Regular Article

Gabriela Chwalik-Pilszyk*, Zygmunt Dziechciowski, Magdalena Kromka-Szydek and Marek S. Kozięń

Experimental identification of the subjective reception of external stimuli during wheelchair driving

https://doi.org/10.1515/eng-2021-0112
received July 27, 2021; accepted October 28, 2021

Abstract: The aim of this article is identification of the subjective reception of external stimuli during wheelchair driving by analyses of vibration signals obtained from measurements. The identification concerns the impact of vibrations generated during crossing various types of pavements on the discomfort feelings of the selected human body parts (mainly the spine). The identification used the measurements of the whole body vibrations received by the user of the wheelchair. The research focuses mainly on the analysis in the frequency ranges corresponding to the vibration resonance of the spine. It is because respondents of the conducted surveys selected the spine as one of the most sensitive parts of the body.

Keywords: human body, spine, wheelchair, vibration, measurement

1 Introduction

The impact of vibrations on a person depends on many factors and can be considered in many aspects (both positively, as vibrations used in the process of e.g. rehabilitation, and negatively, as the cause of emerging health ailments). The impact of vibrations on the human body, through direct or indirect contact with the vibrating system, depends on the amplitude and frequency of the excitation [1]. The most dangerous is vibrations with frequencies from about 1 to several Hertz [1, 2]. In terms of the osteoarticular form of the vibration syndrome, the most harmful effect of vibrations is attributed to low-frequency accelerations, contained in the 8 and 16 Hz octave bands [3]. According to Hostens et al. [4], the human body is very sensitive to the frequency range from 0.5 to 10 Hz, and in particular this range is from 3 to 4.5 Hz.

According to the ISO 2631-1 standard [5], people in a sitting position are exposed to the risk of injury caused by the action of general vibrations. Wheelchair users belong to this group due to prolonged stay and movement in a sitting position. Whole body vibrations (WBVs) affecting the wheelchair user have an impact on his comfort, performance, and health. Despite the seemingly slight vibrations perceived by users, they pay attention to the inconveniences experienced in this respect [6]. Hirsch and Reiser [7] reports that as a result of vibrations, apart from the basic physical disability, wheelchair users may develop secondary diseases. Unfortunately, there are few studies aimed at estimating the amount of vibrations transmitted to the human body via a wheelchair [8]. Research conducted for the value of the amplitude of vibrations occurring while driving a wheelchair shows that this value depends on the type and material of the wheelchair, on the weight of the user, but above all on the type of surface on which the wheelchair moves [9–12]. The amount of vibrations received is also influenced by the pressure in the tires of the device, which is confirmed by Fujisawa et al. in their research [13].

Another issue is the distribution of the vibration energy as a function of frequency. This distribution determines the occurrence of various types of ailments related to the resonance frequencies of vitals and organs of the
human body. This issue is taken into account in many publications. Modern wheelchair suspension systems do not sufficiently suppress vibrations that arise while driving [7]. Therefore, more and more new solutions are sought to reduce the amount of received vibrations [14]. Health risks associated with exposure to vibration include vertebrae, disc degeneration, and back pain, which may result in decreased activity and independence of users [6,15–17]. DiGiovine et al. [18] also reports that people in wheelchairs often report back pain, which reduces their level of activity and participation in society.

People with disabilities often indicate an existing problem related to the orthotic equipment they use, but are not able to diagnose the source of the inconvenience. That is why it is so important to use various types of surveys that relate to subjective feelings. The area of research was defined on the basis of an interview conducted among people in wheelchairs. In the next stage, the respondents’ own feelings were compared to the subjective reactions reported by Rasmussen [19] and Jurczak [20], related to the influence of certain frequencies of vibration excitation on the response of human body organs. Pearlman [21] states that a wheelchair user is exposed to a level of vibration that often exceeds the ISO standard (comfort limit). On the other hand, Seidel and Heide [22] suggest that repeated exposure to this and higher level of vibration contribute to chronic spinal injuries. Ayari et al. [23] point out the negative influence of mechanical vibrations on the lumbar spine, and Garcia-Mendez et al. [15] emphasize that back pain in this area is the most common ailment among wheelchair users. The research of Wolf et al. [24] also showed that wheelchair users may be exposed to serious injuries as a result of WBVs generated while moving on certain surfaces. When driving on uneven surfaces, vibrations are transmitted through the wheelchair, which causes the whole body of the person sitting on it to vibrate. According to doctors, people with spinal cord injuries (SCI) report that these vibrations can cause spasticity [25].

Stockton and Rithalia [26] found that, according to users, the use of pillows is associated with the improvement of the sitting position through proper pelvic positioning and spine support. At the same time, the authors state that driving comfort is perceived individually. The research in refs. [15,24,26] showed that pneumatic seat cushions exhibit better vibration damping properties than polyurethane foam and gel cushions, and should be taken into account when selecting additional wheelchair equipment. Among users who use the cushion while moving in a wheelchair, 67% say the pavement is the cause of inconvenience. Among people who do not use a pillow, it is 77%.

Therefore, the use of a pillow does not significantly affect the comfort of traveling and the perceived ailments.

The direct reference of WBVs to ailments related to the spine is not possible due to the multidimensionality of the phenomenon. It was written in ref. [19] that the range of intramedullary forces under the influence of WBV depends on several factors, such as repeated stimulation of various parts of the body, height and body position of the subject. The influence of these forces on the feelings of a person in a wheelchair depends on the individual’s pain tolerance. Therefore, there is no direct and simple relationship between WBV and lesions in the lumbar spine. Therefore, it seems reasonable to relate the results of vibration tests to the subjective feelings of the person who is affected by the harmful factor (in this case, vibrations).

The aim of this article is experimental identification of the subjective reception of external stimuli during wheelchair driving by measuring the response of vibrations in suitable places and directions. The identification concerns the impact of vibrations generated during crossing various types of pavements, using different types of wheelchairs and during passive or active wheelchair moving on the discomfort feelings of the selected human body parts (mainly the spine).

The article is organized as follows: Section 2 presents the results of the survey conducted among people participating in the experiment. Section 3 describes in detail the methodology of the experimental research conducted. This section covers, among other things, what kind of wheelchairs were used in the study and what kind of surface was analyzed. Section 4 presents the results of experimental studies and focuses on the influence of parameters such as the type of movement in a wheelchair, the type of surface, and the type of wheelchair. Conclusions are presented in Section 5.

2 Introductory survey research

Before starting the main experimental research, as an introduction a questionnaire study was conducted. It was a form of anonymous internet survey in which 65 people (34 women and 31 men), aged 18–80, took part. Most frequently cited causes of disability by the respondents were a congenital defect (49%), as well as post-accident disability and neurological disease (20% each). Other causes are old age, arthritis, cerebral palsy, and cancer. The spine (alone or together with the pelvis and lower limbs) was mentioned as the area of the body particularly sensitive to vibrations received by the human...
body while moving in a wheelchair. Among this group of respondents, 25% use a universal wheelchair, 64% use an active wheelchair, and 11% use an electric wheelchair. More than half of people use additional equipment in the form of a pillow placed on the seat of the device, mainly as an anti-bed sore element, and not to reduce vibrations. People complaining of back problems indicate the type of surface (mainly uneven pavements) as an architectural barrier (64% of respondents), and as many as 57% put it as a criterion when planning the route they will be moving. The conducted survey defined the scope of the research as a measurement aimed at determining possible factors that influence the subjective assessment of wheelchair users. The assessment was to concern the impact of the type of surface on the route traveled by people in wheelchairs on the discomfort sensations of selected areas of the body (mainly the spine). The verification was based on the measurements of WBVs received by the user of the wheelchair. The comparative assessment covered different types of surfaces, typical of contemporary architectural arrangements, as well as people using an active wheelchair (disabled person) and universal wheelchairs (able-bodied people, assuming the possible temporary occurrence of disability). The use of seat cushions was also assessed as potentially reducing the perception of vibrations.

3 Methodology of experimental research

Measurements were carried out on flat, relatively horizontal sections, without a significant slope of the terrain. The contact of the wheelchair with the road while driving was an excitation of vibrations that was transmitted through the wheelchair structure to the body of the tested person. Therefore, the wheelchair user was subjected to WBVs transmitted to the human body mainly through his buttocks (buttocks – seat contact), feet (feet – footrest contact), and back (back – seat contact). The tests were carried out on typical surfaces found in architectural arrangements of contemporary public buildings (Figure 1). The study did not analyze driving over obstacles such as a curb (it is the so-called “jerk” indicator¹).

The measurements were performed with the use of the SVAN 958 four-channel vibration meter by SVANTEK, with the SV 39A triaxial vibration converter (Figure 2). During the tests, changes in vibration acceleration over time were recorded with the sampling frequency of 16 kHz. The digital processor used in the meter allows us to obtain appropriate estimates of the signal of the measured parameters (root mean square acceleration value of vibration in one-third octave bands). The transducer was positioned in the center of the wheelchair seat on which the wheelchair user was sitting (Figure 2).

The signal from the three-axis vibration sensor was sent to the spectrum analyzer, where the signal was recorded. Individual registration files were further processed in the SvanPC++ program. Based on the signal, spectral diagrams of vibrations for 1/3 octave bands and time courses of changes in the acceleration amplitude were made, filtered with the selected band filter. The measurement results were compared with the criterion curves of the impact of vibrations on humans (ISO 2631 standard [5]). The vibrations were measured in three directions of excitation, which are marked in Figure 2. During each of the test runs, time was measured with an accuracy of ±1 s. For all the tests carried out, velocity of moving in a wheelchair was the same in order to eliminate the influence of velocity on the amplitude of the received vibrations.

Three wheelchairs were used in the research: one active wheelchair and two universal wheelchairs (Figure 3). One of the universal wheelchairs had the function of upright standing a person in a wheelchair. Universal strollers were used as active and passive. Passive, i.e., they were

¹ Jerk is the derivative of acceleration with respect to time; it is a measure of the rate of change of acceleration in time and consequently the rate of change of generated inertia force acting on the human body.
guided by a second person while the user sat on the wheelchair, while the active wheelchair was steered by the user himself. The active wheelchair was adjusted to the anthropometric dimensions of the disabled person and the type of disease (the person uses a wheelchair for over 10 years). The wheelchair with the upright function was also a wheelchair dedicated to a specific user, but in the research it was used by all able-bodied people participating in the research. The characteristics of the trolleys used in the tests are included in Table 1. The study compared the value of the amplitude of vibrations for the passage of an active wheelchair (driving performed by a disabled person alone) with the passages of healthy people using a universal wheelchair (people with no experience in this regard), and, as it was written earlier, the non-disabled users moved in such a way in an active and passive way.

4 Results of measurements and analyses

4.1 General remarks

The survey research allowed us to obtain a subjective assessment of the pavements used, which appear in architectural arrangements. There is a connection between the ailments related to back pain and the resonance frequencies of the human body organs. As part of this study, an attempt was made to determine whether while moving in a wheelchair on the surfaces used today, the excitation frequencies perceived by the human body do not coincide with the resonance frequencies related to the spine. The vibrations recorded during these tests were analyzed. It allowed to draw some conclusions, which are presented later in the work. The results of the analysis, in the form of amplitude–frequency characteristics and time characteristics, are presented in Figures 4–10, while these analyses focus on vibrations in the “Z” direction.

The analyses are generally focused on influence of three important parameters:
- Type of movement in a wheelchair,
- Type of pavement,
- Type of wheelchair.

4.2 Different types of movement in a wheelchair

The first group of measurements were done for wheelchair passages on the same surface – granite cube. Figure 4 shows an example of a graph that is a comparison of amplitude–frequency analyzes (averaged values from 1-s recordings for individual third octave bands) for a journey of different people (with different somatic features and anthropometric parameters, disabled and physically fit) on the wheelchair in an active and passive way. The chart applies to two able-bodied persons (marking in Figure 4: “P1” – body weight 58 kg and “P2” – body weight 65 kg) and one disabled person (marking in Figure 4: “P1” – body weight 70 kg).

The diagram also shows the scatter of the vibration measurement results for a given run. In Figure 4, it can be observed that the dispersion of values is significantly
related to the frequency (the largest dispersion within the range of 8–31.5 Hz). There are also significant differences in the value of the signal between persons for 1/3 octave bands from 8 to 31.5 Hz. The lowest values are for the journey of a disabled person (active journey). This difference can be seen as influenced by various factors, such as the type of wheelchair and driving technique, but the somatic features of the respondents and their anthropometric parameters will certainly also be decisive.

### 4.3 Different types of pavements

The surface on which the wheelchair is moving will have a great influence on the value of vibrations. It is the
interaction between the device and the surface that causes the inputs that were registered in the form of vibrations during the tests. It is visible in Figure 5, which shows the vibration values during the travel of a disabled person on various surfaces. The lowest amplitude values were recorded for the 60 cm × 60 cm paving slab and asphalt. For these surfaces, the comfort limit defined by the ISO [5] standard was practically not exceeded. The highest vibration values (above the comfort limit) were found for

Figure 6: Variation in time of the amplitude vibration acceleration $a_{RMS}$ (m/s²) (with the ISO comfort limit marked) during the passage of a disabled person in an active wheelchair on different surfaces – filtration with a 1/3 octave filter 8 Hz, direction “Z.”

Figure 7: Variation in time of the amplitude vibration acceleration $a_{RMS}$ (m/s²) (with the ISO comfort limit marked) during the passage of a disabled person in an active wheelchair on different surfaces – filtration with a 1/3 octave filter 10 Hz, direction “Z.”

Figure 8: Variation in time of the amplitude vibration acceleration $a_{RMS}$ (m/s²) (with the ISO comfort limit marked) during the passage of a disabled person in an active wheelchair on different surfaces – filtration with a 1/3 octave filter 12.5 Hz, direction “Z.”

Characteristics of changes in the acceleration of vibrations $a_{RMS}$ (m/s²) over time (8 Hz filtration, “Z” direction) for passages on a mosaic pavement, for the passage of a disabled person in an active wheelchair and for able-bodied people in a universal wheelchair (passive driving); markings: N/wa – disabled person in an active wheelchair, S/wu – disabled person in a universal wheelchair.

Figure 9: Characteristics of changes in the acceleration of vibrations $a_{RMS}$ (m/s²) over time (8 Hz filtration, “Z” direction) for passages on a mosaic pavement, for the passage of a disabled person in an active wheelchair and for able-bodied people in a universal wheelchair (passive driving); markings: N/wa – disabled person in an active wheelchair, S/wu – disabled person in a universal wheelchair.

Figure 10: Characteristics of changes in the acceleration of vibrations $a_{RMS}$ (m/s²) over time (8 Hz filtration, “Z” direction) for passages on a mosaic pavement, for the passage of a disabled person in an active wheelchair and for able-bodied people on a universal wheelchair with the upright function (passive driving); markings: N/wa – a disabled person in an active wheelchair, S/wup – a disabled person in a universal wheelchair with the possibility of standing upright.
granite blocks. For most of the analyzed surfaces, the comfort limit is exceeded in the range from 10 to 40 Hz. The diagram in Figure 5 also shows that the person using the wheelchair is exposed to vibrations in the ranges that coincide with the resonant frequencies of the spine (i.e., thirds of 8, 10, and 12.5 Hz). Therefore, an analysis was made of the journey of a disabled person in terms of changes in the value of the recorded signal for the filtration of the above-mentioned 1/3 octave filters.

The characteristics in Figure 6 were made on the basis of the passage of a disabled person in an active wheelchair on various surfaces (the initial, marked in the diagram, fragment related to the initial phase of driving, i.e., the acceleration of the wheelchair). As can be seen, the vibration amplitude exceeds the comfort limit for the signal filtering frequency of 8 Hz throughout the entire travel. For driving on asphalt, the comfort limit is slightly exceeded. The highest amplitudes were observed for the passage on the pavement made of hexagonal plates and the so-called mosaics.

Changes in the signal amplitude over time, also for the travel of an active wheelchair user (disabled person), for 10 Hz filtration, are shown in Figure 7. Higher signal amplitudes for this filtering case are visible compared to the characteristics in Figure 6. On the asphalt surface (similar to 8 Hz filtration) the comfort limit is slightly exceeded, while the signal amplitudes (within 0.3 m/s² and also exceeding this value) were recorded for the surface made of hexagonal plates.

The filtering of the signal with a bandpass filter with a central frequency of 12.5 Hz (Figure 8) shows that driving on a bone-type concrete block gives the highest values of vibration excitation (in the order of 0.4 m/s² and exceeding this value). High values were also recorded for the mosaic pavement and the hexagonal slab. However, the comfort limit was not exceeded for the asphalt surface and the surface of concrete slabs with dimensions of 60 cm × 60 cm. The effect is influenced by the number of joints (per unit length) between the elements constituting the pavement. The value of the amplitude of vibrations will depend, for example, on the driving speed or driving technique. However, the measurements were carried out at very low speeds (approx. 1 m/s²), and the user is a person with 10 years of experience in driving a wheelchair. Therefore, it can be assumed that the vibration values shown in Figures 6–8 are mainly the result of the input caused by the type of pavement. The mosaic-type surface is one of those which in each case of filtration (8, 10, and 12.5 Hz) indicated a large energy share in the spectral characteristics presented earlier.

4.4 Different types of wheelchairs

The vibration measurement was performed on the above surfaces for the passage of various types of wheelchairs (their characteristics are included in point 3), which were used by people with different somatic characteristics. The dispersion of vibration values for travel with a universal wheelchair and a universal wheelchair with standing upright function, for individual users, is shown in Figures 9 and 10. These results were related to the travel by an active wheelchair used by a disabled person (characteristic made with a dotted line).

By analyzing the graphs in Figures 9 and 10, it can be observed that the scatter of the results for a travel with a universal (lighter) wheelchair is much smaller compared to a universal wheelchair with the upright function (its weight is more than twice as large). For the Unix Breezy universal wheelchair, this dispersion occurs for lower vibration acceleration values (it practically oscillates around the comfort limit defined by the ISO 2631 standard [5]). For a universal wheelchair with the upright function, the spread of vibration values is much greater. The obtained values often exceed the harmfulness limit according to ISO [5]. It should be remembered here that strollers of this type are selected individually. Based on the conducted research, it seems that parameters such as body weight or anthropometric parameters have a less significant impact on the result of vibration measurements compared to the type of wheelchair or types of surface. Measurements were also carried out consisting in determining the value of the acceleration of vibrations transmitted to the user using a shock-absorbing element in the form of a polyurethane cushion of three different thicknesses: 30, 40, and 50 mm. Measurements were carried out in the frequency range 0.8 – 100 Hz, for the passages of four people of different weights on a universal wheelchair. During the travel, wheelchairs were guided by a second person. Figures 11 and 12 show the change of the damping coefficient K within the analyzed one-third octave bands for the tested pavements. The K factor is given by the formula:

$$K = \frac{a_{\text{seat}}}{a_{\text{footrest}}}$$

where $a_{\text{seat}}$ – value of vibration acceleration in the seat of the wheelchair, m/s², $a_{\text{footrest}}$ – vibration acceleration in the wheelchair footrest, m/s².

If the obtained value of the K coefficient is lower than 1, it means a reduction of vibrations recorded on the seat in relation to the vibrations measured on the footrest. K coefficient values exceeding 1 mean the opposite effect,
i.e., multiplied acceleration of vibrations transmitted to the seat. Four able-bodied people (able-bodied women aged 24) participated in the measurements, the results of which are shown in Figures 11 and 12. People had different body weights, and so person marked with the letter “M” – body weight 55 kg, person “P” – body weight 60 kg, person “G” – body weight 68 kg, person “K” – body weight 85 kg.

Figure 11 shows the variability of the $K$ coefficient for the case of an able-bodied person traveling on a universal wheelchair on a hexagonal slab-type surface, and Figure 12 for a "bone"-type paving stone. As can be seen from the presented characteristics, the use of polyurethane pads does not significantly affect the damping of vibrations or even strengthens vibrations in the ranges corresponding to the resonance frequencies of the spine (frequencies marked with a rectangle made of broken lines). This is partly explained by the fact that in many cases people with disabilities are reluctant to use such solutions.

5 Conclusion

The conducted research showed that in the frequency range considered to be particularly dangerous for the spine area (8–12 Hz), the effective value of $a_{RMS}$ vibrations was exceeded in relation to the criterion curve defined by the ISO standard [5]. This was observed for all analyzed surfaces (regardless of the wheelchair used in the research, as well as the degree of mobility and somatic features of the user). Similar observations were presented by Pearlman [21].

The significant impact of the type and condition of the pavement is confirmed by the results of the surveys that were carried out as part of this study. Among all respondents, 65% state that the source of anxiety when driving along the route is uneven, poorly selected surface, among others. For the group of people complaining of back problems, it is over 71%. Wheelchair users often use various types of pillows (53% of people indicated them in the survey), but not necessarily as an element reducing vibrations, often as an anti-bedsore.

Generally, it is very difficult to describe the relationship between the perceived vibrations and possible spine ailments in wheelchair users. These people pay attention to the discomfort they experience while driving, but are unable to pinpoint its causes. The use of measurement methods and questionnaire research in this type of analysis as complementary to each other may be an effective tool in determining further research directions. The surfaces assessed in this study are typical ones that are used in contemporary architectural arrangements (e.g., public utility buildings or housing estates). The conducted research indicates the need to recognize the needs of wheelchair users, not only in terms of overcoming architectural barriers (such as stairs, high curbs) but also in the context of the surface, bearing in mind that “nice” does not always mean “comfortable.”

Conflict of interest: Authors state no conflict of interest.

References

[1] Desai A, Guha A, Seshu P. Multibody biomechanical modelling of human body response to direct and cross axis vibration.
Hischke M, Reiser R. Effect of rear wheel suspension on tilt-in-space wheelchair shock and vibration attenuation PM&R. 2018;10(1):1040–50. doi: 10.1016/j.pmrj.2018.02.009.

[15] Garcia-Mendez Y, Pearlman J, Cooper R, Boninger M. Dynamic stiffness and transmissibility of commercially available wheelchair cushions using a laboratory test method. JRRD. 2012;49(1):7–22. doi: 10.1682/jrrd.2011.02.0023.

[16] Lariviére G, Chadeaux D, Sauret C, Thoreux P. Vibration transmission during manual wheelchair propulsion: a systematic review. Vibration. 2021;4(2):444–81. doi: 10.3390/vibration4020029.

[17] Amiri S, Naserkhaki S, Parnianpour M. Effect of whole-body vibration and sitting configurations on lumbar spinal loads of vehicle occupants. Comput Biol Med. 2019;107:292–301. doi: 10.1016/j.compbiomed.2019.02.019.

[18] DiGiovine C, Cooper R, Wolf E, Hosfield J, Corfman T. Analysis of vibration and comparison of four wheelchair cushions during manual wheelchair propulsion. RESNA. 2000;20:429–31.

[19] Rasmussen G. Human body vibration exposure and its measurement. J Acoust Soc America. 1983;73(6):2229–50. doi: 10.1121/1.389513.

[20] Jurczak ME. Wpływ wibracji na ustrój. Państwowy Zakład Wydawnictw Lekarskich Warszawa. 1974;10:11–7 (in Polish).

[21] Pearlman J. What we know and need to find out about the health implications of vibrations on wheelchair users. 26-th International Seating Symposium. March, 2010. p. 11–13.

[22] Seidel H, Heide R. Long-term effects of whole-body vibration: a critical survey of the literature. Int Arch Occupat Environ Health. 1986;58(1):1–26. doi: 10.1007/BF00378536.

[23] Ayari H, Thomas M, Doré S. A design of experiments for statistically predicting risk of adverse health effects on drivers exposed to vertical vibrations. Int J Occupat Safety Ergonom. 2011;17(3):221–32. doi: 10.1080/10803548.2011.11076888.

[24] Wolf E, Cooper R, Pearlman J, Fitzgerald S, Kelleher A. Longitudinal assessment of vibrations during manual and power wheelchair driving over select sidewalk surfaces. J Rehabil Res Dev. 2007;44(4):573–80. doi: 10.1682/jrrd.2006.05.0049.

[25] Vorrink S, Van der Woude L. Comparison of wheelchair wheels in terms of vibration and spasticity in people with spinal cord injury. J Rehabil Res Dev. 2008;45(9):1269–80. doi: 10.1682/JRRD.2007.09.0148.

[26] Stockton L, Rithalia S. Pressure-reducing cushions: perceptions of comfort from the wheelchair users’ perspective using interface pressure, temperature and humidity measurements. J Tissue Viabil. 2009;18(2):28–35. doi: 10.1016/j.jtv.2007.09.006.