Acta of Bioengineering and Biomechanics
Vol. 26, No. 3, 2024

Original paper
DOI: 10.37190/ABB-02435-2024-05

Analysis of vibrations transmitted to the feet of a wheelchair user

MAGDALENA KROMKA-SZYDEK[1]*, GABRIELA CHWALIK-PILSZYK[1], ZYGMUNT DZIECHCIOWSKI[2]

[1] Department of Applied Mechanics and Biomechanics, Faculty of Mechanical Engineering, Cracow University of Technology, Kraków, Poland.
[2] Laboratory of Techno-Climatic Research and Heavy Duty Machines, Faculty of Mechanical Engineering, Cracow University of Technology, Kraków, Poland.

Purpose: The aim of the study was to quantitatively evaluate the vibrations received on the wheelchair footrest and to determine whether wheelchair users are at risk of vibration-white foot. This assessment was made using the ISO 2631 standard. *Methods*: The measurements were taken on the footrest of a universal wheelchair. The tests were carried out on five surfaces frequently found in public spaces and measurements were carried out on a study group of eight non-disabled people. *Results*: The vibration values received on the footrest of a universal wheelchair are higher compared to the vibrations received on the seat. It was found that the comfort limit defined by the ISO 2631 standard for frequencies in the range of 30–40 Hz was exceeded. *Conclusions:* Research shows that a wheelchair user is exposed to whole body vibrations occurring on the footrest. It therefore seems reasonable to take steps to minimize this factor.

Key words: *wheelchair, disabled person, whole body vibration, footrest*

1. Introduction

When moving around using a wheelchair, both manual and electric, users of this device are exposed to general vibrations [5], [6], [33]. Whole body vibrations are vibrations transmitted through the surfaces of direct contact/interaction with a person's body to the torso and further onto the internal organs. In the case of a wheelchair, they are carried through the seat, backrest and footrest. These vibrations can be dampened by the structural components of the wheelchair (i.e., frame, seat, suspension components or additional equipment such as seat cushions), while some are absorbed by the human body.

Despite the seemingly small vibrations perceived by wheelchair users, they may have a significant impact on their comfort and health [2], [19], [25]. In addition, they can lead to fatigue of the wheelchair user [5], [10], [30]. Among other things, there is an increased risk of lumbar spine ailments and the connected nervous system due to the long-term and intense effects of whole body vibrations on the human body [25]. In addition, health risks are likely to increase as the duration and intensity of the stimulus increases.

There are a number of publications on the impact of whole body vibrations on the wheelchair user [5], [6], [10], [11], [24]. However, these studies focused on measuring vibrations on the seat of this device, and only a few publications discuss the vibrations received on the footrest of the wheelchair [7], [8], [31], [33]. This may be related to the fact that manual wheelchair users are more likely to complain of ailments in the upper limbs, rather than in the lower limbs [19], [20]. However, it is worth noting that this stimulus transmitted by the footrest can cause the propagation of vibrations in the user's legs, and thus can lead to the formation or aggravation of diseases in this part of the human body.

* Corresponding author: Magdalena Kromka-Szydek, Cracow University of Technology, Department of Applied Mechanics and Biomechanics, Faculty of Mechanical Engineering, Kraków, Poland. E-mail: magdalena.kromka-szydek@pk.edu.pl

Received: April 11th, 2024
Accepted for publication: September 17th, 2024

Wolf and co-authors [33] conducted vibration measurements on wheelchair seats and footrests on nine different surfaces in public spaces. In the tests, they used both a manual and an electric wheelchair, which moved at a speed of 1 m/s and 2 m/s. In this study, regardless of the pavement on which the wheelchair was moving and the travel speed, greater vibrations were observed on the footrest than on the seat of wheelchairs (both manual and electric) [33]. This suggests that wheelchair users may be exposed to long-term vibration effects on their lower limbs.

Long-term exposure of hands to vibration may lead to neurological, vascular and musculoskeletal problems, which are known in the literature as hand-arm vibration syndrome (HAVS) [29]. A similar syndrome may occur in the lower limbs of people exposed to vibrations transmitted through the feet and is called vibration-white foot [29]. It is considered an occupational disease [12], [23], [28], [29]. Due to the fact that this syndrome occurs in people exposed to vibrations for a long time, it may also occur in people using a wheelchair.

Neurologic symptoms in vibration-white foot include tingling and numbness in the feet or reduced sensation of touch and temperature [22], [28]. Vascular symptoms may include increasing loss of circulation, which may lead to blanching and necrosis of the toes [22], [23]. Osteoarticular symptoms may include bone or joint damage and muscle fatigue [22]. According to Tarabini et al. [28], exposure to vibrations in the range of 30–40 Hz is associated with an increased risk of developing vibration-induced white foot. In turn, Nader [26] states that the resonance frequency of the feet is 59.2 Hz, however, these are the results of model studies. These frequencies can be especially dangerous for people using a wheelchair. Cases of wheelchair users developing white foot disease have not been documented. Most publications in the field of whole body vibrations of the wheelchair user have focused on vibrations on the seat of the wheelchair, while vibrations on the footrest are ignored. The motivation for the article was a survey of wheelchair users conducted as part of the 2018 thesis. In this survey, out of 66 people surveyed, 36 indicated their legs as a body area that is particularly sensitive when using a wheelchair.

There are studies in which the authors address the positive effects of WBV in patients with diabetic peripheral neuropathy [27]. The frequencies used by the authors ranged from 15 to 30 Hz, and the vibration exposure time was a maximum of 15 minutes. However, as the authors stated, WBV has only a slight positive effect on this type of condition.

Any vibration exposure experienced by wheelchair users is directly related to their mobility [24]. It is, therefore, important to determine whether the level of vibration exposure is harmful and, if necessary, identify ways to minimize any health risks posed by vibration.

The aim of the study was to determine the amount of vibrations received by the user of a manual wheelchair on the footrest of this device and to determine whether he is at risk of vibration-white foot. When evaluating vibration exposure to humans, the ISO 2631 standard [14] was referred to, taking predominantly vertical and lateral directions into account. The risk associated with receiving vibrations by a person depends on the value of the amplitude of vibration acceleration but also on the duration of the impact of these vibrations on a person (the duration of impact is taken into account in the assessment of the impact of vibrations at the workplace described by ISO 2631).

2. Method of experimental research

In this paper, whole body vibration (WBV) measurements were carried out, with signal reception at the footrest of a universal wheelchair. The measurements were performed using a Unix Breezy Sunrix Medical wheelchair weighing 18 kg. The measured dimensions of the wheelchair are shown in Table 1.

To make the measurement possible, an aluminum plate was placed on the factory-installed footrest, matching the dimensions of the footrest (Fig. 1). On this plate, the measuring disk (with triaxial transducers), which was pressed to the aluminum plate and footrest with the feet was located. The aluminum plate (fluted with a thickness of 5 mm) is a component that conducts vibrations very well, and its stiffness is high enough to not cause generation of vibrations associated with the vibrating plate. The study used a four-channel SVAN 958 vibration meter from SVANTEK, with a tri-direc-

Table 1. Specification of the wheelchair

	Total width [mm]	Internal width [mm]	Total depth [mm]	Seat height from the ground [mm]	Seat height from footrest [mm]	Overall height [mm]	Seat angle [°]	Tire type and size, rear wheels
Dimension	1080	460	390	510	360	960	3	full tire 24″ × 1″

tional SV 39A vibration transducer. The transducer was placed in the center of the wheelchair footrest. Placed in this way, on the footrest, the transducer made it possible to record vibrations in three directions, which are marked in Fig. 2.

Fig. 1. Aluminum plate mounted
on wheelchair footrest together with sensor

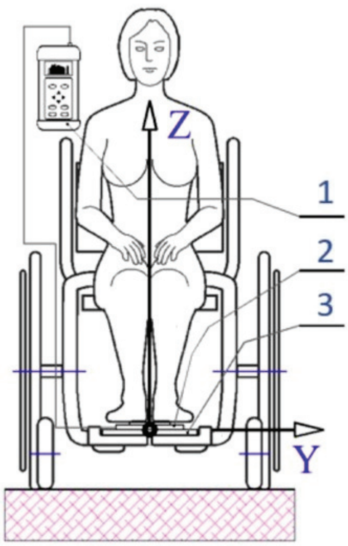

Fig. 2. Measuring stand with directions of vibration reception:
1 – vibration spectrum analyzer,
2 – the triaxial transducer SV 39A, 3 – footrest

During the measurements, the time variation of the vibration acceleration value a_{RMS} was registered, with the signal recorded at a sampling frequency of 12 kHz. Based on the obtained signal, using SvanPC++ software, analyses were performed in the y- and z-axis directions for 1/3 octave bands. According to ISO 2631 [14], the focus was on the range from 0.8 to 80 Hz. During the analysis, particular attention was paid to frequencies of 30–40 Hz, which, according to the literature [22], [26] can adversely affect the lower limbs.

The study was carried out on rectilinear test sections with a length of 40 m, on five different pavements, which are shown in Fig. 3. Time measurements were taken during each run with an accuracy of +/– 1 s. The average run speed was 1.2 +/– 0.1 m/s.

Eight non-disabled people participated in the study. During each of the runs conducted, the participants in the study moved in a wheelchair in a passive manner, so the wheelchair was controlled by an attendant, the same person each time. This way, the influence of the user's wheelchair experience (driving style and speed) on the magnitude of perceived vibrations on the wheelchair footrest was eliminated. The characteristics of the subjects taking part in the study are shown in Table 2.

Table 2. Characteristics of people participating in the study

Identification of subjects	P1	P2	P3	P4	P5	P6	P7	P8
Body mass [kg] (+/– 0.5 kg)	79.0	78.0	68.0	85.0	60.0	55.0	59.0	60.0
Height [m] (+/– 0.01 m)	1.80	1.78	1.75	1.60	1.70	1.60	1.69	1.74

For the P3 user, moving on the PAV_1, PAV_2, PAV_3, and PAV_4 surfaces, the vibration readings measured on the wheelchair footrest were compared to the vibration readings measured on the seat, which were published in the paper by Chwalik-Pilszyk and co-authors, "Experimental Study of the Influence of

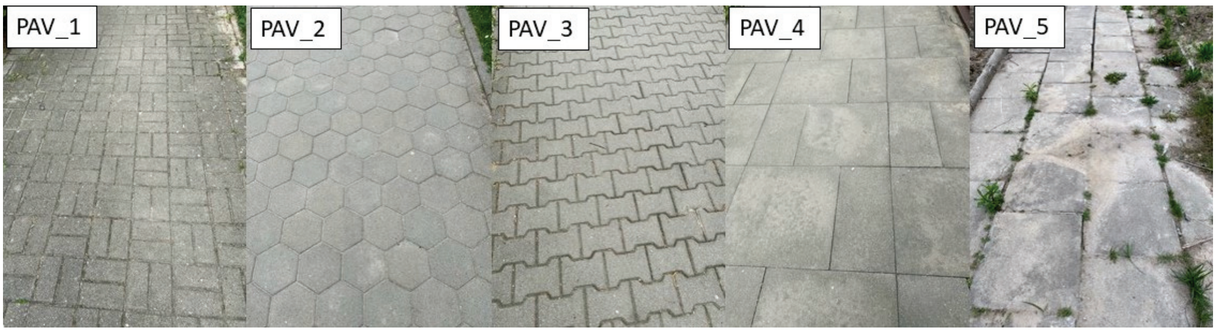

Fig. 3. Types of surfaces used in the tests: PAV_1 – "mosaic" paving stones, PAV_2 – hexagonal slab,
PAV_3 – "bone" paving stones, PAV_4 – 0.6 × 0.6 m slab, PAV_5 – 0.5 × 0.5 m slab (with visible damage)

Using Polyurethane Cushion to Reduce Vibration Received by a Wheelchair User". [5]. Based on the results, the seat-footrest (SF) index, expressed as the ratio of vibrations received on the footrest to those received on the wheelchair seat, was calculated according to Eq. (1).

$$\mathrm{SF} = \frac{a_{\mathrm{footrest}}}{a_{\mathrm{seat}}}, \tag{1}$$

where:

a_{footrest} –acceleration value for a given 1/3 octave band registered on the footrest [m/s^2],

a_{seat} – acceleration value for a given 1/3 octave band registered on the seat [m/s^2].

SF was calculated for each 1/3 octave band in the range of 0.8÷80 Hz, using the average a_{RMS} value of the vibration of each tertian band. A value of coefficient SF = 1 means that vibrations of the same amplitude occur on the seat and footrest of the wheelchair. A value of coefficient SF < 1 means that the vibrations on the footrest were less than the vibrations captured on the seat. On the other hand, a value of coefficient SF > 1 means that there were vibrations on the footrest with a higher value compared to the vibrations on the seat. No analysis of the impact of the SF factor in the context of the occurrence of white foot disease risk has been carried out. Determination of this coefficient made it possible to identify to which part of the wheelchair user's body the largest amount of vibration is transmitted.

At the same time, a questionnaire was administered among those participating in the study, the purpose of which was to subjectively assess the vibrations received while using a wheelchair. Survey respondents were asked three questions in which the subjects were asked to indicate the worst and the best pavement in terms of vibrations perceived while driving. Participants in the study also indicated from which area of the wheelchair (seat or footrest) the highest amount of vibration is perceived.

Preliminary analyses do not allow to determine a clear relationship between the user's weight and the values of parameters describing the vibrations transmitted to the organism. A detailed statistical analysis has not been performed due to the fact that the presented research is of a preliminary nature. The analysis of the obtained results was performed through visual inspection.

3. Results

As previously mentioned, the survey research provided a subjective assessment of vibrations perceived at the footrest of the wheelchair. The survey results are presented in the Table 3. In the first question, respondents were asked to point out the pavement that they felt was the most inconvenient. In this question, 38% of respondents indicated a mosaic paving stones (PAV_1) surface, 37% of respondents indicated a bone type surface (PAV_3) and 25% indicated a surface consisting of 0.5 × 0.5 m slabs (damaged) (PAV_5). The respondents unanimously stated that the greatest driving comfort was experienced when driving on 0.6 × 0.6 m slab pavement (PAV_4). According to all survey participants, vibrations on the wheelchair footrest (compared to the seat) were more noticeable and therefore bothersome, regardless of the type of footwear of the participants.

Table 3. Survey results

Questions		Answers
Indicate the sidewalk on which driving was most uncomfortable	bone type surface	38%
	hexagonal slab	0%
	bone type surface	37%
	0.6 × 0.6 m slab	0%
	0.5 × 0.5 m slab (with visible damage)	25%
Indicate the sidewalk on which driving was most comfortable	bone type surface	0%
	hexagonal slab	0%
	bone type surface	0%
	0.6 × 0.6 m slab	100%
	0.5 × 0.5 m slab (with visible damage)	0%
In which part of the wheelchair were the vibrations felt more?	seat	0%
	footrest	100%

The results of the vibration analysis, in the form of amplitude–frequency characteristics, are shown in Figs. 4 and 5. Because vibrations in the frequency range of 30–40 Hz according to the literature increase risk of occurrence of white foot, special attention was paid to the third octave bands with a frequency of 31.5 Hz and 40 Hz in the analysis [28].

In Figure 4, an example of the amplitude–frequency characteristics in the "Z" direction obtained for a P3 user's ride on all pavements is shown. For all analyzed pavements, the exceedance of the comfort limit between 4 and 22 Hz is evident. The lowest value of acceleration a_{RMS}, at the foot of the wheelchair, was recorded when the wheelchair was driven over a 0.60 × 0.60 m paving slab surface.

For pavements of the 0.6 × 0.6 type, the nuisance limit defined by the ISO standard was not exceeded (the exception is at a frequency of 8 Hz, exceeding the norm by 0.05 m/s^2). A similar trend was observed in all study participants, which finds confirmation in the surveys. For the PAV_1, PAV_2, PAV_3 and PAV_5 surfaces, it is also apparent that the nuisance limit is exceeded in the 6.3 Hz to 16 Hz range, with the PAV_5 surface exceeding the limit in the largest range of third octave bands (5–25 Hz).

ing stones). The largest exceedances of the criterion values (by 0.8 m/s^2) occur at 25 Hz for the PAV_5 pavement (0.5×0.5 damaged slab). At the same time, higher maximum vibration values were observed for the "*Y*" direction compared to the "*Z*" direction.

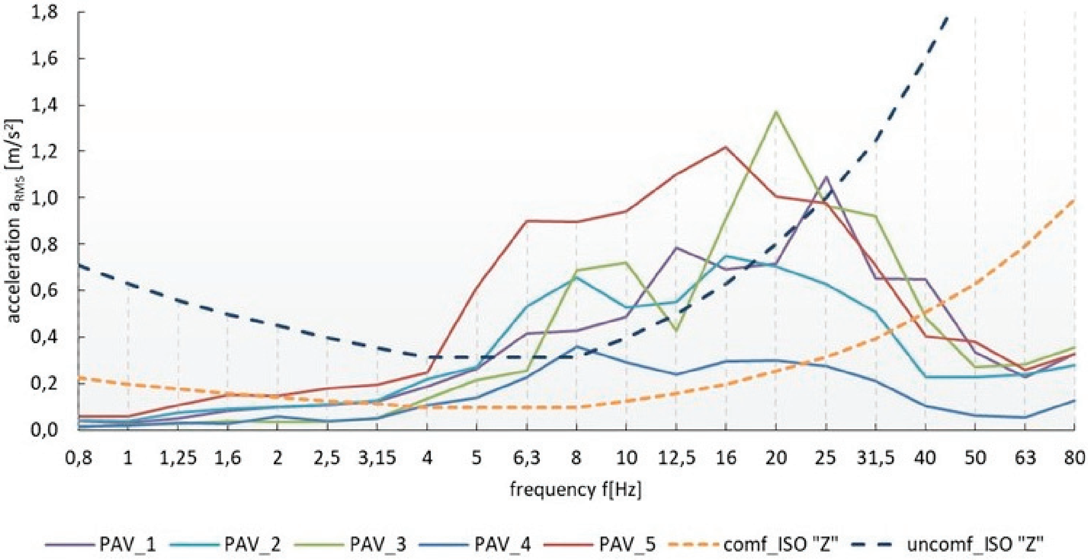

Fig. 4. Amplitude–frequency characteristics (direction "*Z*") for user P3 with reference to the ISO standard (comfort limit)

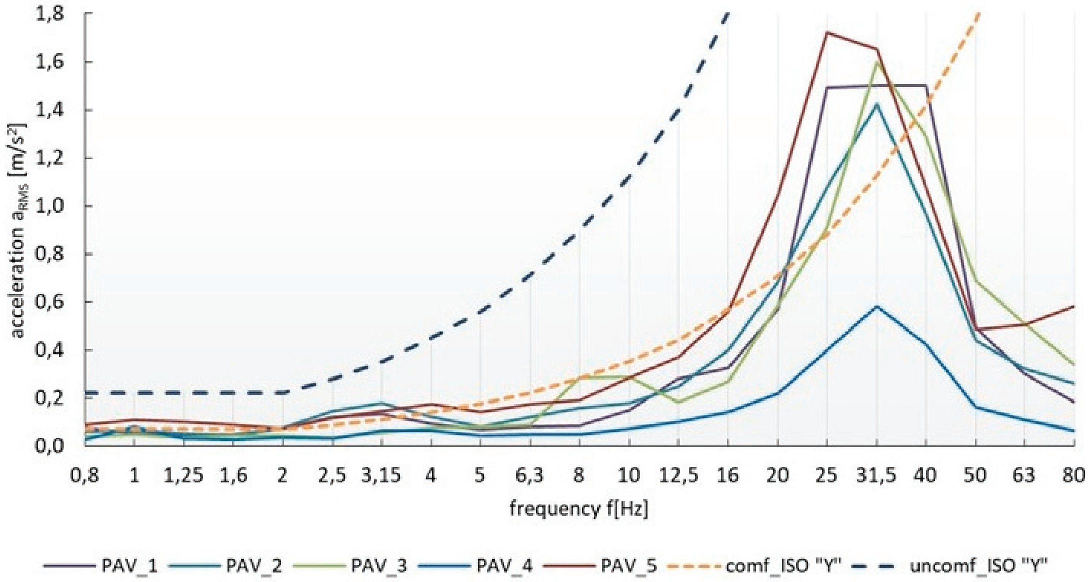

Fig. 5. Amplitude–frequency characteristics (direction "*Y*") for user P3 with reference to the ISO standard (comfort limit)

In the graph in Fig. 5, it is shown that, in the case of vibrations in the "*Y*" direction, the nuisance limit is not exceeded, regardless of the type of surface. Exceeding the comfort limit for the *Y*-axis is evident for third octave bands in the range from 20 to 31.5 Hz, except for the PAV_4 pavement (0.60 × 0.60 m pav-

In Figures 6–9, the a_{RMS} acceleration values for the 31.5 Hz and 40 Hz third octave bands for all test subjects and for all pavements with the ISO comfort limit marked are shown [14].

In the case of the *z*-axis, for a third octave band of 31.5 Hz, the highest values of vibration acceleration

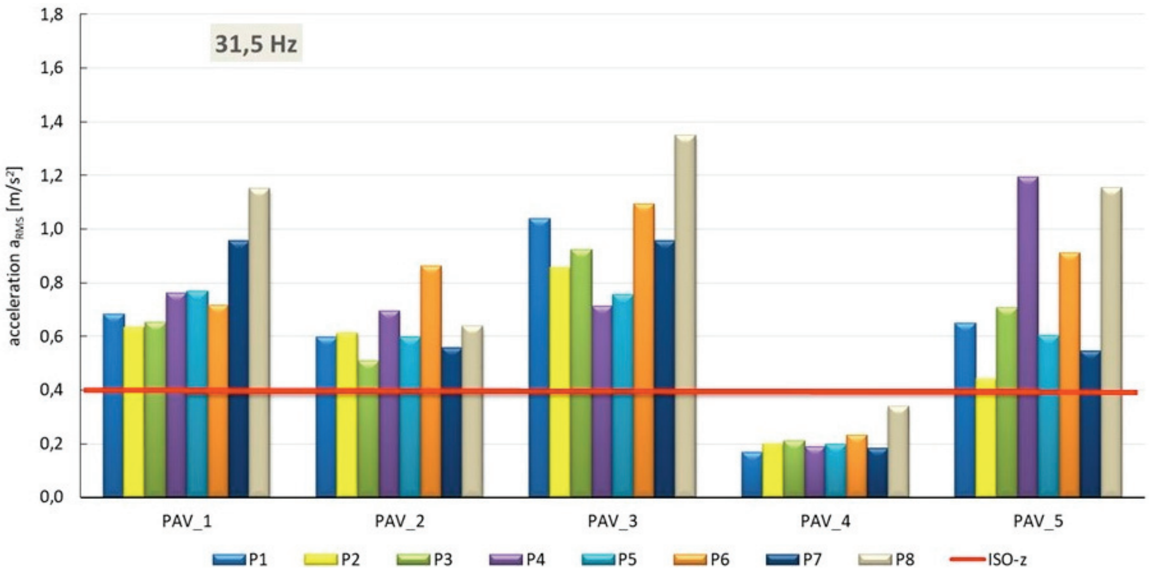

Fig. 6. Comparison of the average a_{RMS} acceleration values for the frequency of 31.5 Hz, for the y-axis, for test subjects, when driving on the analyzed surfaces with reference to the ISO standard (comfort limit)

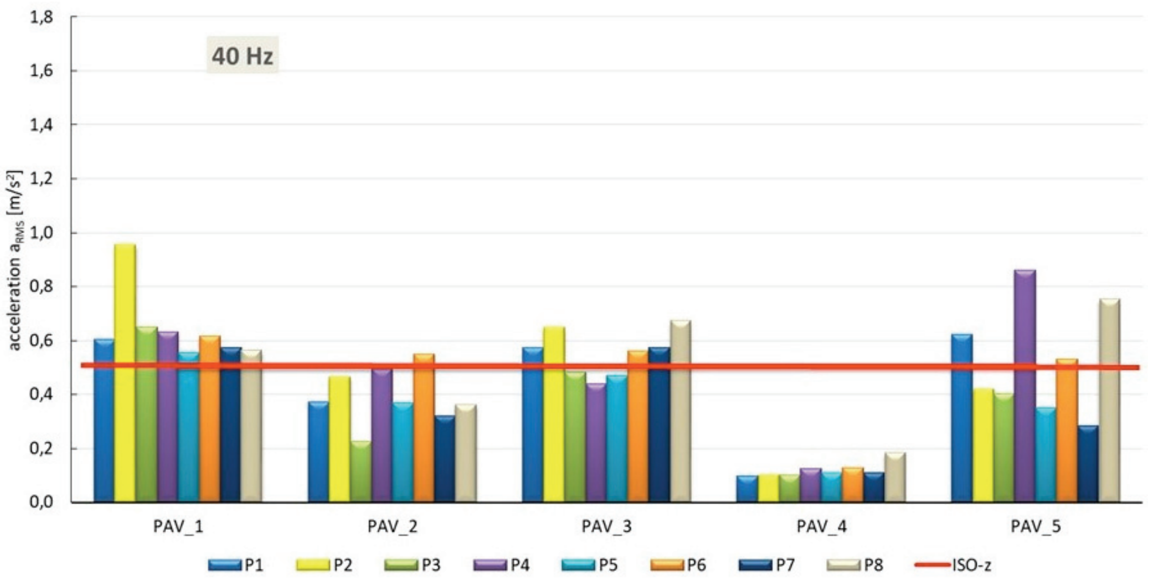

Fig. 7. Comparison of the average values of a_{RMS} acceleration for a frequency of 40 Hz, for the y-axis, for test subjects, when driving on the analyzed surfaces with reference to the ISO standard (comfort limit)

were registered when driving on the PAV_3 pavement (Fig. 6). For vertical vibration, exceeding the comfort limit is evident for all users and pavements except PAV_4. For the 40 Hz third octave band, a decrease in the a_{RMS} value of acceleration is evident, compared to the results obtained for the 31.5 Hz third octave band. Exceeding the comfort limit for all users is evident for the PAV_1 surface (Fig. 7). For PAV_3 and PAV_5 pavements, exceedance of the criterion value occurs only for certain runs, and this is not related to the subject's body weight.

In the case of lateral vibration (Y-axis) (Figs. 8 and 9) at a frequency of 31.5 Hz, the highest value of the a_{RMS} of vibration was recorded for the PAV_3 surface, while the lowest value was recorded for the PAV_4 surface. For the 40 Hz third octave band, exceeding the ISO comfort limit [14] is apparent only for P3 and P6 users when driving over PAV_1 ("mosaic" paving stones). Also for the y-axis, no correlation was observed between body weight on the magnitude of perceived vibrations.

The next step in the analysis was to determine the change in the SF coefficient for each third octave band

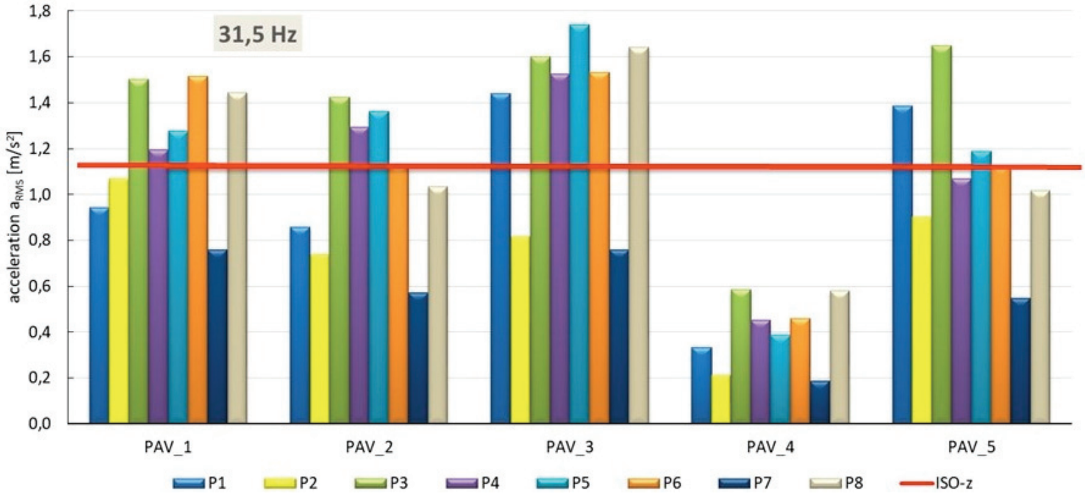

Fig. 8. Comparison of the average values of a_{RMS} acceleration for the frequency of 31.5 Hz, for the z-axis, for test subjects, when driving on the analyzed surfaces with reference to the ISO standard (comfort limit)

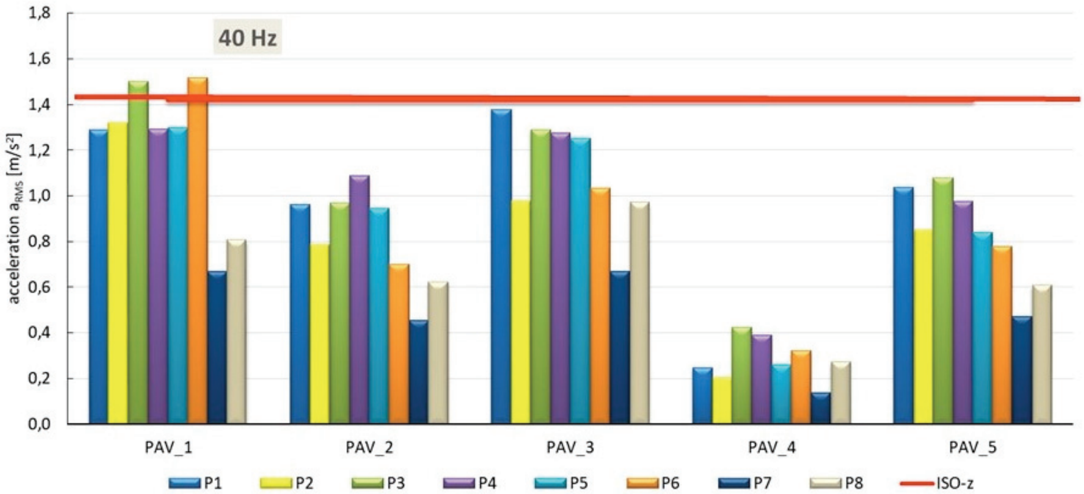

Fig. 9. Comparison of the average values of a_{RMS} acceleration for a frequency of 40 Hz, for the z-axis, for test subjects, when driving on the analyzed surfaces with reference to the ISO standard (comfort limit)

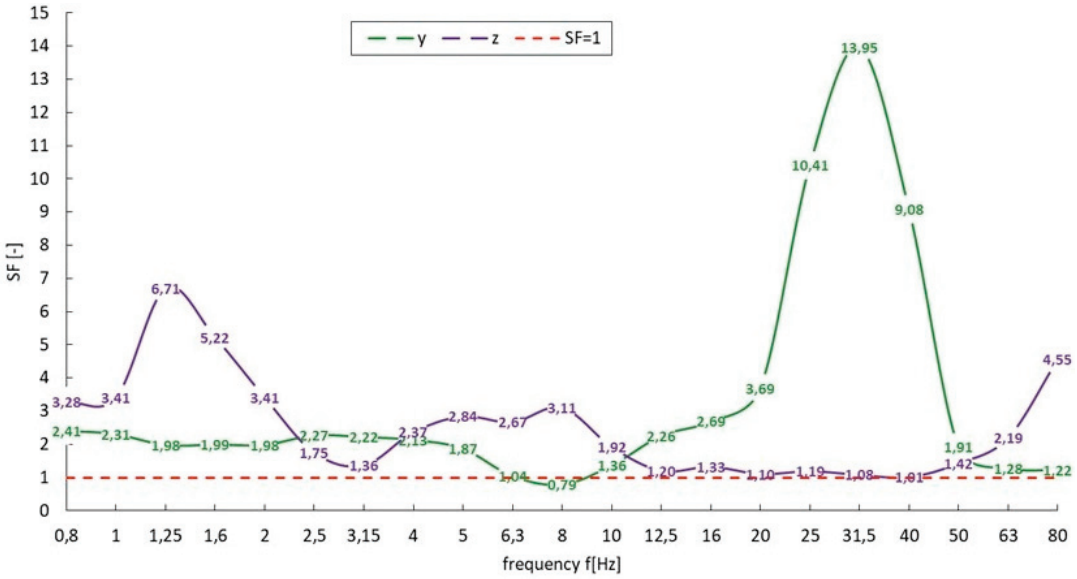

Fig. 10. Values of the SF ratio for user P3 and surface PAV_1

in which the a_{RMS} values of acceleration on the footrest were higher than on the seat. Moreover, it was possible to determine for which axis (vertical or lateral direction) the differences in received vibrations are higher.

For the z-axis, signal amplification is observed at the footrest compared to the seat in the low-frequency range (very noticeable for the third octave bands 1–2 Hz and 5–8 Hz). For the y-axis, signal amplification at the footrest is evident for third octave bands above 16 Hz. The highest SF values (up to 14 times signal amplification on the footrest relative to the seat) were observed for the third octave bands of 31.5. According to a study by Tarabani et al. [28], this is the frequency at which there may be an increased risk of vibration-white foot.

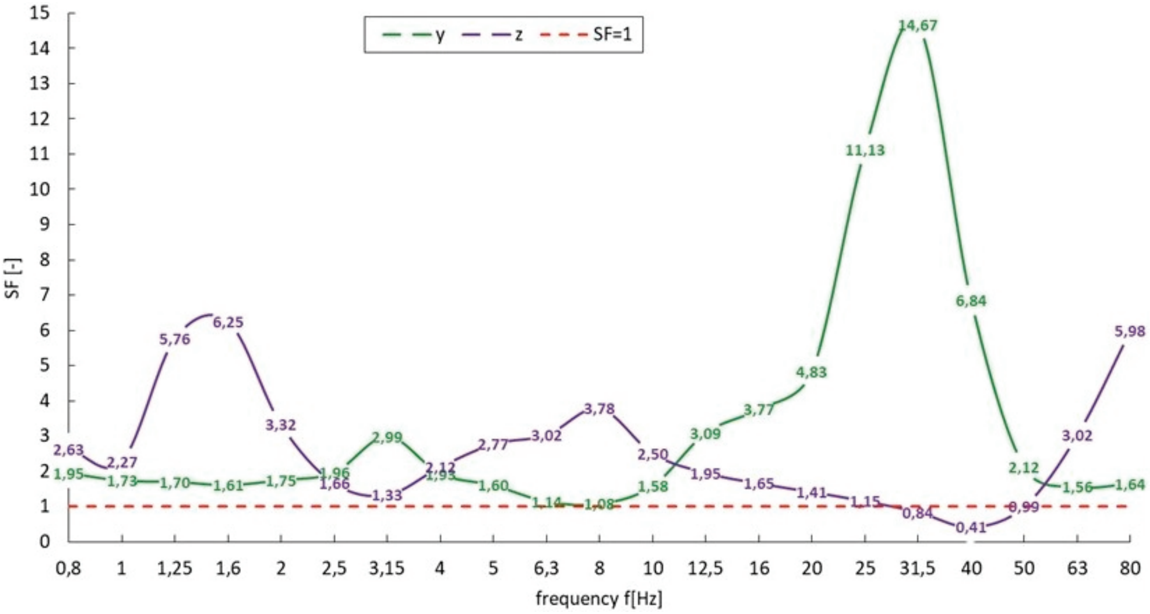

Fig. 11. Values of the SF ratio for user P3 and surface PAV_2

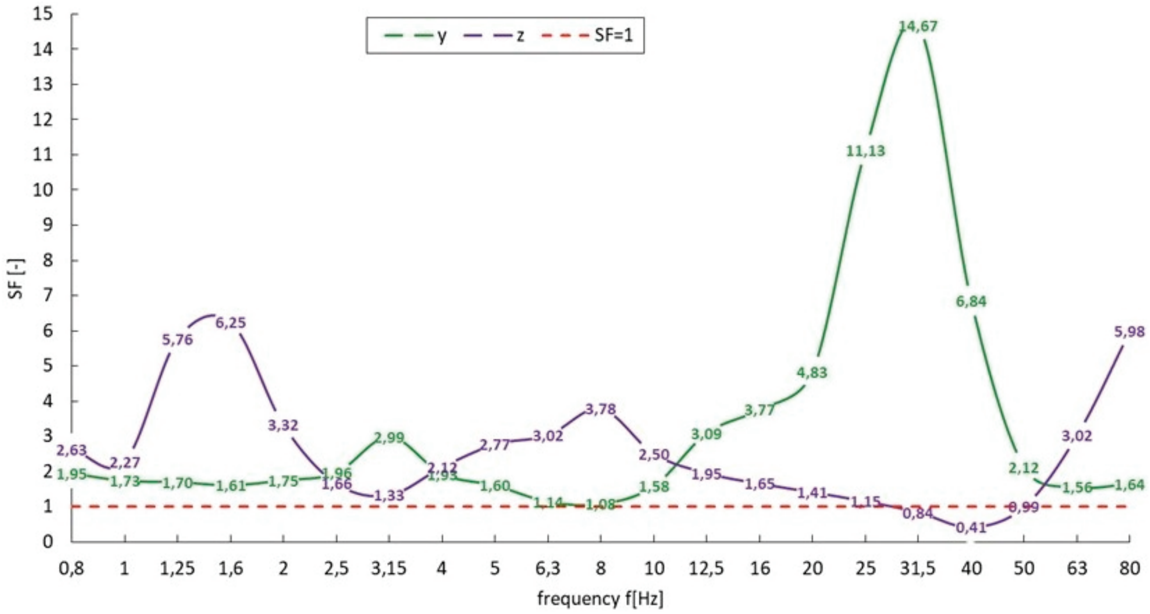

Fig. 12. Values of the SF ratio for user P3 and surface PAV_3

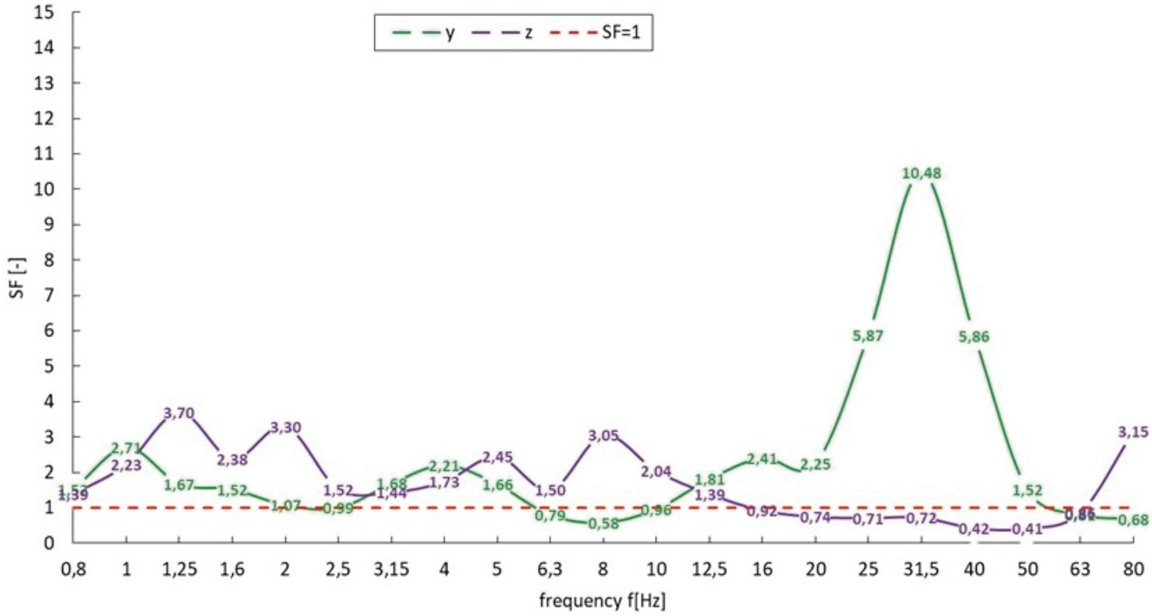

Fig. 13. Values of the SF ratio for user P3 and surface PAV_4

4. Discussion

Participants of the study indicated in a survey that moving on mosaic-type (PAV_1) and bone-type (PAV_3) pavement is the most troublesome. These results are confirmed by experimental studies both for vibrations received at the wheelchair footrest presented in this paper and studies conducted by Chwalik-Pilszyk et al. [5] on vibrations received at the seat. Based on the research, it was concluded that the most suitable surface, in terms of vibrations received, was a 0.6 × 0.6 m slab type surface.

Based on the study, it was concluded that there is no major effect of body weight on the magnitude of vibrations received at the wheelchair footrest. On the other hand, the type of surface on which the user moves is significant. Pavements consisting of smaller components (such as PAV_1, PAV_2, PAV_3) generate vibrations with higher acceleration values compared to pavements with larger components (PAV_4). The magnitude of the whole body vibrations received is also influenced by the technical condition of the pavement, as confirmed by the results obtained when driving on the PAV_5 pavement. This relationship is also apparent on the wheelchair seat, as confirmed by the studies of Chwalik-Pilszyk et al. [5] and Cooper et al. [8].

It was observed that the a_{RMS} value of vibration reaches higher value on the footrest compared to the seat. Similar results were reported by Wolf et al. [32]. Jang and Griffin [15], [16] showed that the relative motion between the seat and the feet can have a significant effect on vibration-induced discomfort evaluations for low frequencies, while it is not significant for high-frequency vibrations. According to Jang et al. [15], there is a relationship between vibration discomfort and frequency, as well as posture (change in torso tilt while sitting).

According to Maeda et al. [20] and Chénier et al. [4], wheelchair users experience the greatest discomfort when exposed to vertical vibrations, which also reach the highest value. This finding is reflected in studies where, for vibrations received on the wheelchair seat, the highest acceleration values were recorded for the vertical axis. For vibrations received at the wheelchair's footrest, maximum acceleration values were observed for horizontal vibrations along the direction of the *Y* axis. It was observed for all pavements analyzed (regardless of the user's anthropometric dimensions). This may have been influenced by the design of the wheelchair; in a universal wheelchair, the footrest is an additional bolted-on component. Thus, the lateral vibration may have been influenced by the rigidity of the design.

The conducted studies show that in the range of frequencies considered particularly dangerous for the lower limb area (30–40 Hz), exceeding of the a_{RMS} value of vibrations in relation to the criterion curve defined by the ISO standard [14] occurred. For this frequency range, the comfort limit was exceeded, while it is worth noting that the wheelchair footrest also surpassed the vibration nuisance limit for frequencies in the range of

5–25 Hz for vertical vibrations on all tested surfaces. Therefore, these vibrations may contribute to vascular diseases in the lower limbs, especially when considering their long-term effects on the human body. The ISO 2631-1 standard requires an 8-hour rest period to cope with (counteract) the harmful effects of any transmitted vibration [26], and since the mobility of a person with a disability depends on a wheelchair, MW (manual wheelchair) users are potentially at high risk of secondary injuries caused by vibrations [33]. It is worth noting that the ISO 2631 standard is used for able-bodied people in workplaces, but due to the lack of a relevant standard for people with disabilities, it is most often used in this type of analysis.

According to Jurczak [17] and Kolarzyk [18], typical symptoms of vibration disease (vasomotor disorders) occur for the frequency range of 35–250 Hz, since in this range (31–40 Hz) the comfort limit defined by ISO 2631 is exceeded. It can be expected that wheelchair users may be among those at increased risk of developing white foot disease. It is also worth noting that the negative impact of whole body vibrations acting on a person does not depend only on the magnitude of the vibrations received but also on the duration of exposure to this factor. Disabled people spend about 10 hours a day in a wheelchair, therefore, it is impossible to limit the time of exposure to whole-body vibrations in this range [3]. It also seems reasonable to extend the analysis to include a frequency range above 80 Hz (i.e., exceeding the values covered by ISO 2631) because above this value a resonant frequency of the toes occurs.

According to Lariviere et al. [19], no article has mentioned improvements to the footrest to reduce the transmission of vibrations to the wheelchair user's feet. Therefore, it seems important to reduce vibrations on this wheelchair component. In addition, modifying the design of the footrest of a manual wheelchair could improve foot stabilization and foot support, which is important not only for handling this device, but also for reducing the risk of falling [19].

It is worth noting that vibrations affecting feet of wheelchair users can not only negatively affect the lower limbs, but also indirectly these vibrations affect the spine [9]. This may cause a cumulative effect of vibrations from the footrest and seat on the spine [9].

5. Conclusions

Studies conducted show that wheelchair users are exposed to whole body vibrations on the lower limbs. In addition, the values of these vibrations reach higher amplitudes than on the wheelchair seat, and their peaks are seen at frequencies that are dangerous to the feet. This may indicate that wheelchair users may be among those at increased risk of white foot disease. In order to confirm this finding, studies of the effects of vibration on the wheelchair footrest should be expanded. Measures should be taken to minimize these vibrations.

References

[1] BASCOU J., SAURET C., LAVASTE F., PILLET H., *Is bearing resistance neglible during wheelchair locomotion? Design and validation of a testing device*, Acta Bioeng. Biomech., 2017, 19 (3), 165–176, DOI: 10.5277//abb-00659-2016-03.

[2] BROWN K., FLASHNER H., MCNITT-GRAY J., REQUEJO P., *Modeling Wheelchair-Users Undergoing*, The Journal of Biomechanical Engineering, 2017, 139 (9), 1–7, DOI: 10.1115/1.4037220.

[3] CHEN W.Y., JANG Y., WANG J.D., HUANG W.N., CHANG C.C., MAO H.F., WANG Y.H., *Wheelchair-related accidents: relationship with wheelchair-using behavior in active communitywheelchair users*, Archives of Physical Medicine and Rehabilitation, 2011, 92 (6), 892–898, DOI: 10.1016/j.apmr.2011.01.008

[4] CHÉNIER F., AISSAOUI R., *Effect of wheelchair frame material on users' mechanical work and transmitted vibration*, BioMed Research International, 2014, DOI: 10.1155/2014/609369.

[5] CHWALIK-PILSZYK G., DZIECHCIOWSKI Z., KROMKA-SZYDEK M., KOZIEŃ M.S., *Experimental Study of the Influence of Using Polyurethane Cushion to Reduce Vibration Received by a Wheelchair User*, Acta of Bioengineering and Biomechanics, 2023, 25 (1), 137–149, DOI: 10.37190/ABB-02223-2023-03.

[6] CHWALIK-PILSZYK G., DZIECHCIOWSKI Z., KROMKA-SZYDEK M., KOZIEŃ M.S., *Experimental identification of the subjective reception of external stimuli during wheelchair driving*, Open Engineering, 2021, 11 (1), 1141–1149, https://doi.org/10.1515/eng-2021-0112

[7] COOPER R.A., WOLF E., FITZGERALD S.G., BONINGER M.L., ULERICH R., AMMER W.A., *Seat and Footrest Shocks and Vibrations in Manual Wheelchairs with and without Suspension*, Archives of Physical Medicine and Rehabilitation, 2003, 84, 96–102, https://doi.org/10.1053/apmr.2003.50069

[8] COOPER R.A., WOLF E., FITZGERALD S.G., KELLERHER A., AMMER W., BONINGER M.L., COOPER R., *Evaluation of Selected Sidewalk Pavement Surfaces for Vibration Experienced by Users of Manual and Powered Wheelchairs*, The Journal of Spinal Cord Medicine, 2004, 27, 468–475, https://doi.org/10.1080/10790268.2004.11752239

[9] DONG R., TANG S., CHENG X., WANG Z., ZHANG P., WEI Z., *Influence of foot excitation and shin posture on the vibration behavior of the entire spine inside a seated human body*, Computer Methods in Biomechanics and Biomedical Engineering, 2023, DOI: 10.1080/10255842.2023.2252956.

[10] DUVALL J., COOPER R., SINAGRA E., STUCKEY D., BROWN J., PEARLMAN J., *Development of Surface Roughness Standards for Pathways Used by Wheelchairs*, Transportation Research Record Journal of the Transportation Research Board, 2013, 2387 (1), 149–156, https://doi.org/10.3141/2387-1

[11] GARCIA-MENDEZ Y., PEARLMAN J.L., BONINGER M.L., COOPER R.A., *Health risks of vibration exposure to wheelchair users in the community*, Journal of Spinal Cord Medicine, 2013, 36 (4), 365–375, DOI: 10.1179/2045772313Y.0000000124.

[12] GOGGINS K.A., TARABINI M., LIEVERS W.B., EGER T.R., *Biomechanical response of the human foot when standing in a natural position while exposed to vertical vibration from 10–200 Hz*, Ergonomics, 2019, 62 (5), 644–656, DOI: 10.1080/00140139.2018.1559362.

[13] GRIFFIN M.J., *Discomfort from feeling vehicle vibration*, Vehicle System Dynamics, 2007, 45 (7–8), 679–698, DOI: 10.1080/00423110701422426.

[14] ISO-2631-1: 2014. *Mechanical Vibration and Shock*. Part 1: *Evaluation of Human Exposure to Whole Body Vibration, International Organization for Standardization*, Geneva, Switzerland, 2014.

[15] JANK H.K., GRIFFIN M.J., *Effect of phase, frequency, magnitude and posture on discomfort associated with differential vertical vibration at the seat and feet*, Journal of Sound and Vibration, 2000, 229 (2), 273–286, https://doi.org/10.1006/jsvi.1999.2489

[16] JANG H.K., GRIFFIN M.J., *The effect of phase of differential vertical vibration at the seat and feet on discomfort*, Journal of Sound and Vibration, 1999, 223 (5), 785–794.

[17] JURCZAK M.E., *The influence of vibrations on the system*, PZWL Press, Warsaw 1974.

[18] KOLARZYK E. (ed.), *Selected problems of human hygiene and ecology*, Jagiellonian University University Press, Cracow 2008.

[19] LARIVIERE O., CHADEFAUX D., SAURET C., THOREUX P., *Vibration Transmission during Manual Wheelchair Propulsion: A Systematic Review*, Vibration, 2021, 4, 444–481, https://doi.org/10.3390/vibration4020029

[20] LIAMPAS A., NEOPHYTOU P., SOKRATOUS M., VARRASSI G., IOANNOU C., HADJIGEORGIOU G.M., ZIS P., *Musculoskeletal Pain Due to Wheelchair Use: A Systematic Review and Meta--Analysis*, Pain and Therapy, 2021, 10, 973–984, https://doi.org/10.1007/s40122-021-00294-5

[21] MAEDA S., FUTATSUKA M., YONESAKI J., IKEDA M., *Relationship between questionnaire survey results of vibration complaints of wheelchair users and vibration transmissibility of manual wheelchair*, Environmental Health and Preventive Medicine, 2003, 8 (3), 82–89, DOI: 10.1007/BF02897920.

[22] MARELLI S., CHADEFAUX D., GOGGINS K., EGER T., SCACCABAROZZI D., TARABINI M., *The Effects of Altering the Center of Pressure in Standing Subjects Exposed to Foot-Transmitted Vibration on an Optimized Lumped-Parameter Model of the Foot*, Vibration, 2021, 4 (4), 893–905, https://doi.org/10.3390/vibration4040050

[23] MARRONE F., MASSOTTI C., GOGGINS K.A., EGER T.R., MARCHETTI E., BOVENZI M., TARABINI M., *Comparison between the Biomechanical Responses of the Hand and Foot When Exposed to Vertical Vibration*, Proceedings, 2023, 86 (34), https://doi.org/10.3390/proceedings2023086034

[24] MISCH J., SPRIGLE S., *Estimating whole-body vibration limits of manual wheelchair mobility over common surfaces*, Journal of Rehabilitation and Assistive Technologies Engineering, 2022, 9, 1–5, DOI: 10.1177/20556683221092322.

[25] MOHAMED E., SIRLANTZIS K., HOWELLS G., DIB J., *Investigation of Vibration and User Comfort for Powered Wheelchairs*, IEEE Sensors Letters, 2022, 6 (2), DOI: 10.1109/LSENS.2022.3147740.

[26] NADER M., *Selected issues of harmful effects of technical vibrations*, Warsaw, 1984.

[27] ROBINSON C.C., BARRETO R.P.G., PLENTZ R.D.M., *Effects of whole body vibration in individuals with diabetic peripheral neuropathy: a systematic review*, J. Musculoskelet. Neuronal Interact., 2018, 1, 18 (3), 382–388, PMID: 30179216; PMCID: PMC6146195.

[28] TARABINI M., EGER T., GOGGINS K., MOORHEAD A.P., GOI F., *Effect of the Shoe Sole on the Vibration Transmitted from the Supporting Surface to the Feet*, Vibration, 2021, 4, 743–758, https://doi.org/10.3390/vibration4040041

[29] THOMPSON A.M.S., HOUSE R., KRAJNAK K., EGER T., *Vibration-white foot: a case report*, Occupational Medicine, 2010, 60 (7), 572–574, https://doi.org/10.1093/occmed/kqq107

[30] VANSICKLE D.P., COOPER R.A., BONINGER M.L., DIGIOVINE C.P., *Analysis of vibrations induced during wheelchair propulsion*, Journal of Rehabilitation Research and Development, 2001, 38 (4), 409–421, PMID: 11563494

[31] VORRINK S.N.W., VAN DER WOUDE L.H.V., MESSENBERG A., CRIPTON P.A., HUGHES B., SAWATZKY B.J., *Comparison of Wheelchair Wheels in Terms of Vibration and Spasticity in People with Spinal Cord Injury*, Journal of Rehabilitation Research and Development, 2008, 45, 1269–1280

[32] WIECZOREK B., WARGUŁA Ł., ADAMIEC J., SOWA T., PADJASEK M., PADJASEK Ł., SYDOR M., *Investigating the Impact of Carbon Fiber as a Wheelchair Frame Material on Its Ability to Dissipate Kinetic Energy and Reduce Vibrations*, Materials, 2024, 17 (641), https://doi.org/10.3390/ma17030641

[33] WOLF E., COOPER R.A., PEARLMAN J., FITZGERALD S.G., KELLEHER A., *Longitudinal assessment of vibrations during manual and power wheelchair driving over select sidewalk surfaces*, Journal of Rehabilitation Research and Development, 2007, 44 (4), 573–580, DOI: 10.1682/jrrd.2006.05.0049