27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-0694
DEVELOPMENT OF AN APPARATUS FOR SIMULTANEOUS MEASUREMENT OF WHOLE-BODY AND HAND-ARM VIBRATION

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Abstract. *The human body is exposed to vibrations during various daily activities, which can represent health risks depending on the intensity range and exposure period. The vast majority of motor vehicles provide discomfort in work posture and safety issues. Furthermore, this condition may be associated with the development of several adverse health consequences, including back/neck pain, cardiovascular disorders, neuropathies, digestive problems, and, in the long term, even cancer. To carry out an assessment of Whole-Body Vibration (WBV) and Hand-Arm Vibration (HAV), a commercial device with local and single measurement point is usually used, requiring multiple devices for accurate diagnosis. This can generate a mismatch of information/data to obtain a complete and accurate study of the case. To fill this gap and perform a complete and synchronous analysis at all points that affect the operator's health, an unprecedented and exclusive device was designed, developed, calibrated, and validated in field tests for the simultaneous measurement of WBV and HAV at multiple points (floor, seat, backrest and steering wheel). Three seat pads and one hand pad were produced, encapsulating triaxle accelerometers for the characterization of the collected vibration values. In the calibration phase, the equipment was taken to a shaker, and tests were carried out at different vibration frequencies, comparing the developed equipment with a commercial one. To process the data during the tests, an exclusive program was developed using MATLAB^{TM} software, which acquired, read, interpreted, and reported to a summary document. This way, it is possible to fully explore and formalize hypotheses regarding: WBV, HAV, comfort and health classification according to ISO 2631, SEAT transmissibility, and compression impact on the spinal column (S_d^A).*

Keywords: *Simultaneous Vibration Measurement Equipment, WBV, HAV, SEAT, ISO 2631.*

1. INTRODUCTION

The human body is exposed to vibrations during everyday activities, such as the use of machinery, equipment, and/or tools. As a result, exposure to vibration can be uncomfortable, exciting, nauseating, stimulating, or even a source of health problems [Griffin, 1996].

Bruel & Kjaer, 1989, state that the vibration received by the body can be classified into two major groups: Hand-Arm Vibration (HAV) and Whole-Body Vibration (WBV). Both forms can pose risks to humans, depending on the intensity and duration of exposure to such vibratory modulations, which can be sources of discomfort and also cause health problems. Due to its structural complexity, each part of the human body can both absorb and amplify mechanical waves.

The exposure to WBV and HAV is concerning in the workforce because this condition is associated with the development of various adverse health consequences, including back and neck pain [Basri and Griffin 2013; Beard and Griffin 2016; Bovenzi *et al.* 2017; Charles *et al.* 2018; Du *et al.* 2018; Palmer *et al.* 2012], increased risk of cardiovascular diseases [Hering *et al.* 2015], development of neuropathies [Stoyneva 2016], digestive problems [Ronchese and Bovenzi 2012], headaches, dizziness, and nausea [Butler and Griffin 2009; Donohew and Griffin 2010; Haward *et al.* 2009], and possibly cancer [Jones *et al.* 2014; Nadalin *et al.* 2012; Waugh *et al.* 2016].

To assess Whole-Body Vibration (WBV) and Hand-Arm Vibration (HAV), a commonly used approach involves the use of a commercial device that measures vibrations at specific contact points (seat, backrest, floor, feet, steering wheel, bars, handles, among others). However, multiple devices are usually required to perform all the necessary measurements for a comprehensive vibrational diagnosis. This can lead to inconsistencies in the information/data, making it challenging to obtain a complete and accurate study of the case.

With a focus on health, comfort, vibration transmissibility, and potential spinal injuries brought on by impact vibrations, the primary goal of this study is to evaluate Whole-Body Vibration (WBV) and Hand-Arm Vibration (HAV) experienced by users of various motor vehicles. The following are this paper's specific goals: (a) Building a single instrument that complies with the geometry, sensitivity, and dimension recommendations specified in the standards for each of these measurements, allowing simultaneous measurement of vibration in WBV and HAV situations at multiple points (floor, seat, backrest, and steering wheel). (b) Laboratory calibration of the created device through comparison with a commercial instrument over a range of vibration frequencies. (c) Development of specific and exclusive routines in MATLAB^{TM} mathematical modeling software for data generation, reading, and analysis from this device.

2. LITERATURE REVIEW

Vibration analysis and the evaluation of its effects on drivers and passengers of vehicles is a recurrent topic in the global literature. In most studies, the focus is on assessing the overall comfort by improving vehicle's seat comfort or the harmful effects that vibration can have on users.

A summary of the connection between low back discomfort and work-related exposures to WBV and mechanical shocks is given by Bovenzi *et al.* (2017). According to their comments, experimental research backs up the conclusions of epidemiological studies by showing that, in controlled settings, exposure to WBV can result in mechanical stress on the human spinal column. Using commercially available instruments, Fedatto Neto and Gomes assessed the levels of Whole-Body Vibration (WBV) in passengers of urban trains in Porto Alegre/RS during typical usage conditions in 2017.

The goal of Roseiro *et al.* (2016) was to examine the amount of Hand-Arm Vibration (HAV) and Whole-Body Vibration (WBV) exposure experienced by cyclists. In this study, two models of bicycles - a speed bike and a mountain bike - were used to quantify bicycle vibration. According to the findings, hits and brief vibrations put a lot of strain on the shoulders, arms, wrists, knees, and spinal column.

In a study by Rampal *et al.* (2009) on operators of armored military vehicles in Malaysia, 159 respondents were evaluated to determine the prevalence of low back pain related to whole-body vibration (WBV), and 64.2% of them reported having such pain. The prevalence was higher in tracked vehicles (81.7%) compared to wheeled vehicles (67%).

A study by Fedatto Neto (2018) examines the levels of Whole-Body Vibration (WBV) affecting comfort and health, vibration transmissibility (SEAT), and spinal impact vibration (R-factor and S_{ed}) in three Leopard I A5BR, Guarani, and Urutu armored vehicles used by the Brazilian Army. For each of the investigated military vehicles, numerical models of vehicle suspension were created in addition to in-situ measurements using the Newmark method for time-domain analysis. For all armored vehicles, accelerations at the center of gravity (CG), on the driver's and passenger's seats, ground reaction forces, and suspension workspace were compared. According to the study's findings, there are different levels of comfort and safety among the vehicles examined in these circumstances.

The vibration that motocross riders' hands felt was assessed by Tarabini *et al.* (2020), and they investigated strategies to make it less intense. They examined how much vibration professional and amateur motocross riders were exposed to on a track with elements typical of those used in the sport. In order to assess various components' abilities to reduce the rider's exposure to vibration, a lab environment was created using an LDS V930 shaker to imitate the vibration patterns.

Mizushima *et al.* (2022) show how to build a hand-arm vibration monitor while a lawn mower operator goes about their everyday business and simultaneously measures the vibration levels on both hands (in accordance with ISO 5349-1/2001). Additionally, recommendations for reducing the risks are offered for the examined circumstance together with the identification of the associated risks.

3. THEORETICAL-NORMATIVE FOUNDATION

Exposure to Whole-Body Vibration causes a complex distribution of oscillatory movements and forces within the body, which may vary among individuals in terms of biological effects. This type of vibration is encountered in vehicles, machinery, buildings, and in the vicinity of workplace equipment. The International Organization for Standardization (ISO) develops and publishes international standards, tests, and certifications. Regarding vibration, the following standards are relevant: ISO 2631-1, 1997(2010) Mechanical Vibration and Shock - Evaluation of Human Exposure to Whole-Body Vibration - Part 1: General Requirements, ISO 2631-5 (2018) Mechanical Vibration and Shock - Evaluation of Human Exposure to Whole-Body Vibration - Part 5: Method for Evaluation of Vibration Containing Multiple Shocks,; ISO 5349-1(2001) Mechanical Vibration - Measurement and Evaluation of Human Exposure to Hand-Transmitted Vibration - Part 1: General Requirements; ISO 8041 (2017) Human Response to Vibration - Measuring Instrumentation; NBR NM ISO 5353 (1999) Road construction machinery, tractors, and agricultural and forestry machinery - Seat Reference Point.

At the Brazilian national level, there is the Regulatory Standard No. 15 (NR-15), which deals with unhealthy activities and operations, and its Annex 8, 2014, specifies about vibrations limit exposure. This aims to establish criteria for characterizing the unhealthy working condition resulting from exposure to Hand-Arm Vibration and Whole-Body Vibration, where the technical procedures for the quantitative assessment of WBV and HAV are established in the Occupational Hygiene Standards (NHO) of FUNDACENTRO. In order to contribute to the control of exposure and prevention of occupational diseases, in 2013, the Occupational Hygiene Standard (NHO) 09 - Evaluation of Occupational Exposure to Whole-Body Vibration, and NHO 10/2013 - Evaluation of Occupational Exposure to Hand-Arm Vibration were drafted.

Simultaneously, the normative Annex No. 1 of NR-09/2021 instrument that regulates the implementation of measures to preserve the health and integrity of workers through anticipation, evaluation, and control of risks in the workplace. Unlike NR-15/2014, which has a compensatory bias, this standard is preventive. It states that organizations must adopt prevention and control measures for exposure to mechanical vibrations that may affect the safety and health of workers, eliminating the risk or, where technology is proven to be unavailable, reducing it to the lowest possible levels.

The European Directive 2002/44/EC, concerning the exposure of workers to the risks arising from physical agents, aims to introduce minimum level requirements for the protection of workers when exposed to risks from vibrations in the course of their work. The Directive establishes 'Action Values of Exposure' (AVE) and 'Exposure Limit Values' (ELV). The AVE is the amount of daily exposure to whole-body vibration above which measures must be taken to reduce the risk, while the ELV is the maximum amount of vibration to which an employee can be exposed in a single day.

Following similar mathematical formulations and correlations, the NR-15 (2014) regulation, NHO-09 (2013) guideline, and European Directive 2002/44/EC have reference values. For a clearer view, Table 1 presents the values:

Table 1. Comparative table of standards and their limit and action values.

	AVE (m/s²)	**ELV (m/s²)**
WBV		
ISO 2631-1 (1997)	0.43*	0.87*
EC 44/EU/2002	0.5	1.15
NR-15 (2014)	0.5	1.1
NHO-09 (2013)	0.5	1.1
HAV		
NHO-10 (2013)	2.5	5.0
ISO 5349-1 (2001)	2.5 (12.04 y**)	5.0 (5.77 y**)
EC 44/EU/2002	2.5	5.0
NR-15 (2013)	2.5	5.0

*Estimated by graphs **for 10% of population with hand disorders

According to Griffin, 1996, an important value to characterize vibration is the root mean square (RMS) value of acceleration. This allows evaluating the average energy contained in the oscillatory movement, thus revealing the damages caused by the vibration effect. The representation of the expression defining the value of the RMS acceleration variable is shown below for a continuous variable acceleration function $x(t)$ defined over a time interval $T_1 \leq t \leq T_2$ (Eq. 1).

$$a_{rms} = \sqrt{\frac{1}{T_2 - T_1} \int_{T_1}^{T_2} [a(t)]^2 dt} \tag{1}$$

Weighting curves were proposed in ISO 2631-1/1997, which assign different weights to RMS acceleration values based on their corresponding frequencies in the human body, resulting in weighted acceleration (a_w) in m/s², as given by Equation 2, where W_i represents the weighting factors specified by the standard for each one-third octave band of frequencies, and a_i is the corresponding RMS acceleration for each band, which will be detailed in the following section.

$$a_{w,j} = [\sum(W_i {a_i}^2)]^{\frac{1}{2}} \quad j = x, y \text{ or } z \tag{2}$$

The respective weighted acceleration values, a_{wx}, a_{wy}, a_{wz} are obtained for the three orthogonal axes representing the values of weighted accelerations obtained in x, y, and z directions, respectively. It is necessary to obtain a single acceleration value in order to facilitate comparisons with ISO 2631-1/1997 standard, using the following Equation 3 (total acceleration):

$$a_v = \sqrt{{k_x}^2 {a_{wx}}^2 + {k_y}^2 {a_{wy}}^2 + {k_z}^2 {a_{wz}}^2} \tag{3}$$

where, k_x, k_y, k_z are the so-called multiplication factors (enhancement factors), which depend on the axis in which the acceleration occurs, the measurement position, and the purpose of the evaluation (comfort or health) defined in the standard, taking into account uncertainties related to the values of vibration exposure limits. For cases where vibration exposure occurs in two or more periods with different durations and magnitudes that correspond to the total duration of vibration, it is possible to calculate the equivalent total vibration (a_{ve}) according to the following Equation 4, where a_{vi} is the vibration in m/s² for the duration of T_i, where i is the index that defines the respective period.

$$a_{ve} = \left[\frac{\sum({a_{vi}}^2 \times T_i)}{\sum T_i}\right]^{1/2} \tag{4}$$

The ISO 2631-1, 1997 establishes the use of the daily exposure value $A_{(8)}$, which is given by the Equation 5:

$$A_{(8)} = a_{ve} \sqrt{\frac{T}{T_0}} \tag{5}$$

where: T_0 refers to a duration of 8 hours and T is the actual exposure time (h). $A_{(8)}$ is understood as the weighted total vibration to which a particular system is exposed during an 8-hour daily period.

Currently, one of the most popular methods used to assess seat comfort dynamics is the SEAT value (Seat Effective Amplitude Transmissibility). This SEAT value can be calculated from a transfer function for various input vibration acceleration spectra in relation to a measurement point (output). It is defined as a percentage obtained by dividing the seat vibration value by the floor vibration value. If the value is greater than 100%, discomfort may be caused by an increase in vibration transmitted through the seat. If the SEAT value is less than 100%, it indicates that the seat has attenuated part of the generated vibration.

ISO 2631-5, revised in 2018, addresses human exposure to multiple mechanical shocks and defines requirements for their measurement using a formula. The results of these measurements are then analyzed to provide information for assessing the risk of adverse health effects on the vertebral endplates of the spinal column for individuals in a seated position due to compression in this region. Two exposure regimes are distinguished: severe conditions and less severe conditions. Both methods are based on the calculation of the daily compression dose (S_d^A) and the risk factor (R_A).

The compression dose (S_A, in MPa) is estimated according to Equation 6, per exposure for all disc levels, where $C_{dyn,i}$ (N) is the sum of peak compressive forces acting on the vertebral endplate area (B, in mm²), and i is the exposure year counter.

$$S^A = \left(\sum_i \left(\frac{C_{dyn,i}}{B}\right)^6\right)^{1/6} \tag{6}$$

The equivalent daily compression dose in the lumbar spine (S_d^A, in MPa) is calculated using Equation 7, where S_j^A is the dynamic compressive stress of the lumbar spine due to vibration exposure in condition j, t_{dj} is the daily vibrational exposure time in condition j, and t_{mj} is the period over which the dynamic compressive stress is measured.

$$S_d^A = \left(\sum_j {S_j^A}^6 \cdot \frac{t_{dj}}{t_{mj}}\right)^{1/6} \tag{7}$$

The risk factor (R_A in Equation 8) for all levels of vertebral discs is defined for use in assessing adverse health effects related to the daily compression dose, where N_i is the number of days exposed per year, i is the year counter, n is the number of years exposed to that vibration, S_{ui}^A is the maximum force (in MPa) on the lumbar spine for a person of age $(b + i)$ years, where b is the initial age of the individual at exposure and i is the number of years exposed. $S_{stat,i}^A$ is the average compression-decompression force divided by the area of the vertebral endplate (B, in mm²).

$$R^A = \left[\sum_{i=1}^{n}\left(\frac{S_d^A \cdot N_i^{\frac{1}{6}}}{S_{ui}^A - S_{stat,i}^A}\right)^6\right]^{1/6} \quad \text{with} \quad S_{ui}^A = 6{,}765 - 0{,}067 \cdot (b+i) \tag{8}$$

Limits for potential health effects derived from exposure to multiple shock vibration are also defined (Table 2).

Table 2. Health effects assessment according to ISO 2631-5/2018.

Probability of health effects	ISO 2631-5:2018	
Low	$S_d^A < 0.5\ MPa$	$R^A < 0.8$
Moderate	$0{,}5 < S_d^A < 0.8\ MPa$	$0{,}8 < R^A < 1.2$
High	$S_d^A > 0.8\ MPa$	$R^A > 1.2$

ISO 5349-1/2001, provides guidelines for the assessment of exposure to manually transmitted vibrations (Hand-Arm Vibration), specified in terms of frequency-weighted vibration acceleration and daily exposure time (it does not define safety limits related to vibration exposure). The method takes into account factors known to influence the effects of hand-arm vibration exposure in working conditions, such as vibration frequency spectrum, vibration magnitude, duration of exposure per working day, and cumulative exposure.

The assessment of vibration exposure is based on the combination of the three orthogonal axes, resulting in a total vibration value (a_{hv}). To facilitate comparisons between daily exposures with different durations, daily vibration exposure can be expressed in terms of an 8-hour equivalent, denoted as $A_{(8)}$, and presented in Equation 9, where T (h) is the exposure time to vibration and T_0 is the reference time of 8 hours or 28,800 seconds.

$$A_{(8)} = a_{hv}\sqrt{\frac{T}{T_0}} \tag{9}$$

Table 3 presents technical considerations and the recommended actions for the assessed exposure condition.

Table 3. Criterion for judgment and decision-making for hand-arm vibration in exposed workers.

Resultant Acceleration (m/s²)	Technical Consideration	Recommended Actuation
0 to 2.5	Acceptable	Maintenance of the existing condition
2.5 to 3.5	Above the action level	Adoption of preventive measures
3.5 to 5.0	Region of uncertainty	Adoption of preventive/corrective measures, to reduce daily exposure
> 5.0	Above exposure limit	Immediate adoption of corrective measures

Preventive measures are actions that aim to minimize the probability that exposure to vibration will cause damage to the hand-arm system and to prevent the exposure limit from being exceeded. The corrective measures aim to reduce the levels of exposure to vibration, and must be adopted based on the recommendations established in the judgment and decision-making criteria.

4. METODOLOGY

4.1 Apparatus Construction

For the experimental determination of vibration values effectively transmitted to the body, accelerometers will be used, properly positioned on a contact plate compatible with the employed reading equipment and specific norm requirements. That is, to generate the input data, three three-axis transducer accelerometers installed in seat pads will be necessary. These seat pads consist of a disk with an outer edge made of flexible material to conform to the shape of the measurement location, and a rigid core where the accelerometers are encapsulated, in a standardized manner to enable triaxle vibration reading. For the determination of vibration values on the hand-arm system, a triaxle accelerometer encapsulated within a glove will be used, aiming to obtain the actual contact point between the hand and the vibrating object of interest. Figure 1 shows all the equipment used to build the device.

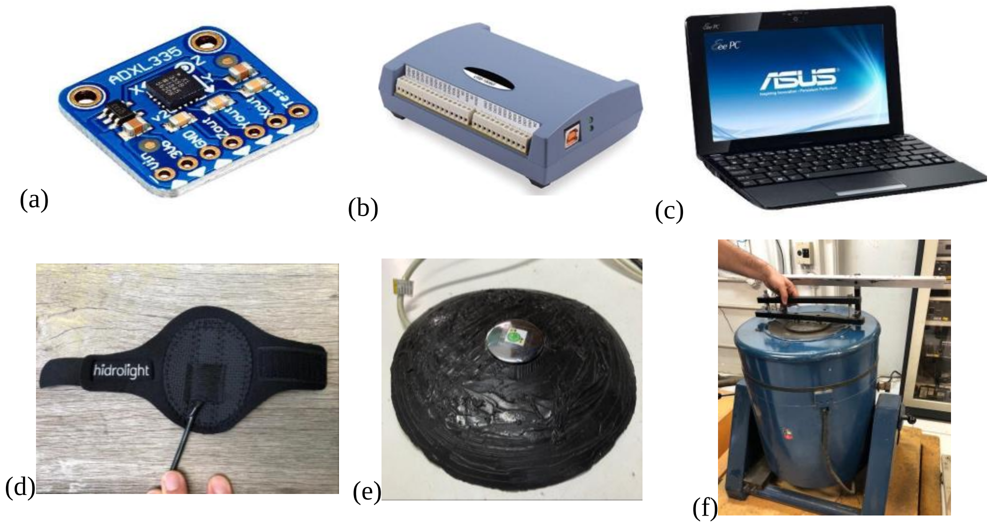

Figure 1. Equipment used for the construction of the simultaneous whole-body and hand-arm vibration measurement device: (a) ADXL335 accelerometer, (b) acquisition board, (c) notebook, (d) hand-pad, (e) seat-pad, (f) Shaker used for the calibration phase (TIRA Vibration Test Systems 5000/300).

4.2 Programming and Interface

To process all the data collected during the tests, an exclusive program was developed using MATLAB™ software. This program acquires, reads, interprets, makes decisions according to international standards and imposed rules, and finally reports the results.

The data collection begins in the field, acquiring them at a rate of 2,000 Hz on four surfaces equipped with tri-axial accelerometers (floor, seat, backrest and steering wheel), resulting in 12 simultaneous channels for storage on the board and streaming recording on the disk. These values are stored in text files in a column and row format, where the first column represents time and the remaining columns represent the respective acceleration values collected on the x, y, and z axes of each accelerometer used on the surface of interest (Figure 2).

TEMPO (s)	EIXO X (1)	EIXO Y (1)	EIXO Z (1)	EIXO X (2)	EIXO Y (2)	EIXO Z (2)	EIXO X (3)	EIXO Y (3)	EIXO Z (3)	EIXO X (4)	EIXO Y (4)	EIXO Z (4)
+0.000000e+00	+3.407776e+00	-1.174632e-01	-3.235779e-01	+9.279117e-01	-4.403939e-01	-4.929087e+00	-2.619597e-01	-1.472599e+00	+5.219716e-01	-4.657859e+00	-1.257664e+00	-4.139351e+00
+5.000000e-04	-3.994591e-01	+7.976289e-01	-4.591471e-01	+2.896066e-01	+7.797290e-01	-4.635354e+00	-2.118721e-03	-1.517789e+00	+7.705151e-01	-6.482395e+00	-1.342395e+00	-2.834497e+00
+1.000000e-03	-2.808361e-01	+9.840366e-01	-4.196061e-01	-4.560240e-01	+6.272136e-01	-1.528559e+00	+4.871973e-02	-1.489545e+00	+7.253254e-01	-8.318228e+00	-1.438423e+00	-3.342882e+00
+1.500000e-03	-1.791592e-01	+7.693853e-01	-7.698266e-01	+5.776912e-01	-3.613119e-01	-2.166864e+00	-1.150931e-01	-1.630763e+00	+5.897562e-01	-1.048734e+01	-3.257310e+00	-5.235202e+00
+2.000000e-03	-2.469438e-01	+7.467905e-01	-4.083087e-01	-7.723522e-01	+5.029418e-01	+8.834428e-01	+1.447479e-01	-1.540384e+00	+5.558639e-01	-1.163402e+01	-4.144159e+00	-7.246146e+00
+2.500000e-03	-2.017540e-01	+5.208418e-01	-3.913625e-01	-1.009598e+00	+4.803470e-01	+4.492973e+00	+2.012351e-01	-1.608169e+00	+3.242665e-01	-1.241355e+01	-3.116092e+00	-9.036789e+00
+3.000000e-03	-3.794125e-02	+2.553521e-01	-9.675317e-01	+3.009041e-01	-2.313914e-01	+2.394891e-01	-5.295718e-02	-1.466951e+00	+2.488448e-02	-1.180914e+01	-3.997292e+00	-1.118330e+01
+3.500000e-03	-4.164053e-01	+1.084854e-01	-9.392881e-01	+8.060411e-02	-5.646657e-01	-2.076485e+00	-1.433366e-01	-1.359625e+00	-1.502258e-01	-1.084320e+01	-3.551044e+00	-1.247686e+01
+4.000000e-03	-2.017540e-01	-4.402992e-02	-6.907445e-01	+3.686887e-01	+4.539575e-02	-9.128492e-01	+1.842889e-01	-1.031999e+00	-2.462539e-01	-9.685217e+00	-2.861900e+00	-1.354447e+01
+4.500000e-03	-1.057259e-01	-3.660068e-01	-4.478497e-01	-1.340471e-01	-1.807383e+00	-2.641357e+00	+2.012351e-01	-9.981071e-01	-8.808986e-02	-8.312579e+00	-2.217946e+00	-1.405850e+01
+5.000000e-03	-1.735105e-01	-5.411170e-01	-8.206650e-01	+5.236052e-02	+3.730213e-01	-2.178162e+00	-2.118721e-03	-8.794840e-01	-1.163334e-01	-6.793074e+00	-3.014415e+00	-1.290616e+01
+5.500000e-03	-9.442842e-02	-5.185222e-01	-5.212830e-01	+4.873117e-01	+5.989700e-01	+7.648198e-01	+2.746684e-01	-7.382661e-01	-7.114371e-02	-3.861390e+00	-2.924036e+00	-1.172558e+01
+6.000000e-03	+6.938438e-02	-8.800401e-01	-3.913625e-01	-3.656445e-01	-8.696964e-01	+1.860671e+00	+2.351274e-01	-3.880456e-01	+7.572294e-02	-2.867216e+00	-2.099323e+00	-8.957707e+00
+6.500000e-03	+1.880074e-01	-9.986631e-01	-1.153939e+00	+3.291477e-01	+3.334803e-01	-8.224698e-01	-2.471359e-02	-2.581251e-01	+4.654844e-01	-2.149829e+00	-2.048485e+00	-7.720638e+00
+7.000000e-03	+3.549208e-02	-8.179042e-01	-6.512035e-01	+2.500656e-01	-6.606939e-01	-4.327083e-01	-1.341616e-02	-1.225559e-01	+5.106742e-01	-2.788134e+00	-2.890144e+00	-6.212430e+00
+7.500000e-03	+3.461715e-01	-1.055150e+00	-7.811240e-01	-9.361650e-01	-2.144452e-01	+1.019012e+00	+2.859659e-01	-4.912258e-02	+6.518921e-01	-3.624144e+00	-7.718747e-01	-4.873684e+00
+8.000000e-03	+3.461715e-01	-1.258504e+00	-9.505855e-01	+1.023940e+00	-4.799350e-01	-8.055236e-01	+1.482743e-02	+1.146902e-01	+8.439485e-01	-5.194487e+00	+8.888481e-01	-3.630967e+00
+8.500000e-03	+4.873894e-01	-9.817170e-01	-6.003651e-01	-6.593778e-01	-1.692555e-01	-1.234826e+00	-2.471359e-02	+4.140722e-01	+7.705151e-01	-7.702518e+00	-4.386004e-01	-3.517992e+00
+9.000000e-03	+4.139561e-01	-9.195811e-01	-1.597651e-01	-8.320869e-02	+1.841688e+00	-3.310314e-01	+2.238300e-01	+5.383440e-01	+8.721921e-01	-8.295633e+00	-1.653075e+00	-3.659210e+00
+9.500000e-03	+4.421997e-01	-9.026349e-01	-5.551753e-01	-8.966240e-01	+3.334803e-01	-1.099257e+00	+1.052069e-01	+5.326953e-01	+9.964638e-01	-7.838087e+00	-5.176824e-01	-1.523995e+00
+1.000000e-02	+3.292254e-01	-7.840119e-01	-7.811240e-01	+3.856348e-01	-4.573401e-01	-2.082134e+00	+7.696332e-02	+7.529953e-01	+6.349459e-01	-7.414433e+00	-1.732157e+00	-2.247031e+00

Figure 2. Fragment cut from the DataStream of one of the conducted tests.

After the battery of tests and storage of collected data, a specific code is run separately for reading, interpreting, and printing final results. This programming phase was internally divided into several cycles of data reading and analysis, including some examples: whole-body comfort evaluation on the seat or backrest, floor to seat transmissibility, evaluation of hand-arm acceleration, SEAT index. As a sample of a fragment of this code, Figure 3 shows a snippet of the code lines from the hand-arm vibration evaluation section.

```
%----------------------------HAV-------------------------------------------
%--------------------------------------------------------------------------
function HAV(path,file,time,xfile,yfile,zfile,HAVcase,point)
% Program for Hand Arm Vibration evaluation (Arms)
% ex. HAV('','1_b_x','1_b_y','1_b_z','1','1')
%      HAV('','med_01_acelNo1_x','med_01_acelNo1_y','med_01_acelNo1_z','1','1')
% PATH - path for the files
% XFILE, YFILE, ZFILE - file names for the measured three axis vibration (time x acceleration)
% HAVCASE - 1-Health, 2-Comfort, 3-Perception
% POINT - measurement point: 1-Hand Arm interface with vibration surface
% Reading vibration values one axis at time
fprintf('\n')
fprintf('***************************HAV*************************** \n')
%% Axis x
if ~isempty(xfile)
    atemp=xfile;
    % Pre-allocating arrays and vectors
    n=size(atemp,1);ax=zeros(n,1);
    % Separation of input time data and measurement data
     ax=atemp(:,1)-mean(atemp(:,1));fs=round(1.0/(time(2)-time(1)));Tx=time(n,1);
    axrms=rms(ax-mean(ax));
    % Plot and print results
    figure;
    plot(time',ax');grid on;
    xlabel('time (s)');ylabel(strcat('a_x acceleration (m/s²)'));
    title(['HAND a_x from file ',file,' f_s=',num2str(fs,'%4.1f'),'  rms(a_x)=',num2str(axrms,'%4.3f'),'(m/s²)']);
    legend(['a_x (m/s²)']);
    %
    aax=ax;
    % Filtering data with the corresponding weighting curve
    if(point=='1')
        if (HAVcase=='1'||HAVcase=='2'||HAVcase=='3') % Comfort
            aax=isofilwh(ax,fs);
        end
    end
    % Plot and print results
    figure;
    plot(time',aax');grid on;
    awxrms=rms(aax-mean(aax));
    xlabel('time (s)');ylabel(strcat('aw_x acceleration (m/s²)'));
    title(['aw_x from file ',file,' fs=',num2str(fs,'%4.1f'),'  rms(a_wx)=',num2str(awxrms,'%4.3f'),'(m/s²)']);
    legend(['aw_x (m/s²)']);
    clear atemp; clear ax;
```

Figure 3. Snippet of code lines from the exclusive program for reading and interpreting each of the conducted tests.

After the completion of the entire program run, the data will be printed (report) in a .docx format, ready for better readability by the researcher and standardized condensation of results into a single file for each test. This file contains values, metrics, assessments, explanations, and graphs generated from the extracted data groups, internally separated into chapters: (1) Whole Body Vibration (VCI); (2) Hand-Arm Vibration (VMB); (3) SEAT; (4) Transmissibility.

In the first chapter, the weighted, total, and maximum accelerations are presented, evaluated according to ISO 2631-1/1997. Subsequently, the comfort is analyzed following the same standard, and a final classification is provided. The extrapolation of values for 8 hours of daily exposure to the collected vibration dose is then performed, demonstrating the total acceleration and equivalent VDV values. The health assessment determines whether the data falls within a safe zone, action zone, or exceeds the limit according to EC 2002-44-EC and ISO 2631/1997. Acceleration graphs, with and without weighting, are generated and saved in the file, along with the formation of the health guidance zone tab, frequency spectra, Fast Fourier Transform (FFT) analysis, and comfort classification.

In the second chapter of the report, the data structure generated from the readings is similar, with the difference being the graph and classification of the values for exposure/action of hand-transmitted vibration according to European Directive 2002-44-EC and the D_y exposure graph for 10% of the exposed population experiencing white finger syndrome (ISO 5349-1/2001).

The third chapter focuses on the SEAT assessment, presenting the values obtained for the three axes and their respective graphs. Finally, in the fourth chapter, the document covers transmissibility, input-output, which was designated in the main program, for example: floor to seat, seat to backrest, etc.

4.3 Device Calibration

Calibration is the process of setting up an instrument to provide a result for a sample within an acceptable range. It involves comparing a known measurement (a defined standard) with the measurement obtained using the instrument in question. In this work, for the calibration phase, it was decided to take the equipment developed to the electrodynamics exciter (shaker) at the GMAP/UFRGS Laboratory (see Figure 1f), where tests were conducted at different vibration frequency/amplitude ranges and compared with the values of the commercially available device QUEST VI-400Pro, which was previously calibrated by an accredited company.

First, a rigid metal device was constructed using screws and nuts to allow the combination of the two vibration meters, enabling them to measure the same intensity simultaneously. Initially, it was positioned horizontally to the exciter, and later in the vertical position (forming a 90° angle). In this second case, the possibility of measuring in two axes simultaneously (X and Y) was created by placing them at a 45° angle to each other. For whole-body calibration measurements, the equipment is activated with the set at 5 (five) different frequencies, (7; 14; 28; 56; 80 Hz) each for a duration of 2 minutes. And for hand-arm vibration calibration measurements, the equipment is set to vibrate at 7 (seven) different frequencies (6,3; 12,5; 25; 50;100; 200; 400 Hz), each for a duration of 1 minute. . These values were chosen because they are the maximum achievable with the signal generator driving the shaker, where the minimum adjusted value is the lower limit that can be achieved with the equipment used, and the subsequent values were set at double the previous value.

It can be observed, in the graphics (Figures 4 to 8), that there was an almost perfect match between all the measured values, and the small 2-second delay is due to the standard delay of the commercial device since the systems (commercial and custom-built) were independent in terms of data recording. Some oscillations occur, probably due to the fact that the system developed for processing and reading data from the custom-built equipment does not have any analog filter between the accelerometers and the A/D data acquisition system, unlike the QUEST VI-400Pro, which has internal analog filters that cannot be removed or turned off.

The peaks appearing in the graphs originated from the signal generation system, resulting in fluctuations of the acceleration generated by the shaker, which were detected by both accelerometers. It can be noted that, despite some fluctuations and small differences, there is good degree of conformity between the values measured by the two devices under the proposed excitations. The plotted graphs are RMS values measured at 20ms, which is the smallest time interval for recording in the commercial instrument. The developed device does not have this limitation, being possible to record all values at the sample frequency (2 kHz). Summarizing the validation study, we have Tables 4 with the data collected to WBV. Tables 5 contain the numerical values of the validation study for HAV (Z and XY axes).

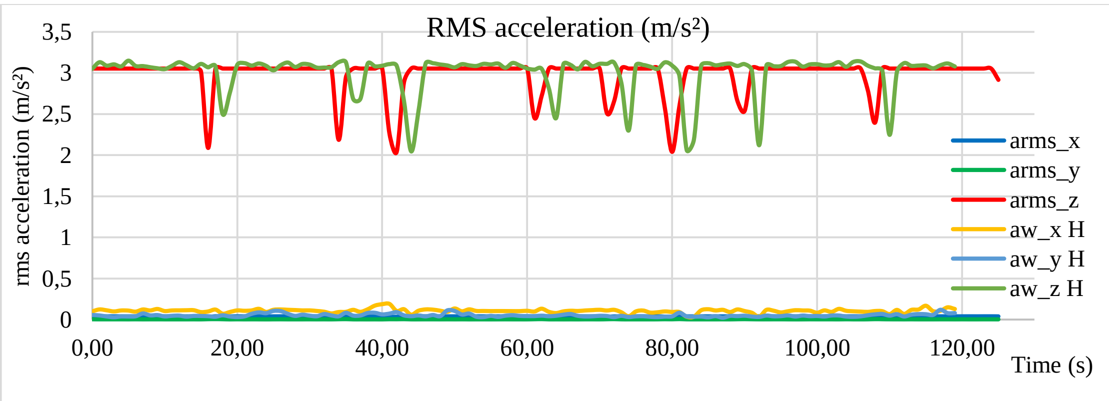

Figure 4. Comparison chart WBV, Z-axis at 7 Hz.

These data generate a satisfactory percentage difference in the comparison between the values. It can therefore be concluded that the constructed equipment is fully capable of performing whole-body vibration measurements. It is presumed that the larger variations observed for the $x - y$ axes are due to the fact that the 45° orientation of these axes relative to the Z-axis reference (gravity acceleration) was not perfect in the experiment between the commercial seat pad and the seat pad developed. Then, the calibration phase is completed, where it is verified and verified that the developed equipment is qualified to carry out Whole Body and Hand-Arm Vibration measurements.

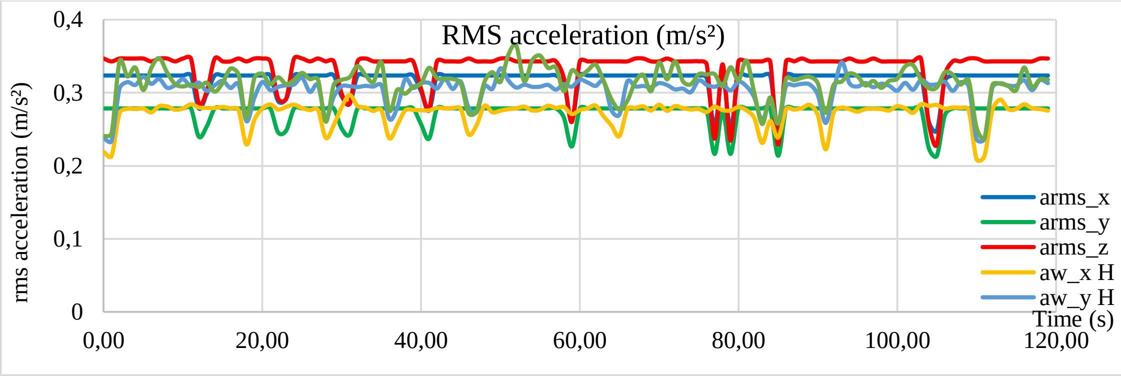

Figure 5. Comparison chart WBV, XY-axis at 7 Hz.

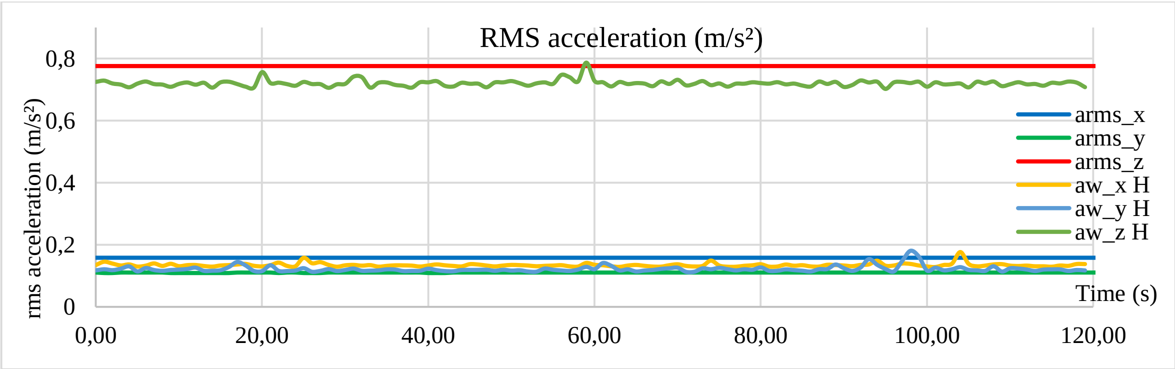

Figure 6. Comparison chart WBV, XY-axis at 80 Hz.

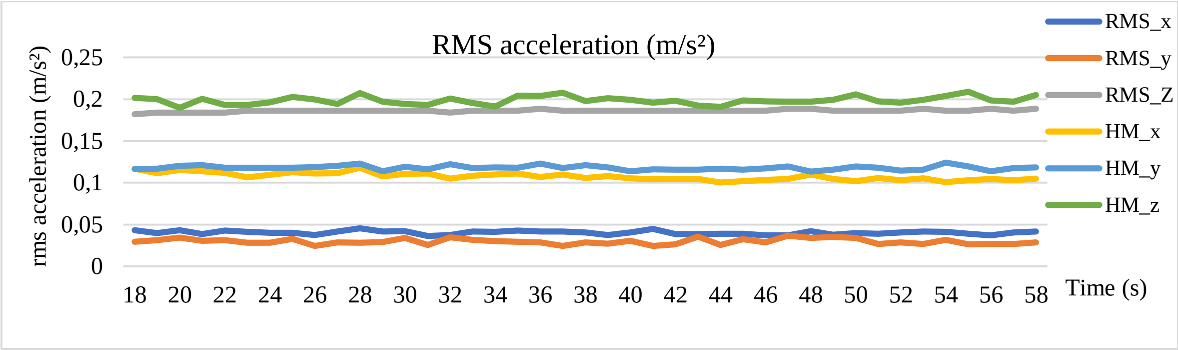

Figure 7. Comparison chart HAV, Z-axis at 400 Hz.

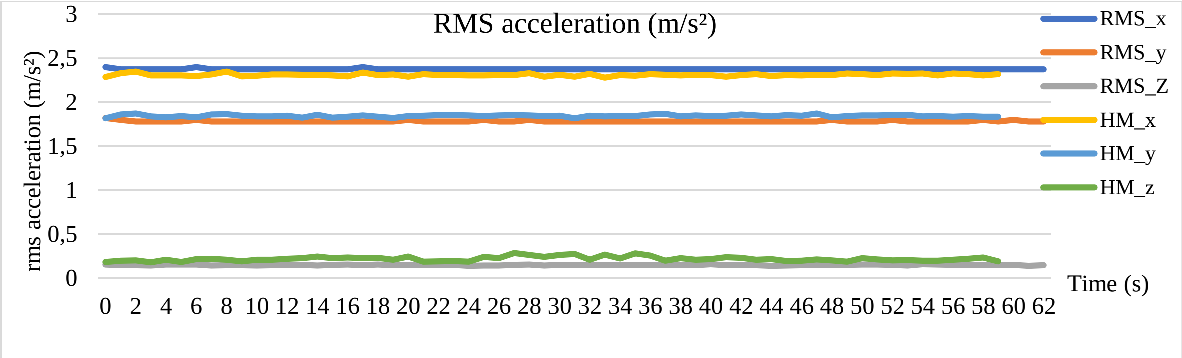

Figure 8. Comparison chart HAV, XY-axis at 12,5 Hz.

Table 4. Data collected and processed with the commercial vibration measuring instrument QUEST VI-400 Pro and with the apparatus developed here for WBV.

QUEST VI-400 Pro (WBV)				
	f(Hz)	RMS (m/s²)	VDV (m/s$^{1.75}$)	A(8) (m/s²)
Z-AXIS	7	2.9861	11.324	0.1927
	14	9.3929	34.5144	0.606
	28	2.95	10.927	0.1903
	56	1.9251	7.0496	0.1242
	80	0.5497	2.0251	0.0355
XY-AXIS	7	0.6768	1.504	0.0437
	14	0.5887	1.4214	0.038
	28	0.3463	0.9987	0.0262
	56	0.8234	2.891	0.0531
	80	0.822	2.8432	0.053

HM Vibration Meter – Developed Apparatus (WBV)				
	f(Hz)	RMS (m/s²)	VDV (m/s$^{1.75}$)	A(8) (m/s²)
Z-AXIS	7	3.0764	11.563	0.1985
	14	9.5715	35.017	0.6175
	28	2.8567	10.467	0.1843
	56	1.9486	7.1455	0.1257
	80	0.5336	1.9702	0.0344
XY-AXIS	7	0.6539	1.5931	0.0422
	14	0.5642	1.4623	0.0364
	28	0.3303	0.9911	0.0263
	56	0.8196	2.9447	0.0529
	80	0.7647	2.7307	0.0493

Table 5. Data collected and processed with the commercial vibration measuring instrument QUEST VI-400 Pro and with the apparatus developed here for HAV.

QUEST VI-400 Pro - HAV			
	f(Hz)	RMS (m/s²)	A(8) (m/s²)
Z-AXIS	6.3	2.3876	0.1089
	12.5	3.3659	0.1586
	25	3.1637	0.1491
	50	1.5916	0.0731
	100	0.8824	0.0402
	200	0.4749	0.0216
	400	0.1790	0.0084
XY-AXIS	6.3	2.3652	0.0865
	12.5	2.9709	0.1083
	25	3.2701	0.1173
	50	1.5293	0.0562
	100	1.0387	0.0383
	200	0.9909	0.0372
	400	0.5655	0.0183

HM Vibration Meter – Developed Apparatus (WBV)			
	f(Hz)	RMS (m/s²)	A(8) (m/s²)
Z-AXIS	6.3	2.3148	0.0961
	12.5	3.0746	0.1386
	25	3.0212	0.1360
	50	1.4524	0.0648
	100	0.8114	0.0362
	200	0.4406	0.0192
	400	0.1893	0.0086
XY-AXIS	6.3	2.3901	0.0849
	12.5	2.9628	0.1054
	25	3.2602	0.1132
	50	1.5915	0.0565
	100	1.1102	0.0389
	200	0.9774	0.0362
	400	0.5809	0.0173

5. CONCLUSIONS

The HM Measuring Device was constructed in accordance with the corresponding standards and calibrated by comparison with a similar commercial device using an electrodynamic exciter encompassing various frequency bands. To process all the data collected during the tests, a unique and innovative program was developed using a mathematical software. This program acquires, reads, interprets, decides according to international standards and imposed rules, and finally prints the condensed results in a document/report in '.docx' format. Data is acquired at a rate of 2 kHz simultaneously on four surfaces composed of three axis accelerometers.

The developed equipment stands out from existing commercial devices due to its ability to measure at four different points in three axes simultaneously and at a high acquisition rate. The constructed equipment is capable and qualified to perform measurements of hand-arm vibration and whole-body vibration.

6. REFERENCES

Basri, B., M. J. Griffin. 2013. Predicting discomfort from whole-body vertical vibration when sitting with an inclined backrest. Appl. Ergon., Vol. 44, p. 423–434.

Beard, G. F., and M. J. Griffin. 2016. Discomfort of seated persons exposed to low frequency lateral and roll oscillation: Effect of backrest height. Appl. Ergon., Vol. 54, p. 51-61.

Bovenzi, M; Schust, M; Mauro, M. 2017. An overview of low back pain and occupational exposures to whole-body vibration and mechanical shocks. Medicina del Lavoro, vol. 108, n. 6, p. 419-433.

Bruel & Kjaer, Primer: Human Vibration. Booklet. Ed. Bruel and Kajer, Denmark, 1989.

Butler, C., M. J. Griffin. Motion sickness with combined fore aft and pitch oscillation: Effect of phase and the visual scene. Aviat. Space Environ. Med., Vol. 80, p. 946–54, 2009.

Charles, L. E., C. C. Ma, C. M. Burchfiel, and R. G. Dong. Vibration and ergonomic exposures associated with musculoskeletal disorders of the shoulder and neck. Saf. Health Work, Vol. 9, p. 25–32, 2018.

Donohew, B. E., M. J. Griffin. Motion sickness with combined lateral and roll oscillation: Effect of percentage compensation. Aviat. Space Environ. Med., Vol. 81, p. 22–29, 2010.

Directive 2002/44/EC of the European Parliament and of the Council of 25 June 2002 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration). Off. J. Eur. Commun. 2002, L177, pp. 13-19.

Du, B. B., P. L. Bigelow, R. P. Wells, H. W. Davies, P. Hall, P. W. Johnson. The impact of different seats and whole-body vibration exposures on truck driver vigilance and discomfort. Ergonomics, Vol. 61, p. 28–37, 2018.

Fedatto Neto, M. *Modelagem dinâmica de viaturas blindadas e avaliação relativa à Vibração de Corpo Inteiro, níveis de transmissibilidade e vibração de impacto na coluna vertebral.* Master Thesis. Graduate Program in Mechanical Engineering. PROMEC, Federal University of Rio Grande do Sul, RS, Brazil, 2018.

Fedatto Neto, M., Gomes, H. M. Análise de níveis de vibração em usuários de trens urbanos. Revista Liberato, vol. 18, n. 29, p. 276-296, 2017.

FUNDACENTRO - Norma de higiene ocupacional - NHO 09: avaliação da exposição ocupacional a vibrações de corpo inteiro: procedimento técnico - São Paulo/SP: Fundacentro. 63 p., 2013.

FUNDACENTRO - Norma de higiene ocupacional - NHO 10: avaliação da exposição ocupacional em mãos e braços: procedimento técnico - São Paulo/SP: Fundacentro. 53 p., 2013.

Griffin, M. J. 1996. *Handbook of human vibration.* Academic Press.

Haward, B. M., C. H. Lewis, M. J. Griffin. 2009. Motions and crew responses on an offshore oil production and storage vessel. Appl. Ergon., Vol. 40, p. 904–914.

Hering, D., K. Lachowska, and M. Schlaich. 2015. Role of the sympathetic nervous system in stress-mediated cardiovascular disease. Curr. Hypertens. Rep., Vol. 17, p. 80.

ISO 2631-1/2010 (AMD). Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General requirements. Amendment 1, Geneva: International Organization for Standardization.

ISO 2631-1/1997. Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General requirements. Geneva: International Organization for Standardization.

ISO 2631-5/2018. Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 5: Method for evaluation of vibration containing multiple shocks. Revised, Geneva: International Organization for Standardization.

ISO 5349-1/2001. Mechanical vibration – Measurement and evaluation of human exposure to hand transmitted vibration – Part 1: General requirements. Geneva: International Organization for Standardization.

ISO 8041-1/2017. Human response to vibration – Measuring instrumentation – Part 1: General-purpose vibration meters. Geneva: International Organization for Standardization.

Jones, M. K., M. A. Harris, P. A. Peters, M. Tjepkema, P. A. Demers. 2014. Prostate cancer and occupational exposure to whole-body vibration in a national population-based cohort study. Am. J. Ind. Med., Vol. 57, p. 896–905.

Mizushima, A.J.; Fedatto Neto, M.; Gomes, H.M. 2022. Níveis de riscos e Vibração Mão-Braço (VMB) em máquinas de corte de grama. Revista Liberato, vol. 23, n. 40, p. 195-206.

Nadalin, V., N. Kreiger, M. E. Parent, A. Salmoni, A. SassKortsak, J. Siemiatycki, M. Sloan, and J. Purdham. 2012. Prostate cancer and occupational whole-body vibration exposure. Ann. Occup. Hyg., Vol. 56, p. 968–974.

NBR NM ISO 5353/1999. Máquinas rodoviárias, tratores e máquinas agrícolas e florestais - Ponto de referência do assento. ABNT - Associação Brasileira de Normas Técnicas.

NR-15/2014. Norma Regulamentadora Nº 15. Atividades e operações insalubres - Anexo Nº 8 Vibrações. <http://www.guiatrabalhista.com.br/legislacao/nr/nr15.htm>.

Palmer, K. T., M. Griffin, G. Ntani, J. Shambrook, P. McNee, M. Sampson, E. C. Harris, and D. Coggon. 2012. Professional driving and prolapsed lumbar intervertebral disc diagnosed by magnetic resonance imaging: A case-control study. Scand. J. Work Environ. Health, Vol. 38, p. 577–581.

Rampal, K.G., Rozali, A., Shamsul Bahri, M.T. 2009. Low back pain and association with whole body vibration among military armoured vehicle drivers in Malaysia. Medical Journal of Malaysia, vol. 64, n. 3, p. 197-204.

Ronchese, F., and M. Bovenzi. 2012. Occupational risks and health disorders in transport drivers. G. Ital. Med. Lav. Ergon. Vol. 34, p. 352–359.

Roseiro, LM; Neto, MA; Amaro, AM; Alcobia, CJ; Paulino, MF. 2016. Hand-arm and whole-body vibrations induced in cross motorcycle and bicycle drivers. International Journal of Industrial Ergonomics, Vol. 56, p. 150-160, 2016.

Stoyneva, Z. Postocclusive reactive hyperaemia in hand-arm vibration syndrome. Int. J. Occup. Med. Environ. Health, Vol. 29, p. 659–666.

Tarabini, M.; Mauri, N.; Gaudio, I.; Cinquemani, S.; Moorhead, A. P.; R. Bongiovanni, R.; Feletti, F. 2020. Hand-arm vibration in motocross: measurement and mitigation actions. Muscles, Ligaments and Tendons Journal, Vol. 10, n. 2, p. 280-289.

Waugh, S., M. L. Kashon, S. Li, G. R. Miller, C. Johnson, and K. Krajnak. 2016. Transcriptional pathways altered in response to vibration in a model of hand-arm vibration syndrome. J. Occup. Environ. Med., Vol. 58, p. 344–350.

7. RESPONSIBILITY NOTICE

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