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Technical Notes

Vibration Transmitted to the Human Body during the Patient's Ride in a Wheelchair

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The study investigates the spectra of vibrations transmitted onto the body of a wheelchair user during the ride on typical floor surfaces in public buildings and in their vicinity. Three wheelchair types are considered in the study (universal and active ones). Selected factors are examined that determine the amplitude of vibration acceleration acting upon humans in the analysed frequency range (wheelchair type, user's body mass, surface type). The spectral analysis gives an insight into some of the factors which lead to a change of the vibration parameters registered at the user's seat.

Keywords: wheelchair; criteria of vibration exposure assessment; threshold of vibration perception; amplitude-frequency characteristics.

1. Introduction

Wheelchair is a vehicle intended for disabled people, propelled by muscle force or by a dedicated motor designed in such a way that the ride velocity should be not higher than the walking speed. Apart from providing body support, a wheelchair enables the rectilinear, curvilinear, and rotational motion. Disabled people using wheelchairs can function well in the society, are capable of moving both inside and outside buildings, and even play sports (using sport wheelchairs).

In accordance with the technical standard PN-ISO 6440:2001, a wheelchair comprises four functional subsystems: the body support (a seat, backrest, armrests, footrest, headrest, devices providing extra support for legs), the frame (seat and backrest frame), the driving system (two small caster wheels at the front and two large ones at the rear, driving hoop, and the mechanism rotating the self-adjusting wheels at the front). Therefore, a wheelchair can be configured to tailor it to the specific needs of an individual user (disability type, dimensions, preferences, intellectual ability, etc.).

Basically, wheelchair users can be categorised into four groups. The first group includes people incapable of walking, some of them are independent, use active wheelchairs (making them self-sufficient and giving them a chance to lead an active life), others need assistance and rely mostly on electric-powered wheelchairs. The latter group includes people with the impaired walking ability dependent on their wheelchairs in the long-term perspective. The third group includes able-bodied people dependent on their wheelchair for a limited period of time, because of an injury, a short-term illness, or other reasons.

Wheelchair ride over various surfaces, both inside and outside buildings, gives rise to vibrations transmitted onto the user via the wheelchair structure. The basic component whose function is to suppress vibration is the frame (Sydor, 2003). A portion of energy is absorbed at the same time by the front and rear wheel tyres and seat. However, during a ride at a high speed or over uneven ground, a large portion of energy is transmitted onto the wheelchair user's body.

Vibrations have a negative impact on the internal organs in humans and may lead to their getting tired easily. The actual impact of vibrations, transmitted directly or indirectly from a vibrating system, is related to the amplitude and frequency of the excitation signal. Vibrations in the frequency range from 1 to over a dozen Hz have proved to be the most dangerous. Long-term vibration exposure disturbs the function of the circulatory system, leads to limb trembling, and causes pain of joints or the lumbar and pectoral vertebrae sections, as well as pains in the chest, also referred to as motion-sickness (Engel, Zawieska, 2010).

Even though research work aimed to give us a better insight into those issues and help develop the measures to be taken to minimise the vibrations generated in everyday life situations is deemed to be important, few authors have attempted to make a quantitative analysis of vibration transmitted onto wheelchair users.

Presently, the vibration exposure evaluation criteria encompassing mostly ergonomic aspects are those set forth in the technical standards ISO 2631-1, ISO 2631-2, PN 88B-02171 and Regulation by the Minister of Labour and Social Policy of 6th June 2014, specifying the highest admissible concentrations and levels of hazardous factors at work. Another option is to rely on criteria established experimentally and compiled in the publications by von Békésy (1939), Miwa (1967), McKay (1971), Benson and Dilnot (1981), Griffin and Parsons (1988), Morioka and Griffin (2008), Bellman (2002), and Ljunggren *et al.* (2007).

As mentioned in the previous section, there are numerous works defining the vibration perception threshold. However, not all of them can be effectively used when investigating the effects of vibration exposure of wheelchair users. Griffin and Parsons (1988) and Morioka and Griffin (2008) investigated the vibration reception by people sitting upright with their backs unsupported (thus neglecting the vibrations transmitted onto the lumbar and pectoral vertebrae sections via the backrest). In those studies the threshold contours for vibration perception in the X and Y direction (horizontal) are different, deviating from the standards ISO 2631-1. In the authors' opinion, the conditions in this case resemble most those encountered by a wheelchair user during the ride. That is why the adopted exposure assessment criterion is the threshold contour of vibration perception presented in (Morioka, Griffin, 2008).

2. The objectives and scope of the study

The purpose of the study was to analyse the spectra of vibration transmitted onto the wheelchair user during the ride over various surfaces. As a basis for the analysis the value of acceleration amplitudes of vibrations perceived by humans, in the investigated frequency range, and observing the behaviour of wheelchair users were used. The authors attempted to find out the extent to which factors such as: wheelchair type, user's body mass, or surface type would be responsible for their vibration perception. Thus obtained amplitude-frequency plots were compared with the vibration perception threshold contours. Due to the risks arising from the resonant frequency of the internal organs and due to the criterion of assessment (limit of perception of feeling vibrations), vibrations in the frequency range 2–100 Hz were a special subject of assessment.

Those taking part in the experiment were both disabled people (well skilled in wheelchair use) and people committed to the wheelchair for a short time period.

3. Test wheelchairs

Testing was carried out on three types of wheelchairs, as shown in Fig. 1. Their technical data are summarised in Table 1. Those taking part in the test were three individuals – two able bodied persons – a woman (50 kg) and a man (109 kg) using universal wheelchairs and one disabled person: a man (70 kg) who used an active wheelchair.

a) b) c)

Fig. 1. Test wheelchairs: a) with electric powered function supporting the patient's erect position, b) Meyra wheelchair, c) active GTM Mustang wheelchair.

Table 1. Test wheelchairs – technical data.

Parameter	Wheelchair type		
	Wheelchair with electric-powered backrest adjustment Vassilli HI-LO M (18.64M)	Universal wheelchair Meyra	Active wheelchair GTM Mustang
Wheelchair designation	**W1**	**W2**	**W3**
Material	Steel + aluminium alloy Rigid seat made of plastic	Steel + aluminium alloy Flexible seat made of plastic	Al7020 + carbon alloy Rigid seat made of plastic
Wheelchair mass m_{wch}	40.5 kg	17.5 kg	8 kg
Wheelchair structure	non folding frame	folding frame	non folding frame construction
Pressure distribution loads due to the user's mass	40% front 50% back	40% front 50% back	10–20% front 80–90% back
Features	Comfortable but with limited mobility, the electric raising function	Comfortable, with limited mobility	Adapted to the user's size, easy to manoeuvre

4. Methodology

The testing aimed at investigating vibrations perceived by wheelchair users during the ride over various types of surfaces. The measurement procedure used the spectrum analyser SVAN 958, equiped with a tri-axial disc for whole-body vibration measurements SVANTEK SV 39A. The positioning and orientation of the disc during the measurements is shown in Fig. 2.

Fig. 2. Measurement instrumentation (directions of the vibration sensors' axis lines).

During the experiment the wheelchair with the sitting user was always propelled by another person (both for the active and universal wheelchair) at the pace of 1–1.5 m/s.

Measurements were taken over straight line sections, with no significant ground inclinations (the largest registered slope was 6%). The input vibrations caused by wheelchair-surface interactions were transmitted onto the user via the wheelchair construction. Thus the user was subjected to whole-body vibration transmitted onto the body via the buttocks (buttocks-seat interaction), feet (feet-footrest interactions) and back (back-seat interactions). The user's back was supported by the backrest (passive ride).

The tests were conducted in the premises of the Department of Mechanical Engineering of the Cracow University of Technology (PK), on surfaces both inside and outside the campus buildings. There were 12 typical surface types widely used in public buildings and in their surroundings. No allowance was made for rides over damaged surfaces or those in a bad working order, or rides over obstacles (such as barrier curbs). Three selected surface types are shown in Fig. 3 and their characteristics are summarised in Table 2.

Measurement signals from the tri-axial sensor were passed to the spectrum analyser where the signals were registered and the loggers were processed using the program SvanPC++. The measurements were performed on different pavement lengths (from several to several tens of meters), which determined the time of signal registration. The different pavement lengths were related to the architectural solutions on the premises of the Department of Mechanical Engineering. On the other hand the authors tried to assess as many diverse surfaces which may occur in public places as possible. Some measurement section have had a shorter length (up to 6 m), and the authors

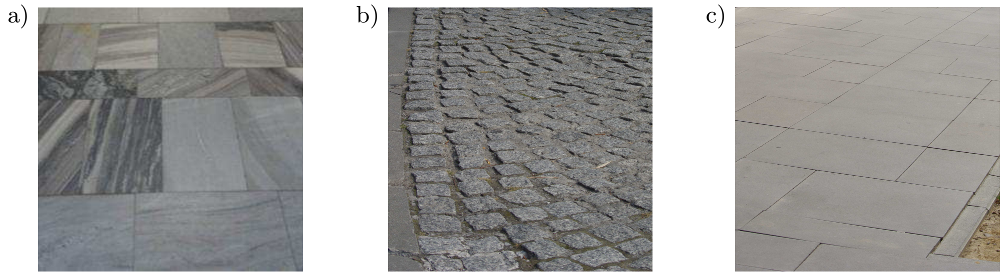

Fig. 3. Test surfaces considered in the comparative study: a) granite slabs inside the building N-1, b) sett pavement N-9, c) concrete boards N-12.

Table 2. Test surfaces.

Designation	Surface type	Features
N-1	Granite slabs	Various slab sizes, no chamfer, joint 2–3 mm
N-9	Sett pavement	Grey granite, variable size (4 types), semi-circular pattern, sett dimensions: 80×80 mm, 110×100 mm, 100×100 mm, 100×90 mm, 25–45 mm joint
N-12	Concrete boards	Board dimension: 600×600 mm with chamfered edges, row by row pattern, 5 mm joint

avoided non-rectilinear movement of the wheelchair. Therefore, time of registration varied and ranged from 7 to 20 seconds.

During the measurements the data interval was set at 1 second. The obtained signal was linear averaged. On that basis vibration acceleration spectrum diagrams were obtained for 1/3 octave bands and compared with the vibration perception threshold contours (vibration exposure of a sitting person), as presented in (Morioka, Griffin, 2008).

A spectrum diagram for X and Y directions obtained from the measurements with superimposed threshold contours for vibration perception are shown in Figs. 4–7.

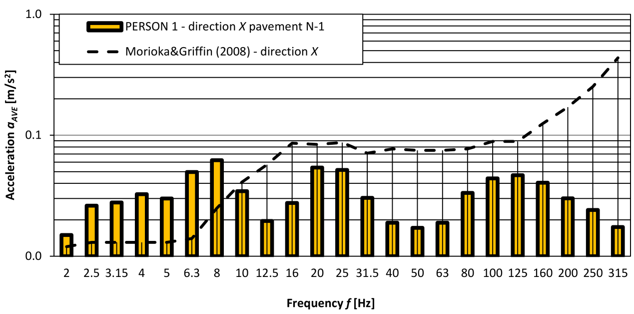

Fig. 4. Amplitude-frequency characteristic for direction X and Person 1 vs the threshold contour (Morioka, Griffin, 2008) for the direction X.

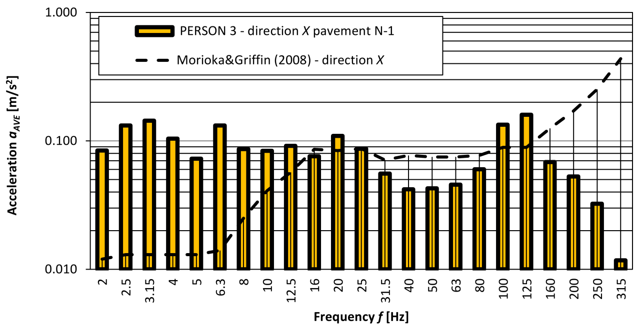

Fig. 6. Amplitude-frequency characteristic for direction X and Person 3 vs the threshold contour (Morioka, Griffin, 2008) for the direction X.

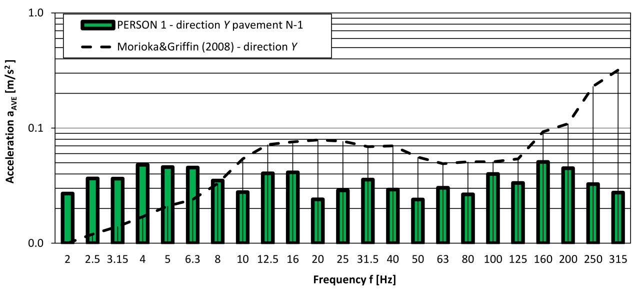

Fig. 5. Amplitude-frequency characteristic for direction Y and Person 1 vs the threshold contour (Morioka, Griffin, 2008) for the direction Y.

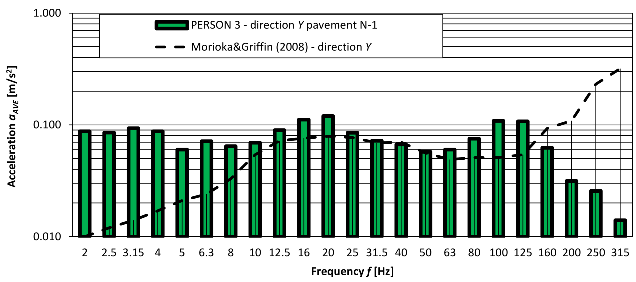

Fig. 7. Amplitude-frequency characteristic for direction Y and Person 3 vs the threshold contour (Morioka, Griffin, 2008) for the direction Y.

5. Results

The measurement results were evaluated basing on the difference between the measured vibration acceleration a_0 and the vibration perception threshold value for humans (in accordance with (Morioka, Griffin, 2008)) for the given octave bands. According to the standard ISO 2631-1, the analysed frequency bands are in the range from 2 Hz to 100 Hz.

Figures 8–11 illustrate the differences Δa between the measured vibration acceleration values a_0 for test wheelchairs W1, W2, W3 during the ride over test surfaces [granite slabs (N-1), sett pavement (N-9) and concrete boards (N-12)] and the threshold contour for vibration perception according to (Morioka, Griffin, 2008). This difference is expressed by the formula (1):

$$\Delta\, a = a_0 - a_{M\&G}, \tag{1}$$

where a_0 is the measured value of 1/3 octave band vibration acceleration for particular wheelchairs on selected pavement surfaces, [m/s^2], $a_{M\&G}$ is the absolute threshold of vibration perception for 1/3 octave band according to (Morioka, Griffin, 2008), [m/s^2].

The wheelchairs W1 and W2 were used by Person 1 (the woman, 50 kg) and Person 2 (the man, 109 kg). The active wheelchair was used by Person 3 (the man, 70 kg). The double dot-and-dash line on the level of ordinate 0.0 m/s^2 corresponds to the vibration perception threshold (the difference (a_0–$a_{M\&G}$)) for particular octave bands and investigated vibration directions equals 0.0 m/s^2). Accordingly, the values above this line indicate the exceeded vibration perception threshold values.

In the stage 1 the measurement results that were obtained for Person 1 and Person 2 using the wheelchairs W1 and W2 and moving over the surfaces N-1, N-9, N-12 were compared.

In the case of vibration produced during the ride over the test surfaces N-1 and N-9 (Figs. 8 and 9) there are considerable differences between the measured vibration acceleration values and the critical perception levels. In the case of a smooth surface N-1, the value plotted on the vertical axis should not exceed 0.15 m/s^2 (the maximum level for 8 and 20 Hz). During the ride over the test surface N-9 (sett pavement) the registered discrepancies approach 2 m/s^2 at 12.5 and 16 Hz. For the test surface N-1 at frequencies in excess of 8 and 10 Hz the acceleration values measured in the directions X and Y do not exceed the threshold level of vibration perception.

Similar results are obtained for the test surface N-12 and for the Person 1 in the wheelchair W1. The maximal difference (a_0–$a_{M\&G}$) is 0.2 m/s^2 and even more for the direction Z (Fig. 10). In the direction of X and Y axes of excitation, the difference should not exceed 0.1 m/s^2 (at 3.15 Hz), whilst in the entire frequency range it fluctuates around 0.0 m/s^2.

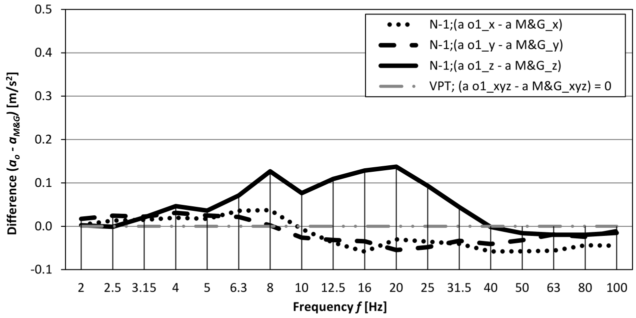

Fig. 8. Difference between measured vibration acceleration values for wheelchair W1 and Person 1 (in the directions X, Y, Z) on the surface N-1 and the absolute threshold of vibration perception according to (Morioka, Griffin, 2008).

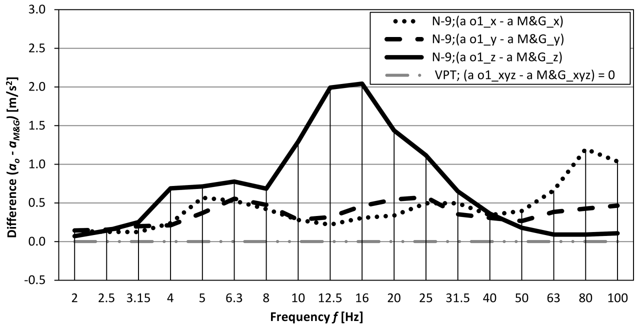

Fig. 9. Difference between measured vibration acceleration values for wheelchair W1 and Person 1 (in the directions X, Y, Z) on the surface N-9 and the absolute threshold of vibration perception according to (Morioka, Griffin, 2008).

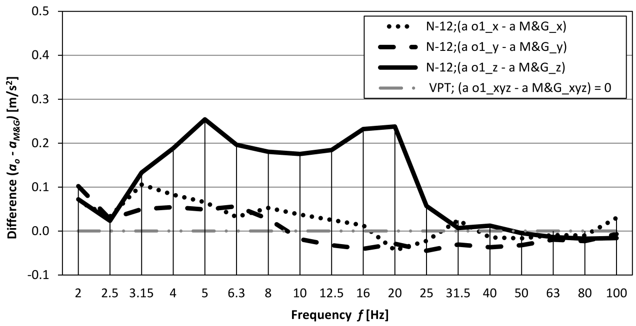

Fig. 10. Difference between accelerations measured for Person 1 and W1 (in the directions X, Y, Z) on the test surface N-12 and the absolute threshold of vibration perception according to (Morioka, Griffin, 2008).

Those studies have investigated the particular user – wheelchair – test surface interactions. Figure 11 shows the results obtained in another test configuration: Person 2 using the wheelchair W1 traversing the test surface N-12 (a level surface, like N-1).

Comparing the plots in Figs. 10 and 11, we observe that in the direction Z (continuous line) the actual values of the difference (a_0–$a_{M\&G}$) are similar

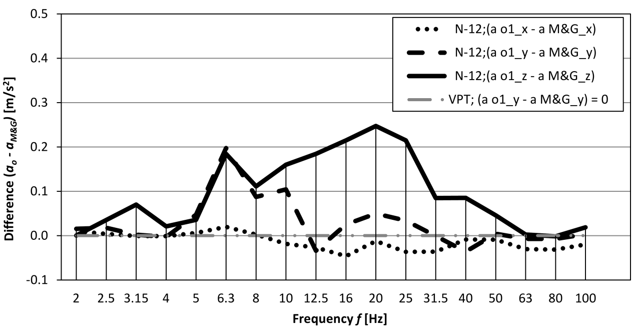

Fig. 11. Difference between accelerations measured for Person 2 and W1 (in the directions X, Y, Z) on the test surface N-12 and the absolute threshold of vibration perception according to (Morioka, Griffin, 2008).

(about 0.2 m/s^2) in the frequency range 6.3–20 Hz for Person 1 and Person 2 riding in the wheelchair W1. The difference in vibration acceleration in the direction Y would exceed the threshold of vibration perception given in (Morioka, Griffin, 2008) in the frequency range 2–16 Hz for the Person 1 and in the range 2–31.5 Hz for Person 2. In the case of Person 1 and for vibration in the direction X, the actual difference would exceed the absolute threshold of vibration perception by about 0.05 m/s^2 in the frequency range 2–16 Hz, and the maximal registered value of this difference was 0.1 m/s^2. For Person 2, whose body mass was nearly twice as large, the value of (a_0–$a_{M\&G}$) fluctuates around 0.02 m/s^2 in the entire frequency range considered in the study. For the direction Y the value registered for the person with a larger body mass (Person 2) was higher in relation to the critical value defined in (Morioka, Griffin, 2008), approaching 0.2 m/s^2 at 6.3 Hz. For Person 1, the value of the difference (a_0–$a_{M\&G}$) fluctuates around 0.0 m/s^2.

When analysing the plots in Figs. 10 and 11 (for Person 1 with the body mass of 50 kg and Person 2 with the body mass of 109 kg), one should bear in mind that the user's body mass is not the only determinant of the vibration perception on the seat in universal wheelchairs. In the direction Z, the values of the vibration acceleration difference for Person 1 and Person 2 were comparable and so they were for the direction X (with minor exceptions in the lower frequency range). For the direction Y, however, the differences obtained for particular users were considerable. Further measurements should be taken to find out whether the wheelchair – user's mass system ought to be treated as just one mass (wheelchair mass plus the mass of object being transported) moving along a specified trajectory, or perhaps the trajectory of the object being transported should be assumed to be quite different from that of the wheelchair itself, which would be the explanation of the results obtained.

Figures 12–17 illustrate the comparison between the acceleration level difference (a_0–$a_{M\&G}$) in the directions of all axes, for Person 1 and Person 2 riding wheelchairs W1 and W2, traversing the same test surface N-9 (sett pavement). Differences $D_{\Delta a}$ between accelerations measured for Person 2 $\Delta a_{\text{Person 2}}$ and those registered for Person 1 $\Delta a_{\text{Person 1}}$ are indicated with the broken line (designations "Diff (Da Person 2 – Da Person 1)"). This difference is given by the formula:

$$D_{\Delta a} = \Delta a_{\text{Person 2}} - \Delta a_{\text{Person 1}} \ [\text{m/s}^2], \qquad (2)$$

where $\Delta a_{\text{Person 1}}$ are the values of vibration acceleration difference in the 1/3 octave band given by formula (1) for Person 2, [m/s^2], $\Delta a_{\text{Person 2}}$ are the values

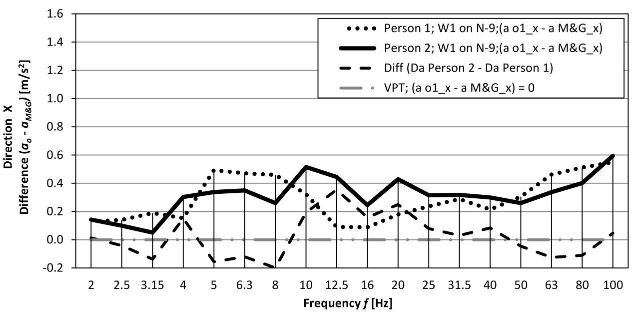

Fig. 12. Difference (a_0–$a_{M\&G}$) for Persons 1 and 2 (for the direction X) during the ride on the wheelchair W1 over the test surface N-9.

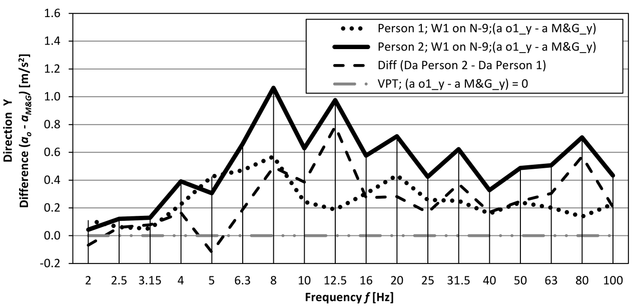

Fig. 13. Difference (a_0–$a_{M\&G}$) for Persons 1 and 2 (for the direction Y) during the ride on the wheelchair W1 over the test surface N-9.

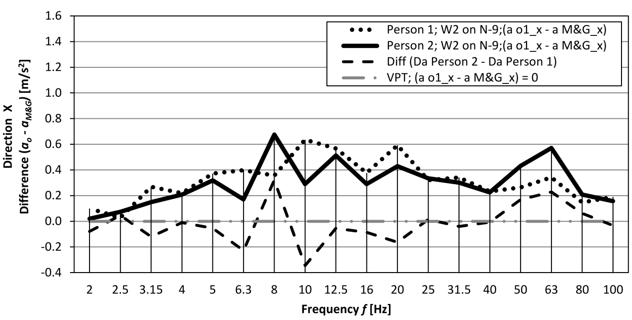

Fig. 14. Difference (a_0–$a_{M\&G}$) for Persons 1 and 2 (for the direction X) during the ride on the wheelchair W2 over the test surface N-9.

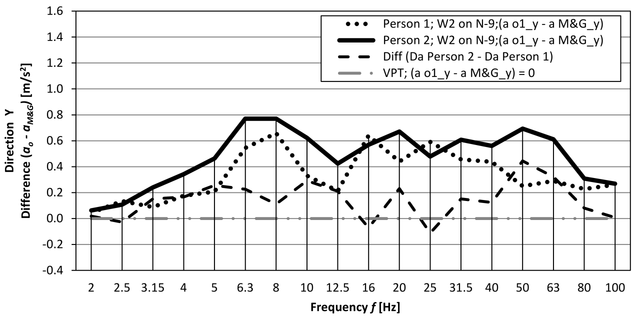

Fig. 15. Difference (a_0–$a_{M\&G}$) for Persons 1 and 2 (for the direction Y) during the ride on the wheelchair W2 over the test surface N-9.

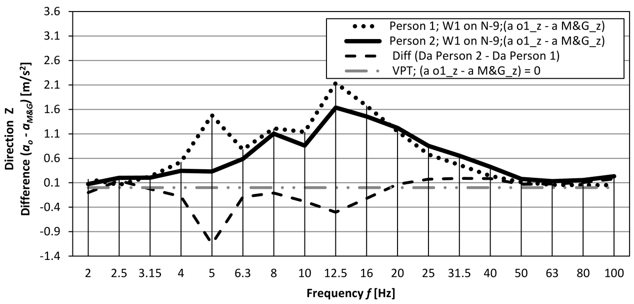

Fig. 16. Difference (a_0–$a_{M\&G}$) for Persons 1 and 2 (for the direction Z) during the ride on the wheelchair W1 over the test surface N-9.

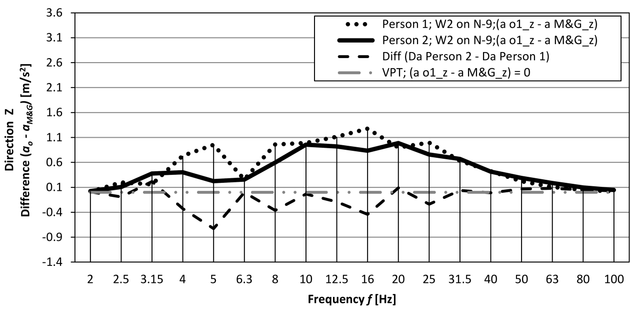

Fig. 17. Difference (a_0–$a_{M\&G}$) for Persons 1 and 2 (for the direction Z) during the ride on the wheelchair W2 over the test surface N-9.

of vibration acceleration difference in the 1/3 octave band given by formula (1) for Person 1, [m/s^2].

In the direction X (the fore-aft direction as shown in Fig. 2), the differences between the acceleration values exceed the threshold of vibration perception for the two test participants and those values are similar in the entire frequency range (maximal differences between the plots are ± 0.2 m/s^2). In the Y axis this difference is nearly 4 times greater and the highest levels are registered for the user with the largest body mass (Person 2).

Figures 14 and 15 show the results obtained for the wheelchair W2. For the vibration direction X (Fig. 14) the discrepancies between the values of (a_0–$a_{M\&G}$) for Persons 1 and 2 are similar to those obtained in tests with wheelchair W1 (the maximal difference being 0.6 m/s^2) and depending on the frequency range, the maximal levels were reached both by Person 1 and Person 2. For the direction Y (Fig. 15), the values registered for the user with a larger body mass (Person 2) would exceed the threshold contour values specified in (Morioka, Griffin, 2008).

The measured vibration accelerations in the direction Z for Persons 1 and 2 moving in wheelchairs W1 and W2 are compared in Figs. 16 and 17. As regards this vibration direction, higher vibration accelerations were registered for a lighter person (Person 1) in the entire frequency range, for both test wheelchairs W1 and W2. Vibration accelerations measured for wheelchair W2 are found to be lower than for wheelchair W1.

Plots in Figs. 16 and 17 indicate that the increase in the wheelchair mass resulted in the enhanced vibration acceleration in the direction Z, whilst the increase in the user's mass led to a decrease of the vibration acceleration registered on the seat even though the overall mass of the wheelchair-user system was increased.

In the stage 2 the measurements were taken of vibration accelerations on the seats of all wheelchairs (W1, W2, W3) through evaluation of the difference in acceleration levels (a_0–$a_{M\&G}$) for two test participants (Person 1 and Person 3) traversing the test surfaces N-1, N-9 and N-12. The results of comparative analysis are summarised in Figs. 18–21.

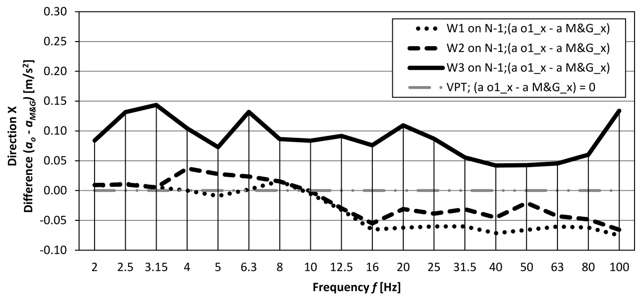

Fig. 18. Difference in vibration accelerations (a_0–$a_{M\&G}$) for wheelchairs W1, W2, W3 on the test surface N-1 (in the direction X).

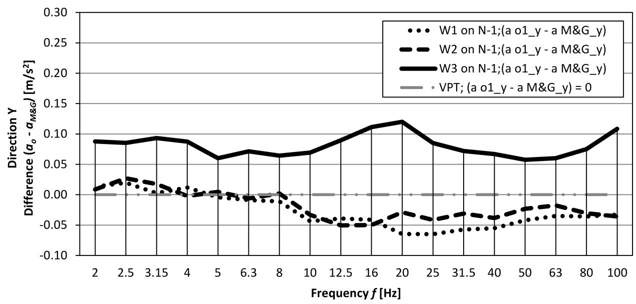

Fig. 19. Difference in vibration accelerations (a_0–$a_{M\&G}$) for wheelchairs W1, W2, W3 on the test surface N-1 (in the direction Y).

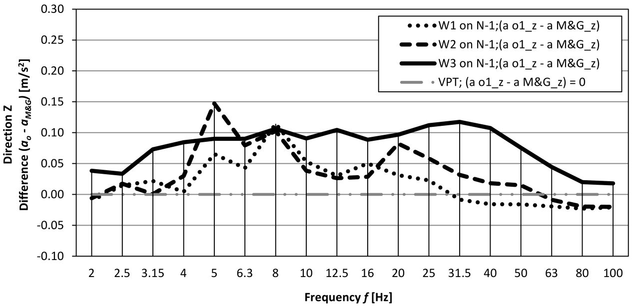

Fig. 20. Difference in vibration accelerations (a_0–$a_{M\&G}$) for wheelchairs W1, W2, W3 on the test surface N-1 (in the direction Z).

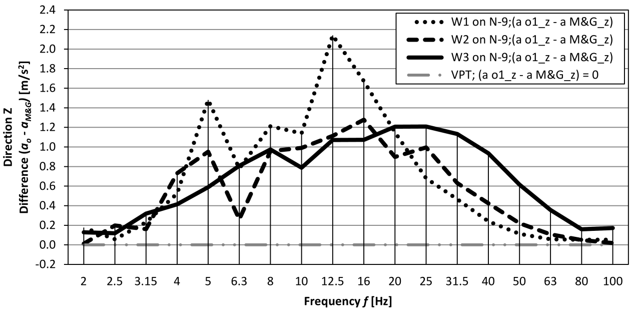

Fig. 21. Difference in vibration accelerations (a_0–$a_{M\&G}$) for wheelchairs W1, W2, W3 on the test surface N-9 (in the direction Z).

Higher vibration acceleration levels are registered for the wheelchair with the lowest mass. The actual values of the difference in accelerations (a_0–$a_{M\&G}$) for wheelchairs W1 and W2 follow a similar pattern (in excess of 8 Hz they are below the threshold contours for vibration perception, i.e. the value 0.0 m/s^2).

Plots in Figs. 20 and 21 show the measurement results for the direction Z and for two test surfaces: N-1 and N-9. It appears that the difference between measured vibration accelerations in this direction is quite insignificant. For the test surface N-1, the highest vibration accelerations are registered for wheelchair W3 and for the test surface N-9 – for wheelchair W1 whose mass is five times larger.

6. Evaluation of uncertainty of the measurement result

In order to evaluate the measurement results the procedure of determination of measurement uncertainty has been performed. It focuses only on the evaluation of the uncertainty the measurement results (without specifying the expanded uncertainty).

In according with (JCGM 100, 2008) a Type A evaluation of standard uncertainty of measured parameters is given by the procedure bulleted below:

- the arithmetic mean $\overline{q}$ of the n observations (q_k – result of the k-th measurement),

$$\overline{q} = \frac{1}{n} \cdot \sum_{k=1}^{n} q_k, \tag{3}$$

- the experimental standard deviation $s(q_k)$, characterises the variability of the observed values q_k,

$$s^2(q_k) = \frac{1}{1-n} \cdot \sum_{j=1}^{n} (q_j - \overline{q})^2, \tag{4}$$

- the experimental standard deviation of the mean $s^2(\overline{q})$

$$s^2(\overline{q}) = \frac{s^2(q_k)}{n}, \tag{5}$$

- a Type A standard uncertainty u_A

$$u_A = \sqrt{s^2(\overline{q})}. \tag{6}$$

6.1. Result of evaluation of a Type A standard uncertainty

Example results of calculation of a Type A standard uncertainty for the obtained measurement values are presented in Tables 3 and 4 and in Figs. 22 and 25.

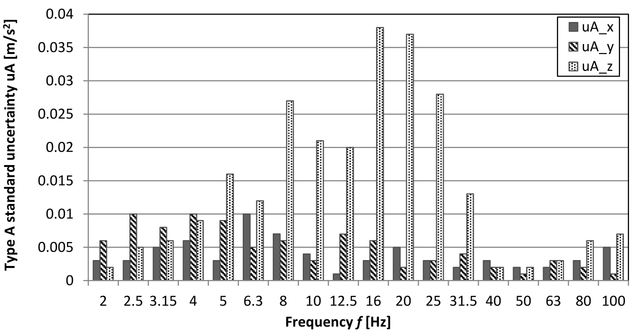

Fig. 22. Distribution of the measurement uncertainty of type A for Person 1 during the ride on the wheelchair W1 over the test surface N-1.

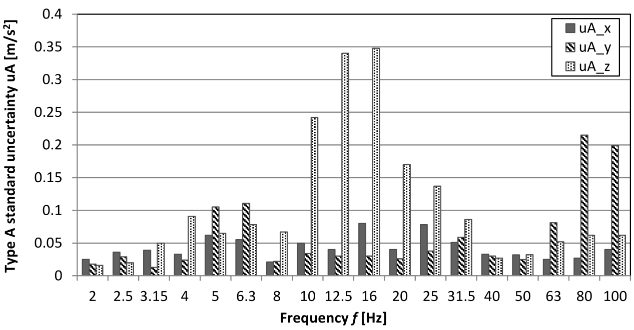

Fig. 23. Distribution of the measurement uncertainty of type A for Person 3 during the ride on the wheelchair W3 over the test surface N-1.

Table 3. Comparison of a Type A standard uncertainty u_A of the measured acceleration values for the pavement N-1 and for Person 1 (on the wheelchair W1) and Person 3 (on the wheelchair W3).

$f_{1/3\ oct}$ [Hz]	A Type A standard uncertainty u_A values of acceleration values a_i (for direction X, Y, Z) for particular 1/3 octave bands											
	Pavement N-1, Person 1, Wheelchair W1						Pavement N-1, Person 3, Wheelchair W3					
	a_{i_x} [m/s^2]	u_{A_x} [m/s^2]	a_{i_y} [m/s^2]	u_{A_y} [m/s^2]	a_{i_z} [m/s^2]	u_{A_z} [m/s^2]	a_{i_x} [m/s^2]	u_{A_x} [m/s^2]	a_{i_y} [m/s^2]	u_{A_y} [m/s^2]	a_{i_z} [m/s^2]	u_{A_z} [m/s^2]
2	0.015	0.003	0.027	0.006	0.017	0.002	0.084	0.014	0.088	0.018	0.038	0.012
2.5	0.026	0.003	0.036	0.010	0.015	0.005	0.132	0.020	0.085	0.013	0.033	0.013
3.15	0.028	0.005	0.036	0.008	0.038	0.006	0.144	0.023	0.093	0.023	0.073	0.020
4	0.033	0.006	0.048	0.010	0.064	0.009	0.104	0.021	0.087	0.012	0.085	0.015
5	0.030	0.003	0.046	0.009	0.051	0.016	0.073	0.010	0.060	0.010	0.090	0.011
6.3	0.050	0.010	0.045	0.005	0.086	0.012	0.132	0.014	0.071	0.009	0.090	0.015
8	0.062	0.007	0.035	0.006	0.146	0.027	0.086	0.005	0.064	0.004	0.106	0.013
10	0.034	0.004	0.028	0.003	0.098	0.021	0.084	0.003	0.069	0.008	0.091	0.009
12.5	0.020	0.001	0.040	0.007	0.131	0.020	0.092	0.010	0.090	0.016	0.104	0.015
16	0.028	0.003	0.041	0.006	0.153	0.038	0.076	0.005	0.111	0.019	0.089	0.011
20	0.054	0.005	0.024	0.002	0.162	0.037	0.109	0.014	0.120	0.019	0.097	0.022
25	0.052	0.003	0.029	0.003	0.121	0.028	0.087	0.008	0.085	0.011	0.112	0.024
31.5	0.030	0.002	0.036	0.004	0.074	0.013	0.056	0.005	0.072	0.005	0.117	0.021
40	0.019	0.003	0.029	0.002	0.025	0.002	0.042	0.004	0.067	0.004	0.107	0.014
50	0.017	0.002	0.024	0.001	0.009	0.002	0.043	0.007	0.057	0.007	0.075	0.010
63	0.019	0.002	0.030	0.003	0.005	0.003	0.046	0.006	0.060	0.004	0.044	0.006
80	0.033	0.003	0.027	0.002	0.006	0.006	0.060	0.007	0.075	0.006	0.020	0.005
100	0.044	0.005	0.040	0.001	0.010	0.007	0.134	0.021	0.108	0.009	0.018	0.017

Table 4. Comparison of a Type A standard uncertainty u_A of the measured acceleration values for the pavement N-9 and for Person 1 (on the wheelchair W1) and Person 3 (on the wheelchair W3).

$f_{1/3\ oct}$ [Hz]	A Type A standard uncertainty u_A values of acceleration values a_i (for direction X, Y, Z) for particular 1/3 octave bands											
	Pavement N-9, Person 1, Wheelchair W1						Pavement N-9, Person 3, Wheelchair W3					
	a_{i_x} [m/s^2]	u_{A_x} [m/s^2]	a_{i_y} [m/s^2]	u_{A_y} [m/s^2]	a_{i_z} [m/s^2]	u_{A_z} [m/s^2]	a_{i_x} [m/s^2]	u_{A_x} [m/s^2]	a_{i_y} [m/s^2]	u_{A_y} [m/s^2]	a_{i_z} [m/s^2]	u_{A_z} [m/s^2]
2	0.154	0.025	0.151	0.018	0.085	0.016	0.117	0.021	0.332	0.063	0.128	0.019
2.5	0.166	0.036	0.139	0.029	0.158	0.020	0.123	0.017	0.314	0.052	0.118	0.016
3.15	0.212	0.039	0.136	0.013	0.270	0.050	0.203	0.036	0.202	0.034	0.318	0.078
4	0.228	0.033	0.250	0.024	0.707	0.091	0.192	0.029	0.268	0.041	0.415	0.070
5	0.391	0.062	0.580	0.105	0.729	0.065	0.283	0.029	0.291	0.037	0.590	0.074
6.3	0.577	0.055	0.543	0.111	0.790	0.078	0.461	0.112	0.449	0.071	0.808	0.090
8	0.507	0.021	0.444	0.022	0.703	0.067	0.614	0.117	0.536	0.068	0.974	0.117
10	0.336	0.050	0.320	0.034	1.315	0.242	0.510	0.087	0.461	0.066	0.788	0.105
12.5	0.389	0.040	0.276	0.030	2.013	0.340	0.808	0.098	0.434	0.062	1.072	0.158
16	0.536	0.080	0.392	0.030	2.067	0.348	0.702	0.045	0.582	0.064	1.072	0.129
20	0.623	0.040	0.421	0.026	1.461	0.170	0.651	0.050	0.541	0.082	1.207	0.135
25	0.653	0.078	0.583	0.038	1.143	0.137	0.381	0.031	0.571	0.071	1.209	0.153
31.5	0.421	0.051	0.566	0.059	0.679	0.086	0.310	0.024	0.654	0.095	1.133	0.158
40	0.377	0.033	0.419	0.030	0.389	0.027	0.293	0.027	0.644	0.101	0.935	0.140
50	0.321	0.032	0.470	0.025	0.203	0.032	0.366	0.033	0.822	0.111	0.615	0.059
63	0.433	0.025	0.737	0.081	0.115	0.052	0.439	0.066	0.754	0.088	0.356	0.045
80	0.477	0.027	1.273	0.215	0.116	0.062	0.612	0.093	0.653	0.069	0.159	0.070
100	0.516	0.040	1.126	0.199	0.132	0.062	1.215	0.158	0.99	0.113	0.173	0.161

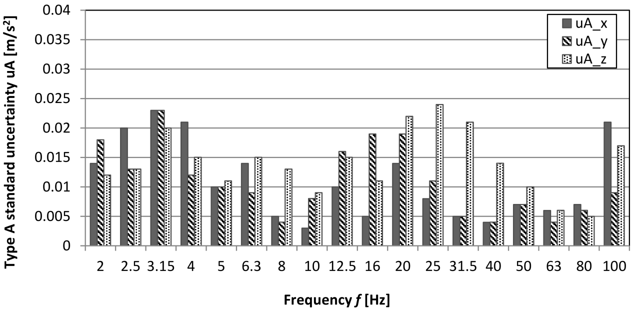

Fig. 24. Distribution of the measurement uncertainty of type A for Person 1 during the ride on the wheelchair W1 over the test surface N-9.

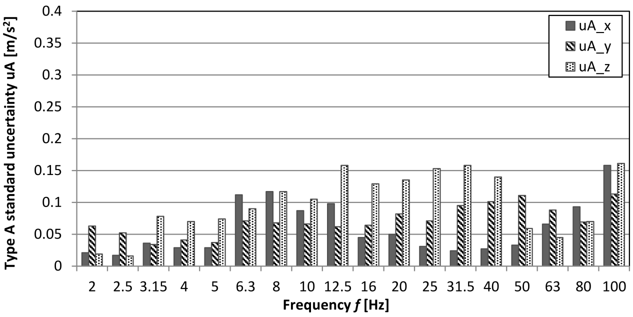

Fig. 25. Distribution of the measurement uncertainty of type A for Person 3 during the ride on the wheelchair W3 over the test surface N-9.

The tables contain the comparisons of 1) measurement uncertainty values obtained for significantly different pavements (pavements N-1 and N-9) and 2) results for Person 1 on the wheelchair W1 *versus* Person 3 on the wheelchair W3.

On the basis of the presented analysis the distribution a Type A standard uncertainty u_A of the measured acceleration values (Figs. 22 and 25) it can be concluded that it is dependent on the type of wheelchair, mass user, and the type of pavements.

7. Discussion and conclusions

Wheelchair users, both those using them permanently or temporarily, are exposed to vibrations generated during the wheelchair ride over various types of surfaces. The proportion of wheelchair users in Poland is only 7% (long-term partial or total wheelchair dependence) (Sydor, 2013). Polish reports and publications lack data about studies investigating this issue and aimed at developing new solutions to improve the wheelchair users' comfort and safety.

A major issue involved in vibration assessment is the selection of the criterion which would provide the reference for further measurements. According to the standard ISO 2631-1 sitting people are at a risk of injuries due to long-lasting whole body vibration exposure. Wheelchair users fit this description perfectly (Wolf *et al.*, 2005). Research work conducted by (VanSickle *et al.*, 2001) demonstrated that a manually-propelled wheelchair user is exposed to vibrations that exceed the levels set forth in the relevant standard ISO 2631-1 (Wolf *et al.*, 2005). Griefahn and Brode (1999) established that the standard ISO 2631-1 is most useful when assessing the impacts of vibrations in one axis and proves to be inadequate in analyses of more than one direction of vibrations. Their measurements revealed that frequency weighing coefficients for lateral vibrations were underestimated in the frequency range in excess of 1.6 Hz, which encompasses the most critical frequencies (Wolf *et al.*, 2004).

According to the standard ISO 2631-1 sitting people run the risk of injury due to long-term whole body vibration exposure. That ISO standard specifies the impacts of the vibration exposure on humans in terms of user comfort, annoyance, and harmfulness of the effects. It appears that assessments of vibration transmitted onto wheelchair users ought to be based on criteria given in this standard. In the authors' opinion, however, relating the levels of vibration perceived by wheelchair users to the normative criteria is unjustified because the person riding in a wheelchair should not only have the vibration comfort provided, but in fact should be free from vibration exposure at all (for example patients with diagnosed aneurysm).

Numerous publications contain proposals to reduce the level of vibration transmitted onto the wheelchair users through the application of additional suspension elements or by providing seat cushions. Reduction of vibration transmitted onto human body is necessary to prevent the occurrence of secondary injuries such as low back pain, disc degeneration. However, experiments conducted by (Kwarciak *et al.*, 2008) and (Wolf *et al.*, 2004) revealed that application of additional mount elements does not significantly reduce the level of vibration transmitted onto the wheelchair user body when traversing certain obstacles and barriers (such as curbs).

The preliminary analysis helped identify some of the factors which caused the change in the value of vibration accelerations registered on the wheelchair seat. Major determinants of the level of vibration include the surface type, wheelchair type, and the body mass of the wheelchair user. Of particular importance is the surface type. The experiments performed as a part of this study showed that the highest vibration accelerations were registered during the ride on the sett pavement, which produced high-level excitations in the three directions and for all wheelchairs used in the study. The work (Wolf *et al.*, 2005) established that heterogeneous surfaces give rise to higher vibration exposure than level surfaces (poured concrete boards). According to the authors, the block pattern (the angle at which blocks are arranged with respect to each other) is of key importance as well. Further, the larger the spacing between individual stones or blocks (joint), the higher vibration acceleration levels.

Measurements were taken to establish how the behaviour of the system "wheelchair-mass of the object in the wheelchair-surface type" should influence the vibration acceleration levels. Experiments showed that an increase in the wheelchair user's mass need not necessarily produce increased vibration levels. It appears that this system's dynamic behaviour is much more complex and cannot not governed by a simple, straightforward relationship. It is impossible to state for which wheelchair type which body mass of the user would be most adequate.

It is worthwhile to mention that only one person among tests participants was a long-term wheelchair user. This fact is of some importance, too. Research conducted by (Pope *et al.*, 1987) established that there is a clear dependence between the posture of the wheelchair user and the vibration perception. Persons who had to maintain the straight position are exposed to higher levels of whole-body vibration than those remaining in the natural, relaxed position. Persons who were not used to wheelchairs did not assume the relaxed position.

Of particular importance was the fact that the active wheelchair was individually tailored to the needs of its user, whilst the remaining wheelchairs were the universal ones. DiGiovine *et al.* (2000) found out that other factors, such as wheelchair configuration and adaptation to the individual user's needs, have a bearing on the level of vibration perception, too.

The results obtained so far implicate the need to develop the procedure of choosing the wheelchair most suited to the particular conditions (user's body mass, surface type).

Wheelchair manufacturers do not provide information about the wheelchair performance in the context of vibration perception by humans. According to (VanSickle *et al.*, 2001) the force and moment values registered in the manually-propelled wheelchairs during the experiments were different from those obtained during the wheelchair tests performed to determine their service life. Most authors emphasise the fact that their experiments use the simulations of environment in which the wheelchairs function (VanSickle *et al.*, 2001). The objective of this study was to evaluate the mobility and vibration perception by individuals using wheelchairs on the grounds of the PK Department of Mechanical Engineering campus. The surfaces investigated in the study are typical ones not only in the vicinity of the campus, but also widely used inside and outside public buildings and in residential areas. The results of the research program can be well utilised in urban development plans (particularly when planning hospitals, high schools, or universities) because one should bear in mind that 'aesthetic aspects' do not necessarily mean 'users' comfort.

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