exposed to vibration above the action limit of 0.5 m/s². Bulldozer operators had the highest WBV values due to working on rough terrain, while excavator operators had the least exposure to vibration. Erdem et al. (2020) analyzed exposure to whole body vibration (WBV) in 105 mining truck drivers and showed that drivers are most exposed to vibration along the vertical (Z) axis but amplify it in the X and Y axes. Older trucks and vehicles with longer service lives produced higher WBV values. Chaudhary et al. (2015) in their study evaluated exposure to WBV using a triaxial seat accelerometer (Nor 1286) in 28 operators working on 10 drills from different manufacturers, and their results showed that more than 90% of the operators were exposed to WBV values above the upper limit recommended in the ISO 2631/1-1997 standard. Marin et al. (2017) conducted a study to characterize the WBV exposure using a triaxial seat accelerometer (Model 356B41, PCB Piezotronics, USA), using an 8-channel (DA-40) and 4-channel (DA-20) data recorder of 38 heavy mining vehicles in surface mines, and the results showed that the majority of mining vehicles exceeded the recommended WBV limits, with the dominant axis of vibration differing depending on the type of vehicle and working conditions. Mahamedi et al. (2021) conducted research to develop an automated system for measuring excavator productivity using deep learning and smartphone sensors, and the results showed that a model based on the DNN algorithm with accelerometer, gyroscope, linear acceleration, and noise data achieves the highest accuracy of 99.78%. Sakinala et al. (2024) conducted a six-month survey in seven underground mines in India using a SV38V triaxial accelerometer on a sample of 81 operators, and the results showed that 88.92% of operators were exposed to WBV values above the lower ISO HGCZ limit (ISO 2631-5:2018, 2018) (0.45 m/s²).

Previous studies show different measuring devices, methodologies used, and different results on different samples, and there is clearly a need for further research.

3. DATA AND METHODOLOGY

In this research, a triaxial accelerometer VM31 by Metra Mess und Frequenztechnik in Radebeul e.K. was used. To assess the vibrations acting on the human body, it is recommended to measure the interval RMS values along the X, Y, and Z axes, as well as their vector sum (aw). The VM31 device measures these four values simultaneously. In addition, it displays the current maximum RMS value (Maximum Transient Vibration Value, MTVV), which may indicate the presence of shock vibrations. MTVV is not necessarily the largest value among the individual RMS values for the X, Y, and Z axes, because these values are multiplied by weighting factors, which is not the case with MTVV. Whole body vibration measurement in the context of health risk assessment, a weighting filter Wd is used for the X and Y axes, and Wk for the Z axis, with weighting factors of 1.4 for X and Y, and 1.0 for the Z axis. Figures 1 and 2 show the frequency response curves of these filters in the VM31 device, in accordance with the ISO 8041-1:2017 standard.

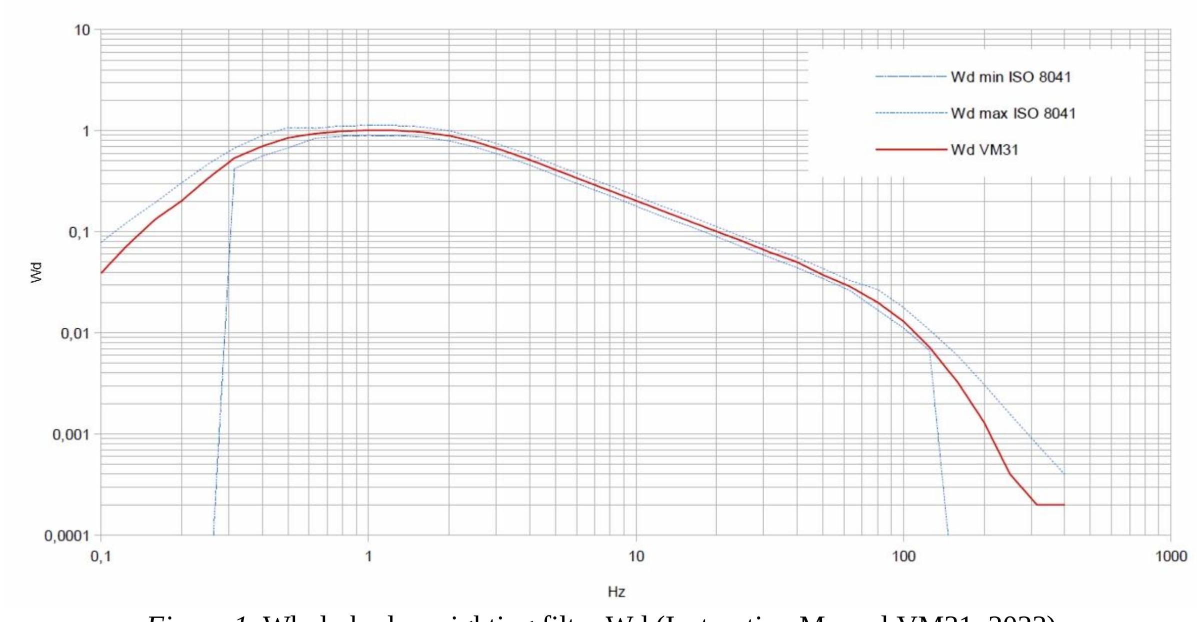

Figure 1. Whole-body weighting filter Wd (Instruction Manual VM31, 2023)

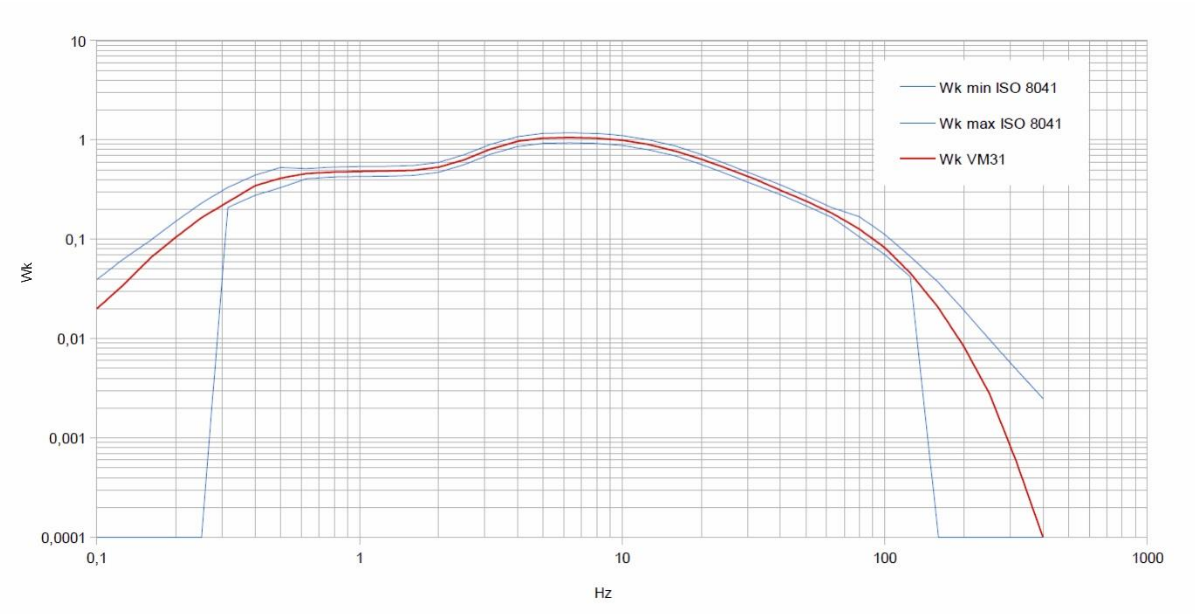

Figure 2. Whole-body weighting filter Wk (Instruction Manual VM31, 2023)

Vibration analysis for WBV is performed based on the formulas outlined in the ISO 2631/1-1997 standard. For each measurement, the frequency-weighted root mean square (WRMS) values along the X-, Y-, and Z-axes were individually calculated for each mining machine using Equation 1 (EU Directive 2002/44/EC, 2022):

$$a_{w,r.m.s} = \sqrt{\int_0^T a_w^2(t)\, dt} \quad (1)$$

where
aw(t) - WRMS acceleration at a particular time t (m/s2)
T - Duration of measurement (seconds)

The individual RMS values of accelerations measured along the x, y, and z axes by the precision vibration meter are denoted as awx, awy, and awz, respectively. For triaxial measurements, the peak accelerations (maximum instantaneous acceleration during the measurement period) are calculated in addition to the WRMS vector sum value (EU Directive 2002/44/EC, 2022):

$$a_{xyz} = \sqrt{(k_x * a_{wx})^2 + \left(k_x * a_{wy}\right)^2 + (k_x * a_{wz})^2} \quad (2)$$

Given that the risk of damage varies along the three axes, WRMS accelerations (awx, awy, awz) are computed by applying the appropriate weighting factors specified in ISO 2631/1-1997 (k = 1.4 for the x-axis and y-axis, k = 1.0 for the z-axis). The value of A(8) is determined using Equation 3 (EU Directive 2002/44/EC, 2022):

$$A_{(8)} = \sqrt{\frac{1}{8}\sum_{n=1}^{N} a_{wn}^2 t_n} \quad (3)$$

The A(8) value is determined by considering the daily exposure times (tn) for each phase, the WRMS vibration for each phase (awn), the number of phases (N), and the estimated daily exposure equivalent to an 8-hour continuous exposure. These calculated values were then used to assess the potential health risk to workers, utilizing the health guidance caution zone (HGCZ) in accordance with Annex B of the ISO 2631/1-1997 standard.

The sample included mining machines in SME at 3 locations (A, B, C), i.e., mines in the fields of surface mining of quartz sand, zinc and lead, and marble and granite, as in Table 1. WBV measurements were carried out on 22 mining machines there.

Table 1. Locations

Location	Surface mining	Company size
A	Quartz sand	medium
B	Zinc and lead	medium
C	Marble and granite	small

3. RESULTS AND DISCUSSION

Table 2 shows the results of WB vibration measurements using the VM31 measuring device. For each mining machine on which WB vibrations were measured, the duration of the measurement on a certain work task, the measured values on the X, Y, and Z axes, the dominant axis was determined, and the A(8) value was calculated.

Table 2. WBV measurement results

Location	Mining machine	kW	Year	Task	Duration (h)	a_{wx} (m/s^2)	a_{wy} (m/s^2)	a_{wz} (m/s^2)	a_{wxyz} (m/s^2)	Dominant axis	A(8) (m/s^2)
A	Excavator	123	2018	1	3	0.17	0.27	0.13	0.34	y	0.26
				2	4.30	0.17	0.27	0.14	0.34	y	
A	Excavator	180	2024	1	5	0.33	0.27	0.30	0.52	x	0.31
				2	2.30	0.29	0.24	0.23	0.43	x	
A	Excavator	180	2024	1	7.30	0.13	0.10	0.11	0.20	x	0.13
A	Loader	140	2017	1	3	0.47	0.58	0.30	0.80	y	0.56
				2	4.30	0.54	0.58	0.39	0.88	y	
A	Bulldozer	120	2015	1	3	0.37	0.33	0.37	0.61	x,z	0.45
				2	4.30	0.52	0.48	0.51	0.86	x	
A	Bulldozer	160	2023	1	7.30	0.57	0.52	0.55	0.94	x	0.55
B	Excavator	370	2017	1	8	0.26	0.17	0.20	0.36	x	0.26
B	Excavator	370	2017	1	8	0.40	0.28	0.23	0.53	x	0.40
B	Excavator	316	2012	1	7.30	0.55	0.34	0.24	0.68	x	0.53
B	Loader	246	2017	1	7.30	0.40	0.42	0.23	0.62	y	0.41
B	Loader	251	2017	1	8	0.15	0.16	0.11	0.24	y	0.16
B	Dumper	386	2011	1	7.30	0.48	0.38	0.43	0.74	x	0.47
B	Dumper	250	2008	1	8	0.36	0.53	0.47	0.79	y	0.53
B	Bulldozer	268	2011	1	7.30	0.64	0.52	0.37	0.90	x	0.62
C	Excavator	220	2023	1	8	0.51	0.36	0.39	0.73	x	0.51
C	Excavator	202	2019	1	7.30	0.39	0.30	0.36	0.60	x	0.38
C	Dumper	298	2010	1	4	0.51	0.49	0.37	0.79	x	0.44
				2	3.30	0.38	0.35	0.25	0.57	x	
C	Dumper	298	2011	1	7.30	0.25	0.30	0.24	0.46	y	0.29
C	Dumper	298	2010	1	1	0.31	0.36	0.33	0.57	y	0.43
				2	6.30	0.43	0.46	0.42	0.75	y	
C	Dumper	248	2006	1	7.30	0.43	0.47	0.45	0.77	y	0.45
C	Loader	250	2020	1	7.30	0.51	0.55	0.32	0.81	y	0.53
C	Loader	250	2020	1	7.30	0.69	0.67	0.41	1.04	x	0.67

In Table 3, a summary analysis of mining machines by location and type. The results show the minimum, maximum, mean value, and standard deviation for groups of similar machines. How it is: "According to ISO 2631/1-1997, the frequency-weighted acceleration values corresponding to the lower and upper limits of the HGCZ (for 8 h of exposure) are 0.45 and 0.90 m/s2, respectively. According to EU Directive 2002/44/EC, a daily exposure action value (AV) of 0.5m/s2 and a daily exposure limit value (LV) of 1.15m/s2 (the frequency-weighted acceleration)" further show the percentage representation of the mean A(8) value for the relevant groups of machines in relation to the limit values given in ISO 2631/1-1997 and the EU Directive 2002/44/EC.

Table 3. Summary analysis of mining machine measurement results by location and machine type

The open-pit mine A								
Mining machines	Number of machines	A(8) (m/s^2)			ISO 2631/1-1997 (8h exposure)		EU Directive 2002/44/EC (8h exposure)	
		Min	Max	Mean±SD	Below	Within	Below action value	Above action value, below limit value
Excavator	3	0.13	0.31	0.23±0.09	100%	-	100%	-
Loader	1	0.56	0.56	0.56±0.00	-	100%	-	100%
Bulldozer	2	0.45	0.55	0.50±0.07	-	100%	50%	50%
The open-pit mine B								
Mining machines	Number	A(8) (m/s^2)			ISO 2631/1-1997 (8h exposure)		EU Directive 2002/44/EC (8h exposure)	
		Min	Max	Mean±SD	Below	Within	Below action value	Above action value, below limit value
Excavator	3	0.26	0.53	0.40±0.14	66,6%	33.3%	66.6%	33.3%
Loader	2	0.16	0.41	0.29±0.18	100%	-	100%	-
Dumper	2	0.47	0.53	0.50±0.04	-	100%	50%	50%
Bulldozer	1	0.62	0.62	0.62±0.00	-	100%	-	100%
The open-pit mine C								
Mining machines	Number	A(8) (m/s^2)			ISO 2631/1-1997 (8h exposure)		EU Directive 2002/44/EC (8h exposure)	
		Min	Max	Mean±SD	Below	Within	Below action value	Above action value, below limit value
Excavator	2	0.38	0.51	0.45±0.09	50%	50%	50%	50%
Dumper	4	0.29	0.45	0.40±0.08	75%	25%	100%	-
Loader	2	0.53	0.67	0.60±0.10	-	100%	-	100%

Figure 3 shows the limit and action value of 8h exposure to WB vibrations according to EU Directive 2002/44/EC, the upper and lower health risk limit according to the ISO 2631/1-1997 standard, and the middle, lower, and upper limit values by machine groups and location.

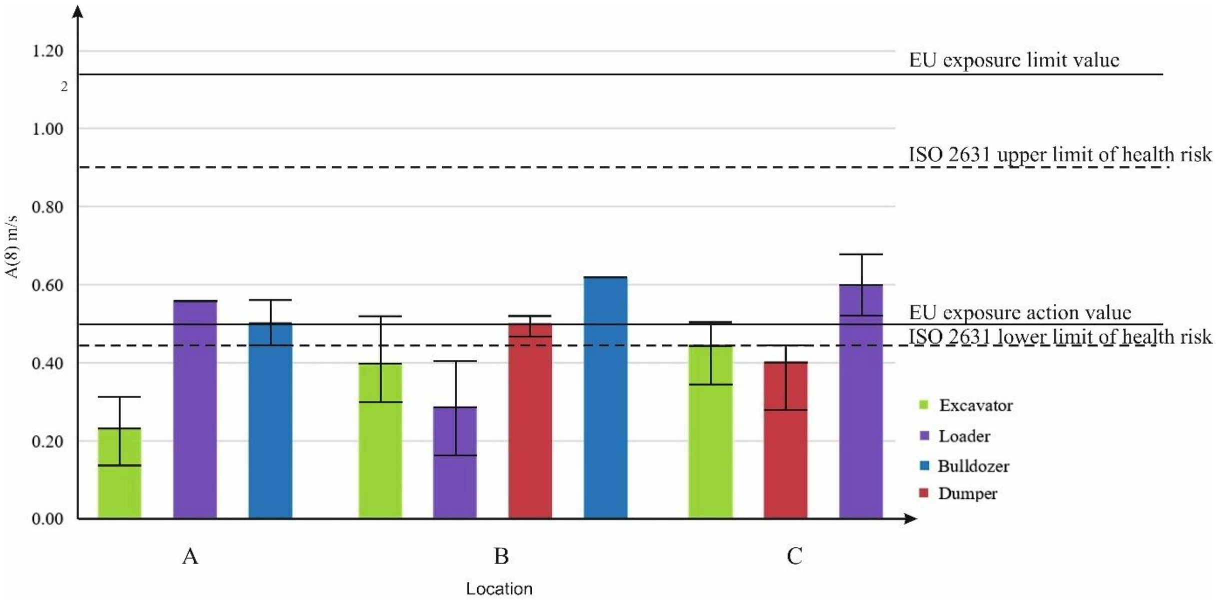

Figure 3. Mean value, upper and lower limit value of A(8) by location and type of mining machine in comparison with the existing regulations

The highest recorded WBV was recorded at the workplaces of bulldozers and loaders at location A, loaders at location C, and bulldozers and dump trucks at location B. No location exposed excavator operators to the harmful effects of WBV. The dominant vibration axes are mostly x and y, while vertical vibrations were dominant only on one of the 22 recorded machines.

4. CONCLUSION

This paper fills an evidence-based research gap in the field. In this research, WBV was analyzed using a triaxial accelerometer V31 by Metra Mess und Frequenztechnik in Radebeul e.K. The goal of the research was to determine whether the action or limit values of WBV prescribed by the EU Directive 2002/44/EC were exceeded, as well as to determine whether the measured WBV were in accordance with the ISO 2631/1-1997standard. The research was conducted at 3 locations of surface mines, and the research sample included 22 mining machines of the following types: excavator, bulldozer, and dumper. Operators' workplaces were recorded during one work shift in order to determine 8 hours of exposure to whole body vibration. The results indicate that the observed machines exceeded the action limit values according to the EU Directive 2002/44/EC, as well as the lower limit values of health risks according to the ISO 2631/1-1997 standard. On 11 observed machines (50% of the observed number of machines), the lower limit value of health risk according to the ISO 2631/1-1997 standard was exceeded. On 8 observed machines (36.5% of the observed number of machines), the action value of WB vibrations according to the EU Directive 2002/44/EC was exceeded. The dominant vibrations on the observed machines were along the x and y axes. Operators on bulldozers and loaders are most often exposed to the harmful influence of WBV.

The research indicates that there is a risk of the harmful impact of WBV on mining machines that needs to be prevented, and in relation to the reference literature, the proposal for the prevention of this risk advocates the implementation of an ergonomically adapted operator's seat that mitigates the mentioned vibrations. Future research direction could be sample enlargement and deeper analysis.

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