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Pilot Studies of Vibrations Induced in Perambulators When Moving on Different Surfaces

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Abstract: The ergonomics of transport is a topic widely described in the literature. One of the fields of ergonomics that researchers are engaged in is vibrometry (both laser and accelerometry) of travel and its translation into NVH (Noise, Vibration and Harshness). However, so far, the influence of baby carriage movement on the generated vibrations has not been described in more detail. The topic seems to be particularly important considering occurrence of vibrations with significant amplitudes, whose frequency range can have a direct bearing on the resonance frequencies of the child's internal organs. The article presents the results of research consisting in the measurement of vibrations to which an infant, lying in two different types of prams, may be exposed when being transported on different surfaces. The author's measurement system, based on accelerometry, was used for the research. The obtained weighted RMS acceleration values not only exceeded human comfort level in all cases (according to ISO standard) but several times were in the range of the highest discomfort (>2 m/s^2). Furthermore, the observed vibration frequency range (≈0 ÷ 32 Hz) coincided with the frequencies of free vibration of organs and parts of the child's body.

Keywords: infant's health; pram; baby carriage; vibrometry

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1. Introduction

The most important element when selecting a baby carriage should be assurance of the child's safety. Especially in unfavourable conditions such as uneven/rough terrain and higher walking speed (increase in kinetic energy), potentially dangerous vibrations and an accident of the infant jumping out can occur [1–4]. The main research objectives in this area are:

- Increasing the current knowledge of vibration characteristics of infants in baby carriages;
- Increasing the current knowledge of vibration effects (amplitude, frequency, exposure time) on infants' health.

It should be noted that in the international scientific literature, there are practically no results of research determining and comparing the parameters of vibration characteristics of the smallest children in prams (in recumbent position). The research about vibrations induced in baby carriages focuses on strollers (seating position, different design) [1–4]. The present paper aims to fill this gap and also demonstrate that some newer prams have a potential for transmission of more vibration compared to older prams, especially due to the lower weight and compact sizes.

The article [1] on vibrations affecting a few-years'-old child sitting in a stroller concerns the measurement of the amplitude of acceleration while entering into a defined obstacle. Although the primary objective of the aforementioned research [2] was vibration exposure during infant inter-hospital transport, the results include not only the ambulance and car transportation but also a stroller (only one) integrated with a car seat (seated position). The research was conducted on "city streets", and vibrations when moving on different types of surfaces were not distinguished. The seat pad equipped with 1-axis (vertical) accelerometer was mounted under the simulated neonate (only 1.3 kg mannequin). Similarly, in another work [3], only the vibration characteristics of a group of 3- to 6-year-old children riding in a stroller (seated position) were determined. Another research [4] revealed the occurrence of an extremely uncomfortable level of vibrations in probable outdoor conditions.

In the worldwide scientific literature, there are many publications on the exposure of small children to vibrations during car travel in a child safety seat. According to the available knowledge, the main resonance frequency for the body of an adult sitting in a car seat is usually between 3–5 Hz [5,6]. The research carried out by Giacomin and Gallo [7] indicates that for children up to 3 years of age sitting in a child safety seat, the main resonance frequency for their body is close to 8.5 Hz, which is caused by the anthropometric and postural differences between children and adults.

According to other works on neonatal inter-hospital transport [8–10] the vibrations acting on a baby's body during ground transport cause elevated heart rate, increase of leucocyte levels and behaviour that indicates pain. In extreme cases, transport vibration can cause even neonatal brain injury [11,12].

Much more research has been conducted on the effects of vibrations on an adult human. The recent works on the whole-body vibration of the supine human during medical transport [13–15] indicate the risk of discomfort or even secondary injuries. This risk is affected by many factors such as the contact surface materials [14], body mass and even gender [13]. Particular mention should be made of the predictive model to evaluate the discomfort of supine humans during transportation [15].

Griffin in his article [16] describes a method of describing and assessing the sensation of the human body to vibrations while moving a vehicle. He points out that an important aspect is to take into account the individual sensitivity of various organs to different vibration magnitudes, frequencies, directions and duration of vibrations. He also talks about the shortcomings in vibration testing standards related to the comfort and health of people, which, in his opinion, depends on many factors, not just the vibrations in the vehicle itself. In addition, small and sudden changes may not be felt according to a subjective opinion but still have an impact on the larger picture in the long term.

When measuring the vibrations transmitted to the human body, it is difficult to clearly identify the relevant standards, and therefore also the exact pattern. In one article [17], Griffin and Lewis try to compare and evaluate the methods defined in three different standards: ISO 2631/1:1985, ISO 2631/1:1997 and BS 6841:1987 [18–20]. They indicate the differences in the methods of correction as well as averaging the frequency and the final evaluation. In addition, they point out that one standard lists different approaches to measuring and evaluating vibration. Measurements involved vibration accelerations on the seats of nine different vehicles, including bus, passenger vehicle, harbour crane, fork-lift, tank, four-wheel drive ambulance, motor boat, pontoon-motor boat and a bicycle. An important conclusion was that there were significant differences in the assessment of the permissible exposure time. This is the time during which the body may be exposed to vibration in a vehicle.

Vibrations, on account of their transmission to the human body, are divided into two groups: general and local [21]. General vibrations refer to vibrations transmitted from the ground or from a seat to the lower limbs or pelvic bones. Such vibrations occur in the vicinity of heavy machinery and means of transport. Man-operated machines generate dynamic forces at various levels. Stationary machines are seated on foundations or support structures. Despite the use of vibration isolation, for example in the form of shock absorbers, low damping of construction materials causes vibrations to be propagated over quite long distances along with being locally reinforced. Large vibration amplitudes occurring here may affect the people in their vicinity. They occur when a person is directly connected to the system (e.g., a child in a pram or a vehicle driver).

General vibrations can cause the internal organs to resonate, which at high intensity can lead to injury. Lower intensity vibration can cause disorders in the central and peripheral nervous system, gastrointestinal tract, locomotor organs as well as in the systemic micro- and macro-metabolism to occur [5,6].

In Poland, ISO 5349 and PN-EN 14253 [22–25] were adopted as binding standards concerning human exposure to mechanical oscillation at the workplace. According to the mentioned standards, the measurement consists in measuring three vibration vectors and then determining the value of the vector sum of the Root Mean Square (RMS) values or the so-called dominant weighted vibration acceleration value, selected from the three components (and thus in fact one directional component) and comparing them with the values specified in the standard as a function of exposure time [26].

The articles [7,27] present a thesis which states that the direction of technological development of child safety seats has in recent years focused primarily on protecting children's lives in road collisions, pushing vibration isolation into the background. As it has been shown experimentally in the above-mentioned work, child safety seats amplified vibrations in most frequencies below 60 Hz in relation to a car seat.

The authors of the following paper formulate the thesis that the technological development of baby carriages pursues, in many cases, a considerably less noble goal, which is to provide the greatest possible comfort for parents at the expense of children being transported in perambulators. This is perfectly illustrated in papers presenting the technological development of baby prams and strollers over the last decade [28,29].

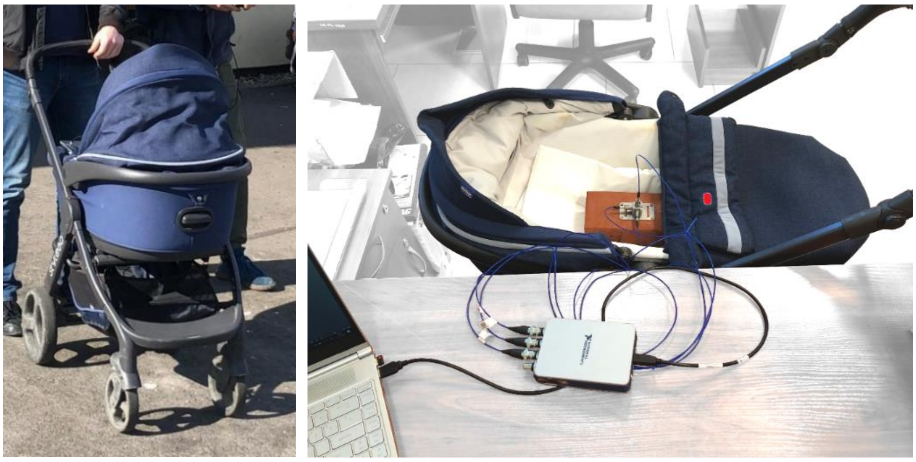
Therefore, the main contribution of this paper in the current knowledge is to show the difference in vibration comfort between the "old type" perambulator and the modern one, foldable to compact size, equipped with a universal frame and enabling the attachment of a child car seat or a stroller-type seat (parameters that can convince many new parents to buy it).

Obviously, there are many models of prams and strollers on the market, and the differences between them are noticeably more significant than in the case of child safety seats. This is primarily due to the higher technical complexity of the product. Also, the standard requirements for child safety seats (example: ECE R44/04 approval) are more restrictive than the standards covering perambulators and baby strollers, which allows them more freedom of design [30]. It should be noted that not all currently produced prams follow the mentioned modern trends, offering considerably better damping properties.

2. Materials and Methods

2.1. Subject

The authors' intention is to show and compare the vibration transmission characteristics of an exemplary compact low weight perambulator (Figure 1a, Table 1) and an exemplary old-type, much heavier and bigger perambulator equipped with pneumatic tyres (Figure 1b, Table 1).



(**a**)

(**b**)

Figure 1. Photograph of the tested perambulators: (**a**)—a lightweight modern "3 in 1" pram (hereinafter the modern pram), (**b**)—an "old type" heavy pram with pneumatic tyres (hereinafter the old pram).

Table 1. Comparison of the tested perambulators' design parameters.

Parameter	Modern Pram	Old Pram
Mass	12.7 kg	17.2 kg
Front wheel diameter	16.5 cm	29.5 cm
Rear wheel diameter	25 cm	29.5 cm
Tyre type	Ethylene vinyl acetate (EVA) foam	Pneumatic; inflation pressure: 2 bar
Front suspension	Longitudinal arm (≈2 cm stroke)	Suspension straps (Figure 1b)
Rear suspension	No suspension (rigid)	Suspension straps (Figure 1b)
Wheelbase	61 cm	54 cm
Front wheel track	34 cm	57 cm
Rear wheel track	46 cm	57 cm
Height of the frame bottom	11 cm	12 cm
Contact surface (mattress) height	53 cm	50 cm

Thanks to the analysis of the registered signals, not only in time domain but also in frequency domain, it was possible to show to what frequencies, falling within the range of natural vibrations of the skeletal system and organs, a child is exposed to while travelling on specific surfaces, as shown in Figure 2 (asphalt road, concrete paving blocks, concrete plates, dirt road, lawn, damaged concrete).

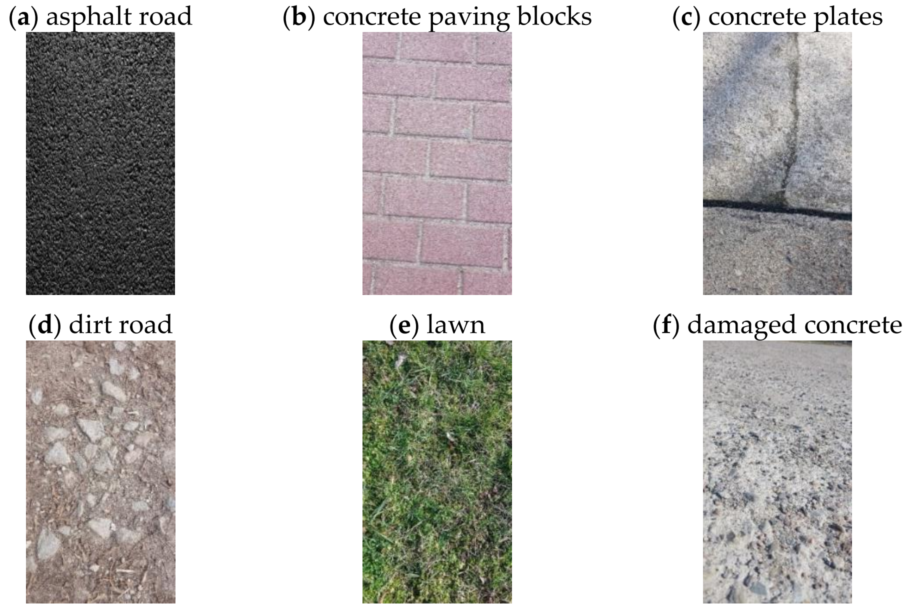


Figure 2. The surfaces on which the research was conducted.

2.2. Test Equipment

The measurements were taken after stabilization of walking speed at 4 km/h (value between "slow" and "usual" human walking speed [31]) and after passing the starting point of the selected straight path. To maintain the defined speed, a cell phone GPS-based speedometer was used, and the perambulators were always driven by the same person. Figure 3 shows a schematic diagram of the research subject weighing 3.8 kg and having an accelerometer system.

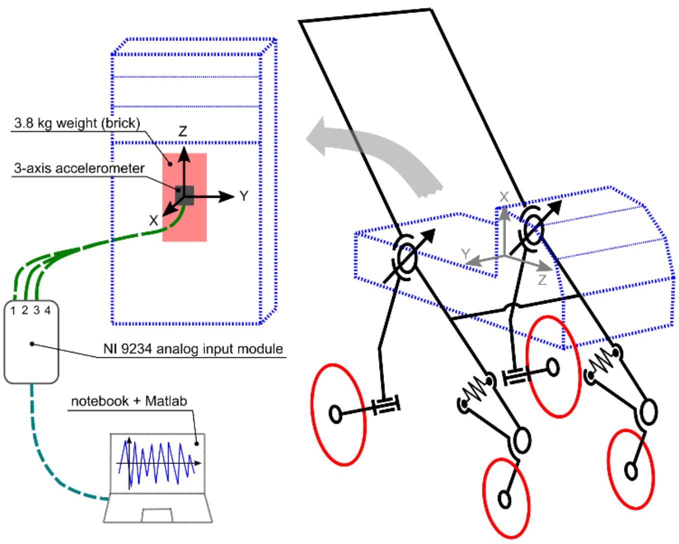


Figure 3. Schematic diagram of the research subject.

The measurements were carried out using a 3-axis high-sensitivity accelerometric sensor, produced by Piezotronics PCBs (sensitivity 10 mV/g, measurement range 50 g, frequency range ±5%: 0.7 to 7000 Hz) for general purpose. A 4-channel National Instruments acquisition card NI-9234 (4-channel, 51.2 kS/s/channel measurement range ±5 V) was used for signal conditioning and acquisition. Single measurement duration was 6 s and the sampling frequency was 2 kHz.

The measurements were conducted according to the rules which allow the avoidance of spectrum leakage and aliasing (according to Shannon−Kotelnikov−Whittaker−Nyquist's law [26]).

It should be mentioned that vibrations were measured on the research subject and not on the surface between the body (object) and that surface, as recommended by ISO 2631-1:1997 [19]; but because the object was characterized by high stiffness and homogeneous density, this different localization should not significantly influence the obtained acceleration values.

A major part of the research has a comparative character, focusing on characteristic harmonics related to different surfaces and not a precise transmission to the body. The simplification of using rigid cuboid instead of an infant dummy can be considered as a constant error. In the normative evaluation, the vibration measurement point is assumed as "under the pelvis". According to ISO 2631-1:1997 [19], "when there is no soft pillow, it is recommended to measure also beneath the head". However, due to the aforementioned reason, it was decided not to add another mass (infant head) or make our own infant dummy (also difficult to reconstruct) for these pilot studies.

2.3. Data Processing

Using the geometrical sum of the registered acceleration in three directions, the point vibration's total values ($\boldsymbol{a}$) and maximal values ($\boldsymbol{a_{max}}$) of the acceleration affecting the research subject (the weight placed in the pram in the space provided for a child) were calculated for each of the research cases (according to Equations (1) and (2)):

$$\boldsymbol{a} = \sqrt{\boldsymbol{a}_x^2 + \boldsymbol{a}_y^2 + \boldsymbol{a}_z^2} = \sqrt{\frac{1}{N}\sum_{n=0}^{N-1}[a_x + (n)^2 + a_z(n)^2}[\mathrm{m/s^2}] \quad (1)$$

$$\boldsymbol{a_{max}} = \max\left\{\sqrt{a_x(0)^2 + a_y(0)^2 + a_z(0)^2},\ \ldots,\ \sqrt{a_x(N-1)^2 + a_y(N-1)^2 + a_z(N-1)^2}\right\}[\mathrm{m/s^2}] \quad (2)$$

where n—the number of the considered sample; N—the number of samples; $a_x(n)$, $a_y(n)$, $a_z(n)$acceleration values with respect to the orthogonal axes x, y and z in sample n $[\frac{\mathrm{m}}{\mathrm{s}^2}]$.

Frequency spectrums of the measured acceleration orthogonal components were obtained using the MATLAB fast Fourier transform algorithm. They were created for each of the 6 tested surface (a–f) cases and 2 types of perambulators (I and II). A least 2 measurement series were made for each variant, and then the values of individual harmonics were averaged. Finally, the square root of the sum of the squares of the orthogonal component of accelerations in frequency domain were calculated (Equation (3)):

$$A(f) = \sqrt{\overline{A}_x(f)^2 + \overline{A}_y(f)^2 + \overline{A}_z(f)^2} \qquad [\mathrm{m/s^2}] \quad (3)$$

In the last step, the ISO 2631-1:1997 evaluation of human exposure to whole-body vibration was performed [19]. In accordance with this normative evaluation method, each translational component of the acceleration has to be filtered with an appropriate frequency weighting curve indicated and defined in the ISO standard. For the comfort assessment of recumbent person, the W_d frequency weighting curve has to be applied for horizontal axes (y, z) and W_k curve for vertical axis (x). The total value of weighted RMS acceleration is calculated as follows (Equation (4)):

$$\boldsymbol{a_w} = \sqrt{k_x^2\boldsymbol{a}_{wx}^2 + k_y^2\boldsymbol{a}_{wy}^2 + k_z^2\boldsymbol{a}_{wz}^2} \qquad [\mathrm{m/s^2}] \quad (4)$$

where a_{wx}, a_{wy}, a_{wz}—orthogonal components of the frequency-weighted RMS acceleration $[\frac{m}{s^2}]$; k_x, k_y, k_z—multiplying factors (for the comfort assessment of the recumbent person, all multiplying factors are equal to 1).

3. Results and Discussion

3.1. Time Domain

The time domain results for each of the research cases, including the point vibration total values (a) and maximal values (a_{max}) calculated in accordance with Equations (1)–(2), are shown in Table 2 and Figure 4.

Table 2. RMS and maximum acceleration values (static acceleration component excluded) applied to the weight placed in the space provided for a child in the tested perambulators.

	Modern Pram—Surface Variants						**Old Pram—Surface Variants**					
	Asphalt Road	**Concrete Paving Blocks**	**Concrete Plates**	**Dirt Road**	**Lawn**	**Damaged Concrete**	**Asphalt Road**	**Concrete Paving Blocks**	**Concrete Plates**	**Dirt Road**	**Lawn**	**Damaged Concrete**
a_x $[\frac{m}{s^2}]$ **(RMS)**	1.82	2.63	4.06	3.97	4.36	4.74	0.45	0.92	2.04	2.20	3.37	3.24
a_y $[\frac{m}{s^2}]$ **(RMS)**	0.84	0.67	1.58	1.66	2.55	2.33	0.32	0.39	0.72	0.79	1.33	1.53
a_z $[\frac{m}{s^2}]$ **(RMS)**	0.70	1.12	2.26	1.71	1.64	1.48	0.32	0.42	0.92	0.80	1.58	1.30
a $[\frac{m}{s^2}]$ **(RMS)**	2.12	2.94	4.91	4.63	5.31	5.48	0.63	1.09	2.35	2.47	3.95	3.81
a_{max} $[\frac{m}{s^2}]$	6.86	11.63	19.02	18.91	20.11	20.07	1.58	3.01	7.87	7.34	13.79	9.86

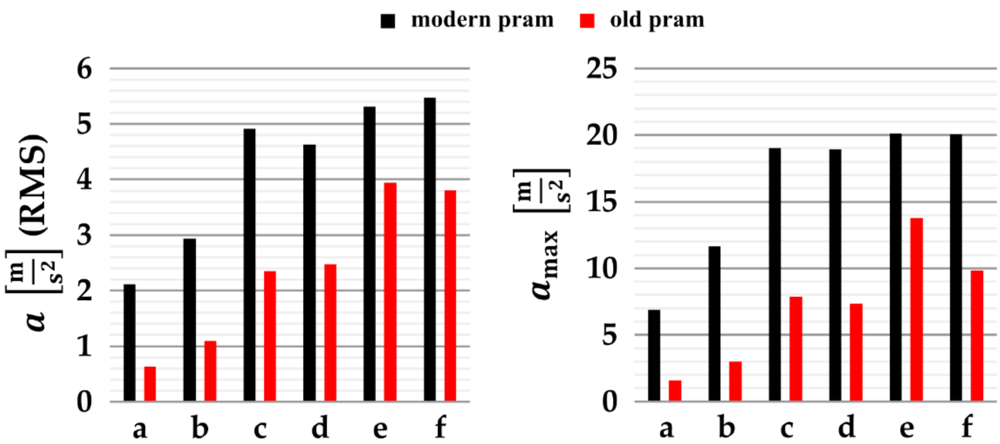


Figure 4. Comparative bar graphs of the RMS and maximum acceleration values from Table 2.

As can be seen, at the same surface variants, both the point vibration total values (a) and maximal values (a_{max}) were noticeably lower for the "old type" perambulator equipped with pneumatic tyres (old pram) in relation to the lightweight modern pram. The greatest difference can be found for the asphalt road (a): 70% lower point vibration total value and 77% lower maximal value. On average, their point vibration total value was 48% lower, and the maximal value was 59% lower for the old pram. Such a difference was most probably due to the lower weight of the modern pram and higher vibration transmissivity of both the frame and its polyurethane foam tyres.

For the modern pram, the RMS accelerations in the x direction (a_x), parallel to the gravity vector, on almost all the surfaces exceeded the value of 2.5 $\frac{m}{s^2}$. The mentioned value was never exceeded in the cited [7,27] child safety seat tests (the accelerometer placed under the child's seat).

3.2. Frequency Domain

The obtained periodograms of $A(f)$ acceleration (calculated in accordance with Equation (3)) are presented in Figure 5:

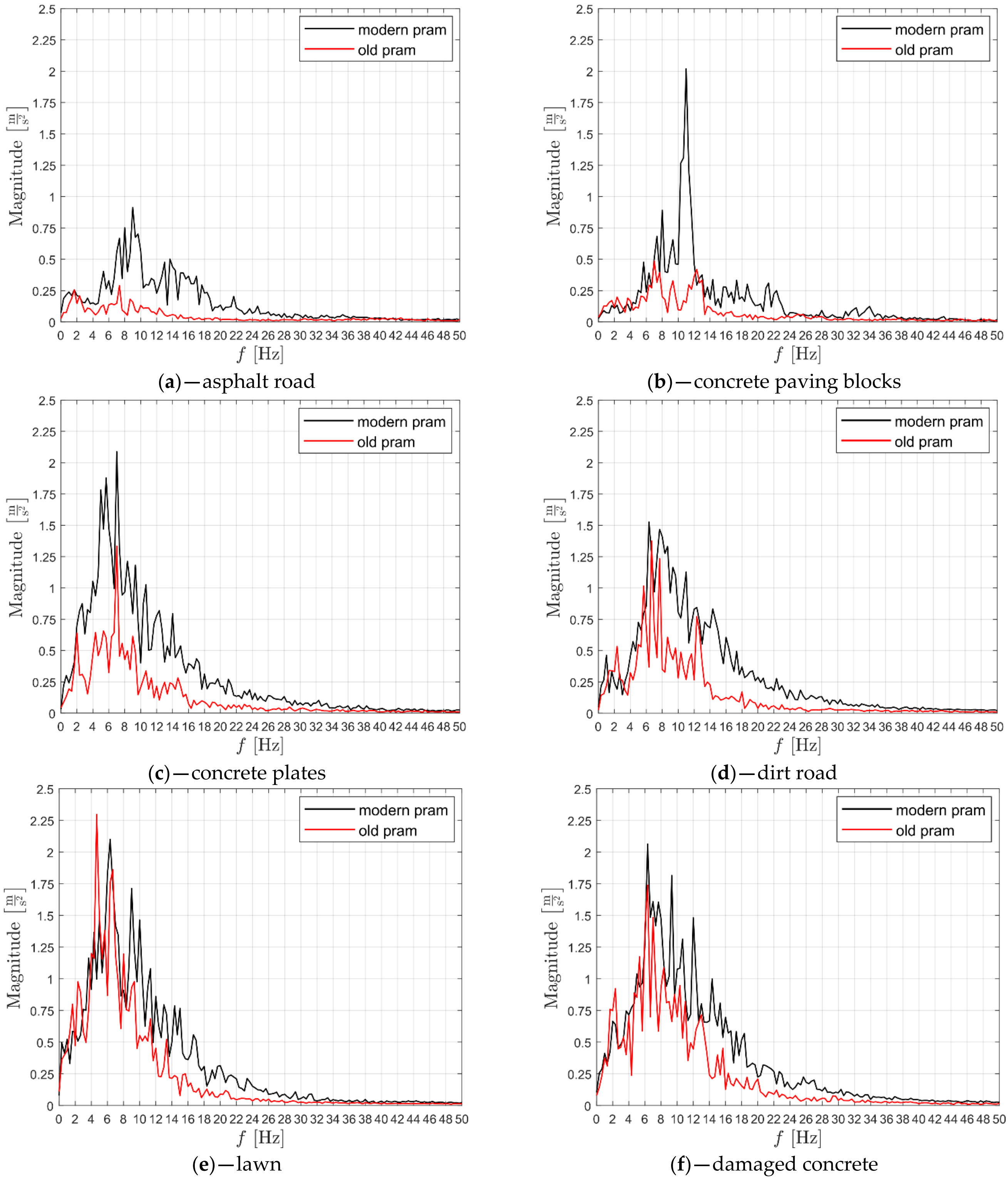


Figure 5. Amplitude-frequency spectra of vibrations of the test object within the frequency range $\langle 0, 50\ \text{Hz}\rangle$ when stimulated by all six considered types of surfaces.

The obtained frequency-domain characteristics show significantly lower vibration magnitudes above 8 Hz for the old pram in relation to the new pram. At the frequencies below 8Hz, the magnitudes for the old perambulator are usually lower as well.

In the case of children of different ages, the values of resonance frequencies are not precisely defined; they were estimated by Więckowski based on proportions of their body length [32]. A diagram based on this numerical data was created (Figure 6).

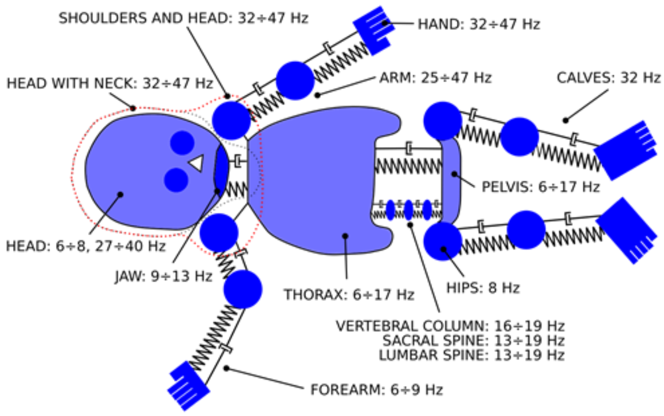


Figure 6. Examples of ranges of the natural frequencies of a child's body parts vibrations on the basis of data from [32].

Although for both perambulators, vibrations were observed in a part of the ranges of the natural frequencies of a child's body parts, the significantly higher magnitudes for the modern pram, especially on the relatively smooth surfaces like asphalt road and concrete paving blocks, can have a negative impact on, e.g., a child's thorax [32].

It should be also noted that determining the natural frequencies of children's organs is even more complicated because they grow unevenly and their mass changes almost daily. However, it can be assumed that, as in the case of the skeleton system, they will be higher than in the case of an adult. This would indicate that the harmful frequencies fall within the range of up to 200 Hz.

Local vibrations originate in direct contact between body parts and an oscillating system. They may cause a vibroacoustic disease, but this is a long-term process (3–5 years), and in the case of children, it shall not be applicable [33].

Local vibrations may also pose a hazard in the event of short-term exposure; they cause stress reactions when stimulating the vegetative system. Subjective reactions are most difficult to determine (and for children, it is virtually impossible to determine the real subjective reaction). The vibrations having the strongest impact are within the range of 2–20 Hz. The resonance frequency affecting the organs of the abdominal cavity in an upright position and with relaxed muscles equals 3 Hz. Abdominal and chest pains may appear in the range of 5–10 Hz. Reactions from the musculoskeletal system occur in the range of 10–20 Hz [33]. As in the case of skeletal system, these values should be expected to be higher (by about 50%). Table 3 presents exemplary adult human resonance frequencies and subjective reactions to them. As can be seen, noticeable amplitudes occurred in the tested prams at practically all of the frequencies from Table 1.

Table 3. Examples of ranges of the resonance frequencies for subjective human reactions [33].

Symptoms from Organs and Other Parts of the Human Body Subject to Vibration	Frequency Ranges Considered to Be Disruptive [Hz]	Frequency Ranges Where Reactions Are Very Intense [Hz]
General wellbeing	1 ÷ 20	4.5 ÷ 9
Dizziness	9 ÷ 20	13 ÷ 20
Strong jaw vibrations	6 ÷ 8	-
Apnoea	-	1 ÷ 3
Breathing disorders	4 ÷ 8	-
Stomach ache	4 ÷ 14	4.5 ÷ 10
Strong increase of muscle tone	10 ÷ 20	13 ÷ 20
Chest pain	4 ÷ 11	5 ÷ 7
Lumbo-sacral pain	6.5 ÷ 20	8 ÷ 12
Urinary urgency	9 ÷ 20	10 ÷ 18
Faecal urgency	9 ÷ 20	10.5 ÷ 16

3.3. Normative Evaluation

Figure 7 shows examples of the vibration of the research subject in the time domain before and after normative frequency-weighting for comfort evaluation. A significant magnitude reduction can be observed for y and z (horizontal) directional components.

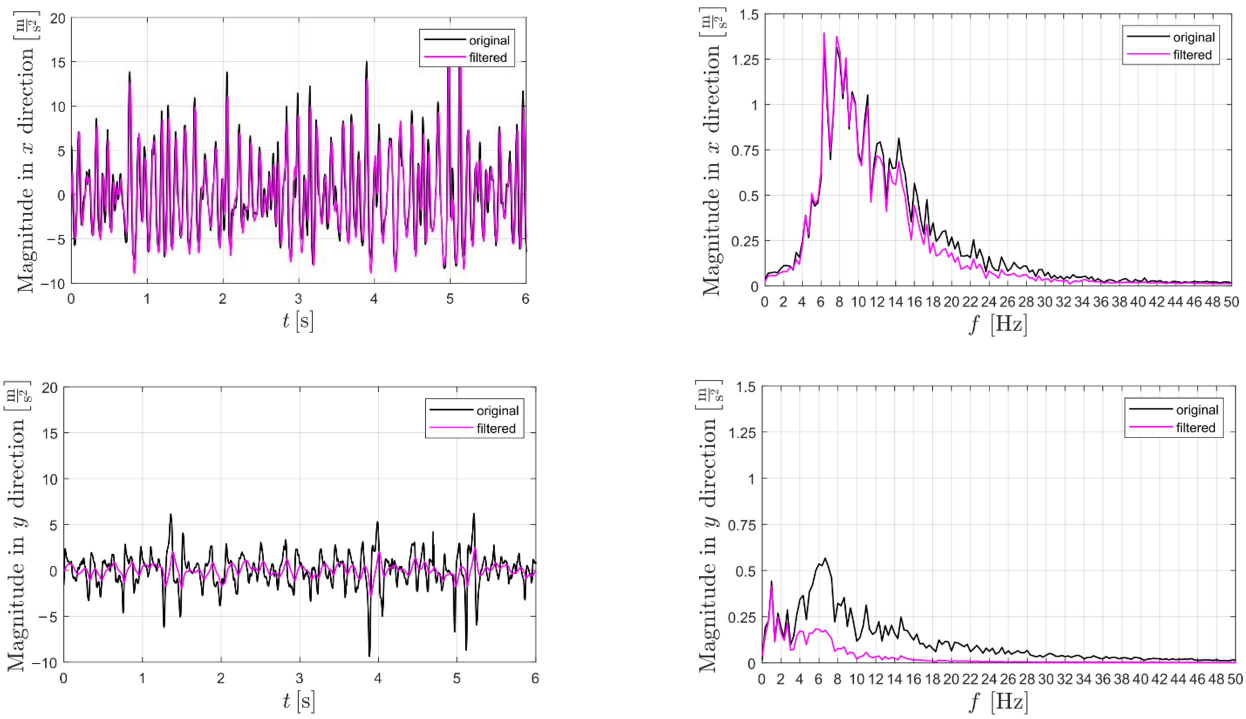


Figure 7. *Cont.*

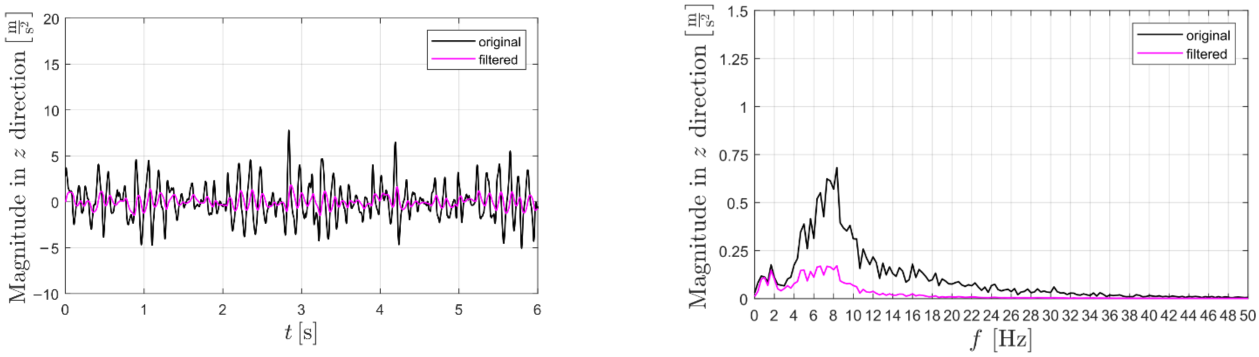


Figure 7. Comparison of vibration acceleration orthogonal components for dirt road (Figure 2d) between original (black) and frequency-weighted (purple) in both time and frequency domains.

The frequency-weighted RMS acceleration values, calculated according to the aforementioned ISO methodology, are shown in Table 4 and Figure 8.

Table 4. Weighted RMS acceleration values (calculated in accordance with ISO 2631-1:1997 [18]) applied to the weight placed in the space provided for a child in the tested perambulators.

	Modern Pram—Surface Variants						**Old Pram—Surface Variants**					
	Asphalt Road	**Concrete Paving Blocks**	**Concrete Plates**	**dirt Road**	**Lawn**	**Damaged Concrete**	**Asphalt Road**	**Concrete Paving Blocks**	**Concrete Plates**	**dirt Road**	**Lawn**	**Damaged Concrete**
a_{wx} $\left[\frac{m}{s^2}\right]$ **(RMS)**	1.70	2.50	4.03	3.81	4.28	4.57	0.44	0.90	2.08	2.23	3.41	3.26
a_{wy} $\left[\frac{m}{s^2}\right]$ **(RMS)**	0.36	0.22	0.81	0.72	1.08	1.09	0.23	0.20	0.51	0.53	0.85	0.97
a_{wz} $\left[\frac{m}{s^2}\right]$ **(RMS)**	0.26	0.27	1.00	0.50	0.80	0.58	0.21	0.20	0.45	0.33	0.77	0.60
a_w $\left[\frac{m}{s^2}\right]$ **(RMS)**	1.76	2.53	4.23	3.91	4.49	4.74	0.54	0.94	2.19	2.31	3.60	3.45

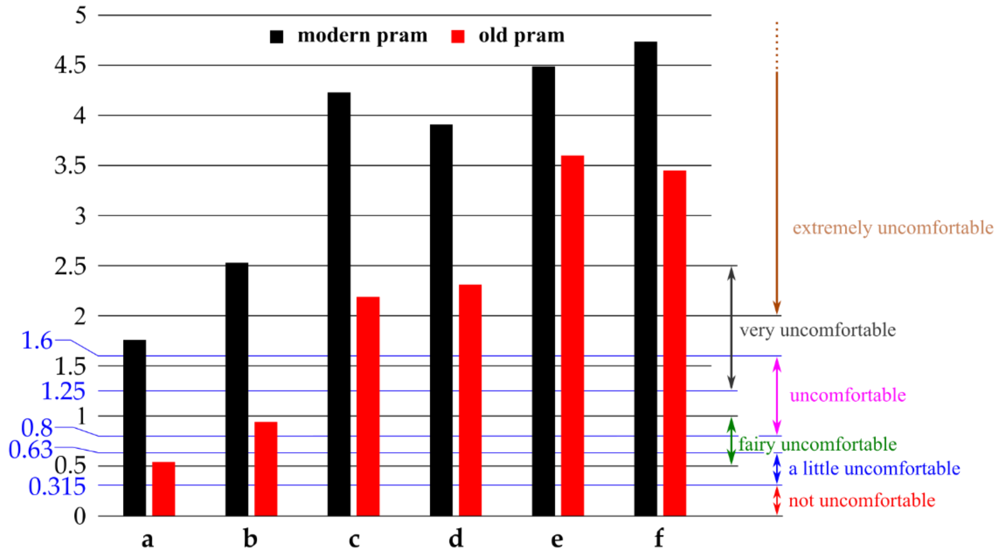


Figure 8. Comparative bar graphs of the weighted RMS acceleration values from ISO 2631-1:1997 [18].

According to the discomfort levels from ISO 2631-1:1997 [18] (Figure 8), all the vibrations whose vibration total values (a_w) exceed 0.315 m/s^2 are not comfortable. Thus, in agreement with the normative assessment, riding in each of the perambulators at a speed of 4 km/h would not be comfortable. However, on the smoothest surface, the asphalt road (Figure 2a), after changing from the modern pram to the old pram, the discomfort level decreases from "very uncomfortable" to between "a little uncomfortable" and "fairy uncomfortable". On the concrete paving blocks (b), the discomfort level for the modern perambulator was already "extremely uncomfortable" while for the old perambulator only between "fairly uncomfortable" and "uncomfortable". On more uneven surface combinations, concrete plates (c) and the dirt road (d), the discomfort level for the old pram was between "very uncomfortable" and "extremely uncomfortable". On the most uneven surface combination, lawn (e) and damaged concrete (f), the discomfort level for both perambulators was "extremely uncomfortable".

4. Conclusions

The obtained RMS acceleration values, although decreased slightly by the weighted acceleration curves, indicate discomfort and health hazard in accordance with the actual standard [19], especially for the modern "3 in 1" lightweight perambulator (modern pram). The smoothest surface (asphalt road) raises the least doubts in this aspect.

In the opinion of the authors, the use of the lightweight perambulators equipped with small, non-pneumatic tyres (worst damping), or without a suspension system, should be avoided on less smooth surfaces because it can have a negative impact on infants' health. This opinion was confirmed by the obtained results for the modern pram showing noticeable vibrations in a part of the ranges of the natural frequencies of child's body parts (Figure 6) for all the surfaces on which the research was conducted (Figure 2).

According to the above conclusion, compact perambulators with relatively small wheels and without suspension system should be used with very high caution as ordinary outdoor baby carriages. This type of baby carriage is destined primarily for very smooth pavements and indoor use.

The conducted research showed the need of standards (in the EU) and guidelines regarding exposure to vibrations by children. Standards available are for adults only (including ISO 2631-1:1997). The need for such standards is also indicated by the authors of the publications on the medical transport of new-borns, indicating the relationship between the presence of too-strong vibrations in transport and the risk of brain injury as well as other alarming symptoms [8–12]. Moreover, the currently functioning standard for the safety of prams [30] does not refer in any way to the exposure of a child to vibrations. In the opinion of the authors, this standard should be enriched with an appropriate procedure for testing mechanical oscillations in terms of their harmfulness to the child.

The tests were performed at the typical walking speed of humans. However, an impact of pushing a perambulator on this average walking speed was not taken into account, and only a constant walking speed case was considered. However, the assumed speed can be considered a probable value which is conducive to unfavorable vibrations and for that reason, it is reasonable from the point of view of the conducted research. In the future, work an average walking speed profiles and speed variations when pushing a perambulator can be considered.

Further research is planned with reference to various pram and stroller constructions as well as urban pavements as such and the comfort they provide. Thanks to the obtained results, a universal mathematical model and a calculation tool to predict the performance of a perambulator based on its features could be derived. Such a tool could help in selecting the most appropriate baby carriage, developing the currently missing standards and designing safer perambulators and strollers as well.

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References

1. Kamio, C.; Aihara, T. Dynamic simulation of baby carriage under running condition: Analyzing vibration when passing over a level difference. *Mech. Eng. Lett.* **2020**, *6*, 19-00376. [CrossRef]
2. Ryan, D.M. Characterization of Whole Body Vibration Exposures in Neonatal Ground Transport. Ph.D. Thesis, University of Washington, Washington, DC, USA, 2018.
3. Okajima, H.; Ota, S.; Ota, R. Dynamic Characteristics of Infants Riding on Stroller. In Proceedings of the ASME 2020 International Mechanical Engineering Congress and Exposition, Online, 16–19 November 2020.
4. Lim, K.S. A Study of Infant Comfort Level in a Baby Stroller. Bachelor's Thesis, Tunku Abdul Rahman University College, Kuala Lumpur, Malaysia, 2018.
5. Dupuis, H.; Zerlett, G. *The Effects of Whole-Body Vibration*; Springer: Berlin/Heidelberg, Germany, 1986.
6. Griffin, M.J. *Handbook of Human Vibration*; Elsevier: Amsterdam, The Netherlands, 1990.
7. Giacomin, J.; Gallo, S. In-vehicle vibration study of child safety seats. *Ergonomics* **2003**, *46*, 1500–1512. [CrossRef] [PubMed]
8. Browning, J.; Walding, D.; Klasen, J.; David, Y. Vibration issues of neonatal incubators during in-hospital transport. *J. Clin. Eng.* **2008**, *33*, 74–77. [CrossRef]
9. Grosek, S.; Mlakar, G.; Vidmar, I.; Ihan, A.; Primozic, J. Heart rate and leukocytes after air and ground transportation in artificially ventilated neonates: A prospective observational study. *Intensive Care Med.* **2009**, *35*, 161–165. [CrossRef] [PubMed]
10. Harrison, C.; McKechnie, L. How comfortable is neonatal transport? *Acta Paediatr.* **2011**, *101*, 143–147. [CrossRef]
11. Joyce, T.; Huecker, M.R. Pediatric Abusive Head Trauma. In *StatPearls [Internet]*; StatPearls Publishing: Treasure Island, FL, USA, 2020.
12. Goswami, I.; Redpath, S.; Langlois, R.G.; Green, J.R.; Lee, K.S.; Whyte, H.E. A Whole-body vibration in neonatal transport: A review of current knowledge and future research challenges. *Early Hum. Dev.* **2020**, *146*, 105051. [CrossRef]
13. Rahmatalla, S.; Kinsler, R.; Qiao, G.; DeShaw, J.; Mayer, A. Effect of gender, stature, and body mass on immobilized supine human response during en route care transport. *J. Low Freq. Noise Vibr. Active Control* **2021**, *40*, 3–17. [CrossRef]
14. Rahmatalla, S.; DeShaw, J.; Barazanji, K. Biodynamics of supine humans and interaction with transport systems during vibration and shocks. *J. Low Freq. Noise Vibr. Active Control* **2019**, *38*, 808–816. [CrossRef]
15. DeShaw, J.; Rahmatalla, S. Predictive discomfort of supine humans in whole-body vibration and shock environments. *Ergonomics* **2016**, *59*, 568–581. [CrossRef] [PubMed]
16. Griffin, M.J. Discomfort from feeling vehicle vibration. In *Vehicle System Dynamics*; Human Factors Research Unit, Institute of Sound and Vibration Research, University of Southampton: Southampton, UK, 2007.
17. Griffin, M.J.; Lewis, C.H. A comparison of evaluations and assessment obtained using alternative standards for predicting the hazards of whole-body vibrations and repeated shocks. *J. Sound Vib.* **1998**, *215*, 915–926. [CrossRef]
18. International Organization for Standardization. *Evaluation of Human Exposure to Whole-Body Vibration—Part 1: General Requirements, ISO 2631-1:1985*; ISO: Geneva, Switzerland, 1985.
19. International Organization for Standardization. *Mechanical Vibration and Shock—Evaluation of Human Exposure to Whole-Body Vibration—Part 1: General Requirements, ISO 2631-1:1997*; ISO: Geneva, Switzerland, 1997.
20. BSI Group. *Guide to Measurement and Evaluation of Human Exposure to Whole-Body Mechanical Vibration and Repeated Shock, BS 6841:1987*; BSI: London, UK, 1987.
21. Hełbin, J. Wybrane problemy higieny i ekologii człowieka. In *Środowiskowe Czynniki Fizyczne Wpływające na Organizm Człowieka*; Kolarzyk, E., Ed.; Wydawnictwo Uniwersytetu Jagiellońskiego: Kraków, Poland, 2008.
22. *Drgania Mechaniczne. Pomiar i Wyznaczanie Ekspozycji Człowieka na Drgania Przenoszone Przez Kończyny Górne. Część 1: Wymagania ogólne, PN-EN ISO 5349-1:2004*; 2004. Available online: https://sklep.pkn.pl/pn-en-iso-5349-1-2004p.html (accessed on 21 August 2021).
23. *Drgania Mechaniczne—Pomiar i Wyznaczanie Ekspozycji Człowieka na Drgania Przenoszone Przez Kończyny Górne—Część 2: Praktyczne Wytyczne do Wykonywania Pomiarów na Stanowisku Pracy, PN-EN ISO 5349-2:2004*; 2004. Available online: https://sklep.pkn.pl/pn-en-iso-5349-2-2004p.html (accessed on 21 August 2021).

24. *Drgania Mechaniczne—Pomiar i Obliczanie Zawodowej Ekspozycji na Drgania o Ogólnym Działaniu na Organizm Człowieka dla Potrzeb Ochrony Zdrowia—Wytyczne Praktyczne, PN-EN 14253+A1:2011*; 2011. Available online: https://sklep.pkn.pl/pn-en-14253-a1-2011p.html (accessed on 21 August 2021).
25. Kowalski, P. Pomiar i ocena drgań mechanicznych w środowisku pracy według nowych przepisów prawnych. *Bezpieczeństwo Pr. Nauka Prakt.* **2006**, *9*, 24–26.
26. Lyons, R.G. *Understanding Digital Signal Processing*, 3rd ed.; Pearson Education: New York, NY, USA, 2011.
27. Giacomin, J. Some observations regarding the vibrational environment in child safety seats. *Appl. Ergon.* **2000**, *31*, 207–215. [CrossRef]
28. Sehat, A.R.; Nirmal, U.; Jin, Z. State of the art baby strollers: Design review and the innovations of an ergonomic baby stroller. *Cogent Eng.* **2017**, *4*, 1333273. [CrossRef]
29. Koh, B.X.; Nirmal, U.; Yuhazri, M.Y. Developments on Baby Strollers over the Last Decade. *Curr. J. Appl. Sci. Technol.* **2019**, *33*, 1–25. [CrossRef]
30. *Artykuły dla Dzieci—Wózki Dziecięce—Część 1: Wózki Spacerowe i Wózki Głębokie, PN-EN 1888-1:2019-02*; 2019; Available online: https://sklep.pkn.pl/catalogsearch/result/?q=1888 (accessed on 21 August 2021).
31. Murtagh, E.M.; Mair, J.L.; Aguiar, E.; Tudor-Locke, C.; Murphy, M.H. Outdoor Walking Speeds of Apparently Healthy Adults: A Systematic Review and Meta-analysis. *Sports Med.* **2020**, *51*, 125–141. [CrossRef] [PubMed]
32. Więckowski, D. An attempt to estimate natural frequencies of parts of the child's body. *Arch. Automot. Eng.* **2012**, *55*, 61–74.
33. Jurczak, M.E. *Wpływ Wibracji na Ustrój Człowieka*; Państwowy Zakład Wydawnictw Lekarskich: Warszawa, Poland, 1974.