Regular Article

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Experimental investigations on transmission of whole body vibration to the wheelchair user's body

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Abstract: The article presents the results of research on the influence of whole body vibrations (WBVs) on a person moving in a wheelchair. The tests were carried out using an electrohydraulic shaker for a kinematic harmonic excitation with a constant amplitude and frequencies, respectively, 2, 5, 10, 15, and 20 Hz. The accelerations caused by vibrations were measured with three-axis accelerometers at three measuring points: on the seat, chest, and head of the examined person. The research included frequency and statistical analyses of vibrations. The analyses were focused on the course of the transition functions over frequency. The range of the disabled person's exposure to the negative factor which is WBVs was assessed.

Keywords: wheelchair, vibration, measurement, PSD, WBV

1 Introduction

A wheelchair is the basic method of transport for people with spinal cord injury and enables adaptation to the life of a disabled person. During locomotion with the use of this device, a disabled person is subjected to whole body vibrations (WBVs) [1–5].

WBVs are vibrations that are transmitted through elements of wheelchair to the entire human body. Many studies confirm the negative impact of long-term effects of WBVs on the human body. Taking into account the fact that a person moving in a wheelchair is exposed to WBVs for about 8 h a day, he is at risk of diseases such as spine diseases or damage to the nervous system. In the case of a wheelchair, vibrations from the movement of the wheelchair on uneven ground are transferred through the seat and footrest of this device to the human body. There is evidence that exposure to vibration (WBV) in a sitting position is a risk factor for spinal diseases, excessive muscle fatigue, and connective nerve damage [6,7]. In addition, the cumulative vibration effect plays an important role in the connection of WBV with low back pain and nucleus herniation. Many studies have described pathological changes in the spine of people exposed to WBV [8–10]. Epidemiological literature reports that people exposed to vibration are approximately 1.4–9.5 times more prone to back pain [11,12]. Apart from pathological changes, WBV influences the mood of a person exposed to this factor or causes a feeling of fatigue [13,14].

The influence on the probability of diseases under the influence of WBV is closely related to the exposure time and is considered an occupational disease in, among others, professional drivers of industrial machines [7,8,10,14]. However, it should be noted that a disabled person who uses a wheelchair for about 8 h a day also belongs to this risk group. The literature has already shown that during daily use of the manual wheelchair (MWC), users are exposed to a higher level of vibrations ($a_{\text{seat}} = 0.83\ \frac{\text{m}}{\text{s}^2}$) than that recommended by the international standard ISO-2631 on human exposure to vibrations [6]. This standard defines the permissible vibration dose of 0.5 $\frac{\text{m}}{\text{s}^2}$ for an 8-h exposure [15]. In their work, Lariviere et al. [16] emphasized that reducing the daily use of a wheelchair is not feasible as it is the only mode of transport for disabled people.

The level of human exposure to WBV is influenced by many factors that can be divided into three main categories. The first one is related to the wheelchair, its type

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of construction (universal, sports, active), the type of suspension used, the size of the wheels, the type of seat, the material from which the frame is made, or additional equipment for absorbing vibrations [4,6,17–19]. The second group includes personal factors such as the age of the wheelchair user, body mass index, or health [13]. The last group includes external factors such as the condition of roads [1,2,20].

The transmission of vibrations to the body is a complicated phenomenon due to non-linearities in the human musculoskeletal system [6]. This study is an experimental investigation of the transmission of sinusoidal vibrations to the human body in the frequency range of 2–20 Hz. The excitations were selected due to the fact that low vibration frequencies are considered the most harmful due to the resonance frequencies of human internal organs. For the spine, the frequencies are considered to be 10 ÷ 12 Hz, and for the abdominal cavity 4 ÷ 8 Hz [21].

There are many experimental studies which aim to assess the degree of exposure of a person sitting in a wheelchair to WBVs and to identify factors that may influence the exposure to vibrations [22]. Experimental tests have shown, *inter alia*, that with increasing tire pressure, vibrations tend to increase, also then the comfort of driving in a wheelchair decreases [23]. These types of analyses are very important from the point of view of assessing the impact of individual factors on the amount of received WBVs, while a better understanding of the dynamic behavior of a wheelchair user who is exposed to WBVs is of key importance.

There are many studies describing the effect of WBV on a human being in the workplace, while still little research has focused on the influence of WBV on a wheelchair user. In addition, the existing works focusing on the influence of various factors, such as the type of ground or the type of wheelchair, on the amount of vibrations received, do not attempt to describe the reaction of the human body to this factor. It seems to be of key importance to know the human reaction to the effects of WBV, because thanks to this it will be possible to effectively prevent the negative effects of this factor on the human body.

The conducted research was aimed at finding out the dynamic response of a person sitting in a wheelchair, of WBV character, to the external excitations of the platform on which the wheelchair was resting. This will allow us to learn about the response of the human body to the given extortion and it may be the basis for the development of a model of the human body in a wheelchair and a shock absorption system that would eliminate these vibrations, which are particularly dangerous for humans.

2 Methodology of experimental research

The methodology of vibration research operating in a whole body way is based on the registration of vibration acceleration signals in three directions: X (horizontal direction normal to the axis of the body; the direction of the axis of the body), Y (horizontal direction normal to the axis of the body), and Z (vertical direction). The orientation of the axes in the coordinate system is shown in Figure 1. The test was performed in a sitting position on a universal wheelchair with a mass of 18 kg. Each of the performed tests was conducted in the same body position on one wheelchair user weighing 60 kg. A vertical sinusoidal excitation with frequencies 2, 5, 10, 15, and 20 Hz was applied. The type of excitation was selected taking into account the fact that low-frequency vibrations are particularly dangerous for the human body [21]. The extortion was applied to the platform (with a mass of 30 kg) on which the wheelchair was placed. During the test, the wheelchair stood freely on the platform with the brake on. The wheelchair user sat in a natural position without any additional security.

Electrohydraulic shaker *HECKERT pz25* with a static load of 25 kN and the operating range from 1 to 100 Hz was used for wheelchair vibration excitation. The three-axis piezoelectric accelerator sensor *PCB PIEZOTRONICS 356B08* was used to measure the acceleration.

One three-axis accelerometer each was placed on the seat, chest, and head of the subject. On the platform, however, a uniaxial accelerometer was used due to the type of extortion. In order to eliminate the interference resulting from the sensor voltage component, the *HBM*

Figure 1: Measuring station.

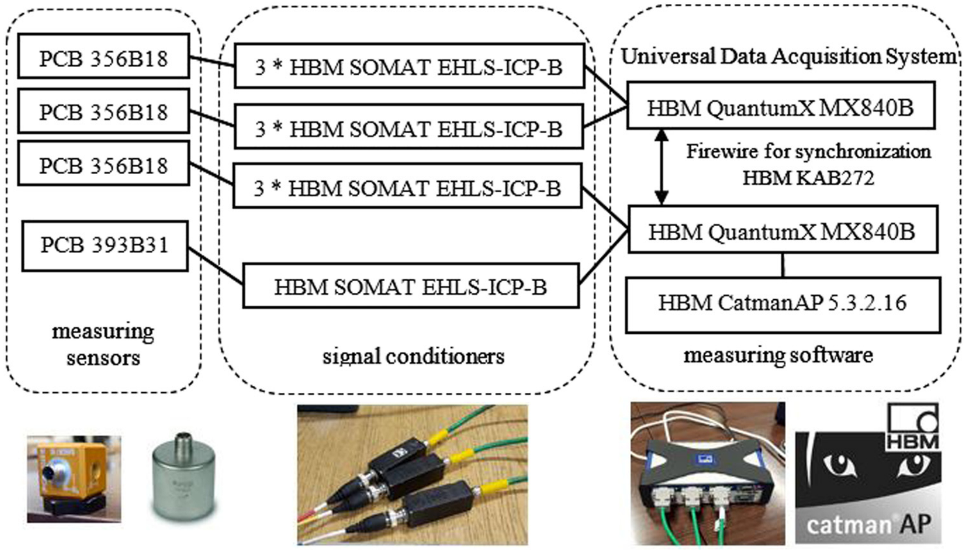

Figure 2: Measurement path.

SOMAT EHLS-ICB-B signal conditioner was used. The *HBM Quantum XMX840A* measuring amplifier was used for the acquisition of measurement data. The measurement path is shown in Figure 2.

Recorded signals were analyzed in both time and frequency domains using *Catman Easy AP* software. Data acquisition parameters are presented in Table 1. A long measurement, divided into several blocks, gives a lot of averages and provides a low spectral noise. The time data are divided into overlapping blocks. Then each block is multiplied with a Hanning window function, which forces amplitudes to zero at the boundaries of each interval and mitigate spectral leakage. Afterward, each block is treated with the mathematical spectral calculations (Welch's method). To produce a single spectrum with low spectral noise, linear averaging is performed. The linear averaged spectrum is the result of several spectra which are summed and divided by their number (overlap 67% was performed).

Based on the obtained data, the effective power of the signals recorded at all measurement points was determined. Power spectral density (PSD) functions for the recorded signals were calculated using the Hanning window from their Fast Fourier Transforms (1) and (2). Since in most applications, it is more interesting to observe the linear units, the square root of the power spectrum is commonly displayed (Sqrt[m/s^2]/Hz)

$$\mathrm{PSD} = \frac{\mathrm{APS} \cdot \sqrt{\mathrm{BBCorr}}}{N \cdot f_s}, \quad (1)$$

where N is the number of all samples, f_s is the sampling frequency, APS is the autopower spectrum, BBCorr is the correction factor for the Hanning window.

$$\mathrm{APS} = \mathrm{FFT} \cdot \mathrm{FFT}^*, \quad (2)$$

where FFT* denotes the signal coupled to the FFT signal.

The frequency-dependent transfer function $M(f)$ is the ratio between the acceleration of platform (input) and the acceleration of the individual segments of the human body on which the sensor (output) is located. Transfer functions, $H(f)$, are defined as the ratio of the output acceleration, $G_{io}(f)$, to the input acceleration $G_{ii}(f)$:

$$H(f) = \frac{G_{io}(f)}{G_{ii}(f)}. \quad (3)$$

For this purpose, the fast Fourier transform was used.

Table 1: Acquisition parameters

Parameters	Value
Sampling frequency	256 Hz
Length of measurement	1,440 s
Block duration	64 s
Windowing	Hanning
Averaging	Linear
Overlap	66.7%

3 Results of measurements and analyses

The analysis of the results focused on frequencies in the range of 0–50 Hz, due to the detrimental effect of low

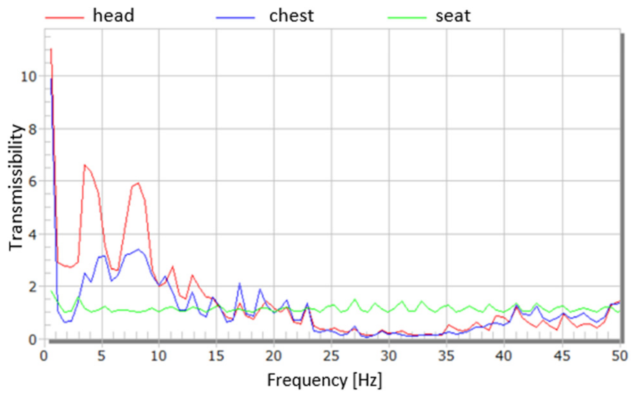

Figure 3: The range of transmissibility of the vertical vibrations of the whole body to the seat, chest, and head as a function of the frequency for the 2 Hz excitation.

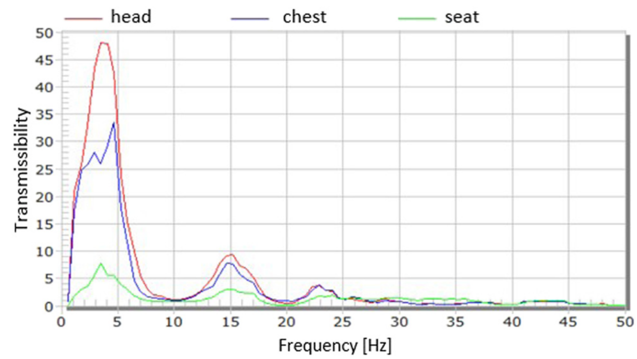

Figure 5: The range of transmissibility of the vertical vibrations of the whole body to the seat, chest, and head as a function of the frequency for the 10 Hz excitation.

frequencies on the human body and due to the fact that a significant resonance response occurred in this frequency range.

Maedy et al. [29] stated in their research that MWC users experience greater discomfort in the case of vibration in the vertical direction (79% of the MWC users compared to 8 and 13% for the antero-posterior and mid-lateral directions, respectively); therefore, this study only analyzed vertical impacts.

The transmissibility of vertical vibrations to the seat, chest, and head in the tested ranges of vibration frequency and amplitude is shown in Figures 3–7. The results were obtained thanks to the application of the transfer function given in equation (3). It was observed that the transferred accelerations were least damped on the head and most on the seat. The exception is the measurement made for the excitation frequency of 5 Hz, where a significant enhancement of the peak acceleration for the chest is observed.

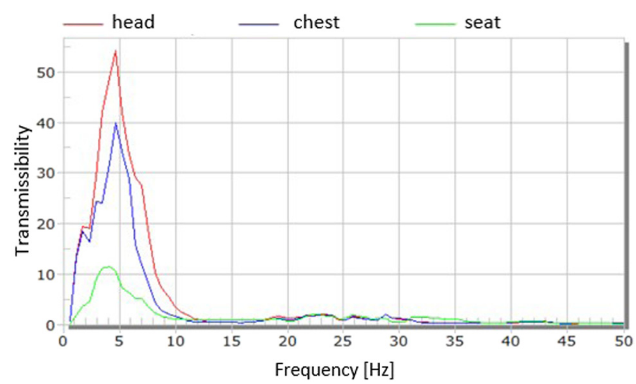

Figure 6: The range of transmissibility of the vertical vibrations of the whole body to the seat, chest, and head as a function of the frequency for the 15 Hz excitation.

For the measurement obtained for the head with the 2 Hz excitation, the transmissibility curve shows two resonances for the frequencies 4 and 8 Hz. Peaks for the Z-direction transfer functions were about 6. On the

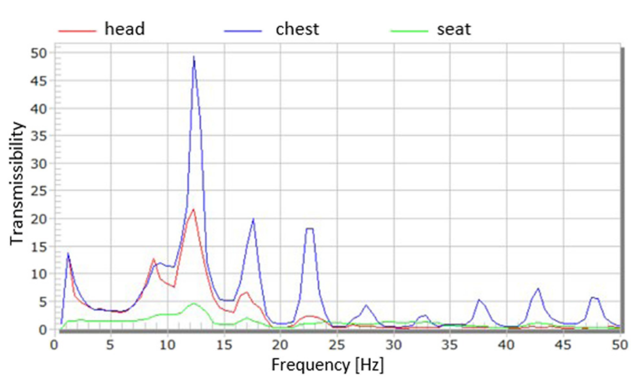

Figure 4: The range of transmissibility of the vertical vibrations of the whole body to the seat, chest, and head as a function of the frequency for the 5 Hz excitation.

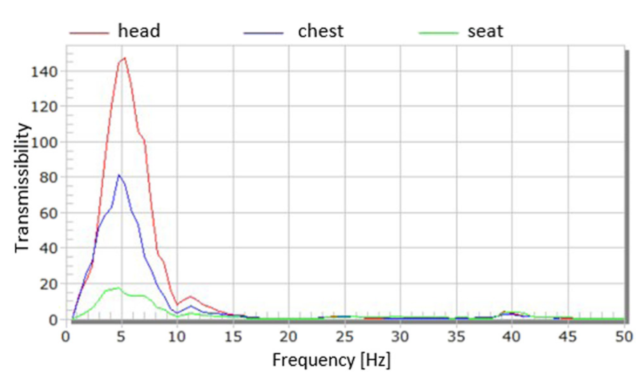

Figure 7: The range of transmissibility of the vertical vibrations of the whole body to the seat, chest, and head as a function of the frequency for the 20 Hz excitation.

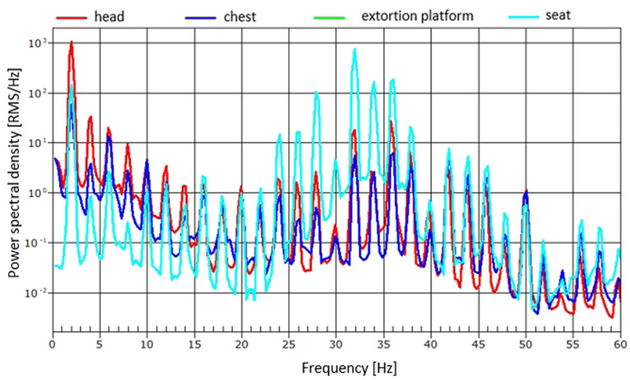

Figure 8: PSD for the 2 Hz excitation for the vertical direction.

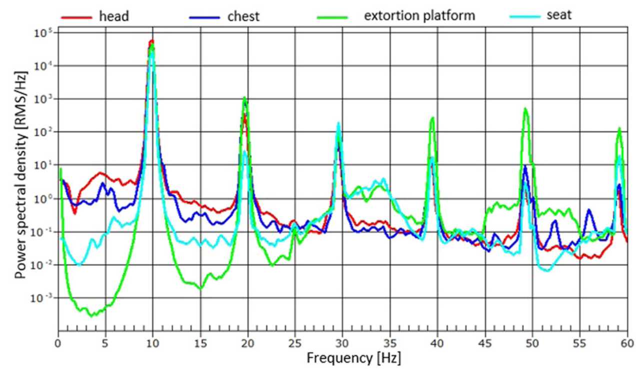

Figure 10: PSD for the 10 Hz excitation for the vertical direction.

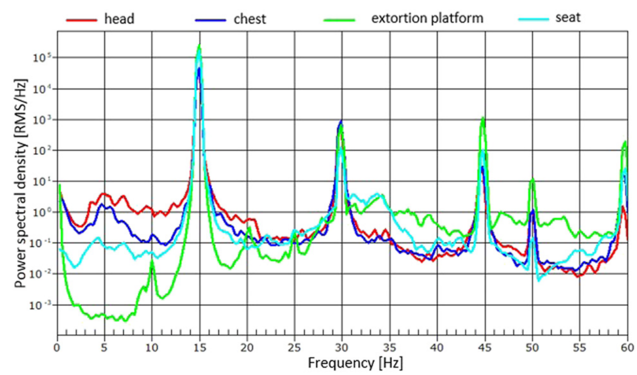

Figure 11: PSD for the excitation 15 Hz for the vertical direction.

other hand, for the chest, the increase in peak acceleration was observed for 5 and 8 Hz.

For the measurement obtained for the head with the 5 Hz excitation, the transmissibility curve shows two resonances for frequencies 1 and 12 Hz. On the other hand, for the chest, the increase in peak acceleration was observed for 1, 12, 18, and 22 Hz and it was for 12 Hz that the highest gain value was observed (around 50).

Significant amplification of the peak acceleration was observed between 4 and 5 Hz for the head and the chest with the input above 10 Hz. This means that the maximum accelerations specific to a given location can be multiple compared to the acceleration imposed on the vibration platform.

On the seat, the gain of peak acceleration for the frequency of 3.5 Hz with the input of 15 and 20 Hz is observed. For these excitations, the obtained profiles were similar in the frequency range of 10–50 Hz.

Figures 8–12 show the PSD values for the head, chest, seat, and vibration platform, determined with the input of 2, 5, 10, 15, and 20 Hz. On the basis of the curves obtained, the influence of harmonics for frequencies being a multiple of the excitation frequency is observed. This effect will be removed in future measurements by application of dedicated compensation systems.

For the 2 Hz excitation, it was observed that the peak value was higher for the head compared to the seat in the frequency range of 2–10 Hz. However, for frequencies from 20 to 40 Hz, higher values were on the seat. In the remaining cases of excitation (5, 10, 15, and 20 Hz), no

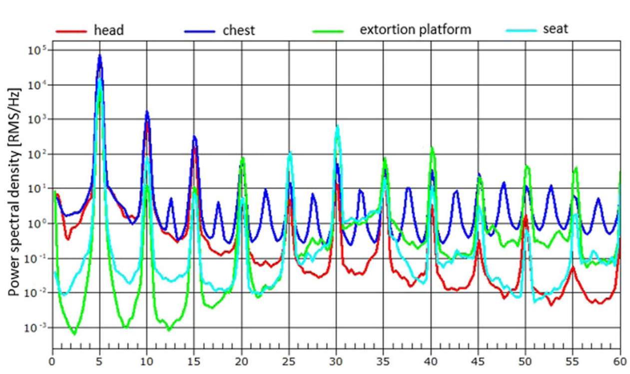

Figure 9: PSD for the 5 Hz excitation for the vertical direction.

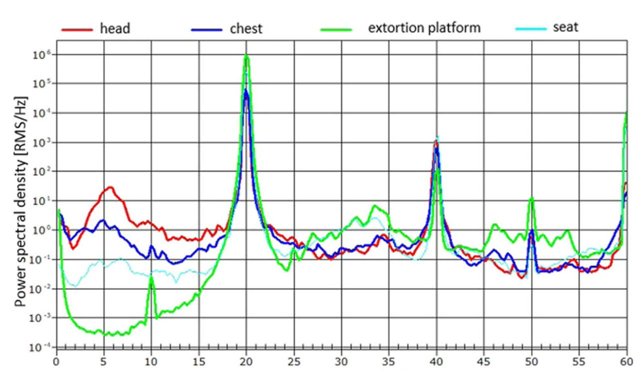

Figure 12: PSD for the excitation 20 Hz for the vertical direction.

similar trend was found. For the 5 Hz excitation, higher PSD values were found for the head, seat and chest compared to the platform at low frequencies (0–15 Hz).

4 Discussion

The human body is a complex biomechanical apparatus and analyzing its response to WBVs is difficult and is subject to several confounding factors.

Biodynamic experiments have shown that in a sitting person, exposed to vertical vibrations, the lumbar spine has a resonance in the frequency range of 2–6 Hz [24]. At these frequencies, the spine may be mechanically overloaded, resulting in pain in a person exposed to vibrations. The conducted experimental studies show the amplification of the signal in the range of these frequencies, which may confirm the possible negative impact of vibrations on the spine of a wheelchair user. In addition, studies show that long-term exposure to WBV increases the risk of deepening deformations within the lumbar spine (e.g., scoliosis) [25]. *In vivo* tests also show horizontal and rotational movements of the vertebrae of the spine under the influence of harmonical WBVs in the range of resonance frequencies [26]. According to Panjabi et al. [26], the resonant frequency of the lumbar vertebrae in the vertical direction is on average 4.4 Hz. However, the horizontal and rotational frequency of the resonance was difficult to define unequivocally. From the point of view of preventing the negative effects of WBVs, it seems crucial to know the full response of the lumbar spine to the vertical excitation.

Research carried out by refs [27,28] emphasizes that high transmissibility of vibrations to the head should be avoided. According to the results they obtained, the head acceleration may increase at frequencies below 20 Hz. The results obtained in this study support this conclusion. In the obtained analysis, the signal amplification for the frequency of 4 Hz was observed. Increased accelerations in the head and neck area may increase the compressive load on the cervical spine [30] and cause sensorimotor disorders, e.g., visual perception [31].

The presented research was carried out on one person and on one type of wheelchair, but it is worth noting that the amount of received vibrations is influenced by many factors. According to Chwalik-Pilszyk et al. [5], the amount of received vibrations is influenced by factors such as the type of wheelchair and the weight of the user. These studies show that people with lower body weight are exposed to higher values of WBV. The weight of the wheelchair itself also has an impact. When moving in a universal wheelchair (wheelchair weight 18 kg), the WBVs are much lower compared to the universal wheelchair with the upright function (wheelchair weight 40 kg).

It should be remembered that without correction of the transfer function, accelerometers mounted on the skin can overestimate the actual peak acceleration by an average of 10–20%, modify the course of the acceleration signal, and increase the inter-subject variance. While these data obtained with skin-mounted accelerometers can be considered indicative only, the observed trends and ranges show the transmission of vertical WBVs to the human body. In particular, these data can help estimate how the transmission of vibration-induced accelerations to body segments is modified by amplitude and frequency.

The obtained results will be used to validate the constructed multibody system model of the human body in a wheelchair. The aim of the presented research was to find out the body's response to the effects of WBVs during passive driving on a universal wheelchair, i.e., for a situation where a person sitting in a wheelchair does not drive it independently. This means that during the movement, the muscular activity (resulting from driving the wheelchair) and the posture of the user of this device do not change. This is important from the point of view of the answer obtained. According to Matsumoto and Griffin [32], differences in the pelvic angle, spine curvatures, and muscle tension are partly responsible for the differences in the transmission of vibrations to the lumbar spine. In addition, flexion in the hip joint and reduced lumbar lordosis increase the pressure on the intervertebral disc and muscle activity, making transmission of vibrations through the spine easier [33].

Damping vertical vibrations at higher frequencies is beneficial from the safety point of view, while vibration amplitudes above 0.5 mm may result in higher accelerations than those applied on the platform, and thus pose a potential threat to fragile bone and cartilage [24].

5 Conclusion

Understanding the dynamic response of the wheelchair user system is essential to improve the comfort of using the wheelchair. The user wheelchair system tends to amplify the vibrations [16]. Conducted research shows that the signal is amplified at low frequencies.

In the human body, the strongest effects of vibration occur at frequencies up to 35 Hz, especially in the range of 2–20 Hz, when organ resonance and irritation of the labyrinth are the cause of the strongest effects of vibration on humans in a vibrating environment.

Particularly dangerous is the amplification of vibrations for the frequency of about 4 Hz obtained for the chest and seat, as it is the resonant frequency of some internal organs such as the liver or arms [34]. Studies have also shown amplification at a frequency of 15 Hz, which in turn has a negative effect on the spine and may explain the pain in the lumbar spine, reported by people using a wheelchair.

Conflict of interest: Authors state no conflict of interest.

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