

Experimental comparison of vibrations from doorstep threshold perturbations on powered wheelchair users.

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BACKGROUND

An estimated 43,000 individuals are power wheelchair (PWC) users in Canada, representing ~15% of all wheeled mobility device use (manual wheelchairs, power wheelchairs and scooters) [1]. A similar proportion of PWC users is estimated in the USA. From a sample of approximately 3.7M users of wheeled mobility devices in the USA, we can estimate the number of PWC users to be around 300,000. Evidence supports that PWC can positively impact the well-being, self-esteem, pain, activity, and participation of those individuals (e.g. [2–4]). Several studies report various problems caused by vibrations experienced during wheelchair use (e.g., low-back and neck pain, muscle aches and fatigue [5, 6]). However, these studies mainly focus on long-term PWC use and do not map the vibration response according to obstacle type, setting preferences or PWC components. Thus, it is difficult to determine the cause and impacts of vibrations, which may inform PWC set-up, positioning and training for an optimal use.

Indeed, during the design or prescription of PWC, different settings and components can be chosen like wheel types, active wheel position, setup of shock absorbing systems, etc. When facing ground perturbations (GP), depending on their capacities and wheelchair characteristics, PWC users can react differently both to perturbations and their reactive vibrations. This can be more or less comfortable. They can slide on the seat or even lose control of their PWC which can generate fatigue or, in the worst cases, injuries. PWC manufacturers provide documentation on their products and some are known to have stiff or smooth shock absorbers. However, to our knowledge, there is currently no study to quantify the effects of GP on PWC users' efforts to remain in control of their device. In a previous study [7], we proposed a method to quantify and analyze the vibrations on PWC users when overcoming an obstacle.

Being able to quantify the vibrations on PWC users in any situation will help to compare designs and settings of PWC to: (i) find the best choices with respect to the PWC users' environments and potential GP; and (ii) give comparative metrics for design improvements. Indeed, as supported by several studies [8–10], PWC design can be improved by considering the potential vibrations experienced by the users.

OBJECTIVES

The study's objectives were to: 1) measure vibrations generated by different PWC designs, and 2) compare these measures to map the vibration quantities that are dependent on different experimental variables (speed, obstacle, and PWC model).

METHODS

The experimental method used to measure the quantity of vibration is based on the method proposed in a previous study [7], but includes a few improvements on the measurement apparatus to respect the requirement from the International Standards Organization 2631-1 standard on human vibration [11] (ISO 2631-1) and the statistical method to take into account repeated measures from sensors.

Measurement apparatus

As a requirement from the ISO 2631-1 [11], the minimum frequency bandwidth to measure vibrations that affect the health and comfort in humans is 1-80Hz. To track motion and vibration, we chose to replace the inertial motion units (IMU) from Xsens (limited sampling rate of 100Hz, bandwidth of 0-50Hz) with those from Endaq (S3-16 Vibration Sensor) (sampling rates up to 3200Hz, bandwidth of 0-300Hz). Additionally, since different PWC models have different frames, the positioning of sensors does not allow standardized comparisons. We chose to measure vibration on the torso and thighs of the dummy, not modifying the sensors' location.

The vibrations are 3D recorded, the x-axis represents the driving forward direction, the y-axis, the lateral direction of the PWC and z-axis, the vertical direction normal to the seat base.

As presented in a previous study [7], the CoP didn't move much while using the headless dummy, which wasn't representative of reality. Thus, we choose not to use the pressure mattress sensors (only keep it for experiments with human subjects).

Signal analysis

IMUs measure accelerations that are used to quantify vibrations. Based on the ISO 2631-1 standard [11], the vibration dose value (VDV, Eq. 1) and signal energy (E_s , Eq. 2) methods applied on measured acceleration should be used to assess the effects of vibration on health and comfort. The VDV primarily characterizes the amplitude of vibration while E_s characterizes the oscillation. Higher scores indicate higher vibrations. The signal analysis was performed using the programming language Julia 1.6.0.

$$a_{VDV} = \left(\int_0^T a_w^4 dt \right)^{1/4} \quad (1)$$

$$E_s = \int_0^T a_w^2 dt \quad (2)$$

Equations (from top to bottom): acceleration (1) vibration dose value (VDV) and (2) signal energy (E_s). Where a_w is the frequency weighted acceleration and T is the time period of the experiment

Statistical analysis

The statistical method used to analyze the data and determine the impact of PWC settings was nparLD [12]. PWC speeds, obstacle types and PWC models were defined as independent variables. The different IMUs were defined as repeated variables. E_s and VDV were the dependent variables. The statistical analysis was done with the package nparLD (version 2.1, 2012-09-19 September 19 2021) using R (version 4.0.2). The nparLD analysis can only analyze two independent variables at a time but we have three of them. We choose to keep: (i) the PWC models the same since our objective was to compare them; and (ii) PWC speeds since we wanted to measure the vibrations according to the type of obstacle. The level of significance is set at 0.05.

Procedure

We used PWC from three different manufacturers, with different mechanical structures and wheel positions: Amylior (Alltrack R3 Hybrid), Permobil (M300), and Quantum (Edge3 Stretto). They were set up as follows: (i) the left armrest was removed to position the dummy; (ii) the original backrest-cushion was removed, and the dummy was placed on the rigid and flat part of the backrest, and (iii) the seat cushion was removed and replaced by two superimposed foam cushions. To control and drive the PWC during the experiment, the right armrest remained on the PWC and the control joystick was activated by an operator who walked alongside the PWC. During the experiments, we used three pre-programmed control speed: Low = 0.6m/s, Medium = 1.2m/s and High = 1.8m/s. Those values were based on measurements from the encoder.

We chose to test door threshold (DT) as a GP simulated using planks (101mm x 1520mm) of different heights (11mm, 16mm and 27mm). Those planks were attached to the floor with brackets on one side and with double-sided tape on the other side, strong enough to avoid movement when the PWC drove over the obstacles. To assess changes in experimental variables, each setup was used at least seven times to ensure statistical strength of the analyses. Each trial was repeated 10 times (9 setups x 10 trials = 90 trials).

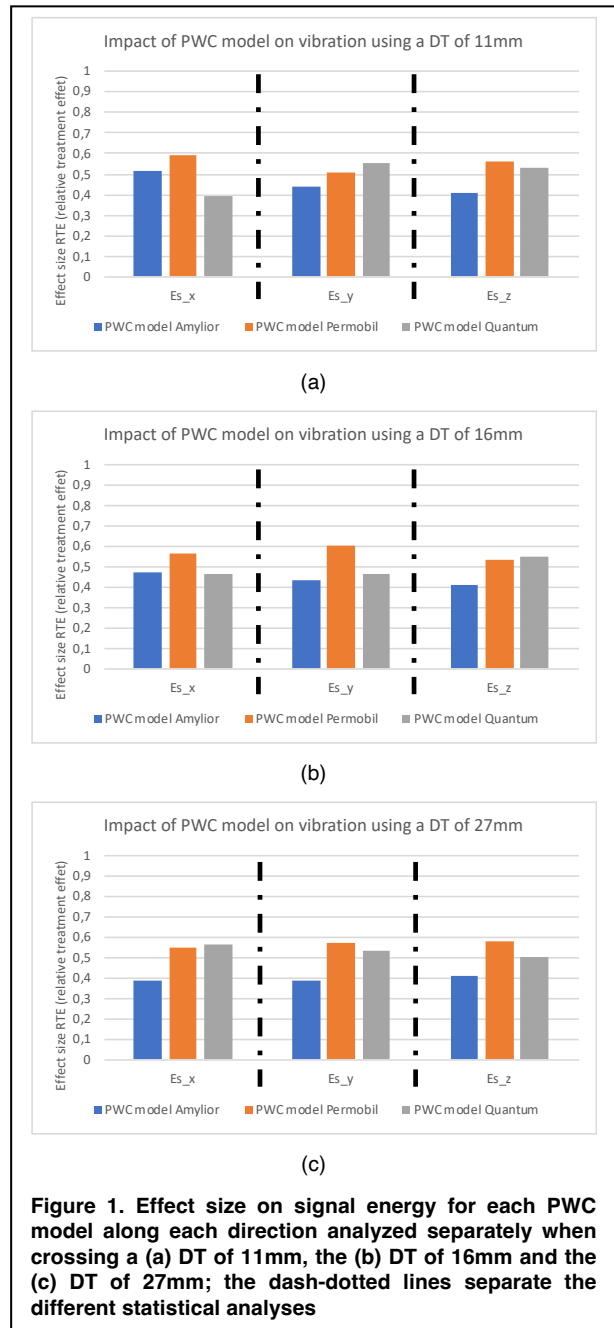


Figure 1. Effect size on signal energy for each PWC model along each direction analyzed separately when crossing a (a) DT of 11mm, the (b) DT of 16mm and the (c) DT of 27mm; the dash-dotted lines separate the different statistical analyses

RESULTS AND DISCUSSION

Table 1 presents the p-value of the impact of the variables and their interactions on the E_s . Note that only the results of E_s were analyzed, since the results in terms of VDV are very similar. In all conditions, the combinations of experimental conditions (speed and position of the sensor) had a significant impact on vibrations ($p < 0.05$). As demonstrated in the previous study [7], the higher the speed and obstacle height, the higher the amplitude of vibrations. Along the x and z-axis, the PWC model had a significant impact on vibrations. This means that at least one PWC model generates more or less vibration on the dummy than the others. This is not the case along the y-axis. This is probably due to the way the PWC approaches the DT. Indeed, the PWC is driven towards the DT, and if the PWC structure is well balanced, the lateral vibration should be almost the same and be smaller than for the other axes (up to 20 times smaller for the highest speed and higher obstacle).

Table 1. p-value of the impact of variable selection on signal energy; the italic font is used for statistically non-significant p-value > 0.05

Variable interactions	p-value								
	DT of 11mm			DT of 16mm			DT of 27mm		
	x-axis	y-axis	z-axis	x-axis	y-axis	z-axis	x-axis	y-axis	z-axis
Speed	>0.00001	0.010	>0.00001	>0.00001	0.0006	>0.00001	>0.00001	>0.00001	>0.00001
PWC model	>0.00001	<i>0,91</i>	>0.00001	>0.00001	0.001	>0.00001	>0.00001	0.001	>0.00001
Sensor	>0.00001	>0.00001	>0.00001	>0.00001	>0.00001	>0.00001	>0.00001	>0.00001	>0.00001
Speed: PWC model	>0.00001	0.031	>0.00001	>0.00001	<i>0.154</i>	>0.00001	>0.00001	<i>0.455</i>	>0.00001
Speed: Sensor	>0.00001	>0.00001	>0.00001	>0.00001	>0.00001	>0.00001	>0.00001	>0.00001	>0.00001
PWC model: Sensor	>0.00001	0.003	>0.00001	>0.00001	>0.00001	>0.00001	>0.00001	<i>0.082</i>	>0.00001
Speed: PWC model: Sensor	>0.00001	<i>0.307</i>	>0.00001	>0.00001	0.034	>0.00001	>0.00001	0.002	>0.00001

Table 2 presents the p-value for the post-hoc impact analysis of the PWC model on the E_s . In the x and z axes, the vibrations are significantly different between all PWC models ($p < 0.05$) for the DTs of 11mm and 27mm. For the DT of 16mm, along the x-axis, the vibrations for the Amylior and Quantum PWCs are equivalent (p -value > 0.05). On the z-axis, the vibrations for the Permobil and Quantum PWCs are equivalent (p -value > 0.05). Hence, any difference of the effect size RTE (relative treatment effect) illustrates a significant difference in vibrations. This is not the case on the y-axis, but, as previously explained, vibrations in this axis are much smaller.

Table 2. p-value of post-hoc analysis of the impact of PWC model on signal energy; the italic font is used for statistically non-significant p-value > 0.05

	PWC model	p-value					
		DT of 11mm		DT of 16mm		DT of 27mm	
		Amylior	Permobil	Amylior	Permobil	Amylior	Permobil
x-axis	Permobil	>0.00001		>0.00001		>0.00001	
	Quantum	>0.00001	>0.00001	0.362	>0.00001	>0.00001	0.007
y-axis	Permobil	<i>0.245</i>		0.0008		0.000	
	Quantum	<i>0.086</i>	<i>0.471</i>	<i>0.690</i>	0.006	0.006	<i>0.565</i>
z-axis	Permobil	>0.00001		>0.00001		>0.00001	
	Quantum	>0.00001	.0.0006	>0.00001	0.547	>0.00001	>0.00001

Fig. 1 shows the effect size RTE [13] of the PWC model for each DT height along all axes on E_s . This represents the vibration intensity with respect to the average, a higher score representing higher vibration. Each three-bar set

represents the effect size RTE for each PWC model (separate statistical analysis). As vibrations without treatment don't exist (you cannot remove the experimental settings to obtain values for vibration), we consider the mean value of all vibrations as the no treatment value with an effect size value H_0 of 0.5. In most cases, the effect size RTE of the Amylior PWC is the lowest or equivalent to the other PWC models. The DT of 11mm is the only experimental condition where the effect size RTE of the Amylior PWC on the x-axis is in second place in terms of vibration intensity. On the other hand, the Permobil PWC generates, in most cases, the highest effect size RTE.

This experiment allowed the comparison of vibration quantity generated by three different PWC models on users when wheeling on three different DT. In general, the Amylior PWC seems to generate less vibrations, while the Permobil PWC seems to generate the most. In future experiments, the number of disturbance types will be increased and other PWC models will be used to map the vibrations generated on PWC users. This will provide clinicians with information for the selection of the PWC model that fits best with the user's environments, according to the most likely and complex disturbances the user has to overcome.

CONCLUSION

In this study, we presented experimental measures of vibrations generated on PWC users. The experiment with the door threshold obstacle (DT) allowed to compare three PWC models from different manufacturers (Amylior, Permobil and Quantum). The results suggest that the Amylior PWC generated less vibrations. Although statistical differences were observed, clinical significance must now be determined. Mechanical design and PWC structure must also be assessed to understand what causes these differences.

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