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Mohamed, Elhassan, Sirlantzis, Konstantinos, Howells, Gareth and Dib, Jihad (2022) *Investigation of Vibration and User Comfort for Powered Wheelchairs.* IEEE Sensors Letters, 6 (2). ISSN 2475-1472.

IEEE Sensors Letters VOL. 6, NO. 2, FEBRUARY 2022 2500204 IEEE Sensors Council

Mechanical sensors

Investigation of Vibration and User Comfort for Powered Wheelchairs

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Manuscript received December 16, 2021; accepted January 22, 2022. Date of publication February 1, 2022; date of current version February 15, 2022.

Abstract—Disabled users who use powered wheelchairs for mobility may suffer back and neck pain. Prolonged exposition to whole-body vibration due to different terrain surfaces may negatively impact the user's health and comfort. This study investigates the impact of whole-body vibration on powered wheelchair users following the ISO-2631 standard. The ISO-2631 standard defines the whole-body vibration limits and quantifies its impact on the user's health and comfort. Four users with a range of different weights drive an electrical powered wheelchair (EPW) on five different terrain surfaces. Results indicate that users' weights can impact vibration perception. Additionally, outdoor surfaces generally produce high vertical accelerations, which can negatively impact the user's health and comfort when the EPW is driven for a long period.

Index Terms—Mechanical sensors, acceleration, disabled users, powered wheelchairs, ride dynamics, whole-body vibration.

I. INTRODUCTION

Seated individuals who are exposed to whole-body vibrations for a long period of time are at the risk of injury [1]. Electrical powered wheelchair (EPW) users can fit into this category as they drive for a prolonged time in dynamic environments, exposing themselves to whole-body vibrations that may cause back and neck pain. There is an increased health risk to the lumbar spine and the connected nervous system because of the long-term and high-intensity whole-body vibrations [1]. According to the ISO-2631 [1], the digestive system, the genital/urinary system, and the female reproductive organs are also impacted but with lower probability. Moreover, the health risks are likely to increase when the duration and the vibration intensity increase, while rest periods can reduce the risk.

There is a significant gap in the literature and the conducted research to evaluate the amount of vibration transmitted to the EPW users and its impact on health and comfort. Our study evaluates the feasibility of integrating ride dynamics measurements (i.e., vertical accelerations) to smart robotic wheelchairs as an expression of user travel comfort assessment.

Two main studies are closely related to our investigation. The first one measures the root-mean-square (RMS) vertical acceleration for ten healthy users with no physical or cognitive disabilities while traversing nine different surfaces using manual and powered wheelchairs [2]. The study recommends using specific paver types that produce low vertical accelerations, as high vertical accelerations can negatively affect users' health. However, the study does not quantify these accelerations to find their impact on the users' comfort and vibration perception with respect to the ISO-2631 standard [1].

The second study by Wang *et al.* [3] investigates the impact of whole-body vibration on the EPW user's comfort with respect to the ISO-2631 standard [1]. Each 10 s of the recorded data is processed using fast Fourier transform. In addition, the users are interviewed to indicate their level of comfort. Four different terrain types have been experimented: 1) Linoleum; 2) Asphalt; 3) Braille block; and 4) Elevator entrance. User's indication of riding comfort, when interviewed, agreed with the measured ones in two cases: Linoleum and Elevator with "Not uncomfortable" and "Extremely uncomfortable" outcomes, respectively, whereas user's opinion slightly disagrees with the measured comfort in the cases of Asphalt (measured: "A little uncomfortable," opinion: "Not uncomfortable") and Braille block (measured: "Extremely uncomfortable," opinion: "Very uncomfortable").

In this letter, we conduct a detailed investigation on the impact of whole-body vibration on the user's health, comfort, and probability of vibration perception according to the ISO-2631 standard [1]. Four users drive an EPW on five different terrain surfaces. Results indicate that users' weights can impact vibration perception. Therefore, terrain surfaces are not the only factor that impacts the user's health and comfort. Additionally, outdoor surfaces generally produce high vertical accelerations, which can negatively impact the user's health and comfort when the EPW is driven for a long period of time.

II. METHODOLOGY

A. System Installation

The ISO-2631 standard [1] defines methods of quantifying whole-body vibration in relation to human health, comfort, and probability of vibration perception. The primary quantity of vibration magnitude is acceleration. Acceleration vibration should be measured at points from which the vibration is considered to enter the human body (see Fig. 1). The considered frequencies for health, comfort, and vibration perception range from 0.5 to 80 Hz [1].

Sensors should be located at the interface between the human and the source of vibration. This study considered three areas of contact for a seated person to quantify the vibration as they represent the points from which the vibrations enter the human body: seat surface "pan" z-axis, seatback x-axis, and feet z-axis (see Fig. 2). Following the ISO standard 10326 [4], an extra sensor is installed on the powered wheelchair chassis/battery for referencing [see Fig. 2(c)]. The sampling frequency employed is more than double the required frequencies ($f_s = 200$ Hz) to cover the whole range of frequencies required by the ISO-2631 standard [1].

For data collection, the sensors are installed on the Roma Reno II Power Chair [see Fig. 2(a)]. The choice of this wheelchair is attributed

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Associate Editor: G. Langfelder.
Digital Object Identifier 10.1109/LSENS.2022.3147740

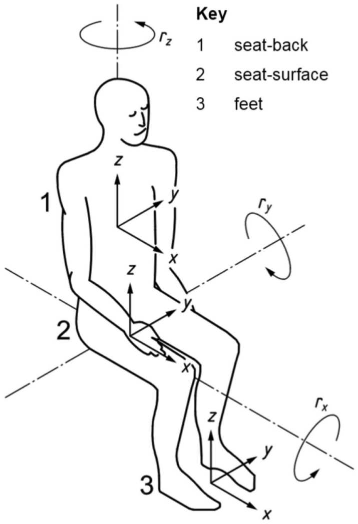


Fig. 1. Points of measuring the vibrations according to the ISO-2631 standard [1].

TABLE 1. User's Information.

User Information	User 1	User 2	User 3	User 4	Mean/Std
Weight (kg)	48	78	94	117	84.2 / 28.9
Height (cm)	160	179	184	183	176.5 / 11.2
Track time (min)	22.4	22.4	21.1	21.2	21.7 / 0.72
Average speed (Km/h)	3.4	3.4	3.7	3.6	3.5 / 0.15

to its design, as it does not have suspension or shock absorption systems. Consequently, we can assume that all the external vibration from the terrain's surface is transferred to the user's body. Four sensors are installed according to the ISO standards-2631 [1] and 10326 [4]. Fig. 2(b) shows the mounting disk with the inertial measurement unit (IMU) sensor. The IMU board uses the high-sampling-rate nine-degree-of-freedom MPU-9250 sensor. The accelerometer range is set to the lowest value ($\pm 2g$) to acquire high resolution readings.

Five different contrasting types of terrains are trialed during the data collection (see Fig. 3). Outdoor types are tarmac, tiled concrete, and pavement bricks, whereas indoor types are carpet and tiled floors. The track containing these terrains starts from a typical research laboratory to the central building of the university campus with a total length of approximately 1.3 km. Four users covering a range of body sizes are asked to follow the same track using a predefined wheelchair speed. The actual powered wheelchair speed and the completion time of the task vary based on the users' weights and the way of driving the powered wheelchair. Table 1 shows the users' weights, heights, average speeds, and the task completion time.

B. Evaluation

Three evaluation metrics are presented: weighted RMS acceleration a_w (m/s^2) [see (1)], maximum transient vibration value (MTVV) [see (2)], and estimated vibration dose value (eVDV) [see (3)]. According to the ISO-2631 standard [1], these metrics can quantify the vibration. Therefore, the impact of vibration on the user's health, comfort, and perception can be measured

$$a_w = \left(\frac{1}{T}\int_0^T a_w^2(t)dt\right)^{\frac{1}{2}} \tag{1}$$

where $a_w(t)$ is the weighted acceleration (m/s^2), and T is the duration of the measurement (s).

The MTVV represents the highest magnitude of $a_w(t_0)$ during the measurement period (T)

$$\text{MTVV} = \max\left[a_w\left(t_0\right)\right]. \tag{2}$$

The eVDV is more sensitive to peaks than basic evaluation methods

$$\text{eVDV} = 1.4 a_w T^{\frac{1}{4}}. \tag{3}$$

According to the ISO-2631 standard [1], the measured frequencies are weighted differently depending on the direction of the vibration. The used frequency weightings are W_k for the seat surface z-axis direction, W_d for seat surface x-axis and y-axis directions, and W_c for the seatback x-axis direction. These weightings are multiplied by a factor k for correction. This factor depends on whether health, comfort, or perception is being assessed. For instance, k is 1.4 for x- and y-axis directions and 1 for the z-axis direction when health is being assessed, whereas k equals 1 for all axes when comfort is being assessed.

III. RESULTS

A. Vibration Effect on Health

The defined limits by the ISO-2631 standard [1] for a health guidance caution zone are indicated by the dashed red and dotted blue lines that are shown in Fig. 4. Below the zone, the health effects due to vibration have not been documented. Inside the zone, caution with respect to health risks due to vibration is indicated. The health risk is likely above the zone. These recommendations are mainly based on the exposures to vibration in the range of 4–8 h [1], where the caution zone is the same for the red and the blue lines. A study of 25 powered wheelchair users over 395 days by Sonenblum *et al.* [5] estimated the mean time spent in a powered wheelchair by 10.8 h and the mean distance traveled by 1.906 km over 61 min per day.

To quantify the vibration impact on the user's health, weighted RMS acceleration is determined independently for each axis of the translational vibration on the surface that supports the person. The effect of vibrations on health is assessed with respect to the highest frequency-weighted acceleration determined in any axis on the seat ban, which is the z-axis in the collected data.

The calculated RMS frequency-weighted acceleration can be compared with the caution zone at the duration of the expected daily exposure. The 4–8 h frequency-weighted acceleration a_w defined by the ISO-2631 standard [1] can be measured or calculated with the corresponding period T. To quantify the vibration impact for a prolonged drive, we calculated a_w for 7.5 h as the measured a_w for the five terrains range from 2 to 6 min.

Fig. 4(b) and (c) shows that the calculated RMS frequency-weighted accelerations for the tiled concrete, pavement bricks, and the overall ride lie in the caution zone for users 2 and 3, respectively. There is a potential risk to the user's health when the EPW is driven for 7.5 h or more on these types of terrains. For user 1 [see Fig. 4(a)], the calculated a_w for tiled concrete and pavement bricks lies above the caution zone. This means that health risks are likely if the powered wheelchair is driven for a prolonged period over these types of terrain. For user 4 [see Fig. 4(d)], a_w of the overall ride lies below the caution zone. However, a_w of the tiled concrete and pavement bricks lies in the caution zone. The results of the pavement bricks terrain for all users are similar to surfaces numbered 5 and 6 (pavement bricks with different chamfer) from [2], at which traveling for 15.98 and 12.82 h at 3.6 km/h represents a possible health risk to the users. It can be observed that as the user's

Figure 1 — Location of the accelerometers on the platform (P), on the seat pan (S) and on the backrest (B)

Key

1 thin metal disc for accelerometer mount and added centre rigidity

2 appropriate cavity for accelerometer(s)

(a) (b) (c)

Fig. 2. System installation for data collection. (a) Powered wheelchair weight: 59.5 kg. (b) Mounting disk with IMU sensor. (c) ISO 10326-1 for mounting disk with sensor and location of installation.

(a) (b) (c) (d) (e)

Fig. 3. Terrain types. (a) Tarmac. (b) Tiled concrete. (c) Pavement bricks. (d) Carpet flooring. (e) Tiled flooring.

weight increases, the implications of whole-body vibrations on health decrease and *vice versa* [Fig. 4(a) versus (d)]. This can be attributed to the ability of heavyweights to damp low vibrations. Driving the powered wheelchair on tiled concrete and pavement bricks for a long time (more than 4 h) can have potential health risks for all users.

According to the ISO standard [1], a_w results are sufficient for assessment as MTVV$/a_w < 1.5$. Nevertheless, we calculated the eVDV as an extra measurement. Limits for eVDV corresponding to the lower and upper bounds of the caution zone in Fig. 4 are 8.5 and 17, respectively [1]. The eVDV for the overall routes calculated for 7.5-h period is 15.24, 12.30, 11.57, and 9.35 for users 1, 2, 3, and 4, respectively, which emphasize and confirm the a_w results.

B. Vibration Effect on Comfort

Whole-body vibration's impact on user's comfort can be measured using the vibration total value (a_v) (4). The metric combines vibration in more than one direction [1]

$$a_v = \left(k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2\right)^{\frac{1}{2}}. \tag{4}$$

Table 2 shows the impact of whole-body vibration on the user's comfort. For all users, the experience is "Fairly uncomfortable" according to the ISO guidance table [1], whereas the lightest user (user 1) has experienced the highest a_v "Uncomfortable," and the heaviest user (user 4) has experienced the lowest a_v "A little uncomfortable."

Combining the vibration at many locations can better represent the complete user experience. For example, if the vibration in all seatback and feet axes is combined with the vibration on the seat pan, the total vibration value is $a_v = 1.145$ m/s^2 for user 2, which can be categorized as "uncomfortable" according to the ISO standard guide.

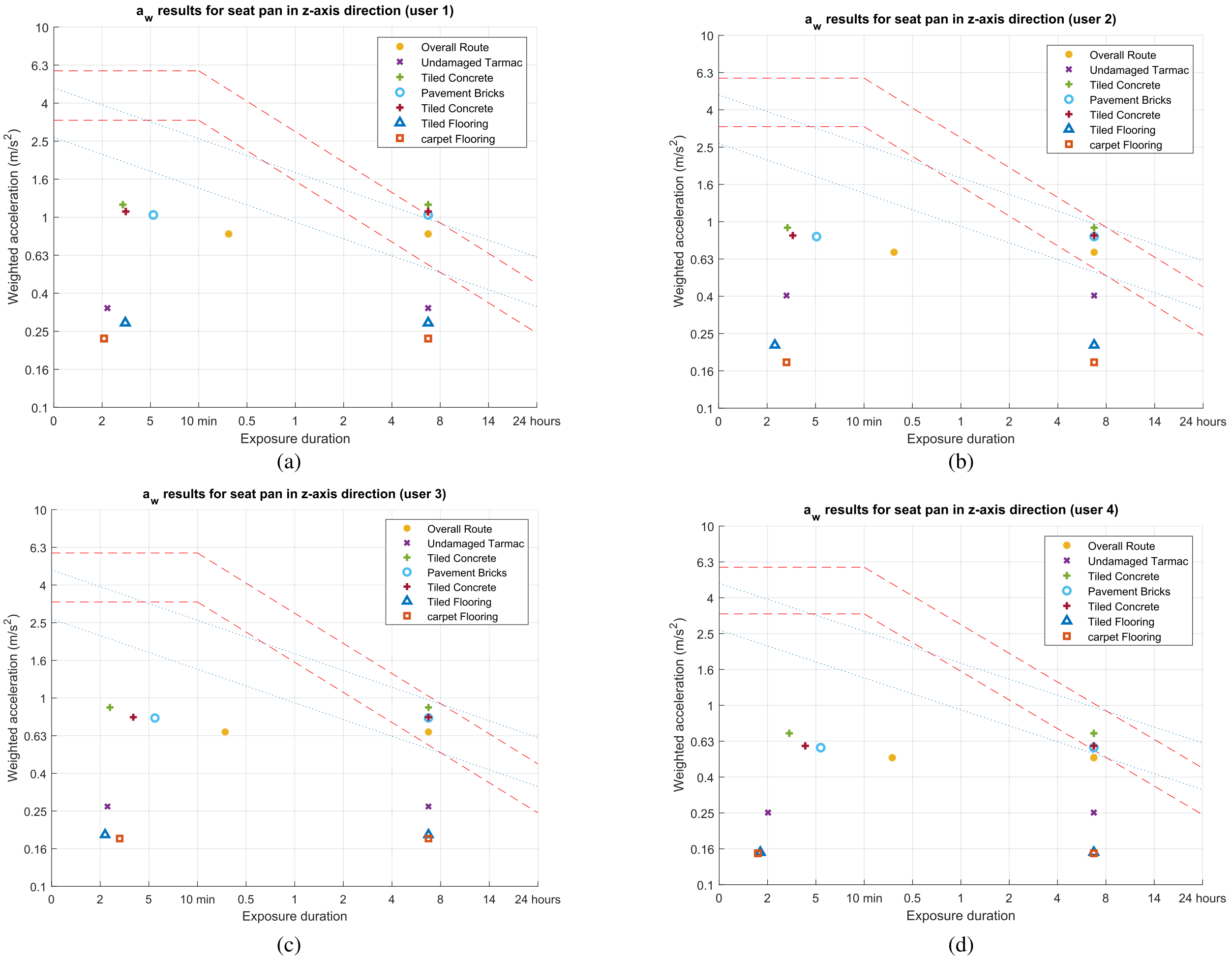
TABLE 2. Vibration Effect on the User's Comfort Using Vibration Total Value (a_v) in All Axes of the Seat Pan.

Metric **User**	$a_v\,(m/s^2)$	**State**
User 1	0.920	Fairly uncomfortable / Uncomfortable
User 2	0.763	Fairly uncomfortable
User 3	0.715	Fairly uncomfortable
User 4	0.583	A little uncomfortable / Fairly uncomfortable

C. Probability of Vibration Perception

The assessment of perceptibility of vibration is made with respect to the highest weighted RMS acceleration determined in any axis at any point of contact [1]. The z-axis has the highest weighted RMS acceleration in our measurements. According to the ISO standard, 50% of alert and fit persons can detect a W_k (z-axis) weighted vibration with a peak magnitude of 0.015 m/s^2. This threshold can decrease slightly with the increase in vibration duration [1].

Table 3 shows the weighted and unweighted RMS accelerations (recommended metric by the ISO standard) for the overall route for all users. Results show high perceptibility of vibration for all powered wheelchair users.



(a) (b)

(c) (d)

Fig. 4. RMS frequency-weighted acceleration for seat pan in the z-axis direction. (a) User 1. (b) User 2. (c) User 3. (d) User 4.

TABLE 3. RMS Weighted and Unweighted Acceleration.

	Unweighted RMS acceleration (m/s^2)	**Weighted RMS acceleration** (m/s^2)
User 1	1.214	0.850
User 2	0.949	0.685
User 3	0.891	0.647
User 4	0.735	0.522

IV. CONCLUSION

In this letter, we presented a comprehensive analysis of the impact of whole-body vibrations on the user's health, comfort, and probability of vibration perception. Results showed the potential risks on user's health due to prolonged drive of a powered wheelchair (which was normally the case) on terrains, such as tiled concrete and pavement bricks. Therefore, we recommend against the usage of such types of terrains that disabled users may use for commuting. The tendency of the health risk increases for lightweight users compared to heavyweight ones as heavyweights users can dampen low vibration. Future work will investigate the impact of weights and types (with or without suspension) of different powered wheelchairs.

ACKNOWLEDGMENT

This work was supported in part by the Assistive Devices for Empowering Disabled People Through Robotic Technologies (ADAPT) project and in part by the Engineering and Physical Sciences Research Council, U.K., under Grant NPIF2018-2112938. ADAPT was selected for funding by the Interreg VA France (Channel) England Program, which was co-financed by the European Regional Development Fund (ERDF). The ERDF is one of the main financial instruments of European Union's cohesion policy.

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