[Environmental Health and Preventive Medicine 8, 82–89, July 2003]

Original Article

Relationship between Questionnaire Survey Results of Vibration Complaints of Wheelchair Users and Vibration Transmissibility of Manual Wheelchair

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Abstract

Objective: Clarify the relation between the complaints of wheelchair users and the vibration characteristics of the wheelchair, to improve wheelchair comfort and design.

Methods: The questionnaires were distributed to 33 wheelchair users directly by the experimenter in order to identify the causes of complaints from wheelchair vibrations that they experienced. The vibration transmissibility of wheelchairs of ten subjects was measured to clarify the causes of complaints of wheelchair vibration according to the ISO 10326-1 standard in the laboratory using a broadband random vibration spectrum with a frequency-weighted vibration magnitude of 0.1 ms^{-2} r.m.s. over the frequency range from 0.2 to 100 Hz. Each vibration exposure lasted 60 seconds.

Results: The following findings were clear from the questionnaire results; (i) the vibration from the wheelchair affected psychological comfort; (ii) the effects of different riding surfaces were important engineering issues affecting wheelchair ride comfort; (iii) the wheelchair users felt the vibration during wheelchair usage at locations on the neck, lower back and buttocks; (iv) vertical vibration was the most noticeable vibration from the wheelchair to each participant's body. The following findings were clear from the results of the transmissibility measurement of the wheelchair; (i) the resonance frequency-ranges of the transmissibility of the wheelchair showed significant differences between the subjects; (ii) intra-subject variability from three repeated transmissibility measurements was small; (iii) the first resonant frequency occurred approximately 5 to 7 Hz and the second resonant frequency occurred at around 8 Hz and the third resonant frequency occurred approximately 13 to 15 Hz; (iv) the magnitude of the peak transmissibility varied from 1.3 to 2.6.

Conclusion: From the comparison of the results of questionnaires and the transmissibility measurement of the wheelchair, the resonance frequency-ranges of the maximum vibration transmissibility of the manual wheelchairs were consistent with the frequency-ranges of the body parts of the causes of the complaints of wheelchair users. In addition, from these experimental results, it was suggested that the main point for improving a wheelchair user's comfort was to reduce the wheelchair seat vibration transmissibility at around 8 Hz and also to design wheelchair stiffness and damping characteristics to minimize vibration transmission at specific frequencies at body locations that caused the discomfort reported by wheelchair users.

Key words: wheelchair, vibration, transmissibility, discomfort, ride comfort

1. Introduction

The population aged 65 years old or older was greater than 22.27 million people, accounting for 17.2% of the Japanese population, in 2000. According to population estimates for the future, the aging rate will be about 27% to reach the world highest level (1). Furthermore, the number of elderly to be cared for is expected to increase throughout the Japan, from 2.8 million (2000) to 3.9 million (2010) (Ministry of Health and Welfare of Japan (1)). Therefore, the creation of a Japanese society in which senior citizens can live comfortably has become increasingly important.

Received Jul. 5 2002/Accepted Mar. 29 2003
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In this aged society, the number of people who will have difficulty in walking and driving will increase. The inevitable reduction in physical and mental ability associated with aging will make travel inconvenient or, in some cases, impossible. At present, senior citizens with such mobility-handicaps are unable to go outside without difficulty, and eventually become bedridden. Currently, wheelchairs are one of the most commonly used devices that aid the mobility of senior citizens and handicapped people. However, as the availability and condition of wheelchair facilities have not improved, for example, most roads are narrow and rough, using wheelchairs is laborious work for senior citizens and handicapped people. In this situation, the wheelchair user assesses the ride comfort based on the presence of discomfort. Ride vibration, postural support, pressure distribution, ergonomics, and material breath ability are important parameters that affect the user's assessment of comfort. These parameters produce physiological changes in the user's body including circulation and nerve occlusion, ischemia, heat buildup, and visual and auditory interference. These changes result in short term human experiences of discomfort such as pain, annoyance, and displeasure. In addition, Viano et al. (2) found that these changes can cause long term damage and deformity such as tissue necrosis, nerve damage, and spinal deformity. Therefore, it is important to clarify the relation between the causes of the vibration complaints of the wheelchair users and the vibration transmissibility characteristics of the wheelchair.

There have been few studies in the field of wheelchair ride comfort. Matsuoka (3), Terauchi et al. (4), Sekiguchi et al. (5) studied the relations between vibration characteristics and the subjective evaluation of wheelchair users. They found that the main cause of complaints of wheelchair users was the vertical vibration of wheelchairs. However, they did not find the location of areas of complaints caused by wheelchair usage. In addition, their results could not be applied to design wheelchair stiffness and damping characteristics to minimize vibration transmission from the wheelchair seat to the wheelchair user's body and did not clarify the relation between the vibration complaints of the wheelchair users and the vibration transmissibility characteristics of males/females on the wheelchair seat. To improve wheelchair ride comfort, it is important to identify the relation between the psychological characteristics (subjective) of the wheelchair users and the biomechanical characteristics (objective) of males/females in the wheelchair.

To assess the effect of variations in the parameters of the seat/person system on the dynamic performance of a seat, Corbridge et al. (6) reported that the seat transmissibility will uniquely describe the dynamic performance of the seat. The seat transmissibility defines the performance of the seat in terms of the amplification or attenuation of the vibration that is received by the seat occupant as a function of frequency. In addition, the amplification of the seat transmissibility depends on the discomfort of vehicle environment.

Therefore, in this study, to understand the complaints about vibrations sustained by active wheelchair users for improving comfort via wheelchair design, questionnaires were distributed to wheelchair users directly by the experimenter to identify the causes of complaints from wheelchair vibrations that they experienced. The vibration transmissibility of the wheelchair was measured to identify the relation between the vibration transfer frequency of the wheelchair on the seat to the person's body, and the vibration frequency of the body location areas of complaints caused by wheelchair usage.

2. Methods

2.1 Questionnaire survey

2.1.1 Aims

There was no previous evidence of body location areas of discomfort caused by wheelchair usage. The aim of the questionnaire survey was to clarify the body locations of complaints from wheelchair vibrations.

2.1.2 Questionnaire

The questionnaire used in this study is shown in the Appendix. The questionnaire used in this study consisted of four sections. Section 1 refers to the physiological characteristics of wheelchair users. Section 2 histories the wheelchair usage and wheelchair type. Section 3 concerns the physiological and psychological conditions. Section 4 consists in other questions. As shown in the Appendix, each of the 33 participants provided a personal description (height, weight, gender, age, disability type, functional abilities, years of using experience) and wheelchair specifications (manual or powered, make, model, age, wheel types and sizes). The type and body positions of complaints from vibrations were recorded. The using situation was characterized in terms of riding surface (rough or smooth).

2.1.3 Method of questionnaire survey

A questionnaire survey was conducted at a rehabilitation center in Osaka City to obtain the degree of complaints concerning vibration due to the wheelchair ride. The 33 wheelchair users who were using their wheelchair everyday were chosen as participants of this questionnaire investigation. The questionnaire survey was conducted through interviews in which basic data from the interviewees and their opinions about human vibration due to the wheelchair ride were obtained. Each interviewee was asked to respond to each of the questions.

2.2 Measurement equipment and method of transmissibility of wheelchair

The seat transmissibility defines the performance of the seat in terms of the amplification or attenuation of the vibration that is received by the seat occupant as a function of frequency. The amplification of the vibration on the seat is an important source of discomfort in the vehicle environment (Corbridge et al. (6)). Therefore, in this study, it was necessary to clarify the seat transmissibility of the wheelchair between the seat surface and the human body.

2.2.1 Equipment and method

During usage of the wheelchair, in order to reduce the discomfort or complaints from the wheelchair users, it is important to clarify the mechanism of transmitted vertical vibration from the wheelchair to the human body. The experiments were conducted on a vertical electro-dynamic vibrator system as shown

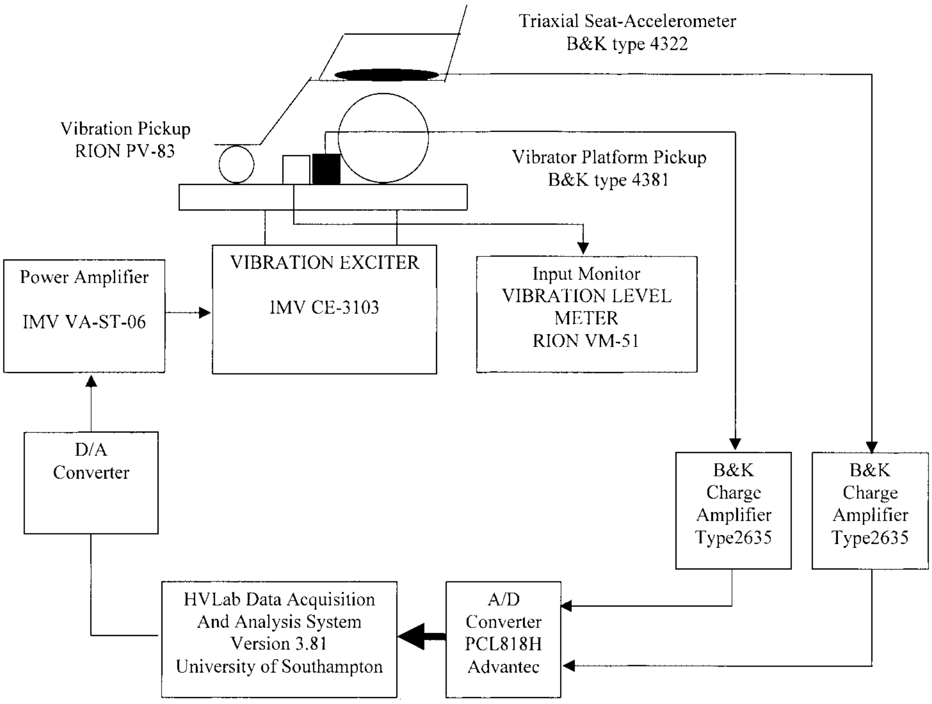

Fig. 1 Wheelchair transmissibility measurement apparatus.

Table 1 Characteristics of subjects taking part in the transmissibility measurement experiment

Subject	Height (m)	Weight (kg)	Age (years)
1	1.65	55	21
2	1.8	66.2	22
3	1.61	62.7	20
4	1.76	65	22
5	1.76	73.5	22
6	1.7	69.7	22
7	1.76	57.6	21
8	1.74	62.1	21
9	1.65	56.4	20
10	1.7	60.6	21
Mean	1.71	62.9	21.2
SD	0.06	5.9	0.8

in Figure 1. The vibrator was capable of producing displacement of up to 0.04 meters and was designed to reproduce motions that are suitable and safe for the study of human responses to vibration. One typical care-type foldaway wheelchair was studied. This wheelchair is used by 70 percent of wheelchair users in Japan (Matsuoka (3)). The wheelchair was located on the vibrator platform as shown in Figure 1. Ten male subjects took part in the study (Table 1). Griffin and Whitham (7) found that there were no correlations between transmissibility and age. Therefore, in this experiment, healthy students were used in the transmissibility experiment as subjects.

Prior to being exposed to the vibration, the subjects completed a questionnaire listing the medical contraindications specified in ISO 13090-1 (8). The subjects were given verbal instructions to maintain a forward facing posture with their hands in the arm of the wheelchair and their back in contact with the wheelchair seat backrest. There were three vibration exposures per subject. The room temperature during the experiment was about 25°C with a relative humidity about 50%.

Acceleration was measured on the vibrator platform and on the wheelchair seat using a semi-rigid mounting disc containing a vertically oriented accelerometer (ISO 10326-1 (9)). The computer-based data acquisition and analysis system, *HVLab*, generated and acquired the signals and analyzed the data. (This portable computer system was developed at the Institute of Sound and Vibration Research, University of Southampton, for acquiring and analyzing time-varying signals.) The waveform was sampled at 500 samples per second and low-pass filtered at 100 Hz before being fed to the vibrator. Signals from two accelerometers (one on the vibrator platform and one on the wheelchair seat) were passed through signal conditioning amplifiers and then low-pass filtered at 100 Hz via anti-aliasing filters with elliptic characteristics; the attenuation rate was 70 dB/octave in the first octave (Techfilter). These signals were digitized into the *HVLab* data acquisition system at a sampling rate of 500 samples per second using a PCL818H board. The duration of each vibration exposure was 60 seconds.

In the real wheelchair propulsion situation, the random vibration with broadband spectrum was reported by DiGiovine et al. (10) and Sekiguchi et al. (5). In addition, the ISO 10326-1 standard defines the simulated input vibration test. This test considers the random vibration with a broadband spectrum. Therefore, in this experiment, a computer-generated Gaussian random waveform having a nominally flat acceleration spectrum from 0.2 to 100 Hz was used with the frequency-weighted acceleration magnitudes of 0.1 ms^{-2} r.m.s. [80 dB: ref=10^{-5} ms^{-2}] (using weighting Wg as specified in Japan Industrial Standard JIS C 1510 (11).

Prior to the transmissibility measurement being performed, the vibration magnitude was measured using the same equipment as shown in Figure 1. The subjects sat in the wheelchair and were asked to answer when they could feel "discomfort" due to vibration in the wheelchair seat. The signals from the accelerometers were acquired into a commercial computer-based data acquisition and analysis system, *HVLab*. The mean magnitude was 0.1 ms^{-2} r.m.s. Therefore, in this experiment, this value chose the vibration magnitude to measure the vibration transmissibility of the wheelchair seat to the person.

2.2.2 Analysis

The transfer functions were calculated between acceleration on the vibration platform (i.e. the input) and acceleration measured on the wheelchair seat surface (i.e. the output) using the 'cross-spectral density function method'. The transfer function, Hc(f), of the wheelchair was determined as the ratio of the cross-spectral density of the input and output accelerations, Gio(f), to the power spectral density of the input acceleration, Gii(f):

$$Hc(f)=Gio(f)/Gii(f)$$

Frequency analysis was carried out with a resolution of 0.195 Hz and 48 degrees of freedom (Griffin (12)).

3. Results

3.1 Results of questionnaire survey

The distribution of participants' disability types is shown in Table 2. Almost all participants had these diseases after birth. As shown in Table 2, 28 participant's diseases consisted of Cerebral palsy (20 participants), Progressive muscular dystrophy (5 participants) and Cerebrovascular disease (3 participants). Thirty-three subjects, 23 males and 10 females, took part in the study (Table 3).

Eighteen participants had used a wheelchair for more than 10 years. Twenty-five participants were using a normal wheelchair and thirteen participants were using an electric wheelchair. Twenty-seven participants were using wheelchairs 7 days per week. Thirty participants were using a wheelchair more than 8 hours per day. In addition, 32 participants felt discomfort during a wheelchair ride in outside use. Thirty-one wheelchair users had the complaints from wheelchair vibration from tiled walkways, gravel walkways and walking blocks. The participants had complaints about transmitted vibrations from the wheelchair ride at their neck and head, lower back and buttocks as shown in Figure 2. The most affected location was the neck.

The vertical vibration was most common vibration from the wheelchair to the participants as shown in Figure 3.

Table 2 Participants' disability types

Characteristics of disabilities	Number of Participants
Cerebral palsy (CP)	20
Pseudohypertrophic Muscular Dystrophy: Duchenne type (PMD)	5
Cerebrovascular accident (CVA)	3
Post-Polio Syndrome	1
Spinal Cord injury (SCI)	1
Werdnig-Hoffmann disease	1
Tay-Sachs disease	1
Other	1
Totals	33

Table 3 Characteristics of 33 subjects taking part in the experiment

	Age (years)	Weight (kg)	Height (m)
Minimum	7	20	1
Maximum	65	80	1.7
Mean	28.2	47	1.49
Standard deviation	15.7	15	16.7

3.2 Results of vibration transmissibility of wheelchairs

Laboratory studies were conducted to investigate the effects of the subjects' physical characteristics on the transmissibility of vibration through the wheelchair seat. The transmissibility of a wheelchair seat was measured in response to random vibration with a magnitude of 0.1 ms^{-2} r.m.s. when the wheelchair seat was occupied by each of 10 subjects. Transmissibility was measured with subjects seated in the 'normal' upright posture. This 'normal' upright posture was when the subjects were seated on the wheelchair seat and were required to place their lower arms and hands on the armrests and leaning on the wheelchair seat back without muscle strain. Figure 4 shows the transmissibility obtained when the wheelchair seat was occupied by

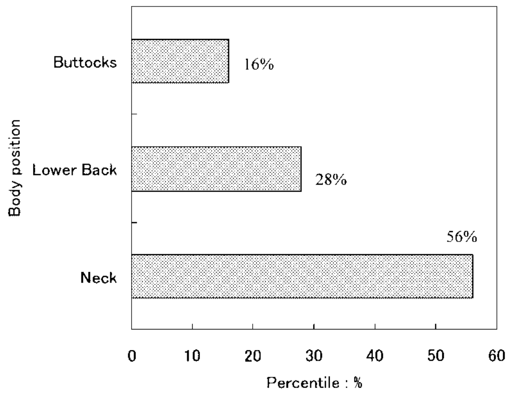

Fig. 2 Relation between discomfort percentile and body position. (Number of answered subjects: Buttocks: 7; Lower Back: 12; Neck: 23)

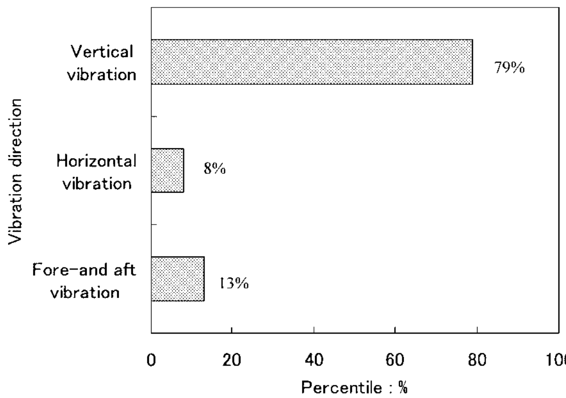

Fig. 3 Relation between discomfort percentile and vibration direction.
(Number of answered subjects: Vertical vibration: 30; Horizontal vibration: 3; Fore-and-Aft vibration: 5)

a single subject. A subject was exposed to the same vibration three times.

Figure 4 shows an example of the variability within a subject (i.e. intra-subject variability). The small differences between the three measurements of the transmissibility occurred in no systematic order and can be explained by intra-subject variability. Transmissibility curves for all ten subjects obtained with vertical random seat vibration are shown in Figure 5. Each subject was exposed to the same vibration three times to obtain an indication of repeatability. Transmissibility in the z-axis shows large inter-subject variability at all frequencies. This variability depended on the body characteristics of the subjects as shown in Table 1.

The first resonant frequency occurred at approximately 5 to 7 Hz and the second resonant frequency occurred at approximately 8 Hz and the third resonant frequency occurred at approximately 13 to 15 Hz. The magnitude of the peak transmissibility at the second resonant frequency varied from 1.3 to 2.6. Figure 6 shows the mean transmissibility from the wheelchair seat to the person.

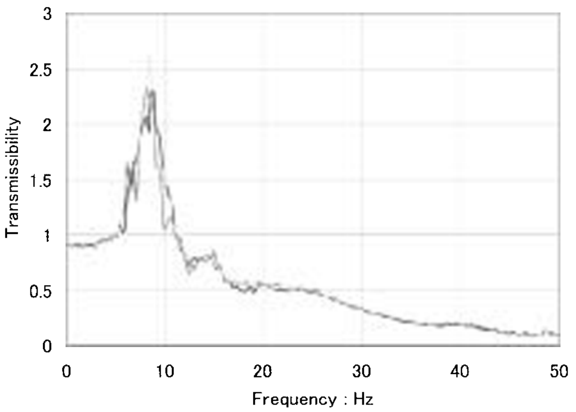

Fig. 4 Example of variability within one subject.

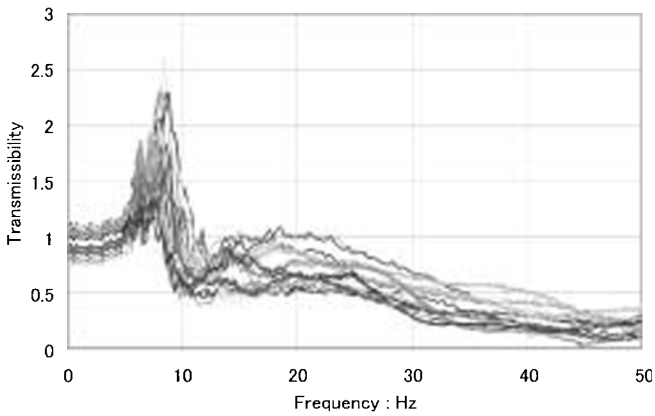

Fig. 5 Transmissibility of inter-subject variability.

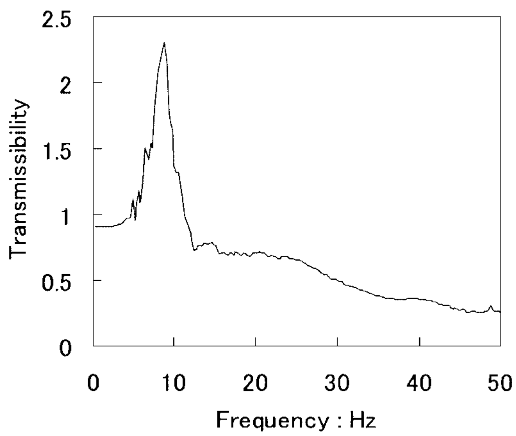

Fig. 6 Mean transmissibility from the wheelchair seat to the person.

4. Discussion

From the questionnaire survey about the body locations of complaints of wheelchair vibrations that the wheelchair users experienced, it was clear that they had complaints about transmitted vibrations from the wheelchair ride at their neck, lower back and buttocks. Whitham and Griffin (13) studied the effects of vibration frequency and direction on the location of areas of discomfort caused by whole-body vibration. They found that the locations of the areas of body discomfort produced by vertical vibration and the maximum sensitivity to vertical vibration acceleration was in the range 4 to 16 Hz with discomfort experienced in the upper torso and head. They also found that there was an obvious difference in the location of maximum discomfort at different frequencies. The largest response was found in the lower abdomen and lower back at 2 Hz moving up the body at 4 and 8 Hz with most responses at the head at 16 Hz. At 32 Hz the responses were divided between the head and lower abdomen while at 64 Hz they are mostly located near the principal vibration input at the ischial tuberosities. Kitazaki and Griffin (14) studied the vibration mode shapes of the body in the mid-sagittal plane, using experimental modal analysis. Their results showed that the modes found at frequencies below 10 Hz contained bending deformation of the spine, vertical motion of the viscera, axial and shear deformation of the buttocks tissue and pelvis rotation. In addition, their results showed that the head moves up and down by compression of the buttocks at 5.06 Hz and the bending mode of the lumber spine due to either a rotation of the pelvis or buttocks compression was found at 7.51 Hz and 8.96 Hz. The head also moved at 7.51 Hz vibration due to the rotation of the pelvis. They also found that the head moves forward and backward due to bending of the spinal column at 0.28, 1.49 and 2.81 Hz. From these findings, it might be suggested that the causes of the wheelchair user's most common complaints at the neck depended on the movements of the head in due to 0.28 Hz, 1.49 Hz, 2.81 Hz, 5.06 Hz, 7.51 Hz and 8.96 Hz transfer frequencies. The complaints at lower back depended on the maximum discomfort in the lower abdomen and lower back at 2 Hz moving up the body at 4 and 8 Hz. The complaints at the buttocks depended on the responses mostly located near the principal vibration input at the ischial tuberosities at 32 Hz and 64 Hz. Although it might be assumed that the causes of the complaints of the wheelchair users at the neck, lower back and buttocks corresponded to the vibration transfer frequency from several studies about the transmissibility from the seat to the person, these vibration transfer frequencies did not result from the transmissibility measurement from the wheelchair seat to the person. In addition, it was not clear whether the wheelchair user's complaints corresponded to the transmissibility characteristics from the wheelchair seat to the person. Therefore, to clarify the relation between the transfer frequency of the causes of complaints of wheelchair users at the neck, lower back and buttocks and the transmissibility characteristics from the wheelchair seat to the person, it is necessary to measure the transmissibility from the wheelchair seat to the person. Although the causes of the complaints of the wheelchair users at the neck, lower back and buttocks corresponded to the vibration transfer frequency from several studies about the transmissibility from the seat to the person, these vibration transfer frequencies did not result from the transmissibility from the wheelchair seat to the person. In the present study, the transmissibility of the wheelchair could be obtained from the measurement of transmissibility from the wheelchair seat to the person.

From Figure 6, the transfer frequency of the main complaint at the neck from the current results of the wheelchair transmissibility corresponded to the frequency of the head movement at 0.28, 1.49, 2.81 5.06, 7.51, 8.96 Hz and lower back at about 4 to 8 Hz and buttocks at 16 Hz, and above 32 Hz. These current results of the transmissibility from the wheelchair seat to the person were consistent with the previous findings of the frequencies of the body locations of the causes of the complaints of wheelchair users by Whitham and Griffin (13) and Kitazaki and Griffin (14). The seat transmissibility defines the performance of the seat in terms of the amplification or attenuation of the vibration which is received by the seat occupant as a function of frequency. In addition, the amplification around 8 Hz of the seat transmissibility may depend on the terrain of the vehicle environment.

Therefore, it was suggested that the improvement point for improving a wheelchair user's comfort was to reduce the wheelchair seat vibration transmissibility at around 8 Hz and also to design wheelchair stiffness and damping characteristics to minimize vibration transmission at the body locations of the causes of the complaints of wheelchair users.

5. Conclusions

In this study, to understand the complaints about vibration sustained by active wheelchair users to improve comfort via wheelchair design, questionnaires were distributed to wheelchair users directly by the experimenter in order to identify the causes of complaints from wheelchair vibrations that they experienced, and the vibration transmissibility of the wheelchair was measured to identify the transfer frequency. The following were clear from the questionnaire results;

(i) the vibration from the wheelchair affected psychological comfort;
(ii) the effects of different riding surfaces were important engineering issues affecting wheelchair ride comfort;
(iii) the wheelchair users felt the vibration during wheelchair usage at locations on their neck, lower back and buttocks;
(iv) the vertical vibration was most common vibration from the wheelchair to the participant's body.

The following were clear from the results of the transmissibility measurement from the wheelchair seat to the person;

(i) the transfer frequency ranges of the transmissibility of the wheelchair showed significant differences between the subjects;
(ii) intra-subject variability from three repeated transmissibility measurements was small;
(iii) the first resonant frequency occurred at approximately 5 to 7 Hz and the second resonant frequency occurred at around 8 Hz and the third resonant frequency occurred at approximately 13 to 15 Hz;
(iv) the magnitude of the peak transmissibility varied from 1.3 to 2.6.

From the comparison of the results of the questionnaires and the transmissibility measurement of the wheelchair, it was clear that the transfer frequencies of the vibration transmissibility of the manual wheelchair were consistent with the body locations of the causes of the complaints of wheelchair users.

Therefore, it was suggested that the improvement of the wheelchair seat vibration transmissibility at around 8 Hz might be able to reduce the vibration complaints or the transmitted vibration to the wheelchair users. In addition, it was suggested that the manufacturers have to measure and to evaluate the transmissibility from the wheelchair seat to the person at the design stage for the user's comfortable wheelchair ride.

Acknowledgements

The authors acknowledge the assistance of participants in this study and undergraduate students, Mr Y Mori, Mr R Fujiyoshi and Mr T Sawada at the Human Factors Research Unit, Kinki University. Their help is greatly appreciated. In addition, the authors acknowledge Mr Renaud Itier for English language corrections.

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APPENDIX

Questionnaire about Wheelchair

Section 1: Physiological characteristics of wheelchair user

Q1: Gender:
A1-Male
A2-Female
Q2: Age (years):
Q3: Height (meters) and Weight (kg):
Q4: Please write current disease condition, characteristics of disease, position
Q5: Please write past disease condition, characteristics of disease, position

Section 2: Histories of wheelchair and types

Q6: How many years have you used the wheelchair?
Q7: Have you distinguished how to use a wheelchair inside or outside?
1: Distinguished go to Q8;
2: Not distinguished go to Q9;
Q8: What type of wheelchair do you use both inside and outside? Is your wheelchair a standard product or a made to order product? Please "O" mark in the following table.

	Inside use	Inside use	Outside use	Outside use
	Standard	Order made	Standard	Order made
Wheelchair				
Wheelchair with helper				
Electric wheelchair				

Q9: What kind of wheelchair do you use both inside and outside? Is your wheelchair a standard product or a made to order product? Please "O" mark in the following table.

	Both inside and outside	Both inside and outside
	Standard	Order made
Wheelchair		
Wheelchair with helper		
Electric wheelchair		

Section 3: Please clarify your physiological and psychological condition when you use outside.

Q11: How many days per week do you use the wheelchair outside?
Q12: How many hours per day do you use the wheelchair outside?
Q13: Do you feel discomfort due to vibrations from the wheelchair when you are riding outside?
1: Yes go to Q14;
2: No go to Q15;
Q14: Which kind of road do you experience discomfort during riding the wheelchair?
(Multiple answers acceptable)
1. Tiled walkway
2. Gravel walkway
3. Walking blocks
4. Other areas
Q15: Which body position did you feel the discomfort during riding the wheelchair? Please "O" mark to the number.
1: Head
2: Neck
3: Shoulder
4: Arm
5: Hand
6: lower back
7: Buttocks
8: Knees
9: Back of Foot
10: Whole-Body
Q16: Which direction of vibration caused the most discomfort? Please "O" mark to the number.
1: Up and down direction vibration
2: Left and right direction vibration
3: Fore and aft direction vibration
4: All vibration directions
5: Don't know
Q17: Did you have some physical problems during and after riding the wheelchair?
1: Yes go to Q18;
2: No go to Q20;

Q18: Please write the details about your problems when you had some physical problems.

What kind of problem?

Which place of your body?

How long did experience these problems?

Q19: Do your physical problems still continue?

1: Yes 2: No

Section 4: Other questions

Q20: Have you taken this kind of questionnaire before?

1: Yes go to 21;

2: No go to 24;

Q21: How many times did you complete a previous questionnaire?

Q22: Are you satisfied using your wheelchair in your current environment? Please “O” mark to only one number.

1: Extremely satisfied

2: Very satisfied

3: fairly satisfied

4: Neutral

5: fairly unsatisfied

6: Very unsatisfied

7: Extremely unsatisfied

Q23: If you marked a number between 5 to 7 in Q22, what kind of unsatisfied things do you currently feel? Please write down.

Q24: Do you make an effort to use the wheelchair comfortably both inside and outside? Please write down.

Thank you for your cooperation.