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Research Article

Exploration of Wheelchair Vibration-Resistance Performance and Health Risks for Power Wheelchair users in Urban Living Environment

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ABSTRACT

Introduction: Previous studies on professional drivers have illustrated the harmful effects of long-term exposure to Whole Body Vibration (WBV), including low back pain, neck and shoulder problems. Wheelchair users in their active working and living style sit on their wheelchairs for an extended period of time every day and their exposure to vibration could vary depending on the vibration-resistance performance of the wheelchair itself. Aside from the design of wheelchairs as well as additional seating systems, namely seat cushions, environmental factors could also contribute to the WBV. Although there was foreign research assessing the relationship between WBV and the health risks of wheelchair users, no local research has been conducted to assess the effects of WBV on wheelchair users traveling on different community terrains.

Aims: The purpose of this study is to explore the vibration-resistance performance of common power wheelchairs and wheelchair seat cushions while driving in local urban living environment, and to evaluate against international health risks standards (ISO 2361-1, 1997).

Method: Experimental factorial designs were conducted on the combinations of 2 common power wheelchairs and 2 wheelchair cushions over 6 common terrains in simulated pavement blocks, concrete surface, kerbs and slope; while vibration was measured by the magnitude of acceleration in 3 planes using the Inertia Measurement Unit (IMU) placed on the back (RMSB), buttock (RMSS) and foot (RMSF) of a weighted 40-70kg dummy? or does weighted hinted weights added on top of the 40kg dummy?.

Results: A total of 144 data (n=144) was gathered for RMSS, RMSF & RMSB respectively. Results showed no significant correlations between the seat cushions (i.e., seat cushion made of foam and gel, air-based seat cushion, and control setup with seat cushion) and the three types of RMS: RMSS, RMSF, and RMSB ($r = -0.076, 0.019, -0.072$, $p = 0.367, 0.817, 0.389$. It was found that the wheelchair weight had a moderate positive correlation with RMSB ($r = 0.334$, $p < 0.001$). Additionally, the simulated body weight of wheelchair users had a weak negative correlation with RMSS and RMSB ($r = -0.248, -0.198$, $p = 0.003, 0.017$). Furthermore, terrains were found to have a moderate positive correlation with RMSS and RMSF ($r = 0.295$,

0.328, p < 0.001, p <0.001). The mixed effect of wheelchair weight and terrains had a significant effect on RMSB (p=0.007). The discomfort produced for long-term wheelchair users (average 4-8 hours per day) transmitted from pavement blocks (0.8-1.6m/s^2), up and down kerbs (1.4-1.6 m/s^2) could likely cause health risks.

Conclusion: WBV had great significance with all common terrains in from highest to lowest: kerbs, slope, pavement blocks, and poured concrete. The simulated BW of wheelchair users and WCW had a significant effect on WBV. However, there is no significant effect of seat cushions on WBV. Urban terrains play an important role in affecting WBV that could increase wheelchair users' health risks in daily community mobility.

INTRODUCTION

People are commonly exposed to vibration every day to various extents. Some occupational groups, as demonstrated by professional vehicle drivers, are regularly exposed to seated whole-body vibration (WBV). Previous studies have illustrated the harmful effects of long-term exposure to WBV, including but not limited to low back pain as well as neck and shoulder problems [1]. WBV, by definition, is the vibration transmission from supporting surfaces to the whole human body. Wheelchair users are another party that is also frequently exposed to vibration. In Hong Kong, there are 320,500 people with body movement restrictions, and 90,700 of them require a wheelchair for mobility to some extent (Census and Statistics Department, 2014). Research regarding the topic has yet to be done in Hong Kong and further exploration is needed. Wheelchair users sit on their wheelchairs for an extended period of time every day and their exposure to vibration could vary depending on the vibration-resistance performance of the wheelchair itself. Aside from the design of wheelchairs as well as additional seating systems, namely seat cushions, environmental factors could also contribute to the WBV.

To reduce the transmission of shock and vibration, some wheelchairs have installed suspension systems that aim to increase comfort and performance. They can be added to the rear wheels, front caster wheels, or both [1]. The main types of design include passive suspension, active suspension, and semi-active suspension.

Passive suspension refers to suspension design without a power supply. It is widely used in wheelchairs as it is simple and inexpensive [2]. There are three common components of passive suspensions: 1) elastomers; 2) springs; 3) springs and damper units [1].

In contrast, active suspension is the suspension that consists of power supply and signal processing. Extra actuators are added to the passive suspension components, and they can effectively dismiss forces [3]. Balancing the characteristics of the two suspension designs, semi-active suspension is less complex but more effective than passive mechanical solutions. It is similar to passive suspension and utilizes positive force actuators with comparable control less band of frequencies than the active one but with higher stability [4].

Despite the aim of suspensions, research revealed that suspension did not necessarily reduce the amount of oscillatory and shock of WBV. For manual wheelchairs, titanium rigid-frame wheelchairs without suspension performed even better than some wheelchairs with suspension and it may be due to the weight of the suspension device, which causes more inertia for the wheelchair to overcome and greater difficulty to propel [5].

Multiple studies suggested that seat cushions influence WBVs from the frame of a wheelchair to the body of the wheelchair user. The efficiency and effectiveness of seat cushions are based on their ability to minimize pressure gradients and maintain an even pressure distribution between wheelchair users and the seating system, and the ability to minimize the impact (shock) and repetitive vibrations transmission during propulsion. The characteristics of wheelchair seat cushions such as density of materials, thickness and can lead to a significant influence on whole-body vibration [6]. There are some common types of commercial wheelchair seat cushions currently available in Hong Kong namely air-based cushions, gel-based cushions, foam-based cushions, or mixed types. Previous research has evaluated the ability of different seat cushions in minimizing WBV from a manual wheelchair to a wheelchair user during propulsion. One suggested that air-based seat cushions outperformed gel-based and foam-based cushions in terms of reduction of vibration exposure of manual wheelchairs [7]. Other studies also have findings that seat cushions made with a combination of foam and air are having fewer impacts and WBV during manual wheelchair propulsion [8,9]. Generally, the gel-layer cushion was found to be most ineffective in suppressing vibrations in a range of literature [9]. Different floor and road materials could account for different WBV transmissions to wheelchairs due to the roughness of the materials [10]. The vibration level of the wheelchair also varies with ground surface properties such as roughness [11]. To cater to their daily needs, wheelchair users experience different vibration exposure during community access in the everyday environment. There are different ground surfaces with different materials and thresholds (heights) such as poured concrete, pavement bricks, uneven sidewalks, curbs, and tactile guide paths in the common housing area. A range of research has suggested that manual wheelchair users are exposed to WBVs when traversing uneven and rough terrains for a long time in daily living [10]. Previous literature also suggested that smooth flat surfaces such as concrete ground may cause lower WBV magnitudes relative to inclined surfaces [2]. The higher WBV is found to cause greater discomfort to wheelchair users. Wheelchair users' comfort should be considered along with all these factors.

Guidelines and standards have been developed by the International Standards Organization (ISO) to protect humans from exposure to harmful levels of vibration. ISO 2361-1 is the international standard of mechanical WBV and shock that a human can expose to, which is the standard for different sectors of which its standard is respected and considered reliable worldwide.

The document states the unit of vibration measurement, guidelines on measurement, evaluation, and related knowledge on health, comfort, and motion sickness. It is to define the methods for quantifying WBV in relation to human health and comfort, excluding direct harm to the limbs caused by vibration [12]. Therefore, the standard in ISO 2631 is believed to be suitable for our research on the relationship between WBV and discomfort.

According to the document, vibration shall be measured by acceleration (ms^{-2}) and measured at the interface between the human body and the vibration source. Below is the caution zone of vibration on the level of discomfort regarding vibration measurement mentioned in the document. Data collected could be analyzed and evaluated according to the guidelines.

Multiple researchers have investigated the relationship between vibration level and users' discomfort through questionnaires and surveys. Results of a telephone interview after subjects received and used the prescribed EPWs over time revealed that more than half of them felt increased pain levels while 17% of the interviewees reported severe pain, [13]. Although the research did not investigate the level of vibration, it shows that usage of the EPWs could lead to an increase in pain and discomfort disregarding the original medical conditions.

Table 1. Caution Zone of Vibration on the Level of Discomfort [12].

Less than 0.315 m/s²	Not uncomfortable
0.315 m/s² to 0.63 m/s²	A little uncomfortable
0.5 m/s² to 1 m/s²	Fairly uncomfortable
0.8 m/s² to 1.6 m/s²	Uncomfortable
1.25 m/s² to 2.5 m/s²	Very uncomfortable
Greater than 2 m/s²	Extremely uncomfortable

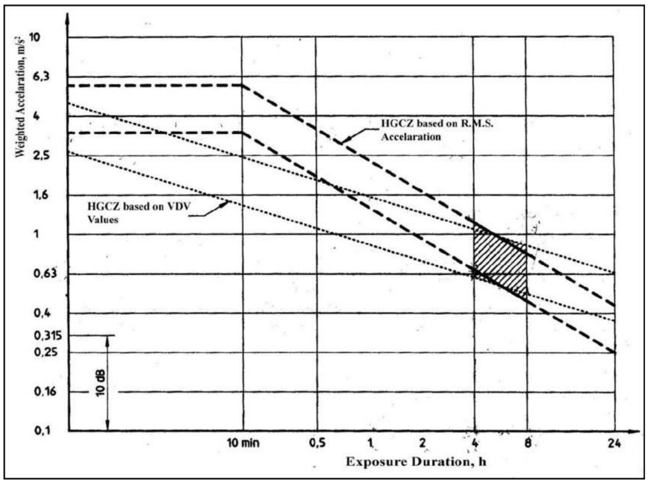

Figure 1: Health Caution Zone [12].

Maeda et al. [14] had done a survey about the type of vibration and road surface causing the greatest discomfort. Results show that discomfort and pain in the neck, lower back, and buttock are common due to WBV. Data also implies that deformity of the spine and neck pain could be found at different vibration frequencies. The physiological pain and discomfort caused by vibration during wheelchair propulsion also result in psychological dissatisfaction.

Research done in Japan investigated the relationship between acceleration and discomfort by pushing spine injury subjects through different surfaces and recording the users' perceptions [15]. A frequency profile is then generated, and all responses show that: the higher the acceleration level, the higher the discomfort level.

OBJECTIVES OF THE STUDY

The presence of WBV on wheelchair users and the relationship between WBV and the discomfort of wheelchair users are documented. However, the relevant studies found are all carried out by foreign countries, such as the United States [2] and Japan [15]. These countries studied the effect of WBV on wheelchair users traveling on different surfaces that are common in their countries' environments. The generalization of foreign countries' research cannot be applied to Hong Kong since each literature has its differences that could potentially affect the results. Moreover, most existing studies used manual wheelchairs as instruments for testing WBV. There was a lack of research exploring the relationship between wheelchair design and WBV except a study mentioned suspension devices might help reduce the transmission of shock and WBV. There is also little research studying the effect of seat cushions on WBV.

The study was to provide better insights into the vibration-resistance performance of EPWs used in Hong Kong. It aimed to give a more in-depth understanding of the interrelationship between the combinations of weight, EPW designs, seat cushion materials, and floor surface materials. No research regarding this topic has been done in Hong Kong currently and findings from this research could facilitate health professionals in EPW selection processes which in turn lay down the foundation for the development of EPW prescription criteria, eventually being able to provide EPW users with the most suitable EPW with maximum comfort.

In this paper, we investigated whether the body weight would affect the level of WBV of EPWs and which combinations of EPWs with the seat cushion or just the EPW alone 1) could start causing discomfort to wheelchair users according to the ISO standard; 2) have the best ability in minimizing vibration exposure to EPW users. We hypothesized that the body weight of the dummy, differences in wheelchair design, and different terrains would affect WBV separately. We also expected the air-based seat cushions would lower WBV.

METHODOLOGY

Instrumentation

Measurements: This study followed the ISO-2631 standard, which quantified WBV in relation to health, comfort, and probability of vibration perceived by wheelchair users. The magnitude of vibration was primarily quantified by root-mean-square (RMS) accelerations (m/s^2) which were measured at the points where vibration was transmitted to the body of the wheelchair user. The data collection device utilized in this study was Inertial Measurement Units (IMUs)-based and conformed to ISO 10326-1:2016 standards. It was specifically designed by rehabilitation engineers from the Community Rehabilitaion Service Support Centre (CRSSC), which were able to collect acceleration data across three planes (x, y, and z axes) and incorporated a noise reduction feature to ensure data accuracy. Vibration should be measured simultaneously in all three directions. Z-axis is always along the main body axis, X-axis is aligned with the fore-and-aft motion and Y-axis is along with side-to-side motion.

The disc-shaped data collection device was installed at the body parts between the wheelchair user and the source of vibration to measure the subject's vibration experience. All three data collection devices were designed to be the same size, which provided large surface areas for more effective vibration data collection. With reference to the ISO-2631 standard, this study only focuses on three major contact areas namely seat surface, lower seatback, and footrest, and the IMUs were mounted on the area shown in Figure 2. The data collection devices are mounted with double-sided tape and packing tape. Calibration of measurements was done after the wheelchair user was seated on the wheelchair and the data collection devices were secured in between to ensure the baseline all measurements across all planes were equal.

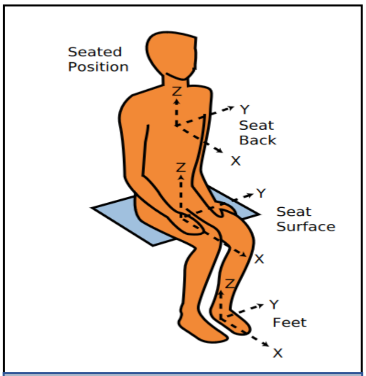

Figure 2: Different measurement positions at WBV assessment [23].

Wheelchair

Two commonly prescribed EPWs were borrowed from two local medical supply companies, and their differences were listed in Table 2. Two wheelchairs consist of add-on devices to remotely operate the joystick control of the testing routes.

Table 2: Wheelchairs Information.

	Wheelchair 1	Wheelchair 2
Type	Rigid frame	Folding
Frame material	Aluminium alloy	Aluminium alloy
Top speed	6 km/h, 7.2km/h or 10km/h	6km/h
Battery capacity	50Ah (C5) AGM batteries/63Ah (C5) gel batteries	10Ah Lithium batteries
Range	25/35 km	12-15km
User weight	140 kg	125 kg
Net weight	95 kg	24.1 kg
Climbing ability	12°	12°
Width	58 cm	59.4cm
Length	106 cm	105.4cm
Seat height	40–57 cm	53.3cm
Seat width	38–48 cm	40.6cm
Seat depth	36–50 cm	45.7cm
Back height	45/55 cm	40.6cm
Back width	40/44 cm	N/A
Tire type	Solid pneumatic (solid rubber)	Solid pneumatic (solid rubber)
Suspension device	Chassis suspension device	N/A

Table 3: Seat cushions information.

Cushion Label	Type
Cushion 1	No cushion
Cushion 2	Mixed type: gel & foam
Cushion 3	Air

Seat cushions

Hong Kong commonly prescribed seat cushions namely foam, gel, air, and mixed seat cushion. Two seat cushions were borrowed from the college, including an air-based cushion and a foam & gel cushion. Detailed information on the cushions were listed in Table 3.

Weighted dummy

The weight of the wheelchair user was simulated by a weighted dummy and additional weights of sandbags. The dummy had a fixed weight of 40kg and weighted sandbags were added to the trunk, upper limb, and lower limb of the dummy as shown in Figure 3. The weights were added according to the normal weight distribution of human body parts [16] as shown in Table 4. The seat belt, leg strap, and chest guard were fastened to secure the dummy in a proper position in the wheelchair.

Table 4: Weight distribution of human body parts.

	Dummy Weight	Added weights (average weight distribution of body parts)		
		Trunk (50%)	Upper Limb (50%)	Lower Limb (50%)
50 kg	40 kg	5 kg	1 kg	4 kg
60 kg		10 kg	3 kg	7 kg
70 kg		15 kg	4 kg	11 kg

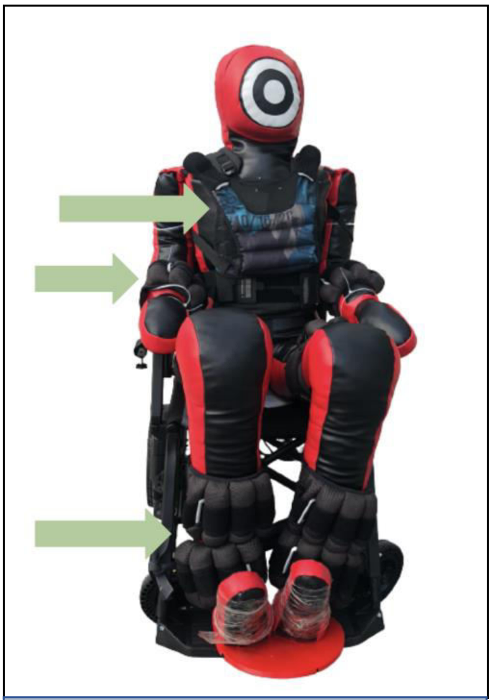

Figure 3: Weighted sandbags attached in the trunk, upper limb and lower limb.

Terrains

6 simulated road surfaces (i.e. poured concrete, pavement blocks, up slope, down slope, up kerb, down kerb) in CRSSC were utilized as the comprehensive representation of the common terrains in Hong Kong urban living environment,

including but not limited to other public housing estates, private estates, etc.

(A) (B) (C) (D)

Figure 4: (A) Poured concrete, (B) 1-inch kerb, (C) 60°slope, (D) Pavement blocks.

Experiment protocol

Design of experiment: During the experimental process, three data collection devices were used to measure the WBV of EPWs when driving on 6 different terrains in rehabilitation centre. Before the start of the experiment, the distance of the surfaces (i.e., 6 meters) was measured to maintain control of distance and speed in trials. The 3 data collection devices were respectively placed at the seatback, seat surface, and footrest of the EPWs in every trial. 3 separate sets of RMS (measured in seconds) were obtained from these 3 data collection devices in each trial. The driving speeds of the EPWs were controlled remotely by researchers to be set to 1.5-2.0 m/s, which is suggested to be the speed limit of class 2 vehicles [17]. The speed set was also commonly seen in community for power wheelchair users.

With different combinations of wheelchairs, seat cushions, and body weight (Table 5), there were a total of 144 setups, and five trials were done for each setup, thus, 720 trials were done. No human subjects were involved in this experiment so there was no ethical concern.

Table 5: Design of the experiment per each terrains.

Body weight	Setup 1	Setup 2	Setup 3	Setup 4	Setup 5	Setup 6
	WC1+CU1	WC1+CU2	WC1+CU3	WC2+CU1	WC2+CU2	WC2+CU3
40kg	5 trials	5 trials	5 trials	5 trials	5 trials	5 trials
50kg	5 trials	5 trials	5 trials	5 trials	5 trials	5 trials
60kg	5 trials	5 trials	5 trials	5 trials	5 trials	5 trials
70kg	5 trials	5 trials	5 trials	5 trials	5 trials	5 trials

Data collection

The acceleration data were collected from the three data collection devices and streamed to computer via Bluetooth. Then, the data were processed by Excel with ISO formula and consequently interpreted into mean RMS of three axes.

DATA ANALYSIS

Data reduction

Data recorded by the data collection devices was frequency weighted by the standard vibration evaluation methodologies with reference to ISO-2631-1 [12].

As aforementioned, the vibration measurement is triaxial. The frequency weighting of the accelerations in different axes was determined by the affected aspect (i.e. health, comfort, perception). For the assessment of the comfort effects of vibration, it should be using the frequency weighting Wk on the Z-axis and Wd on the X and Y axes. The multiplying factors k for Wd and Wk are both when it is measuring comfort. It is recommended to use the vibration total value in the vibration assessment for comfort, so it was used for the calculations for all necessary parameters.

STATISTICAL ANALYSIS

After data collection, data generated from the data collection devices were analyzed by SPSS 26 software. Descriptive statistics were used to take standard deviation (SD) for detecting whether there were any extreme data that had SD greater than 2 that needed to be eliminated. Besides, the Pearson correlation test was used to assess the possible linear association between RMS and independent variables. ANOVA test was also used to test the significant differences of RMS of seat surface (RMSS), footrest (RMSF), and backrest (RMSB) between different setups to evaluate the vibration-resistance performance of different EPWs designs, body weights, and seat cushions. The level of significance was set at $p<0.01$ as significant. Furthermore, Multivariate Analysis was done to compare which independent variables affect RMS and their significance. Also, a post-hoc test in multivariate analysis was used to assess the mixed effects of independent variables on RMS. Lastly, Regression Analysis was used to explore the predictive power of one or more independent variables related to RMS. The RMS accelerations were also used to compare the ISO-2631-1 standard for the prediction of possible comfort reactions to different magnitudes of WBV.

RESULTS

In the following, WCW, CU, BW, and TE represent wheelchair weights, seat cushions, body weight, and terrains respectively.

Descriptive statistics

A total of 144 data (n=144) was gathered for RMSS, RMSF, and RMSB from the seat surface, footrest, and backrest respectively. No extreme data (i.e., SD > 2) were investigated and needed to be eliminated (Table 6).

Table 6: Descriptive statistics showing the amount of RMS data analyzed and standard deviation of each data.

Descriptive Statistics

	N Statistic	Minimum Statistic	Maximum Statistic	Mean Statistic	Std. Deviation Statistic	Skewness Statistic	Skewness Std. Error
WCW	144	24.1	95.0	59.550	35.5737	.000	.202
CU	144	1	3	2.00	.819	.000	.202
BW	144	40	70	55.00	11.219	.000	.202
TE	144	1	6	3.50	1.714	.000	.202
RMSS	144	.408994937	1.16322402	.779981767	.168492201	-.372	.202
RMSF	144	.514105223	2.12160243	1.19281696	.373444422	.297	.202
RMSB	144	.507762560	2.71645595	1.02086461	.317735513	1.579	.202
Valid N (listwise)	144						

Correlation analysis

Results showed no significant correlations between the CU (i.e., seat cushion made of foam and gel, air-based seat cushion, and control setup with seat cushion) and the three types of RMS: RMSS, RMSF, and RMSB ($r = -0.076, 0.019, -0.072$, $p = 0.367, 0.817, 0.389$) (Table 3).

On the other hand, it was found that the WCW had a moderate positive correlation with RMSB ($r = 0.334$, $p < 0.001$). When WCW increased (decreased), the RMSB also increased (decreased). Additionally, the BW of wheelchair users had a weak negative correlation with RMSS and RMSB ($r = -0.248, -0.198$, $p = 0.003, 0.017$). When the BW of wheelchair users increased (decreased), the RMSS and RMSB may be decreased (increased). Furthermore, TE was found to have a moderate positive correlation with RMSS and RMSF ($r = 0.295, 0.328$, $p < 0.001$, $p < 0.001$) (Table 7).

One-way ANOVA Test

Using TE as a fixed variable and WCW and BW as the covariates, the results demonstrated that all RMSS, RMSF, and RMSB had high significance levels between different terrains ($p < 0.001$). In all RMSS, RMSF, and RMSB ($F=36.688$, $F=24.001$, $F=26.430$), the null hypothesis was rejected which indicates the group means are different from the rest (Table 8).

Table 7: Pearson correlation test showing the correlations between different independent variables (i.e., WCW, CU, BW, and TE) and the dependent variables (i.e., RMSS, RMSF, and RMSB)

Correlations

		WCW	CU	BW	TE	RMSS	RMSF	RMSB
WCW	Pearson Correlation	1	.000	.000	.000	.064	-.054	.334**
	Sig. (2-tailed)		1.000	1.000	1.000	.447	.524	.000
	N	144	144	144	144	144	144	144
CU	Pearson Correlation	.000	1	.000	.000	-.076	.019	-.072
	Sig. (2-tailed)	1.000		1.000	1.000	.367	.817	.389
	N	144	144	144	144	144	144	144
BW	Pearson Correlation	.000	.000	1	.000	-.248**	-.027	-.198*
	Sig. (2-tailed)	1.000	1.000		1.000	.003	.750	.017
	N	144	144	144	144	144	144	144
TE	Pearson Correlation	.000	.000	.000	1	.295**	.328**	.130
	Sig. (2-tailed)	1.000	1.000	1.000		.000	.000	.122
	N	144	144	144	144	144	144	144
RMSS	Pearson Correlation	.064	-.076	-.248**	.295**	1	.557**	.683**
	Sig. (2-tailed)	.447	.367	.003	.000		.000	.000
	N	144	144	144	144	144	144	144
RMSF	Pearson Correlation	-.054	.019	-.027	.328**	.557**	1	.497**
	Sig. (2-tailed)	.524	.817	.750	.000	.000		.000
	N	144	144	144	144	144	144	144
RMSB	Pearson Correlation	.334**	-.072	-.198*	.130	.683**	.497**	1
	Sig. (2-tailed)	.000	.389	.017	.122	.000	.000	
	N	144	144	144	144	144	144	144

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table 8: One-way ANOVA showing the significance levels of RMSS, RMSF, and RMSB between different terrains.

ANOVA

		F	Sig.
RMSS	Between terrains	36.688	.000
RMSF		24.001	.000
RMSB		26.43	.000

Multivariate analysis

After ruling out CU which was the insignificant factor, the mixed effect of the significant factors was investigated by a post-hoc multivariate test. Results showed that mixed effects of WCW and BW ($p<0.001$) whereas WCW and TE ($p=0.002$) both had high significance on the RMS (Table 9).

Results showed that different combinations of independent variables may not affect all of the RMS. The mixed effect of BW and WCW affected RMSS ($p=002$) and RMSF ($p=0.023$) significantly while the mixed effect of WCW and TE had a significant effect on RMSB ($p=0.007$) (Table 10).

Table 9: Multivariate test showing the significance of the mixed effects of the wheelchair weights, body weights, and terrains with RMSS, RMSF, and RMSB.

Multivariate Tests

Effect	Test	Sig.
WCW	Wilks' Lambda	.000
BW		.001
TE		.000
WCW*BW		.000
WCW*TE		.002
BW*TE		.998
WCW*BW*TE		.919

Table 10: Tests of between-subject effects on RMSS, RMSF, and RMSB.

Tests of Between-Subjects Effects

Source	Dependent Variables	Sig.
WCW*BW	RMSS	.002
	RMSF	.023
	RMSB	.408
WCW*TE	RMSS	.219
	RMSF	.299
	RMSB	.007
BW*TE	RMSS	.980
	RMSF	.976
	RMSB	.806
WCW*BE*TE	RMSS	.636
	RMSF	.996
	RMSB	.777

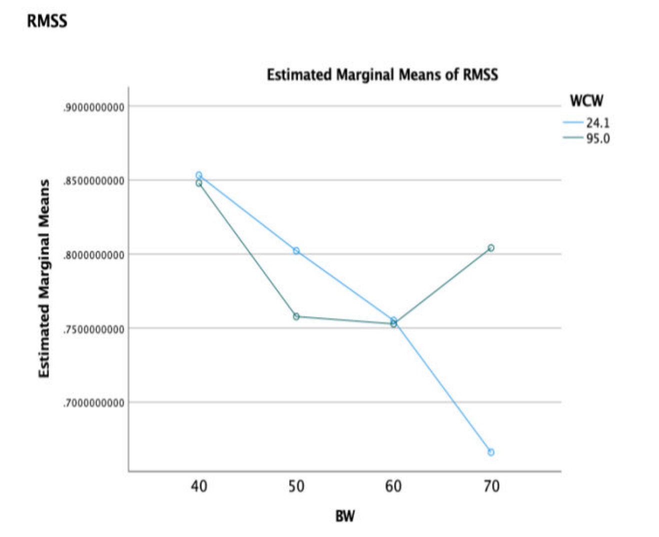

Figure 5: Estimated Marginal Means of RMSS of the mixed effect of WCW and BW.

Mixed effect of BW and WCW

As mentioned, the mixed effect of BW and WCW significantly affected RMSS and RMSF. Results showed that there was a significant difference in RMS for subjects of different BWs in different WCWs.

In RMSS, an interception point was shown in Figure 5. The RMSS of subjects below 60 kg BW in 95 kg EPW was lower than that in 24.1kg EPW and the RMSS for subjects that had more than 60 kg BW was the opposite. This indicated the inflection point for RMSS was 60 kg BW.

In RMSF, an interception point was shown in Figure 6. The RMSF of subjects below 55 kg BW in 95 kg EPW was lower than that in 24.1kg EPW and the RMSF for subjects that had more than 55 kg BW was the opposite. This indicated the inflection point for RMSS is 55 kg BW.

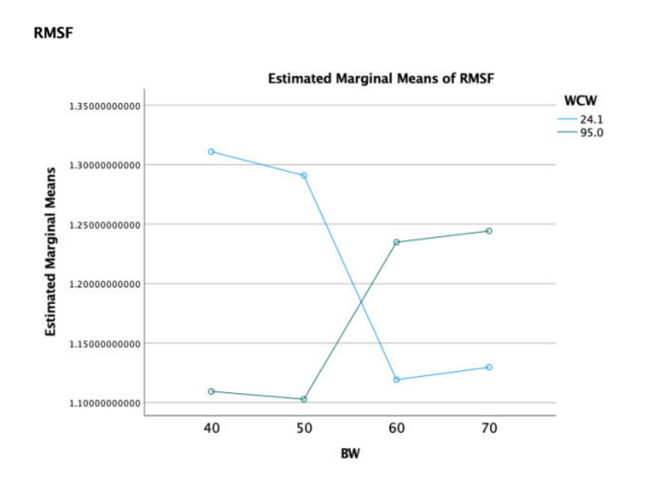

Figure 6: Estimated Marginal Means of RMSF of Mixed Effect of WCW and BW.

Mixed effect of WCW and TE

It was also mentioned that the mixed effect of WCW and TE significantly affected RMSB. The RMS was therefore compared to the ISO 2631-1 standard to understand the level of discomfort of the user on different TEs of different WCWs. Results showed that in the 95 kg EPW, up kerb, and down kerb ranked at a very uncomfortable level. Up slope, down slope, and pavement blocks ranked at a comfortable level while poured concrete was at a fairly uncomfortable level. In the 24.1 kg EPW, poured concrete ranked at a fairly uncomfortable level whereas all other terrains were at an uncomfortable level (Figure 7).

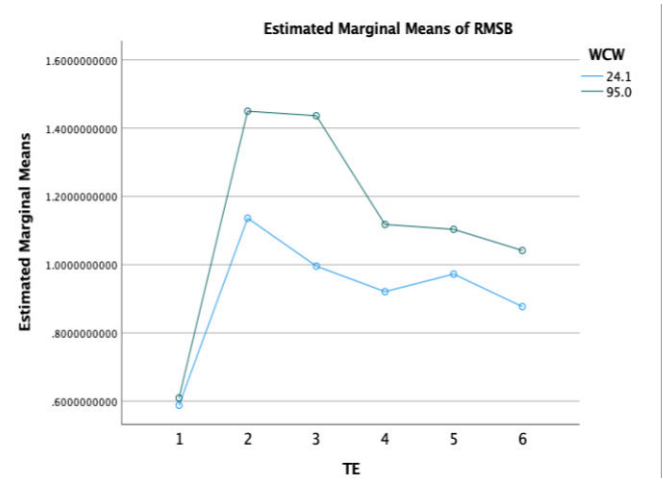

Figure 7: Estimated Marginal Means of RMSB of the mixed effect of WCW and TE. 1= poured concrete, 2 = up kerb, 3 = down kerb, 4 = up slope, 5 = down slope, 6 = pavement blocks.

Linear regression analysis

Simple linear regression was used to develop a prediction model for each RMS. Higher adjusted R square value in the model represents that it can explain more variability. It was found that TE and BW significantly predicted RMSS ($p<0.001$) whereas WCW and BW significantly predicted RMSB($p<0.001$) (Table 11,12). It was also found that TE significantly predicted RMSF ($p<0.001$) (Table 13).

Table 11: Regression test on RMSS.

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.354	1	.354	13.550	.000[b]
	Residual	3.706	142	.026		
	Total	4.060	143			
2	Regression	.603	2	.302	12.304	.000[c]
	Residual	3.456	141	.025		
	Total	4.060	143			

a. Dependent Variable: RMSS

b. Predictors: (Constant), TE

c. Predictors: (Constant), TE, BW

Table 12: Regression test on RMS.

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1.607	1	1.607	17.784	.000[b]
	Residual	12.830	142	.090		
	Total	14.437	143			
2	Regression	2.176	2	1.088	12.509	.000[c]
	Residual	12.261	141	.087		
	Total	14.437	143			

a. Dependent Variable: RMSB

b. Predictors: (Constant), WCW

c. Predictors: (Constant), WCW, BW

Table 13: Regression test on RMSF.

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	2.142	1	2.142	17.091	.000[b]
	Residual	17.800	142	.125		
	Total	19.943	143			

a. Dependent Variable: RMSF

b. Predictors: (Constant), TE

DISCUSSION

The aim of this study is to explore the vibration resistance performance of power wheelchairs and seat cushions in meeting the daily needs of wheelchair users in urban living environment. To the best of our knowledge, this is the first study exploring power wheelchairs and seat cushions' vibration resistance performance. Whole body vibration had great significance with all common types of terrain in urban city. The body weight (BW) of wheelchair users and wheelchair weight (WCW) had a significant mixed effect on WBV, specifically on the seat surface and footrest.

Terrains effect on WBV

The findings of this study imply that Hong Kong common urban terrains significantly affect WBV, across all surfaces (seat surface, back seat, and footrest). As not only the roughness of the road surface materials like pavement blocks but also the gap of materials being paved apart could increase the vibration [11], Hong Kong urban terrains play an important role in affecting WBV that could increase wheelchair users' discomfort in daily community mobility.

Our study further revealed that the pattern of WBV, from highest to lowest, was arranged as follows: kerb, slope, pavement blocks, and poured concrete. While up kerb and down kerb resulting in WBV levels (1.4-1.6 m/s^2) that were very uncomfortable and could likely cause health risks [12] in 4-8 hours of exposure (Figure 8), wheelchairs users rarely would expose to such condition in Hong Kong for that long period of time. Still, 1-2 hours of exposure to 1.4-1.6 m/s^2 WBV levels could also pose potential health risks. However, commonly speaking, wheelchairs users are likely to ride over terrains like pavement blocks for a long period of time as most pedestrian roads in Hong Kong are paved with bricks. The RMS transmitted from pavement blocks, as documented in our research, fell in the 0.8-1.6m/s^2 range, indicating that 4-8 hours of exposure to this level of vibration could impose likely potential health risk (Figure 9). Whereas the RMS of poured concrete fell in the 0.5-1.0m/s^2 range, which posed less likelihood of health risk and discomfort (Figure 10). A potential reason for high WBV in pavement blocks could be that the width and depth of the gap between bricks causes continuous bumps every time the wheelchair passes through them. In Hong Kong, sand is a common medium as filler for gaps in between pavement blocks and loss of sand over time from rainfalls could lead to wider gaps and uneven pavement [18]. In this regard, poured concrete could be more preferable for pedestrian road materials for the lower WBV levels, discomfort level, and reduced health risks for power wheelchair users. In combination with future urban planning, wheelchair-user education would be appropriate to increase awareness of road surface choices. For instance, to minimize the use of kerbs and use slopes instead.

BW and WCW effects on WBV

Findings from this study indicated that BW and WCW were respectively highly correlated to WBV. Our study showed that the heavier the BW, the lower the WBV. One possible explanation is that a heavy body has a higher inertia, therefore lowering the acceleration. However, the exception to this trend occurred between WCW and WBV, where increased WCW led to higher WBV.

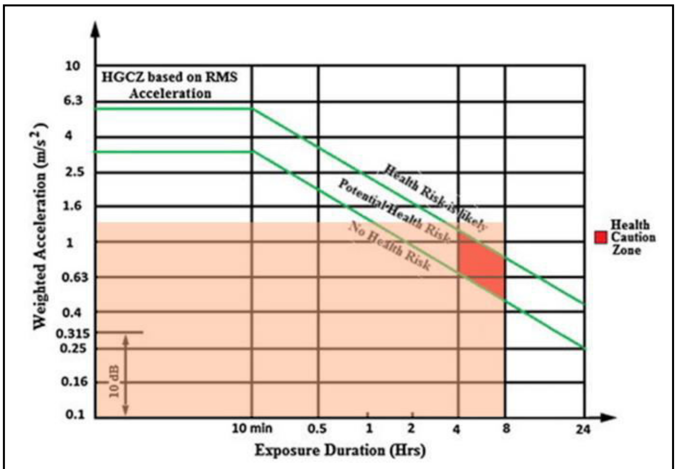

Figure 8. WBV at up kerb and down kerb levels in 4-8 hours of exposure [12].

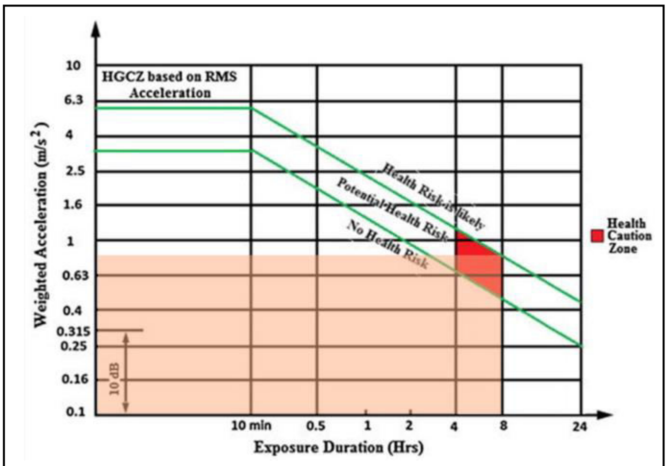

Figure 9. WBV levels at pavement blocks in 4-8 hours of exposure [12].

Furthermore, the results of our study evidenced the significant mixed effect of BW and WCW on WBV, specifically at the seat surface and footrest. Our studies further revealed that for above 60kg wheelchair users, the use of light wheelchairs would lower RMSS and for below 60kg users, heavy wheelchairs would lower RMSS. Likewise, a 55kg inflection point was found for RMSF. For above 55kg wheelchair users, the light wheelchair would lower RMSF. As for users under 55kg, a heavy wheelchair would lower RMSF. This finding may be explained by the fact that in our study, the weight of our wheelchairs also comprises other elements that could contribute to this trend, namely the heavy wheelchair is a rigid frame with a passive suspension device and the light wheelchair is a foldable frame with no suspension device. Another possible explanation is the height difference of the wheelchair, which eventually led to a change in height of center of gravity and stability of the dummy. Further investigation is needed to precisely identify the factors involved.

Nevertheless, it can be inferred that in clinical practice, healthcare professionals should consider BW and WCW when prescribing power wheelchairs for maximum comfort and minimum health risks.

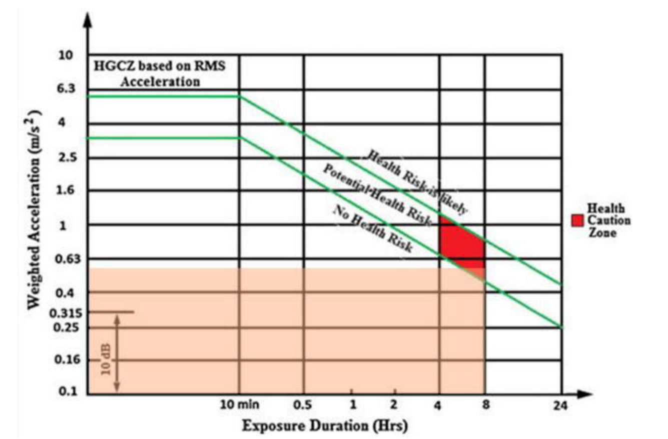

Figure 10. WBV levels at poured concrete in 4-8 hours of exposure [12].

Differences in WBV levels in between positions

Moreover, our study demonstrated the differences in WBV levels at the seat surface and footrest while running over the same terrains. Our study has shown that at 40kg BW, the RMSF has reached beyond 1.3m/s² which if users are exposed for 1-2 hours, the level of WBV at the footrest would cause potential health risks and be very uncomfortable for wheelchair users (Figure 11). On the other hand, under the same circumstances, the RMSB is at 0.85m/s², which poses no health risks even though it remains uncomfortable in terms of users' experience in the ISO-2631-1 standard (Figure 12). The WBV variation of different body parts indicates that there are different levels of health risks and discomfort from different body sites in one event, which signifies the importance of considering the history and site of musculoskeletal pain and pathology of wheelchair users. WBV and its harmful effects on the body are well studied. Former research documented that WBV would result in inflammation and degeneration of the intervertebral disc which could contribute to low back pain. It is also suggested that long exposure to WBV could cause large relative displacements between lumbar vertebrae, extra compressive loading, and shear stress on the spinal tissues [19]. Aside from low back pain, other research indicated after 4-8 weeks of exposure to WBV, meniscus tears, and focal articular cartilage damage were induced in the knee joints of mice [20]. However, these studies do not specify the transmission origin of the WBV. In combination with previous studies on WBV's harmful effects on low back and knee, our study's finding further suggests that if wheelchair user has a history of low back pain, the healthcare professional should elect a combination of wheelchairs that has relatively lower WBV at the seat surface, which could potentially prevent the aggravation of low back pain. Similarly, patients with a record of knee pain or discomfort should opt for a wheelchair combination that elicits lower WBV levels at the footrest.

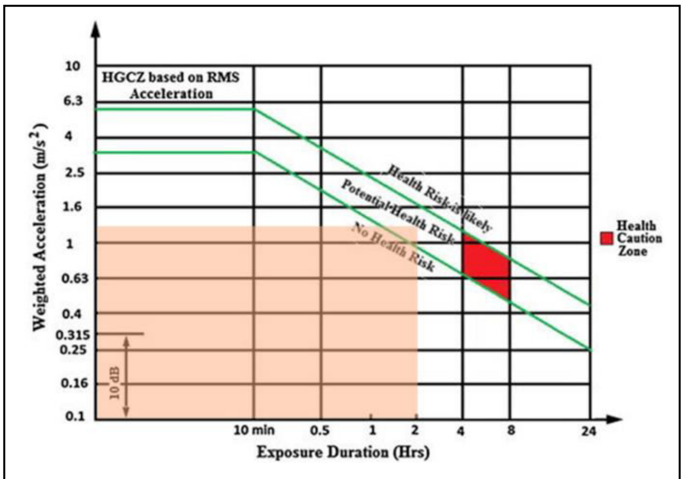

Figure 11. Health risk of WBV in RMSF [12].

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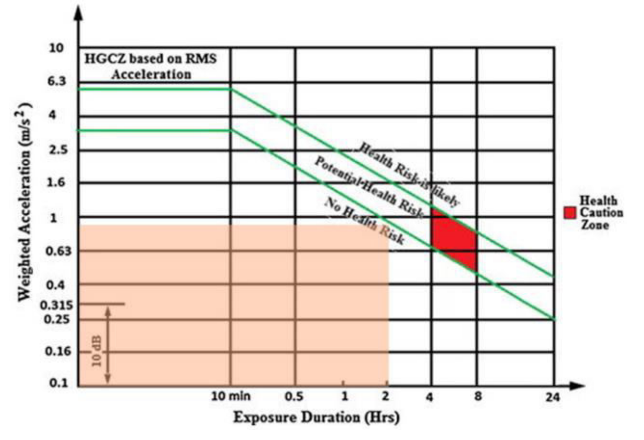

Figure 12: Health risk of WBV in RMSB [12].

Seat cushions on WBV

Lastly, our study suggests seat cushions had no significant effects on WBV across all planes. This goes against the findings of previous research, which suggested air-based cushions and air and foam cushions have contributed to the whole vibration-resistance performance [7-9]. A possible explanation of our results is that our experiment designs, for example, the brands of seat cushions used, differ from other studies, which could vary the results. The measurement units of other research also differ from ours as they adapt vibration dose value (VDV) instead of RMS in our research. It is also possible that the main function of the seat cushion is to evenly distribute pressure instead of reducing WBV (Brienza et al., 2010). But further investigation is needed to explore the vibration resistance performance of seat cushions.

LIMITATIONS

Despite the new findings about the vibration resistance performance of power wheelchairs and seat cushions in local urban living environment, several limitations need to be acknowledged. First, we were not able to single out wheelchair designs factors in the experiment, therefore limiting our understanding of which specific design features affect WBV the most. Studies about different power wheelchair designs and WBV effects should be done. Second, the small sample size of wheelchairs and seat cushions limits us to understanding the vibration resistance performances of other commonly prescribed power wheelchairs in Hong Kong which may increase the significance of the research. Besides, we were only able to collect objective quantitative data from the dummy. Real human subjects would be able to provide the actual human data, user's experience and subjective discomfort. Moreover, the speed control of the power wheelchairs was manual instead of mechanical or computerized which could provide smaller variation in speed in each trial, eventually reducing the noise of the experiment. Lastly, our study was carried out on simulated road surfaces instead of real Hong Kong public venues that power wheelchair users experience daily, hence there may be some Hong Kong terrains we could not test, for example, unpaved roads near village houses.

CONCLUSION

In summary, WBV had great significance with all common types of TE in Hong Kong. The BW of wheelchair users and WCW had a significant effect on WBV, specifically on the seat surface and footrest, while seat cushions' effect on WBV remained inconclusive and further investigation is needed.

PATENTS

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The data presented in this study is not available on request.
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