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The influence of changing the road pavement and the method of using a wheelchair on the vibration perception in accordance with ISO 2631

Wpływ zmiany podłoża oraz sposobu użytkowania wózka inwalidzkiego na odbiór drgań w oparciu o ISO 2631

Abstract
The aim of the study is to research the influence of pavement types and the position of wheelchair a user on driving comfort. The tests have been done for six different pavements and positions of the wheelchair user, as passive and as active. The assessment has been done on the basis of vibration measurements on the seat of a wheelchair for three perpendicular directions. The obtained characteristics for the selected frequency band have been compared to the criteria curves by ISO 2631. In the next stage of the study, the multiplicity of the exceedances of the vibration perception threshold and the vibration comfort have been calculated. The values of the multiplicity of exceedances have been used in the carried-out assessment process.

Keywords: wheelchair, wheelchair driving comfort, whole body vibration measurement, criteria curves of vibrations receiving

Streszczenie
Artykuł dotyczy badania wpływu rodzaju nawierzchni i rodzaju pozycji przyjmowanej przez użytkownika wózka inwalidzkiego na komfort jazdy. Badania przeprowadzono dla sześciu różnych nawierzchni i dwóch pozycji odpowiadających jeździe pasywnej i aktywnej. Ocenę przeprowadzono w oparciu o pomiar drgań na siedzisku wózka w trzech prostopadłych kierunkach. Otrzymane przebiegi dla odpowiednich pasm tercjowych porównane zostały do krzywych kryterialnych dla normy ISO 2631. Następnie obliczono krotności przekroczeń otrzymanych wartości w stosunku do granic odczuwania drgań oraz komfortu. Wartości krotności przekroczeń wykorzystano w przeprowadzonej ocenie.

Słowa kluczowe: wózek inwalidzki, komfort jazdy, pomiar drgań ogólnych, krzywe kryterialne oceny odbioru drgań

1. Introduction

The wheelchair is a wheeled vehicle driven by muscular force or by a motor. It is intended for people with physical disabilities. The main task of the wheelchair is to help a person, who lost the function of locomotion due to injury or congenital defect, adapt to life. The wheelchair has an influence on the stabilisation of the body, but it also allows a disabled person to move. A wheelchair is composed of basic modules, such as:

- body support system, i.e. items that are in direct contact with the user's body,
- drive system, i.e. allowing for movement (among others: pushrims and caster forks),
- tires and casters,
- frame, which connects all the components together [1, 2].

In Poland, there are about 110-150 thousand people moving in a wheelchair, and about 50% of them use universal manual wheelchairs [3]. Universal wheelchairs are designed for people who have temporarily lost their function of locomotion. A wheelchair is equipped with a push handles and cross braces for easy folding of the stroller. It is characterised by high stability and provides good damping of vibrations, affecting the ride comfort. The disadvantages of such wheelchairs include their large mass, large rolling resistance and that they are difficult to manoeuvre. It is important that the wheelchair user should not feel discomfort associated with everyday mobility and independent locomotion should not require much effort [1, 2].

The centre of gravity of the human-wheelchair system is changed together with the change of the body position (Fig. 1). During independent driving, as a result of an inclination of the thorax and the arms, the centre of gravity moves closer to the front wheels, thus the rolling resistance of the wheels increases.

In the case of active wheelchairs, about 80-90% of the total weight falls on the rear wheels, where as in universal wheelchairs, only 60 % of body weight falls on the rear wheel [2].

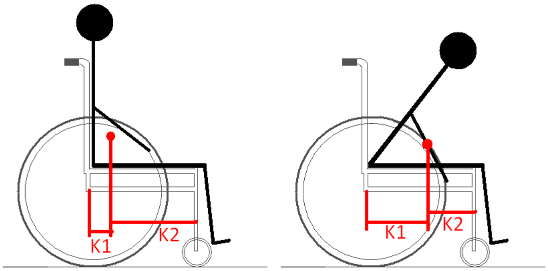


Fig. 1. Changing the centre of gravity depending on the inclination of the wheelchair user; K1, K2 – the distance between the centre of gravity and the axles of the wheels

When driving a wheelchair over uneven surfaces, vibrations are generated, which are transmitted from the seat through the pelvis bone and back into the user's body. Prolonged exposure of a user's body to vibration can cause permanent lesions in the skeletal system and the internal organs of that person. It can also reduce driving comfort and cause quicker tiring of the wheelchair user. A part of the vibrations is absorbed by the front and rear tires of the wheels, and the wheelchair frame, but when driving on an uneven surface, a part of the energy is transmitted to the human body, where it is also partly absorbed [1, 2]. The type of surface also affects the rolling resistance, which has an influence on the energy expenditure of the wheelchair user when driving.

The influence of mechanical vibrations on the human body is evaluated on the basis of the vibration acceleration values. The majority of Polish and international standards are related to this parameter (ISO 2631-1 [4], ISO 26-31-2 [5], PN 88/B-02171 [6]). The Regulation of the Minister of Labour and Social Policy of 6 June 2014 on the Maximum Permissible Concentration and Intensity of Agents Harmful to Health in the Working Environment [7] states that the value of vibration acceleration is also accepted as a criterion of the assessment of harmful vibrations received by the human body. The reaction of the human body on mechanical vibrations depends on many factors i.a. the frequency value and the time of exposure to vibrations. It is also possible to refer the measurement results directly to the criteria set out experimentally and contained in the publications by Bekesy (1939) [8], Miwa, 1967 [9], McKay 1971 [10], Benson and Dilnot 1981 [11], Griffin and Parsons 1988 [12], Morioka and Griffin 2008 [13], Bellman 2002 [14], Ljunggren et al. 2007 [15]. Some of these studies became the basis of current standards.

In order to assess the measurement, vibration acceleration values in three mutually perpendicular directions shall be corrected, and then the dominant corrected vibration acceleration should be determined. In the case of short-term vibrations (which last less than 30 minutes), the corrected RMS acceleration value is determined in accordance with the formula:

$$a_{w,30\text{minmax}} = \max\{a_{wl1}, a_{wl2}, \dots a_{wln}\}\ [\text{m/s}^2], \tag{1}$$

where:

- n – the number of performed operations during the exposure to vibrations,
- i – the number of operations,
- l – the direction of vibrations (x, y, z),
- a_{wli} – effective (RMS) frequency corrected vibration acceleration determined for direction l, after taking into account the appropriate direction coefficients ($1.4a_{wxi}, 1.4a_{wyi}, a_{wzi}$) [m/s²].

The permissible values of mechanical vibrations, determined according to the procedures described in [16], are shown in the Minister of Labour and Social Policy of 6 June 2014 on the Maximum Permissible Concentration and Intensity of Agents Harmful to Health in the Working Environment [7].

According to the ISO [4], there are three characteristic states of the effect of vibrations on the human body, which determine appropriate working conditions, namely: comfortable, burdensome and harmful. The relevant criteria by which the states are separated from each other are shown there in the form of the so-called criteria curves. The criteria curves are referenced to the human vibration perception, which has been obtained on the basis of research.

In the assessment of vibrations in the workplace, the multiplicity of exceedances of the measured vibration acceleration value in relation to the limited (permissible) value is also administered. It can be calculated by the formula:

$$k_a = \frac{a_{\text{meas}}}{a_{\text{perm}}},$$

a_{meas} – the RMS value of vibration acceleration [m/s²],
a_{perm} – the permissible values of vibration acceleration [m/s²].

The occupational hazard is calculated based on the established values. When assessing occupational hazards, the principle described in the PN-N-18002 [17] can be accepted. According to the principle, it is assumed that a small risk and a medium risk are acceptable; a high risk is not acceptable. The following intervals of k_a index variability are assumed, as follows: $k_a \leq 0{,}5$ – small risk, $0{,}5 < k_a \leq 1$ – medium risk, $k_a > 1{,}0$ – high risk.

Not all the existing studies, which describe the problem of the determination of the vibration perception threshold, can be used directly in the research of vibration influence on the wheelchair user.

The researches carried out by Griffin & Parsons [12] and Morioka & Griffin [13] were performed for the case of vibration reception by a person in a sitting position without back support (the transmission of vibrations through the back on the thoracic and lumbar spine is not included). In these works, the criteria curves for the x and y axis (horizontal directions) have a different course, which differentiates them from the criteria given in ISO 2631-1 [4]. The authors concluded that this case is the most similar to the conditions that are met for a man during active driving in a wheelchair. The criteria curves, according to ISO [4], are more restrictive. Because both cases analysed in the work relate to the ride on a universal wheelchair (which – by definition – is used to ride with the support position back), the authors decided that referring the obtained results to the more general ISO standard is more preferred. The ISO standard also allows the determination of the limit of perception and comfort thresholds because, in some cases, it may be important (transport of people with various medical conditions and pregnant women). The obtained values corresponding to the thresholds of comfort, burden and harm (and intermediate values) are obtained by multiplying the acceleration value by appropriate coefficients (specified in the standard), which are formed by given criteria curves.

In the subsequent stages of the research, the reference of the obtained results to the criteria curves established by Morioka & Griffin [13] seems reasonable, especially with regard to the active position, in which there is no full contact between the backrest and the back of the wheelchair user.

2. The aim of the study

The aim of the study was to determine the effect of selected factors on driving comfort of a universal wheelchair. The study takes into account the impact of the pavement type and the change in load distribution on the wheels, which takes place during active and passive drives.

The authors have determined the extent to which the obtained results refer to the limit values of the characteristic quantities of mechanical vibrations. The authors also evaluate in which of the frequency bands the values of vibrations, which are related to the perception threshold and comfort, were exceeded. The risks associated with the occurrence of mechanical vibrations as the multiplicity of exceedances of the measured values compared to the defined limit, which is determined by the limit of perception and comfort thresholds according to the ISO, has been determined.

On the basis of studies, it was undertaken to attempt to determine the impact of additional factors, such as driving technique and the position of a person moving by wheelchair associated with the body.

3. Methodology of research

The comfort of wheelchair use has been determined on the basis of vibration measurements. In the studies, a manual, universal wheelchair with the possibility of folding was used, which was produced by Meyra model Budget 9.050 (Figs. 2a and b). The wheelchair has a frame made of steel and a cross braces that provide strut support between the two side frames, along with arm rests and suspension of wheels without dampers. The seat and the back rest were made of textile. The analysed wheelchair had wheels with solid rubber tires. The total weight of the wheelchair was 18 kg.

a) b) c)

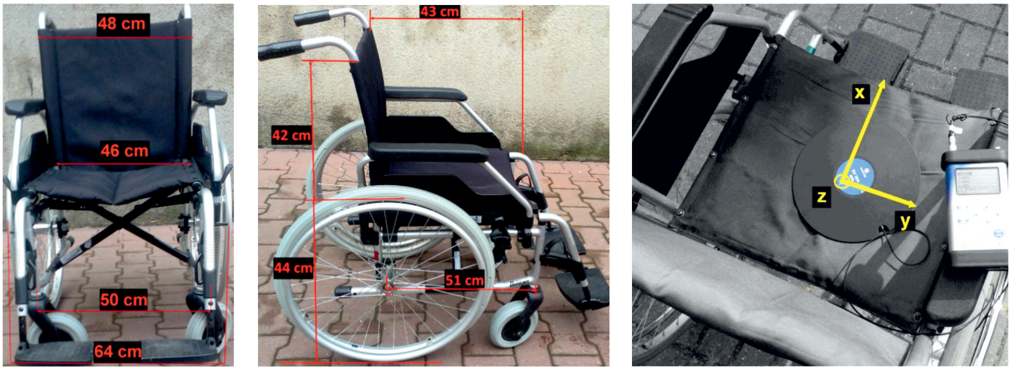


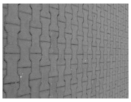
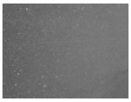
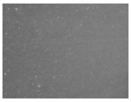
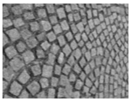
Fig. 2. The universal wheelchair used during measurement: a) a front view; b) a back view; c) location of 3-axis accelerometer

The measurement was carried out using a four-channel vibration analyser SVAN 958 SVANTEK. In the measurements, a three-axis seat accelerometer SV 39A/L was used for the whole-body vibration measurements. The vibration transducer was located in the middle of the wheelchair seat. The location of the accelerometer and the vibration directions are presented in Figure 2.

The measurement process was made for three directions of excitation, for 5 different pavements, on the campus of the Department of Mechanical Engineering at the Technical University of Cracow. The characteristics of particular pavements have been included in

Table 1. In each of the runs, the time was measured with an accuracy of +/- 1 [s]. During the measurement process, a constant speed of passage by the wheelchair was kept. The average values of speed on the various pavements are shown in Table 1.

Table 1. Characteristics of analysed pavement

Type of pavement	**N-1 Behaton Pavers**	**N-2 Square paving 500 x 500 mm**	**N-3 Square paving 600 x 600 mm**	**N-4 Bituminous surface of the bicycle path**	**N-5 Bituminous surface of the roadway**	**N-6 The granite sett**
						
The length of the route [m]	27	40	55	36	22	24
Average values of speed [m/s]	1.30	1.20	1.35	1.23	0.85	0.95

The wheelchair speed on the road pavement of N-6 was lower compared to the other surfaces because of the difficulty in moving along granite sett. A similar speed value has been reached on the pavement N-5, which is relatively easy to move (compared to N-6), which was included in order to compare the behaviour of the wheelchair in extremely different conditions. It was done in order to differentiate the behaviour of the wheelchair in extremely difficult conditions.

Two operable women aged 22 took part in the studies, identified in the measurements as follows: person 1 (58 kg, 158 cm tall) and person 2 (64 kg, 175 cm tall). For each of the analysed surfaces, two attempts to ride were made: the passage corresponding to passive drive and active drive:

- position A (Fig. 3a) – the user in an upright position, the wheelchair pushed by a second person,
- position B (Fig. 3b) – a user in an inclined position, the wheelchair driven by the user as an active driving.

Fig. 3. The position of the person's body during the tests: a) passive drive – position A; b) active drive – position B

The vibration analysis was conducted using SvanPC ++ software by SVANTEK. The results of the analysis have been presented as plots of changing RMS acceleration values for a particular 1/3 octave band, in the range of 1 Hz to 80 Hz. The frequency range of the analysis was determined by the frequency range of the applicability of ISO 2631.

The analysis does not take into account the initial and final stage of the ride. This was due to the occurrence of transients generated at the time of the initial and final movement of the wheelchair.

4. Results of the analysis

The obtained characteristics (1/3 octave band analysis in the range from 1 Hz to 80 Hz) for the directions *x*, *y* and *z* (Figs. 4-7) have been compared to the criteria curves by ISO 2631, and then the multiplicity of exceedances of the vibration perception threshold and the vibration comfort have been calculated (analogously to the formula (2)). The results obtained in this way are shown in Figures 8-11.

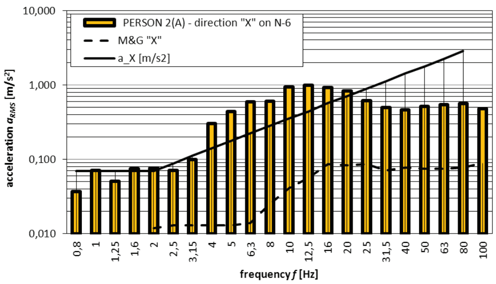


Fig. 4. The results of vibration measurement 1/3 octave band analysis for the pavement N-6 (a person 2, passive position, x-direction)

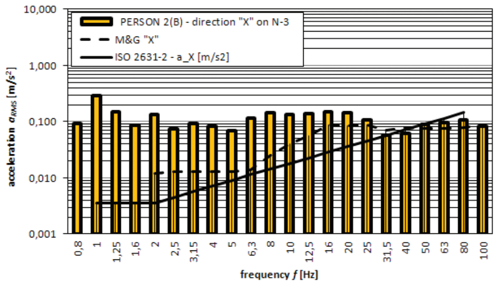


Fig. 5. The results of vibration measurement 1/3 octave band analysis for the pavement N-3 (a person 2, active position, x-direction)

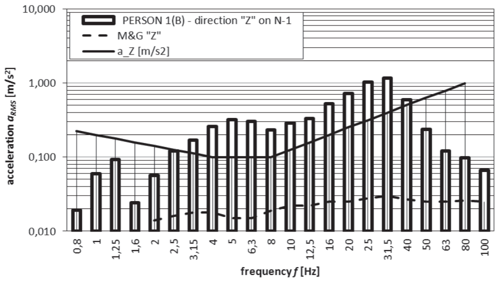


Fig. 6. The results of vibration measurement 1/3 octave band analysis for the pavement N-1 (a person 1, active position, z-direction)

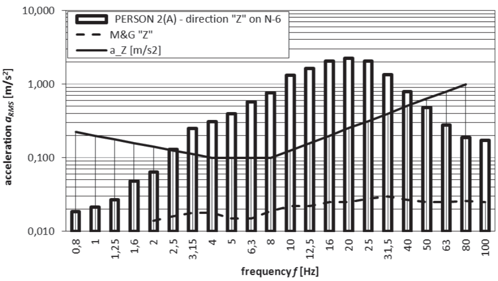


Fig. 7. The results of vibration measurement 1/3 octave band analysis for the pavement N-6 (a person 2, passive position, z-direction)

f [Hz]	N-1/1A/D-X	N-1/2A/D-X	N-1/1B/D-X	N-1/2B/D-X	N-1/1A/D-Z	N-1/2A/D-Z	N-1/1B/D-Z	N-1/2B/D-Z
1	15	10	70	70	2	2	5	10
1,25	10	10	135	10	2	2	10	2
1,6	5	10	25	25	2	2	5	5
2	10	15	30	25	2	5	10	10
2,5	5	5	25	20	5	5	20	10
3,15	5	5	30	15	15	15	30	15
4	10	5	25	10	20	20	50	35
5	15	10	25	15	30	25	65	45
6,3	20	10	20	15	30	20	60	35
8	15	5	20	15	25	25	45	45
10	20	15	15	15	40	60	45	55
12,5	5	5	15	15	30	35	40	50
16	5	5	15	10	25	40	50	50
20	5	10	15	10	35	55	55	55
25	5	5	5	5	55	45	65	55
31,5	5	5	5	5	55	30	60	35
40	5	5	5	5	20	10	25	15
50	5	2	5	2	5	5	10	5
63	2	2	2	2	5	2	5	2
80	2	2	2	2	2	2	2	2
	N-1							

f [Hz]	N-2/1A/D-X	N-2/2A/D-X	N-2/1B/D-X	N-2/2B/D-X	N-2/1A/D-Z	N-2/2A/D-Z	N-2/1B/D-Z	N-2/2B/D-Z
1	10	10	60	80	2	2	5	10
1,25	5	5	145	40	2	0	15	5
1,6	5	5	30	25	2	2	5	5
2	10	10	45	35	5	2	5	10
2,5	5	5	35	15	5	5	15	10
3,15	5	5	25	15	10	5	15	15
4	5	5	20	10	10	10	25	20
5	10	5	15	10	10	10	35	20
6,3	10	5	15	10	15	20	30	20
8	5	5	10	10	15	15	20	20
10	5	5	5	5	25	15	15	15
12,5	5	5	5	5	20	20	20	20
16	5	5	5	5	30	25	25	20
20	5	2	5	5	30	25	25	20
25	2	2	2	2	30	25	25	20
31,5	2	2	2	2	15	15	15	10
40	2	2	2	0	5	5	5	5
50	0	0	2	2	2	2	2	2
63	0	0	0	0	2	2	2	2
80	0	0	0	0	0	0	0	0
	N-2							

f [Hz]	N-3/1A/D-X	N-3/2A/D-X	N-3/1B/D-X	N-3/2B/D-X	N-3/1A/D-Z	N-3/2A/D-Z	N-3/1B/D-Z	N-3/2B/D-Z
1	10	5	95	40	2	0	10	5
1,25	5	5	25	15	2	0	5	2
1,6	5	5	25	40	0	0	5	10
2	10	10	30	20	2	2	10	5
2,5	5	5	20	15	5	5	10	10
3,15	5	5	15	15	5	5	20	15
4	5	5	15	10	10	10	25	20
5	10	5	15	10	10	10	35	25
6,3	10	5	15	5	10	15	30	25
8	5	5	10	5	15	10	20	15
10	5	5	5	5	15	15	15	15
12,5	5	5	5	5	10	10	10	15
16	5	2	5	5	10	10	10	15
20	2	2	2	5	15	15	10	15
25	2	2	2	2	10	15	5	15
31,5	2	2	0	0	10	10	5	10
40	0	0	0	0	5	5	5	5
50	0	0	0	0	2	2	2	2
63	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0
	N-3							

Fig. 8. The multiplicity of exceedances of the vibration perception threshold according to ISO for the pavements N-1, N-2 and N-3

f [Hz]	N-4/1A/D-X	N-4/2A/D-X	N-4/1B/D-X	N-4/2B/D-X	N-4/1A/D-Z	N-4/2A/D-Z	N-4/1B/D-Z	N-4/2B/D-Z
1	15	15	80	50	2	2	5	5
1,25	10	10	110	70	2	2	10	5
1,6	5	10	40	30	2	2	5	5
2	10	15	40	30	2	5	10	10
2,5	5	5	30	15	5	5	10	10
3,15	5	5	25	10	5	5	25	15
4	5	5	20	10	10	5	35	20
5	5	5	15	10	15	10	40	25
6,3	5	5	15	10	10	10	35	20
8	5	5	10	10	10	10	25	15
10	5	5	5	5	10	10	20	10
12,5	5	2	5	5	10	10	15	10
16	2	2	5	5	15	10	15	15
20	2	2	5	5	15	10	20	15
25	2	2	2	2	20	10	20	15
31,5	2	2	2	0	15	10	15	10
40	2	0	2	0	5	5	10	5
50	2	2	2	2	5	5	5	2
63	2	2	2	2	2	2	2	2
80	2	2	2	2	0	0	0	0
	N-4							

f [Hz]	N-5/1A/D-X	N-5/2A/D-X	N-5/1B/D-X	N-5/2B/D-X	N-5/1A/D-Z	N-5/2A/D-Z	N-5/1B/D-Z	N-5/2B/D-Z
1	10	5	135	15	2	0	10	5
1,25	5	5	70	10	0	0	5	2
1,6	5	5	30	35	2	0	5	10
2	10	10	60	20	2	2	15	5
2,5	5	5	35	15	2	2	15	5
3,15	2	2	45	15	5	2	30	10
4	5	5	40	10	5	5	40	20
5	5	5	25	10	10	10	45	25
6,3	5	2	10	10	15	10	35	20
8	5	5	10	10	10	10	25	10
10	5	5	5	5	10	10	15	10
12,5	5	2	5	5	10	15	15	10
16	2	2	5	5	10	15	15	10
20	2	2	5	5	20	15	20	15
25	2	2	2	2	30	20	25	20
31,5	5	2	2	2	30	15	25	15
40	5	2	2	0	15	10	15	15
50	5	2	2	2	10	5	5	5
63	2	2	2	2	5	5	5	5
80	5	2	2	2	2	2	2	2
	N-5							

f [Hz]	N-6/1A/D-X	N-6/2A/D-X	N-6/1B/D-X	N-6/2B/D-X	N-6/1A/D-Z	N-6/2A/D-Z	N-6/1B/D-Z	N-6/2B/D-Z
1	20	15	135	65	5	2	10	10
1,25	15	15	60	20	5	5	10	5
1,6	20	15	40	25	5	5	5	5
2	20	20	45	40	10	10	20	15
2,5	15	20	35	25	20	20	20	20
3,15	20	35	40	25	45	45	40	40
4	40	80	40	25	90	60	70	70
5	50	75	45	35	75	80	85	90
6,3	50	60	60	50	115	115	75	95
8	40	40	55	55	155	150	110	140
10	50	50	45	50	185	215	135	160
12,5	45	40	40	40	170	205	165	160
16	30	35	30	35	160	205	145	160
20	25	25	20	20	175	180	155	105
25	15	15	10	10	130	130	115	75
31,5	10	10	5	5	70	70	55	50
40	5	5	5	5	35	30	25	25
50	5	5	5	5	15	15	10	10
63	5	5	5	5	5	5	5	5
80	5	5	5	5	5	5	5	5
	N-6							

Fig. 9. The multiplicity of exceedances of the vibration perception threshold according to ISO for the pavements N-4, N-5 and N-6

f [Hz]	N-1/1A/D-X	N-1/2A/D-X	N-1/1B/D-X	N-1/2B/D-X	N-1/1A/D-Z	N-1/2A/D-Z	N-1/1B/D-Z	N-1/2B/D-Z
1	1	0	4	4	0	0	0	1
1,25	1	0	7	0	0	0	1	0
1,6	0	0	1	1	0	0	0	0
2	1	0	2	1	0	0	0	0
2,5	0	0	1	1	0	0	1	0
3,15	0	0	1	1	1	0	2	1
4	0	0	1	1	1	0	3	2
5	1	0	1	1	1	0	3	2
6,3	1	0	1	1	1	0	3	2
8	1	0	1	1	1	0	2	2
10	1	0	1	1	2	5	2	3
12,5	0	0	1	1	1	0	2	2
16	0	0	1	1	1	0	3	2
20	0	0	1	1	2	5	3	3
25	0	0	0	0	3	0	3	3
31,5	0	0	0	0	3	0	3	2
40	0	0	0	0	1	0	1	1
50	0	0	0	0	0	0	0	0
63	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0

N-1

f [Hz]	N-2/1A/D-X	N-2/2A/D-X	N-2/1B/D-X	N-2/2B/D-X	N-2/1A/D-Z	N-2/2A/D-Z	N-2/1B/D-Z	N-2/2B/D-Z
1	1	0	3	4	0	0	0	1
1,25	0	0	7	2	0	0	1	0
1,6	0	0	2	1	0	0	0	0
2	0	1	2	2	0	0	0	1
2,5	0	0	2	1	0	0	1	0
3,15	0	0	1	1	0	0	1	1
4	0	0	1	1	1	0	1	1
5	0	0	1	0	1	0	2	1
6,3	1	0	1	1	1	1	1	1
8	0	0	1	1	1	1	1	1
10	0	0	0	0	1	1	1	1
12,5	0	0	0	0	1	1	1	1
16	0	0	0	0	1	1	1	1
20	0	0	0	0	2	1	1	1
25	0	0	0	0	1	1	1	1
31,5	0	0	0	0	1	1	1	1
40	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0
63	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0

N-2

f [Hz]	N-3/1A/D-X	N-3/2A/D-X	N-3/1B/D-X	N-3/2B/D-X	N-3/1A/D-Z	N-3/2A/D-Z	N-3/1B/D-Z	N-3/2B/D-Z
1	1	0	5	2	0	0	0	0
1,25	0	0	1	1	0	0	0	0
1,6	0	0	1	2	0	0	0	0
2	0	0	2	1	0	0	0	0
2,5	0	0	1	1	0	0	0	0
3,15	0	0	1	1	0	0	1	1
4	0	0	1	1	0	0	1	1
5	1	0	1	0	1	1	2	1
6,3	0	0	1	0	1	1	2	1
8	0	0	0	0	1	1	1	1
10	0	0	0	0	1	1	1	1
12,5	0	0	0	0	1	1	1	1
16	0	0	0	0	1	1	0	1
20	0	0	0	0	1	1	0	1
25	0	0	0	0	1	1	0	1
31,5	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0
63	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0

N-3

Fig. 10. The multiplicity of exceedances of comfort threshold in accordance of ISO for pavements N-1, N-2 and N-3

f [Hz]	N-4/1A/D-X	N-4/2A/D-X	N-4/1B/D-X	N-4/2B/D-X	N-4/1A/D-Z	N-4/2A/D-Z	N-4/1B/D-Z	N-4/2B/D-Z
1	1	1	4	2	0	0	0	0
1,25	0	0	6	3	0	0	0	0
1,6	0	1	2	1	0	0	0	0
2	1	1	2	2	0	0	1	0
2,5	0	0	2	1	0	0	1	1
3,15	0	0	1	0	0	0	1	1
4	0	0	1	0	0	0	2	1
5	0	0	1	0	1	0	2	1
6,3	0	0	1	1	1	0	2	1
8	0	0	1	0	1	0	1	1
10	0	0	0	0	1	1	1	1
12,5	0	0	0	0	1	0	1	1
16	0	0	0	0	1	1	1	1
20	0	0	0	0	1	1	1	1
25	0	0	0	0	1	1	1	1
31,5	0	0	0	0	1	0	1	0
40	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0
63	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0

N-4

f [Hz]	N-5/1A/D-X	N-5/2A/D-X	N-5/1B/D-X	N-5/2B/D-X	N-5/1A/D-Z	N-5/2A/D-Z	N-5/1B/D-Z	N-5/2B/D-Z
1	0	0	7	1	0	0	0	0
1,25	0	0	4	1	0	0	0	0
1,6	0	0	2	2	0	0	0	0
2	0	0	3	1	0	0	1	0
2,5	0	0	2	1	0	0	1	0
3,15	0	0	2	1	0	0	1	1
4	0	0	2	1	0	0	2	1
5	0	0	1	0	0	0	2	1
6,3	0	0	1	0	1	0	2	1
8	0	0	0	0	1	0	1	1
10	0	0	0	0	0	0	1	1
12,5	0	0	0	0	1	1	1	1
16	0	0	0	0	1	1	1	1
20	0	0	0	0	1	1	1	1
25	0	0	0	0	1	1	1	1
31,5	0	0	0	0	1	1	1	1
40	0	0	0	0	1	0	1	1
50	0	0	0	0	0	0	0	0
63	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0

N-5

f [Hz]	N-6/1A/D-X	N-6/2A/D-X	N-6/1B/D-X	N-6/2B/D-X	N-6/1A/D-Z	N-6/2A/D-Z	N-6/1B/D-Z	N-6/2B/D-Z
1	1	1	7	3	0	0	1	0
1,25	1	1	3	1	0	0	0	0
1,6	1	1	2	1	0	0	0	0
2	1	1	2	2	0	0	1	1
2,5	1	1	2	1	1	1	1	1
3,15	2	1	2	1	2	2	2	2
4	4	2	2	1	4	3	4	4
5	4	2	2	2	4	4	4	5
6,3	3	3	3	3	6	6	4	5
8	2	2	3	3	8	8	5	7
10	2	3	2	3	9	10	7	8
12,5	2	2	2	2	8	10	8	8
16	2	2	2	2	8	10	7	8
20	1	1	1	1	9	9	8	5
25	1	1	1	1	6	6	6	4
31,5	0	0	0	0	4	3	3	2
40	0	0	0	0	2	2	1	1
50	0	0	0	0	1	1	1	1
63	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0

N-6

Fig. 11. The multiplicity of exceedances of comfort threshold in accordance of ISO for pavements N-4, N-5 and N-6

5. Discussion of results

The analysis of the arrays shown in Figures 4 and 5, containing the results of the measurements, allows the comparison of individual surfaces in terms of vibration comfort. Certain frequency ranges that these arrays show can be identified, for example, with various types of ailments occurring in humans. Forces that occur in the given frequency range may affect the comfort of the wheelchair user.

For the pavement (N-1), the maximum of the vibration perception threshold for the x-direction (on average approximately 15 times), were recorded for the 1/3 octave band from 1 to 20 Hz. For frequency ranges 1.0, 1.25, 2.0, and 3.15 Hz the exceedances are much higher, even 135 times for the active position of a user (position B). For the passive position (position A) and z-direction the multiplicity of exceedances of the vibration perception threshold (in the range of 1/3 octave bands from 40 Hz to 3.15 Hz) take high values (minimum 10 times, the maximum 60 times). For the active position the exceedances of the vibration perception threshold present in the frequency range of 1 to 50 Hz, (maximum value in the range of 10 to 25 Hz).

For the pavement N-2 and N-3 (square paving), in the x-direction, for the B user position, for the low frequency, are exceeded for the perception threshold (the 1/3 octave bands to 2.5 Hz – 145 times). For the z-direction, the exceedance are for 1/3 octave bands in the range of 3.15 Hz to 31.5 Hz, for passive position, and from 2 Hz to 31.5 Hz for active position. The maximum value of exceedances for the z-axis were recorded for the 1/3 octave bands 5 Hz and 6.3 Hz. The higher values of vibration were recorded for the pavement N-3. It can be caused by the method of square paving arranged. Above the frequency range of 63 Hz was not observed exceedances of the vibration perception threshold, for both pavement (N-2 and N-3) and for both vibration directions, for the active position and the passive position.

For bituminous surface N-4 and N-5 (bicycle path and the roadway), for passive position and vibration in the x-direction, maximum exceeding values of the perception vibration threshold are observed for the 1/3 octave band from 1 to 2 Hz. For the roadway the multiplicity of exceedances varies between 5 to 10 times, but for the bicycle path even 10 to 15 times. In the remaining 1/3 octave bands, for both bituminous surfaces, the exceeding are much lower (maximum up to 5 times). For the active position the wheelchair user were observed much more diverse values of multiplicity of exceedances of the vibration perception threshold. The highest exceeding are observed for the 1/3 octave band of 4 Hz. For the very low frequency ranges (1 and 1.25 Hz) is reported, even more than 100 times compared to the limit of perception limits. For the vibration in the z-direction and the position A – it can be seen similarity of exceeding value of vibration perception threshold for both bituminous surfaces. For this case the multiplicity of exceedances, for the frequency ranges from 4 to 40 Hz, are amounted to 10-15 times, but for the 1/3 octave bands from 20 to 31.5 Hz even 30 times. For the position B of user, higher values of exceeding (about 10-25 times) can be seen for the frequency range of 2 to 40 Hz. The maximum values (from 25 to 45 times) have been recorded for the user who had lower body weight.

For the case of the wheelchair moving on the pavement N-6 (granite sett) and the receiving of vibration for the x-direction, the highest exceeding was recorded for the passive position for the 1/3 octave bands from 3.15 Hz to 20 Hz. For that frequency bands the values of multiplicity of exceedances are 25-80 times. For the active position the high values of the multiplicity of exceedances include a similar ranges of the 1/3 octave bands (the values of exceeding are lower and amount maximum up to 60 times). For the vibration in the z-direction, for the passive position, were observed significantly higher values of the exceeding of the vibration perception threshold in relation to the active position. For both positions, very high exceeding was observed for the 1/3 octave bands from 6.3 to 25 Hz (100 and 200 times), the lower values (40 times) was recorded for the 1/3 octave bands 2.5 Hz, 3.15 Hz and 31.5 Hz. For the 1/3 octave bands from 1 Hz to 1.6 Hz as well as 63 Hz and 80 Hz the values of multiplicity of exceedances are not more than 10 times.

For all tested pavements, for the vibration in the x-direction, was observed exceedance in the low frequency range (1/3 octave bands from 1 to 2 Hz). There was any exceedance above the frequency range of 40 Hz for both directions, and both methods of use of the wheelchair.

For the pavement N-1 (behaton pavers), during the studies, it was registered exceeding of the perception vibration threshold about 5 times for 1/3 octave bands 10 and 20 Hz. In the remaining frequency bands have not been found the exceeding of the perception threshold. It seems reasonable to check the influence of pavement unevenness or structure of the wheelchair. In the z-direction, for the position B (active drive), it can be observed the exceeding of 2-3 times for the 1/3 octave bands from 4 to 31.5 Hz.

For the pavements N-2 and N-3 the exceeding of comfort threshold according to ISO standard is observed for the x-axis, an active position, for 1/3 octave bands of 2.5 Hz. For the pavement N-3 the exceeding were higher. In the other frequency ranges, for both pavement, there were any exceeding. Only for the 1/3 octave bands from 5 and 6.3 Hz, for the direction z and active position of user, the exceeding of comfort threshold are twice.

For bituminous surfaces (N-4 and N-5), the differences of values of the multiplicity of exceedances of the comfort threshold have been observed for 1/3 octave bands from 1 to 2 Hz (for the x-axis) only. Additionally for the vibration in the z-direction were recorded that the exceeding of comfort threshold, for an active position and the frequency bands from 4 to 6.3 Hz, are twice.

For the pavement N-6 (granite sett), for the vibration excitation in the z-direction, the largest exceeding of comfort threshold (from 5 to 10 times) are for 1/3 octave bands from 8 to 20 Hz. The higher values of the multiplicity of exceedances of the vibration comfort threshold refer to the case of passive user's position (position A). The lower values the multiplicity of exceedances (from 2 to 6 times) were recorded for 1/3 octave bands from 3.15 to 6.3 Hz and from 25 to 40 Hz. For the vibrations perception in the x-direction, the maximum exceeding of the comfort threshold (from 2 to 4 times) appear for 1/3 octave bands from 4 to 16 Hz.

6. Conclusions

The major impact on the value of the vibrations, which are received by the wheelchair user, is had by the type of pavement on which the wheelchair is moving. It can be specified items, such as: the size of the plate, from which the surface is made of (arranged), the pavement pattern (determined by the pavement elements), the size of the gap, surface roughness and its condition (in the case of new surfaces associated with the accuracy of the performance). These factors affect the change of rolling resistance. These factors are important, and in the case of a wheelchair, they are not entirely recognised, which is confirmed in other studies [18].

The highest values of vibration acceleration have been recorded for the granite pavement, which has the most uneven pavement of all the analysed types. This is due to both the technological performance of a single element, as well as its technology of laying. The method of its arrangement (granite fan pattern) could determine the frequency of the vibration excitation and values of the parameter that describes the vibration excitation. The lowest values of the vibration acceleration can be observed for surfaces made of concrete paving slabs with dimensions of 600 mm x 600 mm. In the range of above 31.5 Hz, for the x-axis, excessive vibrations are not observed.

When changing the load distribution of the wheelchair wheels, which is different for active and passive driving, a change of the value of the parameter describing the vibrations transmitted to the user's body has been observed. For movement carried out in the active position, the vibration acceleration values are higher. The relationship between the experience when using the wheelchair (driving technique) and the level of received vibration can be recognised. It should also be noted that the tests were carried out in a wheelchair, which had a solid tire that significantly affects the achieved results.

The tested wheelchair is a universal wheelchair, which means that, by definition, it is not intended to move actively on rough ground, but it is used to transport people on different surfaces, over short distances. Bearing in mind that the users of this means of transport are people with different diseases and, for example, pregnant women, it seems important to ensure adequate comfort of drive, the criterion of which may be the multiplicity of exceedances of the vibration perception threshold.

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