Test Bench for Analysis of Harmful Vibrations Induced to Wheelchair Users

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Abstract: In this paper, a test bench for analysis of harmful vibrations that can be transmitted by manual wheelchair ti its user is presented. The vibration generating device developed in the laboratory and sensors positioning are described. Vibration measurements were carried out using four tri-axis MEMS accelerometers and a position sensor. Experimental data were noisy, so they were first filtered before acceleration amplitude can be assessed using two methods that we propose: a so-called 'cyclogram method' and 'DFT principal peak signal magnitude' on the other hand. The second one is faster and results showed that the prototype developed in the laboratory can provide harmful vibrations in 2-10Hz frequency range and can be used to check the vibration transmissibility of wheelchair.

1 INTRODUCTION

According to the World Health Organization more than one billion people in the world live with some form of disability, of whom nearly 200 million experience considerable difficulties in functioning. In the years ahead, disability will be an even greater concern because its prevalence is on the rise (World Health Org. and World Bank, 2011) The results of studies conducted by Van Sickle et al. and Wolf et al. (Van Sickle et al., 2001; Wolf et al., 2005) have shown that a wheelchair user is subjected to vibrations that often exceed the limits specified by the International Standard Organization ISO 2631-1standard. Directive 2002/44/EC of the European Parliament and of the Council dated June 25 2002 lays down minimum requirements for the protection of workers from the risks arising from vibrations. Manufacturers of machines and employers should make an adjustment regarding risks related to exposure to whole-body vibration. The directive lays down the exposure action to 0.5m/s² and the exposure limit value to 1.15m/s² (European Commission Directive, 2002). These limits have been set to indicate the level of vibration that results in productivity loss of workers and it seems to be analogous to wheelchair users by reducing their activity levels (Pearlman et al., 2013). Whole-body vibrations (WBV), acting via the buttocks, the back and the feet of a sitting person may cause chronic spinal cord injuries (Johanning, 2011). Rather than measuring vibration exposure on a road, Maeda et al. (Maeda et al., 2003) used a vibrating table to vibrate on subjects sitting in a wheelchair. Subjects were subjected to vertical vibration inducing more discomfort, and reported the neck as being the place where localized pain resulting from vibrations. Other studies have been focused on how the selection of the cushion and backrest can affect WBV absorption by the body and examined the influence of different surfaces on the sidewalk vibration exposure of wheelchair users (Garcia-Mendez et al., 2012; Qiu and Griffin; 2012; Wolf et al., 2007).

Frequencies associated with the effects of WBV on health, activities and comforts vary between 0.5Hz and 100Hz (ISO, 1997). According to ISO 2631-1 standard on human vibration, individuals in a seated position are at risk of injury due to whole-body vibrations when exposed for long periods of time. Exposure to vibrations in the range of 4-10Hz frequency may cause pain in the chest and abdomen. Back pain occurs frequently with vibrations in the frequency range of 8-12Hz, and vibration in the frequency in 10-20Hz range can cause headache, eyestrain, and irritation in the intestines (Kittusamy and Buchholz, 2004; Bovenzi, 2010; Johanning,

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2011).

Human exposure to vibration may be measured using accelerometers. However, weighting filters are required to correlate the physical vibration measurements to the human's response to vibration. ISO 2631 standard describes suitable weighting filters, but does not explain how to implement them for digitally recorded acceleration data. Rimell and Mansfield described in their paper the implementation of the weighting filters used in three different standards as digital IIR (Infinite Impulse Response) filters and provided all the necessary formulae to directly calculate the filter coefficients for any sampling frequency (Rimell and Mansfield, 2007).

In this paper a test bench developed in our laboratory is presented. It can produce harmful vibrations that can be transmitted by a wheelchair to its user on one hand, and can give quantitative assessment of vibration magnitude on the other hand. Vertical as well as rocking strokes can be generated at frequencies in 2-10Hz range. As a first step, the characterization of the vibrations generated by the device is investigated.

2 BASIC VIBRATIONS

When a manual wheelchair user moves outdoor, one can consider that he can be submitted to multidirectional vibrations that can be a composition of three basic vibrations, i.e. vertical (along z-axis), lateral (along x-axis) and fore-and-aft (along y-axis) vibrations as shown schematically in Fig.1. The vertical vibration noted V.V. is generally induced by the quality of the tires and the road conditions (Pearlman et al., 2013). The lateral vibration noted L.V. corresponding to a roll, may be due to veiled wheels, to the passage of a single wheel above a small drop, or uneven road surfaces (Cooper et al., 2011). The fore-and-aft vibration noted F.V. corresponding to a pitch, may be caused by corrugation of the road, by crossing small steps, a door sill or by certain sort of floor tiles or for all-terrain wheelchairs riding (Burton et al., 2010; Rispin and Wee, 2013).

Vertical, lateral and fore-and-aft vibrations in this work are generated by a device that can be configured so that only vertical vibration or rocking vibration is selected. The magnitude of vibration can be quantified either by its amplitude (mm), its velocity (m/s) or its acceleration (m/s²).

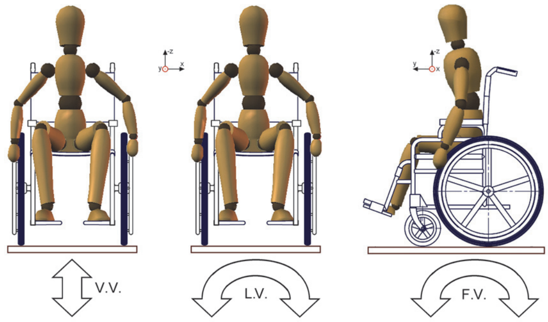

Figure 1: Basic vibrations that can be induced on a manual wheelchair: vertical vibration V.V, lateral vibration L.V and fore-and-aft vibration F.V.

3 EXPERIMENTAL

3.1 Experimental Set-up

The test bench schematic shown in Fig. 2 consists of vibrating table which comprises three blocks: a base anchored to the ground and supporting four coil springs, a movable plate having guide tubes and a vibration generator controlled by a variable-speed drive.

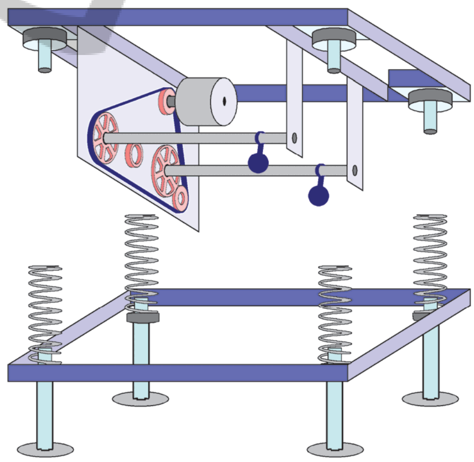

Figure 2: Schematic of the vibrating table.

The base consists of a framework based on four feet on the ground and secured with 4 coil springs. Theses springs allow the upper part of the test bench to vibrate freely along the three axes so as to produce vertical as well as lateral and fore-and-aft movements. The vibration plate is composed of a rectangular frame surface with ties for supporting a motor with its guiding device, two cogwheels, two pinions and a tensioner pulley. Each cogwheel shaft sustains an eccentric weight which generates mechanical vibration at each rotation.

Figure 3 shows the details of the transmission of the movement using a toothed belt (CC). In the case (a), the motor M drives the two wheels R1 and R2 in the same direction, the belt tension is provided by the tensioner T. Resulting movement of eccentric weights B and B' causes rocking motion left to right and right to left. In the case (b), the pinion P is used to invert the rotation of the toothed wheel R2 relative to that of the wheel R1. The resulting movement of the eccentric weights B and B' generates a vertical vibration.

Rotational speed of the induction motor M was controlled by a Siemens Micromaster variable-speed drive (VSD).

Rotational speed of the motor evolution versus the VSD excitation frequency has been investigated using a DT-2269 digital stroboscope from Digital Instruments and a linear behaviour of rotational speed has been observed.

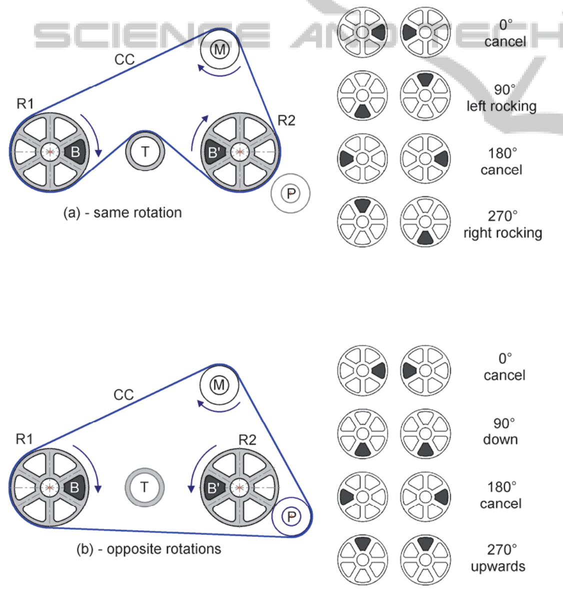

Figure 3: Patterns of the transmission system of the movement - (a) generation of rocking vibration due to the resulting force-couple : left rocking (90°) and right rocking (270°) - (b) generation of vertical vibration resulting from centrifugal force action up (270°) and down (90°) on the two eccentric weights. Positions of B and B' when rotated by 90°, 180°, 270° and 360°.

3.2 Sensors Positioning

For vibration amplitude measurements four MMA7260Q tri-axis MEMS accelerometers with analog outputs have been used. A linear potentiometric position sensor has also been placed under the vibrating table to measure the amplitude (in mm) of the generated mechanical vibrations. Accelerometers static and dynamical calibrations were performed before measurements have been carried out. Experimental data of the position sensor calibration curve have been adjusted by a line whose slope was equal to 1.93V/mm with a correlation coefficient equal to 0.99997.

The sensors were arranged as shown in Fig. 4. The four accelerometers were placed in a horizontal plane so that the x-axis pointed to the left of the subject, the y axis and the z-axis pointed to forward and downward respectively. Their sensitivity was set to 200mV/g and they were also equipped with analog anti-aliasing filters with cutoff frequency equal to 40Hz.

Figure 4: Sensors positioning on the vibrating table, the manual wheelchair and the user: (1) position sensor; (2) Acc-T; (3) Acc-F; (4) Acc-W; (5) Acc-H.

Acc-T, Acc-F, Acc-W and Acc-H are respectively the accelerometers placed on the vibrating table, footrest, frame of the manual wheelchair and on the head (vertex) of seated subject. The accelerometer Acc-T placed on the table gives the same signal as the vibration provided by the vibration generator. Accelerometers Acc-W and Acc-F respectively placed on the wheelchair frame and footrest are used to compare the signal supplied by the vibration generator and the vibration transmitted to two extreme points of the wheelchair in order to quantify the vibration magnitude transmitted by the wheelchair. The last accelerometer placed on the vertex of the subject sitting in the wheelchair provide information on the quality of vibration transmitted to the point of the subject is seated furthest both the wheelchair system for generating vibration. The level of vibration transmitted to the subject's head can then be assessed.

3.3 Acquisition and Data Processing

For acquisition and processing the analog data ssued from the four tri-axis accelerometers and position sensor, a 12-bit acquisition DAQCard-6062E from National Instruments has been used and data sampled at 1kHz. Measurements have been carried out for duration equal to 10s on a healthy male subject 1.75m tall and 75kg weight seated in a manual wheelchair for eight different values of vibration frequency: 2, 3.2, 4.4, 5.6, 8, 9, 10 and 10.6Hz. The selected vibration duration can be considered as sufficiently short to avoid health problems for the subject (ISO, 1997). Fig. 5 shows an example of signal acceleration output along z-axis at a vibration frequency equal to 4.4Hz provided by the accelerometer Acc-W located on wheelchair frame after analog filtering. For more convenience, raw acceleration data are displayed only for duration equal to 5s. The signal remains noisy after analog anti-aliasing filtering.

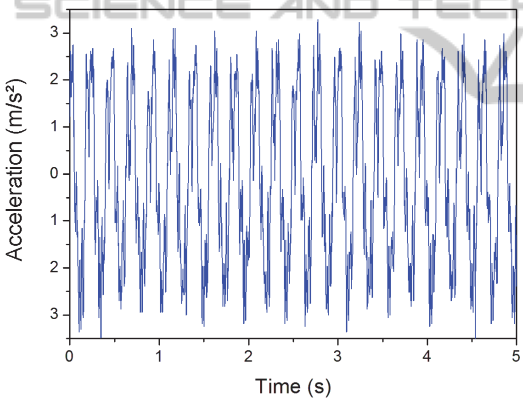

Figure 5: Example of z-axis signal issued from accelerometer (Acc-W) located on wheelchair frame.

The DFT of the vibration signal expressed in m/s² and depicted in Fig. 5 is presented in Fig.6. One can notice the presence of one principal peak at 4.4Hz and several harmonics at higher frequencies. The first principal peak has been observed for all the eight vibration frequencies applied to the wheelchair.

Because of lack in the DFT response of other peaks with appreciable magnitude compared to the first one, we did not consider in this work the weighting filters usually used in literature to correlate the physical vibration measurements to the human's response to vibration and described in ISO2631 standard. A digital band-pass filter has been applied to the vibration signal of Fig.5. Selected low and high cutoff frequencies for the filtered signal presented in Fig.7 have been set to f_{cl}= 3Hz and f_{ch}= 7Hz respectively.

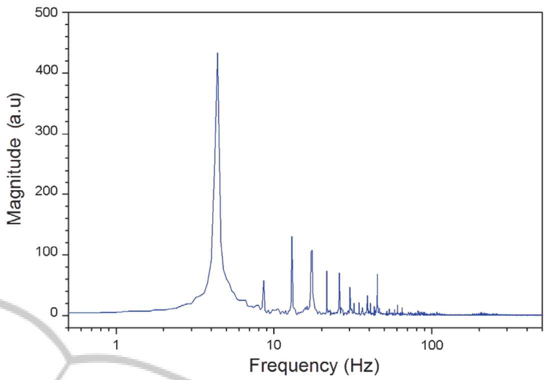

Figure 6: DFT response in semi-log plot of the raw acceleration signal presented in Fig. 4.

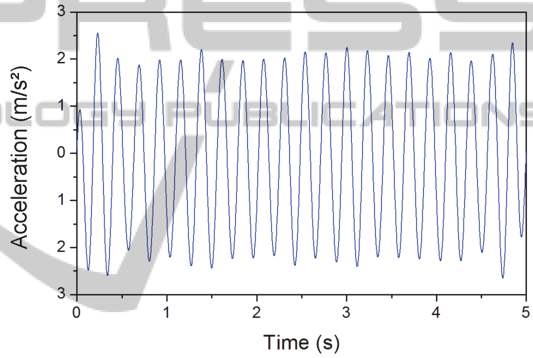

Figure 7: Acceleration signal depicted in Figure 5 after band-pass filtering (fcl= 3Hz ; fch= 7Hz).

4 RESULTS AND DISCUSSION

In order to assess quantitatively the vibrations magnitude along x, y and z axis measured by all accelerometric sensors, the frequency of the variable-speed driver has been varied from 10Hz to 50Hz. These values correspond to vibrations delivered by the test bench to the wheelchair-user system with a frequency varying in 2-10.6Hz range.

The graphs shown in Fig. 8 depict for a column from top to bottom an example of measured then filtered 10.6Hz vibration magnitude at the vibrating table (T), the wheelchair frame (WF), footrest (F) and the user head (H) along one axis(x, y or z). When considering a raw, from left to right, the measured accelerations correspond respectively to vertical acceleration along z-axis, fore-and-aft acceleration along y-axis and lateral acceleration along x-axis at one of the four selected locations.

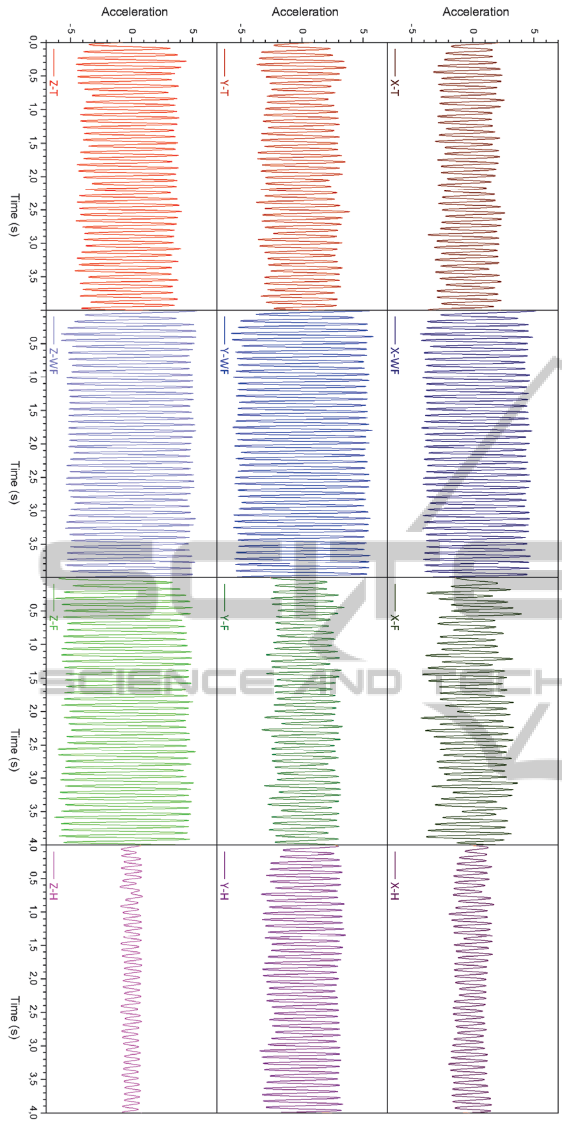

Figure 8: Example of vibration signals measured by the four accelerometers. In this example, vibration frequency f=10.6Hz.

Thus, for a given vibration frequency generated by the test bench, a comparison between different points of measure along the same axis (x, y or z) can be achieved by considering one column (among three columns) and between different accelerations patterns at one location (vibrating table, wheelchair frame, wheelchair footrest or user head) is obtained by considering one raw (among four raws). One can note on these graphs that acceleration amplitude varies with both time and location. To assess the amplitude of vibration measured by the accelerometers for different values of vibration frequency, we have represented cyclograms corresponding to the evolution of the acceleration value (in one direction and for one accelerometric sensor) versus the position of vibrating table plate of the test bench. The cyclogram associated with vertical wheelchair acceleration at f=4.4Hz (See Fig.5 and Fig.7) is presented in Fig. 9.

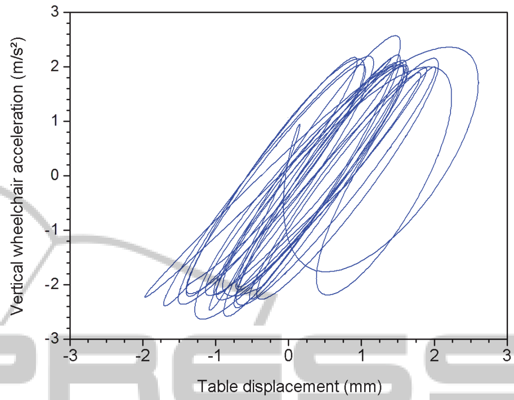

Figure 9: Example of cyclogram corresponding to acceleration value versus table displacement.

From the different cyclograms obtained from experimental measures, acceleration amplitudes along z-axis (vertical vibration), y-axis (fore and aft vibration) and x-axis (lateral vibration) have been quantitatively assessed for the eight values of vibration frequency delivered by the test bench at the four selected locations.

Furthermore, for each temporal acceleration signal, we considered the principal peak magnitude of the DFT signal. Fig.10 shows the variation of the acceleration amplitude obtained from cyclograms as a function of the DFT magnitude, expressed in arbitrary units due to scaling factor. It is worth noticing that a correlation between these two variables seems to be present. Experimental data were fitted by a straight line with a slope found to be equal to $4.83.10^{-3}$. Hence, acceleration amplitude can easily be deduced from DFT principal peak height with a relative uncertainty less than 20%.

According to ISO2631-1 and European Commission Directive (European Commission Directive, 2002) the vibration should not exceed the weighted acceleration a_w =0.8m/s² in the case of long-term exposure and a daily exposure time of 8h. Furthermore, ISO2631-1 recommends weighting the frequencies of the measured vibration according to the possible deleterious effect associated with each frequency.

Frequency weightings are required for three orthogonal directions (x -, y – and z -axes) at the interfaces between the body and the vibration.

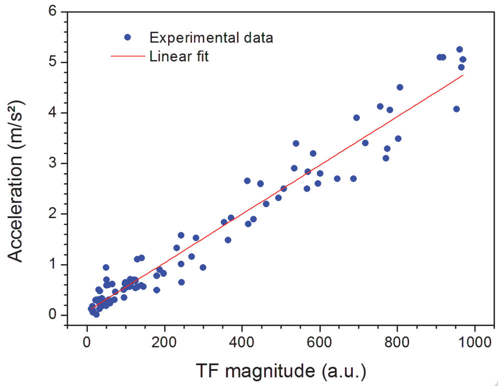

Figure 10: variation of acceleration amplitude obtained from cyclograms versus DFT signal magnitude.

The weighted acceleration in the case of whole-body vibration is expressed (Bovenzi, 2005) by the relation (1)

$$a_w = \sqrt{(1.4a_x)^2 + (1.4a_y)^2 + (a_z)^2} \quad (1)$$

Once the values of a_x, a_y and a_z has been obtained from cyclograms, the weighted acceleration has been calculated for the vibrating table, the wheelchair frame and footrest, and the user head for the eight different values of frequency vibration. Deducing acceleration amplitudes directly from DFT vibration magnitude for a given frequency is another method which is simpler than considering the cyclogram method.

We used the DFT magnitude method and equation (1) to obtain weighted accelerations for different vibration frequencies. The results presented in Fig. 11 are associated with the test bench in rocking vibration configuration while those depicted in Fig.12 are associated with the test bench in vertical vibration configuration. Weighted acceleration values are expressed in m/s².

For vibration frequencies lower than 5Hz, the obtained weighted acceleration values are sufficiently low to consider the vibration not harmful when the test bench is in rocking vibration configuration. When vibration frequency exceeds 5Hz, the weighted acceleration value associated with the wheelchair increases drastically, reaching almost 10m/s² for f > 8Hz. In the second case, except for f = 2Hz, all other values of weighted acceleration show that the test bench generates harmful vibrations for vibration frequencies effects.These frequencies are principally inducing back pain and backbone disorders. Hence, the device developed in the laboratory can be used to check the quality of the wheelchairs that are marketed in developing countries from the vibration transmissibility point of view.

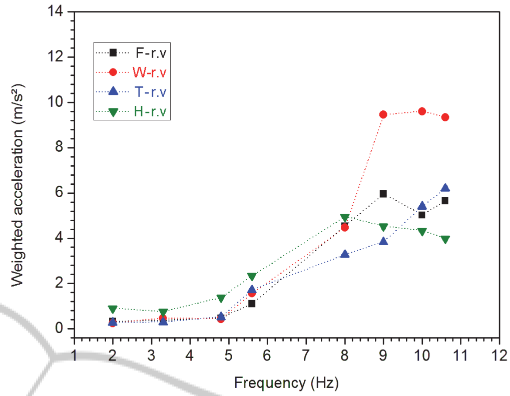

Figure 11: weighted acceleration versus vibration frequency with test bench rocking vibration (r.v) configuration. F: wheelchair footrest; W:wheelchair frame; T: vibrating table; H: user head.

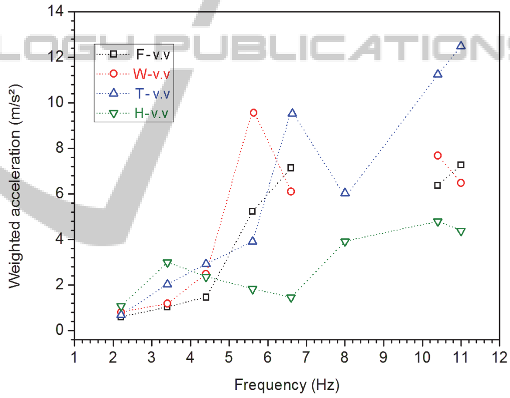

Figure 12: weighted acceleration versus vibration frequency with test bench in vertical vibration (v.v) configuration. F: wheelchair footrest; W:wheelchair frame; T: vibrating table; H: user head.

5 CONCLUSIONS

A test bench for analysis of harmful vibrations that can be potentially induced to a manual wheelchair user has been developed in the laboratory. Vibrations generated by the device were measured using MEMS accelerometers and a position sensor. The experimental signals were noisy and were first filtered before being processed. Two methods have been used to assess vibration magnitude, the cyclogram method and DFT principal peak magnitude method. The obtained weighted acceleration values showed that the device developed in the laboratory provides harmful vibrations and can be used to check the vibration transmissibility of manual wheelchair.

In further work, this test bench will be used to investigate the vibration effect and the wheelchair design (rigid frame, foldable, wheel camber) as well as tires and cushion damping effects on the harmful vibration magnitude.

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