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Wheelchair User Perception of Road Roughness

Yoshinao Oeda
Tomonori Sumi
Department of Civil Engineering,Kyushu University
Hakozaki 6-10-1, Higasi-ku, Fukuoka 812-8581 Japan
E-mail: oeda@civil.doc.kyushu-u.ac.jp
Telephone and Facsimile: 81-(0) 92-642-3274

and
Upali Vandebona
School of Civil and Environmental Engineering
The University of New South Wales
Sydney 2052 Australia
E-mail: u.vandebona@unsw.edu.au
Telephone: +61 (2) 9385-5056
Facsimile: +61 (2) 9385-6139

Abstract

Wheelchair users often complain about uncomfortable vibrations as a result of road asperity. This paper proposes a method to evaluate road roughness and pavement gaps from the viewpoint of wheelchair users.

For quantification purposes, field experiments were conducted in city of Fukuoka in Japan. Several wheelchair users travelled over surfaces with known level of roughness. The perceived level of discomfort is recorded in a graded scale. The scale range is from 1 to 5. The larger number is relatively more painful. This allowed the research team to identify the function form for the relationship between the degree of vibration and the perceived degree of discomfort.

Also, in order to predict a vibration of road surface, this paper proposes a theoretical model based on the spring-mass analogy. The field results have been compared with this model. The results show a good agreement between the theoretical model results and field observations. Using the function form for the discomfort and the theoretical model is able to allow planners to estimate the vibration induced discomfort on wheelchair users using roads. This is reliable tool for new road construction authorities as well as maintenance agencies. Furthermore, the methodology is useful in understanding the root cause of complaints by users of uneven road surfaces.

1. INTRODUCTION

This study proposes a method to evaluate road roughness from the viewpoint of the level of discomfort caused to wheelchair users. Wheelchair users have often complained about the roughness when riding over certain types of block pavements. (Ministry of construction, 1996). Interlocking brick pavements and stone block pavements are typical examples causing difficulties to wheelchair users. However, these types of pavements and sidewalks are increasingly popular among traffic professionals for local area traffic management applications to improve the street outlook and neighbourhood character.

The focus of this work is to explore what textural improvements should be implemented to develop wheelchair friendly surfaces. This would enable application of block pavements to achieve the desired neighbourhood outlook and character while maintaining navigable roads for wheelchair users. For this purpose, this project investigates the relationship between the road roughness and level of discomfort experienced by wheelchair users. This involves understanding the user perception of wheelchair vibrations caused by bumpiness of surface.

The research work presented here is based on pushing wheelchair bound patients on different types of surfaces. Some experiments were conducted on laboratory surfaces whereas others were conducted on field sidewalks. These results were compared with a mathematical model as well. This mathematical model relies on the spring-mass analogy from mechanical systems.

This research work is based on a series of experiments carried out in Japan where there is a growing awareness of the needs of wheelchair users. The significance of this type of research is important in other countries including Australia and New Zealand, where the relative size of the elderly and disabled population is on the increase.

2. SURFACE CHARACTERISTICS

This paper addresses discomfort caused by three types of road surfaces. The first category causes low frequency vibrations whereas the second type causes high frequency vibrations. The third type causes isolated impulses.

The first type of surface is a textured surface consisting of small scale humps. These are generally available in the form of artificial surfaces. These are mats or carpets rolled out from industrial quality material containing regular patterns of surface imprints. The interesting aspect is that the sense of discomfort caused by these surfaces is a result of the unpleasant shaking of internal organs. This mechanism is different from the mechanism observed in the connection of other two types of surfaces.

The second type of surface is similar to brick pavements and concrete blocks. These cause discomfort through small amplitude high frequency vibrations. These are unpleasant to the certain parts of the skeleton of the wheelchair bound person. This research project focussed on the impact on the spine and lower limbs.

The third type of surface irregularity is a simple kerb that causes one off bump. This is more applicable to the Japanese road designs where the standards stipulate the need for a sharp demarcation for visually impaired. In Australia, the standards allow for a gradual slope of the kerb (Austroads, 1995). These irregularities do not cause persisting vibrations.

3. METHODOLOGY

Ideally, the effect of surface characteristics on wheelchair users should be investigated using the psychophysical approach. In such experiments, a volunteer would be subjected to a specific stimulus (such as noise or vibration) and the reported level of perception would be recorded (Guilford, 1954; Thurstone, 1927; Torgerson, 1958. This allows the researchers to investigate the perceived level of satisfaction or dissatisfaction against the change in level of stimulus. But that approach requires large-scale equipment in the current project. Also there are possible safety implications in subjecting wheelchairs and users to stay on vibrating platforms.

Therefore, this research team concluded that it is not feasible to subject the wheelchairs to specific frequencies and record the user response. Instead, the wheelchairs were pushed along different surfaces and the resulting frequency profile and the corresponding user perception are recorded.

The volunteers selected for the experiments were all adult males. They are in the age range 32 to 52 years. All five volunteers are from Fokuoka (Japan) and are members of local chapter of the Welfare Association for the Disabled. They all have spinal column injuries but have an active outdoor life without assistants.

A standard wheelchair was used for the experiments. Specifications of such wheelchairs are shown in Table 1. A diagram of the wheelchair is shown in Figure 1.

Table 1. Wheelchair specifications

	Specification
Type	NiCK-N-112p type self-driven and folding
Approx weight	12.5 kg
Material	Aluminium alloy
Wheel size (cm)	Front: 15; Rear: 55
Size (cm)	Length : 97; Width : 62; Height : 66
Armrest Height (cm)	23
Seat size (cm)	Height: 44; Width: 40; Depth: 40
Backrest Height (cm)	38

Figure 1 shows the locations of the accelerometer sensors installed for the purpose of measuring accelerations of vibrations during the experiments. These sensors are directly linked to a data recorder and a Fast Fourier Transformation (FFT) analyser by connecting cables. During the experiments, there were two helpers to manage the movement of the wheelchair. One helper is the pusher who would attempt to maintain a uniform speed. The other person is in charge of holding the connecting cables above ground when the wheel chair is in motion.

The speed of the wheel chair is measured by a photo transistor device that monitors the angular velocity of the wheel. The main wheel has been marked with a series of black adhesive tapes to enable the photo transistor to track clear markers. The black tapes were about 6 cm long and set at about 12 cm intervals.

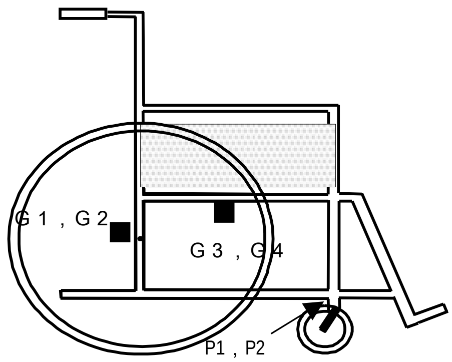


Figure 1. Wheelchair instrumentation locations

The volunteer user of the wheelchair has to report the perceived level of discomfort after each trial. This response was recorded in a five point scale where one was no discomfort and five was most discomfort. The trials would continue until the respondent reports a value of 4 or 5 on the discomfort scale.

4. IMPACT DUE TO LOW FREQUENCY GENERATING SURFACES

Test surface used for this experiment was made from acrylic boards which had regular block pattern on surface. The block pattern had a rectangular plane view and a trapezoidal cross section. This shape is shown Figure 2. There were three different cross-sectional profiles used in the experiments. The dimensions of these shapes in mm are shown Table 2.

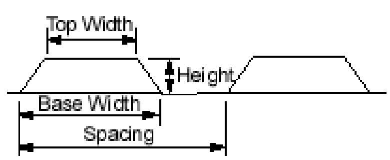


Figure 2. The cross-section of the acrylic surface

The power spectrum acceleration and frequency profile produced by the FFT analyser for one trial over shape 1 surface is shown as an example, in Figure 3. These measurements relate to the under the seat sensor of the wheel chair. Sensor locations were already shown in Figure 1.

Table 2. Dimensions of the three patterns

	Shape 1	Shape 2	Shape 3
Top width (mm)	60	30	60
Base width (mm)	90	50	90
Height (mm)	2	2	3
Spacing (mm)	150	30	60

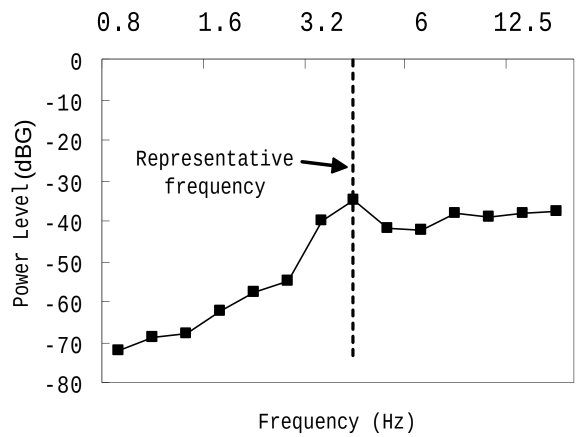


Figure 3. Example of the power spectrum acceleration and frequency profile

The frequencies shown in Figure 3 are obtained from one-third octave band of the spectrum. Here the range is from 0.8 to 12.5 Hz. The accelerations are designated by power level (dB). The datum acceleration, or 0 dB, is set to 1 g in these experiments.

For the purpose of analysis, what is important from Figure 3 is the representative frequency. This is the frequency with the highest level of power for the particular trial. It is observed that each combination of surface shape and wheelchair speed results in a unique representative frequency.

The next step is the sensitivity correction. This step is to account for the differences in sensitivity of human sensory ability at different frequencies. An elaborate experiment may be required to apply the correction in an accurate manner. This would require recording the human sensory ability at different frequencies. However, it was decided to develop a workable correction by applying theoretical properties (linear shape) of the frequency and discomfort relationship so that we do not require an additional experiment.

This sensitivity correction can be now produced by a trial and error process where the objective is to maximise the r-squared value of the linear fit between discomfort and power spectrum acceleration.

The sensitivity correction curve is shown in Figure 4. It is seen that for sufficiently low frequencies (below 3.15 Hz) there is no correction required. The equation form of this correction function is:

$$\left.\begin{aligned} K_v(f) &= (f/3.15)^{-0.86} && \textit{when } f > 3.15 \\ &= 1 && \textit{elsewhere} \end{aligned}\right\} \quad (1)$$

Where $K_v(f)$ is correction amount at frequency of f. The effective of power level (in dB) is computed by applying the correction to the power level of the representative frequency.

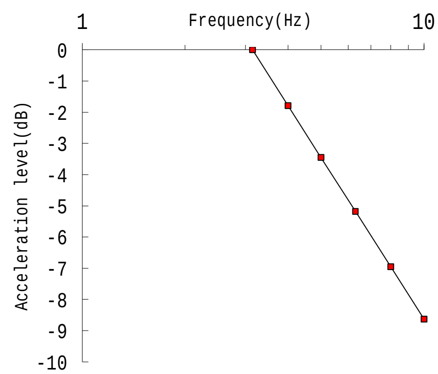


Figure 4 Sensitivity correction curve

That relationship between the level discomfort and the level of acceleration causing it for individual participants are shown in Figure 5. There were only four subjects used for this series of experiments. As the level of power experienced by wheelchairs is less than 1g, the datum level is reset to 0.01 g for the purpose of Figure 5.

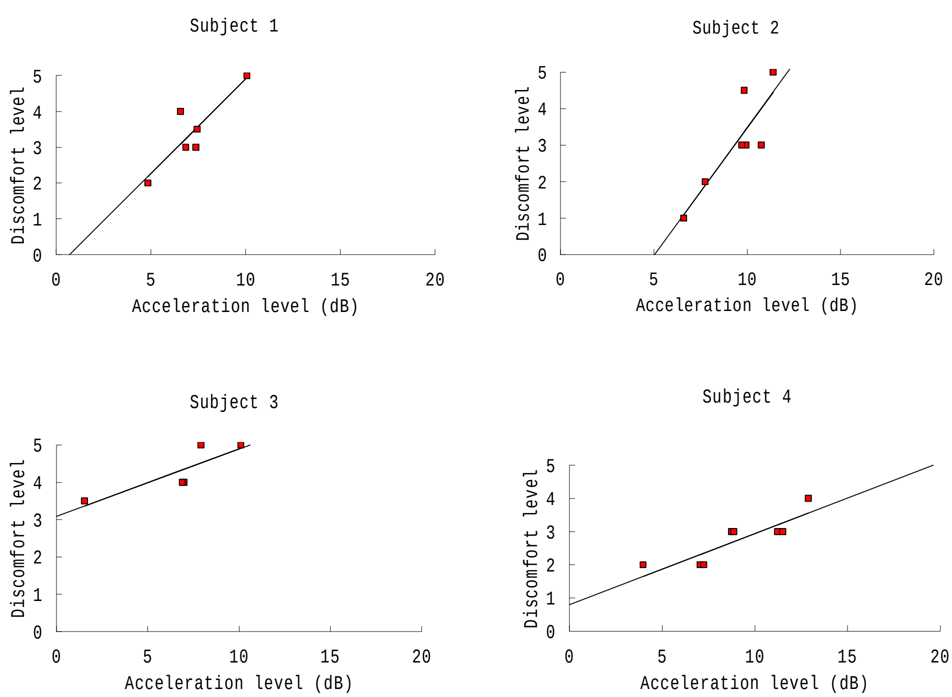


Figure 5. Relationship between discomfort and power spectrum acceleration for individual participants

It was observed that individual participants have not utilised the full range of responses (1 to 5) available to them. This may be result of the differences of either (a) the actual feeling of pain or (b) range of sites of pain. Each participant has his own range of responses. Therefore the discomfort level has been rescaled to 1 to 5 from the response range for each individual.

Figure 6 shows the resulting relationship for all trials in this series of experiments. The regression coefficient (R value) is 0.63. This relationship provides useful guidance in selection of roughness of travel surfaces as shown in the next section.

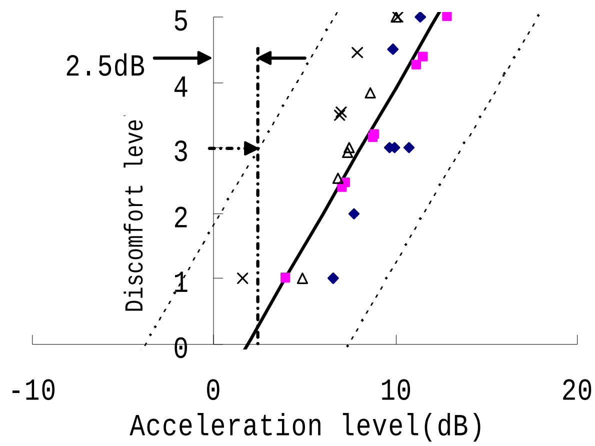


Figure 6. Consolidated relationship between discomfort and power level for low frequency generators

5. DESIGN STANDARDS FOR SURFACE ROUGHNESS

The objective of good surface design is to achieve the least discomfort level. For the purpose of preparing preliminary standards the level of 3 in the five point scale is selected as the maximum acceptable level of discomfort.

It is also important to allow for variability of responses from the field trials. Therefore, 95% limit is selected, as shown by the dotted lines in Figure 6. It is also decided to focus on the vibrations at the location G3 in Figure 1, that is under the seat of the wheelchair, because that sensor location is closest to the internal organs. The low frequency vibrations considered in this series of trials cause discomfort because of the unpleasant shaking of the internal organs.

Consider the level of discomfort at 3 in the vertical axis of Figure 6 to obtain the frequency that would allow for 95% significance. This is found to be 2.5 dB as shown in the figure. This means the low frequency related discomfort is within acceptable levels when the surface is designed with an upper limit frequency of 2.5 dB. This equates to a maximum of 0.013 g acceleration level.

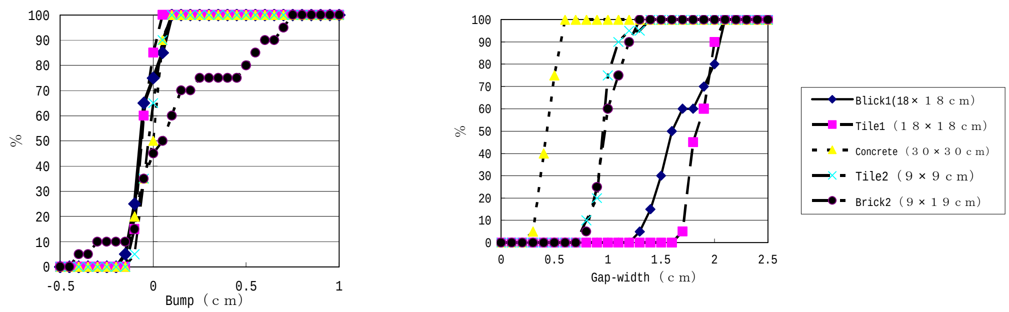
For example, if the representative frequency is 2 Hz, at the above limit of acceleration level, the maximum allowable height of patterns (see Figure 2) is 0.8 mm.

6. HIGH FREQUENCY VIBRATIONS

Jolting the human skeleton is the reason wheelchair users find high frequency vibrations uncomfortable. This series of tests focussed on surfaces that cause such vibrations. The test surfaces used in this series of experiments were from outdoor locations. Five sites were used. One site was a concrete pavement (plate block size: 30×30cm). Two locations were brick pavements (plate size: 18×18cm & 9×18cm). And the other two locations were tiled pavements (plate size: 18×18cm &

9×9cm). The experiments involved pushing the wheelchair on these surfaces and taking measurements as mentioned in a previous section. The trials were repeated by increasing the push speed.

Surface properties of the five sites are shown in Figure 7. Figure 7a shows the elevation differences between neighbouring tiles. This is referred to as the bump size in the diagram. This data were obtained from profile measurement device. Figure 7b shows the gap width between neighbouring tiles. The legend of Figure 7 shows the size of tiles as well.



(a) Bump size (b) Gap width

Figure 7. Surface characteristics

Figure 8 shows an example of the power spectrum acceleration profile related to concrete block surface. The representative frequency is selected as explained earlier. Also, as in the previous series of trials, the next step is to apply the sensitivity correction. The sensitivity correction that applies in this series of trials is shown in Figure 9. The equation form of this correction is:

$$\left.\begin{aligned} K_s(f) &= 1 && \textit{when } f \le 6.3 \\ &= (f/6.3)^{-0.169} && \textit{elsewhere} \end{aligned}\right\} \qquad (2)$$

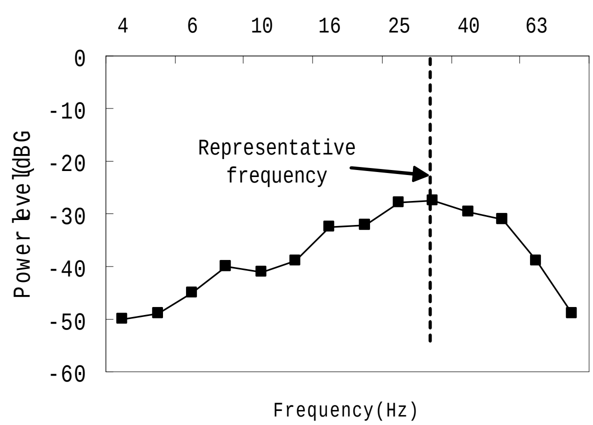


Figure 8. Example of the power spectrum acceleration and frequency profile for concrete block surface

The sensitivity correction $K_s(f)$ is flat up to 6.3 Hz. The graph is plotted at intervals of one-third octave band. The slope of the line shows that the correction is increased by minus 0.33 dB by for each one-third octave increment after 6.3 Hz.

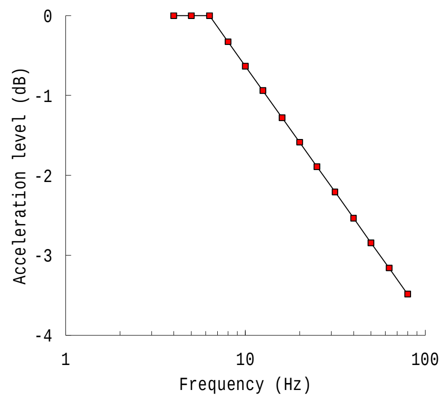


Figure 9. Sensitivity correction for high frequency trials

For these trials, the relationship between the level discomfort and the level of power causing it for individual participants are shown in Figure 10. The datum level for zero dB is set to 0.01 g in Figure 10 as well. The shapes of these diagrams have similarities to Figure 5. However, the magnitudes are different. Figure 5 relates to low frequencies. Figure 10 relates to high frequencies.

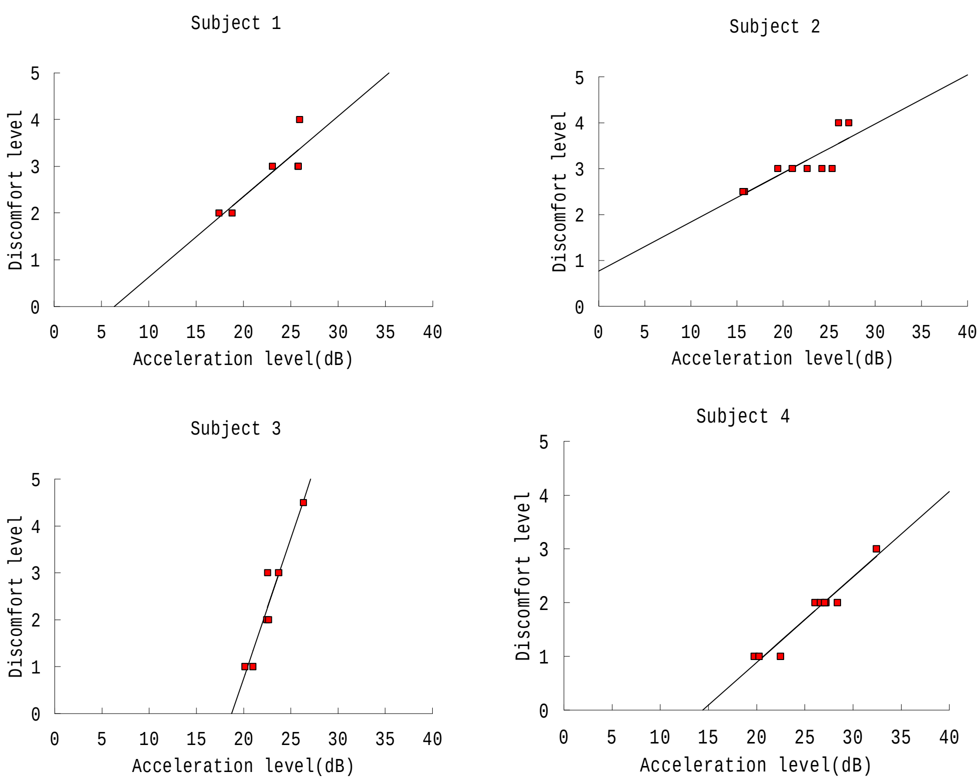


Figure 10. Relationship between discomfort and power spectrum acceleration for individual participants of the high frequency trials.

It is now possible to combine the findings to produce the relationship shown in Figure 11. As mentioned before, the data has been rescaled to account for respondents not using the full range of discomfort scale specified by the researchers. The correlation coefficient (R value) is 0.70.

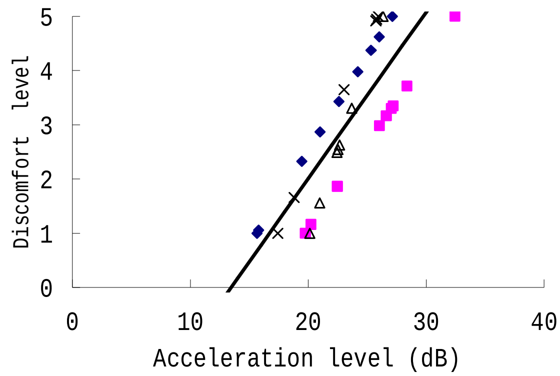
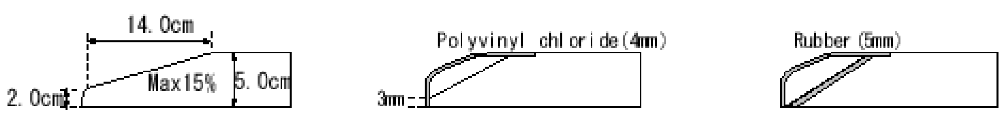


Figure 11. Consolidated relationship between discomfort and power level for high frequency generators

7. DISCOMFORT CAUSED BY IMPACTS

The next series of trials relate to wheelchair motion over a ledge. The focus here is in climbing a kerb from road surface. These tests covered kerbs made from three types of materials. These kerbs are shown in Figure 12. The first type shown is an example of a typical kerb edge found in Japanese streets. This type is made from concrete. The other two types have some kind of cushion arrangement to minimise the impact to wheelchairs. The second type is a hollow polyvinyl ledge fixed to the edge of the concrete sidewalk. Third type is similar, but made from rubber. There is an inner rubber layer at the face of the sloping concrete surface and a rubber outer rubber surface forming a curved ledge.



(a) Standard kerb (b) Vynyl kerb (c) Rubber kerb

Figure 12. Kerbs tested

In Japan, the kerb is a design requirement to enable safety of visually impaired. The ledge provides a distinct barrier for blind pedestrians using a white cane. However, this is inconvenient and sometime painful from the point of view of wheelchair users.

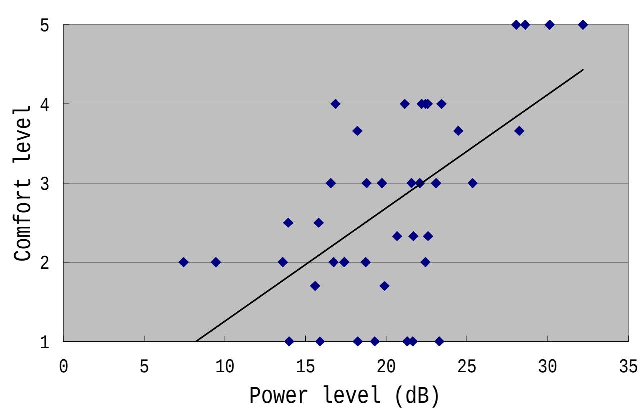


Figure 13. Impact discomfort with the three types of kerbs

For analysis of the effect of an impact (such as hitting the kerb ledge), the range of frequency is of little use. What is important is the value of total deceleration. This is similar to evaluating the area under the curve of the power spectrum acceleration profile shown before. The measurements obtained from two volunteer wheelchair users are shown in Figure 13. The discomfort scale is 1 to 5 as used in the previous trails.

As expected, Figure 13 shows that higher values of impacts cause more discomfort. The relationship shown has an R value of 0.75 indicating that the linear model is applicable.

8. MATHEMATICAL MODEL OF USER AND WHEELCHAIR SYSTEM

A model of the user and wheelchair system can be made using the spring mass model. This method is a favoured method in mathematical model building in mechanical engineering work (Pestel, 1963; Snowdon, 1968). Figure 14 shows the schematic diagram of the spring mass model. To save space here, the details of each component is tabulated and shown in Table3. Values reported in Table 3 are based on the wheelchair and owner properties measured in the lab. In a typical application, the mass values (m values) could be changed to suit the particular wheelchair and owner weights. Values of k (spring rates) and c (damping values) are common to all applications.

There is a difference between system models prepared to analyse vehicles such as cars and model developed here for wheelchairs. In the context of cars, the weight of the human passenger is relatively low. However, in the context of the wheelchair, the weight of the occupant is substantial. Therefore, the model has a similarity to the human and bicycle system where the weight of the user has to be included in the analysis. In Figure 14, this concept is taken further by considering the human body in three parts as head, upper body and lower body (hip and below).

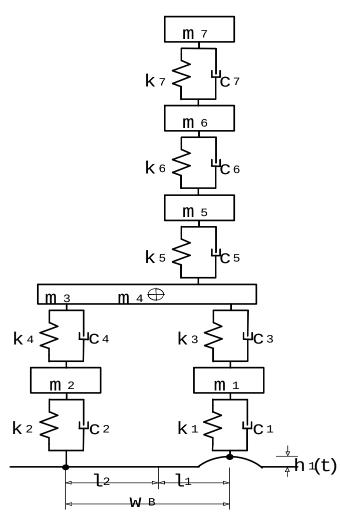


Figure 14. Spring mass model of man wheelchair system

Table 3. Spring mass model properties

Label in Figure 14	Item	Value	unit
m 1	front shaft unsprung mass	0.540	kg
m 2	rear shaft unsprung mass	4.300	kg
m 3	sprung mass	16.000	kg
m 4	pitdhing moment	0.576	$kg \cdot m^2$
m 5	seat and waist weight	20.500	kg
m 6	stomach and chest weight	27.600	kg
m 7	head eight	3.500	kg
k 1	front shaft unsprung spring rate	42,000.0	N/m
k 2	rear shaft unsprung spring rate	11,000.0	N/m
k 3	front shaft sprung spring rate	800,000.0	N/m
k 4	rear shaft sprung spring rate	800,000.0	N/m
k 5	seat spring rate	65,300.0	N/m
k 6	waist and stomach spring rate	26,600.0	N/m
k 7	shoulder and head spring rate	55,200.0	N/m
W b	wheel base (= l 1+ l 2)	0.400	m
l 1	horizontal interval from center of the body to front shaft	0.254	m
l 2	horizontal interval from center of the body to rear shaft	0.146	m
l s	horizontal interval from center of the body to center of seat	0.045	m
c 1	front shaft unsprung damper rate	100.0	NS/m
c 2	rear shaft unsprung damper rate	54.5	NS/m
c 3	front shaft sprung damper rate	2,500.0	NS/m
c 4	rear shaft sprung damper rate	2,500.0	NS/m
c 5	seat unsprung damper rate	928.0	NS/m
c 6	waist and stomach unsprung damper rate	170.0	NS/m
c 7	shoulder and head damper rate	87.0	NS/m
h 1	road surface position at front shaft		m
h 2	road surface position at rear shaft		m

Consider a wheel chair at position x along the path moving at v velocity. The surface could be either a low frequency or high frequency generator. Thus time t is obtained by $t = x/v$. The front wheel is moving over a bump of height $h_1(t)$. The rear wheel will pass over that point with a time lag. The bump for rear wheel is of height $h_2(t) = h_1(t + t_w)$ at a lag time t_w. It can be shown that $t_w = w_b / v$ where w_b is the wheel spacing. The equation of motion incorporating these bumps can be expressed as:

$$M\ddot{X} + C\dot{X} + KX = F(t) \qquad (3)$$

Where

$$X = (x_1, x_2, x_3, x_4, x_5, x_6, x_7)^{\mathrm{T}} \qquad (4)$$

$$F(t) = (k_1 h_1(t) + c_1 \dot{h}_1(t), k_2 h_2(t) + c_2 \dot{h}_2(t), 0,0,0,0,0) \qquad (5)$$

T in equation 4 is the vector transpose operator. M, C, and K stand for the matrices of inertia, damping factors and stiffness. These matrices are:

$$M = \begin{pmatrix} m_1 & & & 0 \\ & \cdot & & \\ & & \cdot & \\ 0 & & & m_7 \end{pmatrix}$$

$$C = \begin{pmatrix} c_1 + c_3 & 0 & -c_3 & l_1 c_3 & 0 & 0 & 0 \\ 0 & c_2 + c_4 & -c_4 & -l_2 c_4 & 0 & 0 & 0 \\ -c_3 & -c_4 & c_3 + c_4 + c_5 & -l_1 c_3 + l_2 c_4 - l_S c_5 & -c_5 & 0 & 0 \\ l_1 c_3 & -l_2 c_4 & -l_1 c_3 + l_2 c_4 - l_S c_5 & l_1^2 c_3 + l_2^2 c_4 + l_S^2 c_5 & l_S c_5 & 0 & 0 \\ 0 & 0 & -c_5 & l_S c_5 & c_5 + c_6 & -c_6 & 0 \\ 0 & 0 & 0 & 0 & -c_6 & c_6 + c_7 & -c_7 \\ 0 & 0 & 0 & 0 & 0 & -c_7 & c_7 \end{pmatrix}$$

$$k = \begin{pmatrix} k_1 + k_3 & 0 & -k_3 & l_1 k_3 & 0 & 0 & 0 \\ 0 & k_2 + k_4 & -k_4 & -l_2 k_4 & 0 & 0 & 0 \\ -k_3 & -k_4 & k_3 + k_4 + k_5 & -l_1 k_3 + l_2 k_4 - l_S k_5 & -k_5 & 0 & 0 \\ l_1 k_3 & -l_2 k_4 & -l_1 k_3 + l_2 k_4 - l_S k_5 & l_1^2 k_3 + l_2^2 k_4 + l_S^2 k_5 & l_S k_5 & 0 & 0 \\ 0 & 0 & -k_5 & l_S k_5 & k_5 + k_6 & -k_6 & 0 \\ 0 & 0 & 0 & 0 & -k_6 & k_6 + k_7 & -k_7 \\ 0 & 0 & 0 & 0 & 0 & -k_7 & k_7 \end{pmatrix}$$

For the analysis of the effects of impact, as in the kerb tests shown before, the model requires a fourth vector to fully explained $F(t)$. However, this situation is not discussed in this paper to avoid unnecessary complexity.

Fitness of the model can be shown using scenarios already mentioned. For example, consider the shape 1 type surface (low frequency generator) and a wheelchair moving at a speed of 0.47 m/s. Figure 15 shows the power spectrum obtained by the FFT analyser for the laboratory test (shown by dotted line in figure 15) and the mathematical model. The graphs show a good agreement between the laboratory tests and the mathematical model.

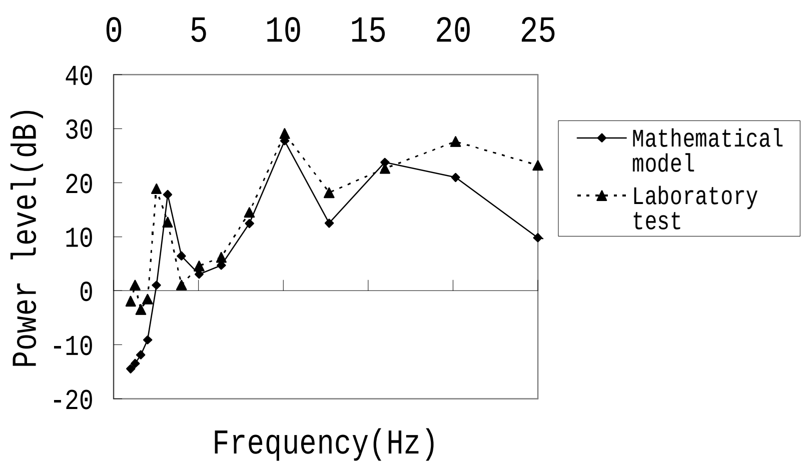


Figure 15. Comparison between the laboratory test and the mathematical model

9. CONCLUSIONS

This research project investigated the discomfort caused to wheelchair users by asperity of surfaces. The research work uncovered differences in low frequency impacts and high frequency impacts. This is associated with the nature of the discomfort. Three types of surface irregularities are analysed in this project to cover the range of possible surface characteristics.

The data collection presented in this paper is based on pushing wheelchair bound spinal injury patients on different types of surfaces. Some experiments were conducted on laboratory surfaces whereas others were conducted on field sidewalks. These results were compared with a mathematical model as well. This mathematical model relies on the spring-mass analogy of mechanical systems.

It is acknowledged that the work presented here is limited by the small sample size and range of surfaces covered. However, this paper provides the basic methodology to evaluate different surface designs from the point of view of wheelchair friendliness. There are three important elements covered in the methodology presented. These elements are interconnected and an attempt has been made to briefly explain technical details of each of these methodological elements. The first of these elements covers the method of measuring discomfort caused by vibrations. The equipment, terminology and basic steps of this processes has been documented. The second element relates to the method of incorporating the wheelchair user perceptions in the design context, particularly in the selection of allowable limits to surface features. Third methodological element is the application of the theoretical model. This provides another reliable method of predicting the vibration profile resulting from a given surface.

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