


# Estimating whole-body vibration limits of manual wheelchair mobility over common surfaces

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## Abstract

Whole-body vibration (WBV) experienced during manual wheelchair use was quantified across several types of terrain (tile, sidewalk, decorative bricks, expanded metal grates). Over-ground travel was controlled using a robotic propulsion system. Vibrations along the vertical axis were measured with a triaxial accelerometer mounted to the seat of the wheelchair. Root-mean-square acceleration values were compared to the health guidance exposure limits established by the European Council using the WBV calculator tool published by the Health and Safety Executive (HSE). Vibrations along the vertical axis were well below the exposure values associated with health risks. Even the most aggressive tactile surface (grates) tested in this study would require more than 14 h of daily travel to reach the “exposure action value,” and more than 24 h would be required to reach the “exposure limit value”. Considering the average cumulative duration of active self-propulsion among manual wheelchair users is around an hour or less, none of the tested conditions were deemed unsafe or damaging.

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## Introduction

Prolonged exposure to whole-body vibration (WBV) can be damaging to tissue health and the overall well-being of the human body. For commercial drivers and heavy machinery operators especially, certain levels of WBV have been linked to neuromuscular fatigue, spinal injury including disc degeneration, and lower back, and neck pain.<sup>1</sup> Industrial workplaces monitor WBV by measuring the magnitude and duration of vibration exposure for able-bodied individuals experiencing passive vibrations from a seated position, following the procedure defined by ISO 2631–1.<sup>2</sup> Interpretation of the data is nuanced and complex but can be simplified by online resources, such as the WBV calculator published by the Health and Safety Executive (HSE).<sup>3</sup> The HSE is a UK government agency responsible for workplace health, safety and welfare, and for research into occupational risks. Tools like their WBV calculator have great potential in streamlining the data analysis for research purposes in myriad situations where vibration exposure is common and/or unavoidable. For example, the HSE WBV

calculator can be used to interpret the vibration exposure risks of manual wheelchair (MWC) users during their daily routine. These individuals utilize MWCs as their primary means of travel and, while manual propulsion has many associated health risks,<sup>4</sup> MWCs are often their best available mode of transportation. Any vibration exposure they experience is directly tied to their mobility. Therefore, it is vital to determine if their level of exposure is harmful and, if necessary, identify ways to minimize any vibration-induced health risks.

Prior studies have insufficiently concluded that wheelchair vibration is harmful to the user based on inaccurate

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assumptions about wheelchair usage. For example, Garcia-Mendez et al.<sup>5</sup> calculated their manual wheelchair vibration assessments using an average of 13 h of “daily exposure” despite measuring only an hour of self-propulsion per day. This implies 12 h, on average, of vibration exposure occurred when the user was not propelling the wheelchair, but merely occupying the chair. This is a misrepresentation of the actual conditions of real-world wheelchair use, and consequently the associated health risks. Actual wheelchair use involves short ( $\leq 20$  s) bouts of motion at slow ( $\leq 0.44$  m/s) speed with frequent stops, starts, and turns.<sup>6</sup> Studies on MWC vibrations either need to have better understanding of wheelchair use, or better report the testing conditions. Other studies present continuous vibration alongside shock-induced vibration by testing wheelchairs traveling over large and aggressive obstacles on a simulated road course.<sup>7</sup> Trials involving frequent obstacle-induced, high-magnitude accelerations (i.e., “shock”) appear to have much larger vibration magnitudes which necessitate complementary assessments (e.g., vibration dose value). Shocks are intermittent, such as traveling over door thresholds, and should not be conflated with constant and unavoidable vibration.

The objective of this study was to demonstrate the use of the WBV calculator tool published by the HSE<sup>3</sup> to analyze vibration exposure of a wheelchair traveling over four common flooring surfaces: linoleum tile, decorative brick, sidewalk pavers, and metal grates. A robotic propulsion system was utilized to ensure consistent propulsion (wheel speeds) and occupant characteristics (loading, weight distribution) across trials, resulting in vibration measurements from highly repeatable propulsion trials. With that said, variations in occupant characteristics are not expected to affect vibration measurements at the frame.<sup>8</sup> Exposure values were calculated from the vertical component of the vibrations only, because vertical vibrations are induced by floor surface characteristics, are isolated from the fore-aft accelerations of the active propulsion cycle, and are aligned with the physiological locations associated with back pain and soreness from the seated posture.<sup>9</sup>

## Method

One rigid ultra-lightweight wheelchair frame (Rogue, Ki Mobility, LLC) was equipped with solid polyurethane caster wheels (Primo 5"x1", Xiamen Lenco Co., Ltd) and pneumatic drive tires (Primo Orion 24"x1-3/8", Xiamen Lenco Co., Ltd) on metal spoked wheels. These component choices reflect a typical ultra-lightweight wheelchair configuration for a full-time wheelchair user.

Propulsion was controlled using the robotic Anatomical Model Propulsion System (AMPS). The mechanical design and validation have been published previously.<sup>10</sup> The AMPS mass (80 kg) and weight distribution (70% over the rear axle) were informed

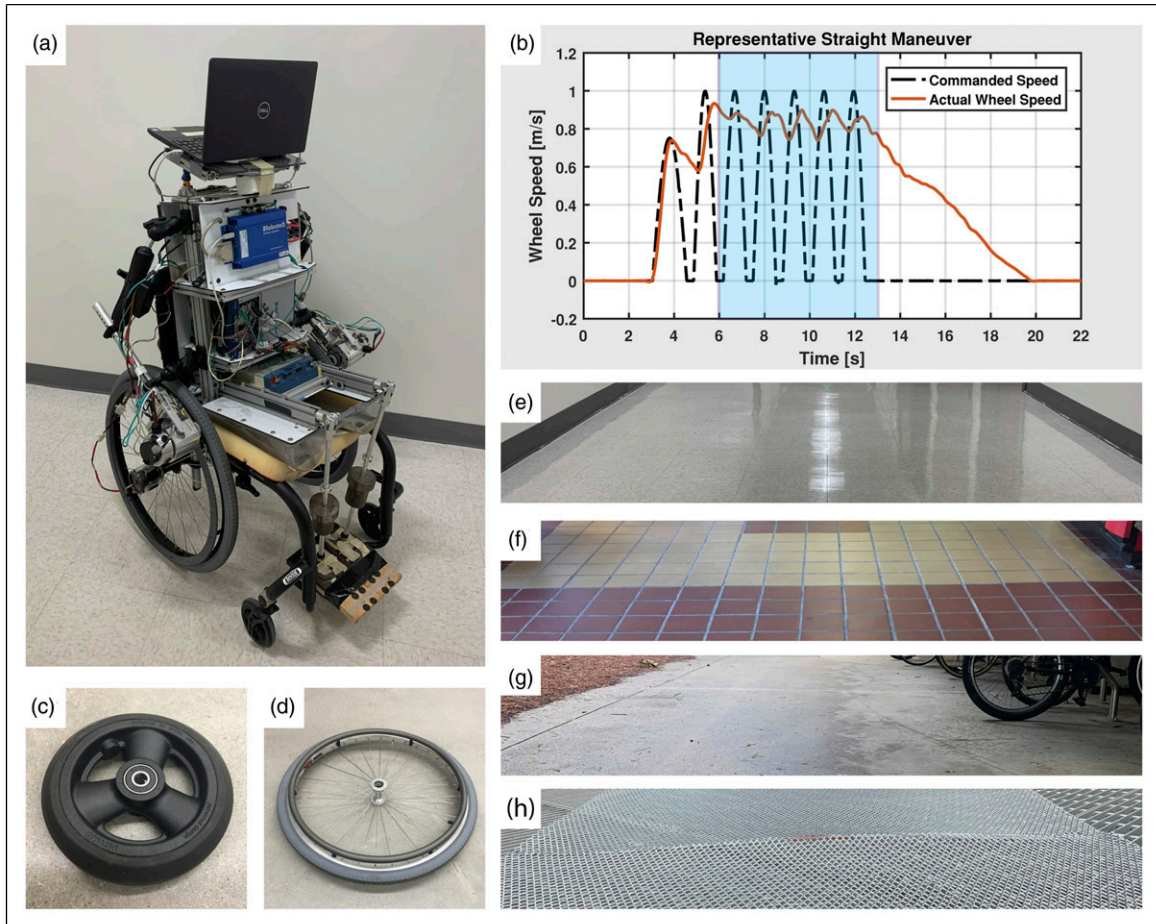
from wheelchair testing dummy standards and by recent measurements of representative wheelchair user populations.<sup>11</sup> The AMPS propelled the wheelchair in a straight line over each of the four surfaces with identical series of pushes. This straight trajectory comprised two initial pushes to accelerate the wheelchair, followed by five pushes to maintain a steady-state travel speed, concluding with a coast-down deceleration period to a stop. Twelve over-ground trials were conducted on each surface. The AMPS, the commanded wheel speeds for the straight maneuver, the surfaces, and the wheelchair components can be seen in Figure 1.

One triaxial accelerometer (X16-1D, Gulf Coast Data Concepts, LLC) was securely fastened to the top surface of the seat cushion, beneath the AMPS. The cushion was made from 3" of standard high-resiliency foam with an indentation load deflection rating of 45 lbs. The accelerometer was aligned with the primary axes of the wheelchair ( $x$ -axis for anteroposterior,  $y$ -axis for mediolateral, and  $z$ -axis for vertical). The  $z$ -axis acceleration was sampled at 200 Hz. Accelerometer data were collected during the steady-state phase of motion (shown in the shaded region of Figure 1(b)) to isolate the consistent vibrations from the transient vibrations induced in the acceleration and deceleration phases.

Vibration data were processed with a custom MATLAB script in accordance with the ISO 2631-1 standard for evaluation of vibration. Raw acceleration values were converted to units of  $m/s^2$  and normalized through mean-subtraction. The accelerations were then passed through a combination of four frequency-weighting filters (high-pass, low-pass, acceleration-velocity transition, and upward step), as prescribed by the ISO 2631-1 standard.<sup>2</sup> Finally, root-mean-square (RMS) values of the frequency-weighted vertical accelerations ( $a_{wz}$ ) were calculated for each trial. Average values ( $N = 12$ ) for each surface were inserted into the HSE WBV calculator.<sup>3</sup>

For analysis of datasets with multiple axes of measurement, the HSE WBV calculator includes an option to apply additional weighting factors ( $k_x, k_y = 1.4, k_z = 1.0$ ). It then bases its calculations on the largest of the three acceleration values. As this study utilized only the  $z$ -axis, the additional  $k$ -factor weighting was unnecessary.

The output of the WBV calculator is the estimated exposure time required to reach the region of potential health effects. This region is defined by two values assigned by Council Directive 2002/44/EC.<sup>12</sup> The exposure action value (EAV) is the daily amount of vibration exposure above which employers are required to take actions to control exposure. As such, the EAV is a threshold that triggers the need to address and reduce vibration exposure. The exposure limit value (ELV) denotes the maximum amount of vibration a worker may be exposed to on any single day. It represents vibration to which the worker should not be



**Figure 1.** Images of (a) the AMPS and (b) the wheel speed trajectory for the Straight maneuver with shaded steady-state phase. The default components are (c) Primo 5" x 1" caster wheels and (d) Primo Orion 24" x 1-3/8" drive tires on metal spoked wheels. The tested surfaces were (e) tile, (f) decorative interior brick, (g) poured concrete sidewalk, and (h) expanded aluminum grates.

exposed. WBV is not proven to have any effects on health below the EAV ( $0.50 \text{ m/s}^2$ ), whereas potential health effects are "likely" to occur above the ELV ( $1.15 \text{ m/s}^2$ ).<sup>12</sup>

## Results

Table 1 summarizes the RMS  $a_{wz}$  values for each of the four surfaces and the output of the WBV calculator, presented as time to reach the EAV and ELV.

Brick, sidewalk, and expanded aluminum grates experienced similar vibration values at the seat. Smooth tile induced the smallest magnitude of vibration. All over-ground propulsion trials had RMS  $a_{wz}$  values below the EAV. Coefficients of variation reflect the low variance in the measurements compared to the mean value. Interpretation of the WBV Calculator output shows that it would take over 14 h of travel on brick, sidewalk, or grates to reach the EAV, and more than 24 h over tile. None of the surfaces would reach the ELV in under 24 h.

## Discussion

None of the surfaces induced any vibrations that posed health risks. The continuous vertical vibrations measured during MWC travel over the four surfaces remained below the health guidance caution zone, according to the HSE guidelines on WBV exposure. These vertical vibration measurements represent vibrations transmitted through the frame to the seat in conditions representing everyday traversal of the tested surfaces.<sup>7</sup> Whereas carbon fiber frames<sup>13</sup> and viscoelastic cushions<sup>14</sup> may reduce the vibration transmitted to the seat, occupant characteristics like weight are mostly influential on how the vibration is transmitted through the body.<sup>8</sup> In other words, any user traveling over these surfaces at this speed is expected to experience similar magnitudes of vibration at the seat, and these vibrations are expected to pose little to no health risks. Seat vibrations are not expected to widely differ between the AMPS and a human occupant. In support of this, human subjects experienced highly comparable vertical vibrations at the seat

**Table I.** Frequency-weighted vertical vibration measurements and the output from HSE WBV Calculator.

Surface	RMS $a_{wz}$ (m/s <sup>2</sup> )		Time to reach: (hh:mm)	
	Mean	Coeff.Variation, %	EAV 0.5 m/s <sup>2</sup> A (8)	ELV 1.15 m/s <sup>2</sup> A (8)
Tile	0.181585	7.4	>24 h	>24 h
Brick	0.368941	5.8	14:41	>24 h
Sidewalk	0.347091	10.2	16:36	>24 h
Grate	0.375417	12.9	14:11	>24 h

when propelling over smooth and textured flooring surfaces, as measured by Chénier and Aissaoui.<sup>13</sup>

It is important to interpret these vibration results within the context of actual MWC use. More than 1 hour of active propulsion is uncommon,<sup>5,6</sup> and bouts of mobility are slower (0.4 m/s) than the wheel speeds used in this study (0.8–1.0 m/s). Higher travel speeds generally induce higher magnitudes of vibration. Therefore, we can speculate that typical WBV exposure induced by MWC travel should be lower than the exposures observed in this study. Conflicting results from Garcia-Mendez et al. are based on multi-axis measurements taken *under* the seat cushion, where the vibrations are considerably higher but not reflective of the vibrations that the user directly experiences, rather than *above* the seat cushion as per ISO 2631-1. Similarly, the “harmful” levels of WBV reported by VanSickle et al.<sup>7</sup> may be caused by the use of series of rumble strips in their simulated road course. These rumble strips impart high-magnitude accelerations, or shock, to the system in addition to the continuous rolling-induced vibrations measured in this study. MWC users will naturally and unavoidably experience some level of shock through daily travel, such as traveling over the expansion joints between sidewalk pavers. However, these shocks are infrequent and often avoidable or minimizable by avoiding direct impact with the obstacle. Vibration, on the other hand, is constant and unavoidably imparted to the vehicle during its use.

Chénier and Aissaoui noted that ISO 2631-1 was developed specifically for able-bodied individuals in a seated posture passively experiencing WBV, and that the standards may not be applicable to individuals with spinal cord injuries or other impairments.<sup>13</sup> Thus, a greater discussion is required to determine the applicability of the measurement and analysis techniques (e.g., data filtering and guidance values) to the highly variable and vulnerable population using MWCs.

Tools like the HSE WBV Calculator simplify analyses by outputting directly interpretable results. Values that are below 8 h suggest that the RMS acceleration inputs were larger than the established values for either EAV or ELV, and exceed known risk levels for health effects. RMS accelerations below 0.5 m/s<sup>2</sup> cannot reach the EAV below 8 h.

Above that value, further action or investigation is required to properly assess risk levels. These observations can be made quickly and efficiently.

From a clinical perspective, our results suggest manual wheelchair propulsion does not inherently pose any notable health risk according to WBV guidelines, but many questions about wheelchair vibrations still remain. Current knowledge could be expanded by studying the vibration transmissions through frames using different wheelchair components (e.g., wheels, tires, and/or frames), with special focus on components with built-in elastomeric suspension elements to determine if they appreciably dampen vibrations and/or incur other performance-based tradeoffs such as rolling resistance. Travel speed should be considered as an additional test parameter. Outdoor travel is typically at higher speeds over rougher surfaces than indoor travel which could potentially induce larger vibrations than those seen in this study.

## Conclusion

This work demonstrates the use of the HSE WBV calculator to compare and easily interpret the vertical vibration exposure levels induced during manual wheelchair travel. Four surfaces were traversed with a robotically driven wheelchair. Vertical vibrations at the seat were measured and compared to the health guidance values published by the HSE. We found that all of the surface-induced vibrations remained below the exposure action and limit values, where there are no known health risks. Tactile surfaces like decorative brick and expanded metal grates induce greater magnitudes of vibration than smooth tile, but all would require more than 14 h of use per day to reach a level that could pose potential health risks. Our results conflict with results from prior WBV studies with MWC users. We believe these differences can be largely attributed to either external vibrations unrelated to the wheelchair propulsion, or shocks imparted to the frame by frequent obstacles used in the prior studies. It is advised that future studies should strongly consider the contributions of intermittent, infrequent shock versus continuous vibration exposure during wheelchair use.

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### Guarantor

Jacob Misch, PhD

### Contributorship

JM and SS researched literature and conceived the study. JM and SS were involved in protocol development. JM collected empirical data. JM and SS conducted data analysis. JM wrote the first draft of the manuscript. All authors reviewed and edited the manuscript and approved the final version of the manuscript.

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