Research article

# Health risks of vibration exposure to wheelchair users in the community

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Objective: The purpose of this study was to evaluate whole-body vibration (WBV) exposure to wheelchair (WC) users in their communities and to determine the effect of WC frame type (folding, rigid, and suspension) in reducing WBV transmitted to the person.
Design: An observational case-control study of the WBV exposure levels among WC users.
Participants: Thirty-seven WC users, with no pressure sores, 18 years old or older and able to perform independent transfers.
Main outcome measures: WC users were monitored for 2 weeks to collect WBV exposure, as well as activity levels, by using custom vibration and activity data-loggers. Vibration levels were evaluated using ISO 2631-1 methods.
Results: All WC users who participated in this study were continuously exposed to WBV levels at the seat that were within and above the health caution zone specified by ISO 2631-1 during their day-to-day activities (0.83 ± 0.17 m/second$^2$, weighted root-mean-squared acceleration, for 13.07 ± 3.85 hours duration of exposure). WCs with suspension did not attenuate vibration transmitted to WC users ($V = 0.180$, $F(8, 56) = 0.692$, $P = 0.697$).
Conclusions: WBV exposure to WC users exceeds international standards. Suspension systems need to be improved to reduce vibrations transmitted to the users.

**Keywords:** Wheelchair, Manual, Vibration exposure, Wheelchair design, Paraplegia, Tetraplegia, Low back pain, Spinal disorders, Wheelchair sports, Veterans

## Introduction

Whole-body vibration (WBV) is the vibration transmitted by supporting surfaces to the entire human body.[1] There is evidence that seated WBV exposure is a risk factor for spinal disorders, excessive muscle fatigue, and damage to the connecting nerves.[2–9] Many factors can affect the amount of transmitted WBV, including postural position and the amplitude and frequency of the vibration exposure.[4, 10] In addition, the vibration's cumulative effect plays an important role in WBV association with low back pain (LBP),[6, 10] which is one of the most disabling conditions in the United States' working population.[2, 10, 11]

The effects of WBV on the spine have been studied in the past in order to mitigate risks in vehicle drivers and heavy equipment workers. Many studies have reported pathological changes in the spine of this group after WBV,[4, 5] and as a result the International Organization for Standardization (ISO) has developed guidance to evaluate occupational exposure levels of vibration. This standard defines methods for assessing the effects of amplitude and duration of WBV on health and establishes acceptable threshold-limits for WBV exposure in different body positions.[1]

It has been documented during simulated laboratory and 4–8 hour field tests that wheelchair (WC) users are exposed to WBV that exceed exposure limits set by ISO 2631 and that riders seem to be absorbing most

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of this energy,[12, 13] thereby increasing the risk of spine injuries in WC users.

Studies carried out to evaluate the effectiveness of seating systems to reduce vibration transmission to WC users have demonstrated that cushions are not effective in reducing vibration transmitted to the riders, and in some cases may amplify it.[2, 14–18] In addition, WC users may not be provided with the most effective seating systems in terms of vibration suppression.[14] The potential discomfort caused by prolonged WC riding and vibration exposure has motivated the development of WC suspension systems to reduce external reaction forces transmitted to WC users during daily WC use.[19] Suspension systems can be designed with coil springs attached to the WC frame, single spring-damper units supporting the WC seat, or polymer-based units supporting each wheel.[19] A few studies have been carried out to evaluate the vibration-reduction effectiveness of rear-wheel suspension and shock absorbing caster forks.[19–21] The results of these studies demonstrated that suspension casters can significantly reduce peak accelerations transmitted to users (at the seat and footrest) and that rear-wheel suspension systems do reduce some of these vibrations, although they do not outperform traditional frame designs and still transmit vibration in the frequency range most harmful for humans.[20] Although the vibration-dampening characteristics of WC suspension components might be satisfactory during simulated laboratory-tests,[19] their performance in real-world conditions is currently unknown.

To our knowledge, only controlled laboratory tests or short (4–8 hour) community-based trials,[12, 13, 22, 23] with small exposure duration data and sometimes stationary WC users, have been performed to evaluate levels of vibration and the effectiveness of WC suspension systems. These laboratory studies and 4–8 hours of exposure data in the community are not likely to provide a full picture of vibration exposure of a person because of day-to-day variations and the lack of real environmental factors. There is a need to collect more information about WBV exposure levels during daily mobility-related activities in the community (i.e. real world settings) for representative periods of time and determine whether WC frame design has any impact on the vibration levels transmitted.

This study uses current ISO techniques to evaluate the health risk associated with WBV exposure to WC users in real-world environments and different types of WC frames. Results of this study could potentially help in the development of more effective WC suspension systems and protect WC users from the risks associated with WBV exposure. We hypothesized that (1) suspension systems would have an effect on vibration transmitted to WC users during propulsion at real-world environments; and (2) WBV exposure to WC users in real-world environments would exceed safe vibration-level thresholds set by IS0 2631-1 (as shown in laboratory and short field trials.[13]).

## Methods

### *Protocol*

Individuals were asked to participate in an institutional review board-approved community-based study to record vibration exposure for at least 2 weeks. Subjects participated in a national veterans sporting event during the first week, followed by an additional week in their home environment. At the beginning of the study demographics, participation in physical activities, contact information, presence of LBP in the past month, and manual WC information (make, model, and frame style) were recorded. A vibration datalogger (VDL) and a manual wheelchair datalogger (MDL) were then mounted on the subject's WC frame and wheel spokes, respectively. Participants were provided with a self-addressed, stamped package to return the VDL and MDL after at least two weeks had passed. The subjects were contacted by mail or phone 2 weeks after recruitment and reminded to remove and return the VDL and MDL.

### *Instrumentation*

Each participant agreed to have a custom-built VDL[24] and an MDL[25] attached on their WC. The VDL is an instrument designed to record WBV levels that WC users are exposed to during their day-to-day lives. The VDL records acceleration (only when the person is in the WC) at the supporting surfaces of the seated individuals where vibration was considered to enter the human body (seat, backrest, and footrest). Two triaxial accelerometers were used to measure vibration data in two orthogonal axes at the seat and the backrest for two weeks. An accelerometer was located at the WC seat below the seat cushion and midline beneath the ischial tuberosities to prevent damage to the skin. Whenever possible, the accelerometer at the backrest was centered at the interface between the subject's lumbar spine and the backrest of the WC. However, if the accelerometer caused discomfort, the subject was allowed to relocate the accelerometer at the same centered position but at the back of the backrest or behind the backrest's cushion. Figure 1 illustrates common location of the accelerometers attached to the participants' WC.

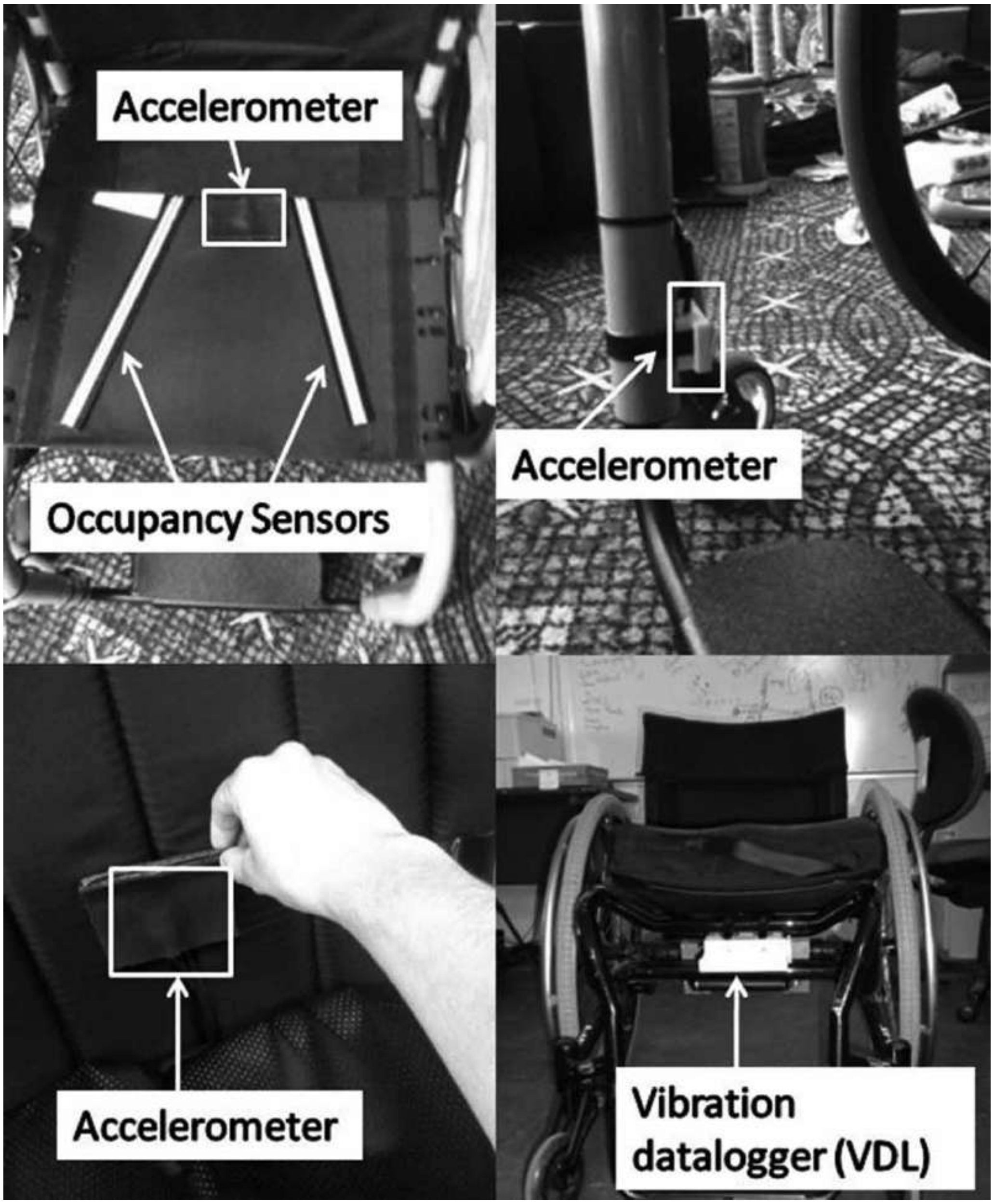

**Figure 1 Vibration datalogger, occupancy sensors and accelerometers localization.**

The accelerometers' direction of measurements were oriented relevant to the axes of the WC at the point from which vibration was considered to enter the human body, which were assumed to be the same as the seated body and in accordance with ISO 2631-1 specifications.[1] In this right-handed coordinate system, the $x$ axis was positively oriented in the forward direction, the $y$ axis was positively oriented to the individual's left, and the $z$ axis was positively oriented in the upward direction. A low-pass filter was implemented with a 0.5–22 Hz (−3bB) bandwidth and a linear phase to limit acceleration measurements up to the first two resonance frequencies of humans (0–20 Hz). The VDL collected acceleration data at 60 Hz sampling rate and logged into the memory card. Only accelerations of the $z$ and $x$ axes at each surface were recorded.

The MDL used in this study was developed by researchers to objectively measure long-term WC-related activity (distance, speed, and continuous movement time) in real world environments[25] without interfering with the WC rider's activities. The MDL has been validated and used in previous studies.[25]

### *Participants*

The participants included individuals with a physical impairment who use a manual WC as their primary source of mobility. The inclusion criteria for the study were: no active pressure sores, 18 years old or older, and able to perform independent transfers. Subjects were recruited at the National Veterans (NV) Summer Sports Clinic 2010 in San Diego, CA, USA; at the National Disabled Veterans (NDV) Winter Sports Clinic 2011 in Snowmass, CO, USA; and at the NV Wheelchair Games 2011 in Pittsburgh, PA, USA. All participants gave written informed consent before data collection or subject screening. Only data collected from individuals who showed activity during the 2-week data collection were included in the analysis.

### Data reduction

Data recorded with the VDL was divided into individual files for each axis of measurement at each point of vibration transmission (seat and backrest). A Matlab algorithm (The MathWorks, Inc., Natick, MA, USA) was developed to analyze cumulative vibration exposure per day. In this algorithm, vibration data were frequency weighted according to standard vibration evaluation methodologies and parameters as indicated in ISO 2631-1,[1] before performing any data reduction. The ISO 2631-1 recommends different frequency weightings for the assessment of seated vibration with respect to its effects on health, comfort and perception depending on both the direction of the vibration and the surface of transmission. The following weighting values were used to evaluate the vibration effect on health: (1) at the seat surface: weighting filters $W_k$ and $W_d$, multiplying factor $k_z = 1$ and $k_x = 1.4$, respectively; and (2) at the backrest surface: weighting filters $W_d$ and $W_c$, multiplying factor $k_z = 0.4$ and $k_x = 0.8$, respectively.

According to ISO 2631-1, two basic evaluation metrics must be included in any vibration assessment: the weighted root-mean-squared (r.m.s) acceleration and the vibration crest factor.

The frequency-weighted r.m.s. acceleration, $a_{\text{rms}}$, is expressed in meter per second squared (m/second$^2$) and is calculated according to the following equation:

$$a_{\text{rms}} = \left[\frac{1}{T}\int_0^T a_{\text{w}}^2(t)\text{d}t\right]^{\frac{1}{2}} \tag{1}$$

where $a_{\text{w}}$(t) is the frequency-weighted acceleration as a function of the time in each direction of measurement, and $T$ is the duration of the measurement.

The crest factor, *cf*, is a metric used to determine whether $a_{\text{rms}}$ alone is appropriate to describe the severity of the effects of the vibration on health, and is defined as the modulus of the maximum peak value of $a_{\text{w}}$ to $a_{\text{rms}}$ determined over $T$.[1] *cf* values greater than 9 indicate the presence of occasional shocks and the need for an additional evaluation method such as the fourth-power vibration dose value (VDV).

VDV is a shock-sensitive vibration evaluation method defined by ISO 2631-1. The VDV unit is meters per second to the power of 1.75 and is defined as

$$\text{VDV} = \left\{\int_0^T [a_{\text{w}}(t)]^4\,\text{d}t\right\}^{\frac{1}{4}} \tag{2}$$

where $a_{\text{w}}$(t) is the frequency-weighted acceleration as a function of the time at each direction of measurement, and $T$ is the duration of the measurement. The use of VDV in this study was included because studies have shown that WC users are exposed to infrequent but high magnitude shocks and that the use of $a_{\text{rms}}$ alone could underestimate its effects on the human body.[7, 12]

The ISO 2631-1 indicates that vibration shall be evaluated independently along each axis of exposure. For the assessment of the health effects of vibration at the seat surface, the vibration evaluated shall be the highest $a_{\text{w}}$ determined in any seat axis. However, when vibration is comparable in two or more axes, it is permitted to combine the vibrations in more than one direction to perform the assessment.

To combine vibrations measured in two directions ($x$ and $z$ axis), the point vibration total value, $a_{\text{v}}$, was calculated for the seat surface by the equation:

$$a_{\text{v}} = (k_x^2 a_{\text{rms}x}^2 + k_z^2 a_{\text{rms}z}^2)^{\frac{1}{2}} \tag{3}$$

where $a_{\text{rms}x}$ and $a_{\text{rms}z}$ are the $a_{\text{rms}}$ each with respect to the orthogonal axes $x$ and $z$, respectively; and $k_x$ and $k_z$ are the multiplying factors specified in ISO 2631-1.[1]

Point vibration total dose value, VDV$_{\text{v}}$, at the seat surface was calculated by substituting $a_{\text{rms}}$ for the respective VDV of each direction of measurement.

Vibration exposure levels measured in two directions of the seat surface ($z$ and $x$ axis) were combined and reported as $a_{\text{v}}$ and VDV$_{\text{v}}$ at the seat surface.

Vibration exposure levels in the $x$-axis of the backrest were evaluated independently along this direction of measurement. Therefore, only $a_{\text{rms}}$ and VDV were calculated for this axis of the backrest.

Duration of vibration exposure was calculated based on the length of vibration data collected every time a person was seated in the WC. Exposure time was then based on the number of acceleration data samples to 60 (i.e. the sampling frequency).

Data recorded with the MDL were decompressed and analyzed with a previously validated Matlab algorithm to estimate mobility characteristics variables such as daily distance the WC user traveled, average daily speed, daily accumulated movement time, maximum distance traveled during a continuous movement and maximum period of continuous movement.[25] Average daily speed provides an indication of the level of activity of the WC user in the real world environment.[25] Daily accumulated movement time refers to the total amount of time the WC user moved in their WC a given day. Maximum distance and maximum time period refers to those maximum values per day between consecutive stops.

### *Statistical analysis*

Data collected from the VDL and MDL were analyzed using descriptive statistics, mean and standard deviation (SD) or median and standard error (SE) for data at the interval level, and frequencies for categorical data.

After checking for assumptions, Mann-Whitney tests were performed to test whether significant differences in age and length of time of manual WC use existed among LBP and no LBP in the past month groups. Fisher's exact test and the Likelihood ratio were used to determine whether gender and type of WC frame (folding, rigid, and suspension), respectively, were significantly different among the same groups.

Mobility characteristics were analyzed using three-way mixed multivariate analysis of variance (MANOVA) that included two between-subjects variables: type of WC frame, and presence of LBP in the past month; and one within-subjects variable: type of environment (home or national event). This test was used because (1) participants only had one type of WC frame and either had LBP or not in the past month, and (2) because mobility characteristics were measured for all participants in two environments (repeated measure design): at home and during a national event. Dependent variables analyzed included average daily distance traveled, speed, and accumulative driving time.

Vibration levels were analyzed using the same approach as activity levels above: three-way mixed MANOVA. This also included the same two between-subjects variables (type of WC frame and LBP presence) and the same within-subjects variable (environment). Dependent variables analyzed included $\mathrm{VDV}_\mathrm{v}$ and $a_\mathrm{v}$ at the seat, and $a_\mathrm{rms}$ and VDV at the $x$-axis of the backrest.

All analyses were performed using SPSS software version 19.0 (SPSS, Inc., Chicago, IL, USA) and significance level of 0.05.

## Results

### *Subjects*

A total of forty-eight subjects consented to participate in the study. One subject did not meet the inclusion criteria. Two subjects did not return the VDL. Eight subjects did not finish the protocol because either they did not use their WC for the second week of the study or the seat sensor of the VDL did not turn off, thereby collecting data even when the participant was not seated in the WC. Follow-up contact with these participants revealed that they were not using their WC the week after the national event for different reasons, such as a WC repair or a long trip that required them to be out of their WC, and which did not represent daily use. The remaining 37 individuals were included in the data analysis, of whom five were women and 32 were men. The participants ranged in age from 26 to 64 years, with a mean ± SD of 47.6 ± 11.6 years. The amount of time participants had used a WC ranged from 1 to 43 years, 15.0 ± 11.5 years. Of the 37 subjects, 25 (67.6%) used a WC because of spinal cord injury (SCI). Of these individuals, 20 had paraplegia and 5 had tetraplegia. The rest of the participants reported lower extremity amputation ($n = 6$), multiple sclerosis ($n = 2$), arthritis, post-polio, and traumatic brain injury ($n = 3$). Nineteen percent ($n = 7$) of the participants had been diagnosed with curvature of the spine, 16.2% ($n = 6$) with vertebral fracture, 13.5% ($n = 5$) with arthritis of the spine, and 8.1% ($n = 3$) with pinched nerve in neck. Sixty-two percent ($n = 23$) indicated other secondary conditions. There were no demographic differences between individuals completing the study and those who did not complete the study. Eighteen subjects (48.6%) of the 37 reported LBP within the past month. There was no significant difference in age, length of time of manual WC use, gender, or type of WC according to the presence of LBP.

### *WC characteristics*

All individuals independently propelled their manual WC and indicated it as their primary means of mobility. Thirteen subjects (35.1%) used a folding frame WC and 24 (64.9%) used a rigid frame WC. Of the folding frame WCs, 9 (69.2%) had no suspension, 3 (23.1%) had suspension in the casters, and 1 (7.7%) had suspension in both the casters and frame. Of the rigid frame WC, 20 (83.3%) had no suspension, 2 (8.3%) had suspension in the casters, and 2 (8.3%) had suspension in both the casters and the frame. WCs with rear-wheel suspension included the Quickie Q7, TiLite TR, and Colours Shockblade.

### Mobility characteristics and vibration exposure levels

Average levels of vibration exposure at the seat and in the $x$-axis of the backrest, as well as mobility characteristics of participants during the 2-week period of data collection, are shown in Table 1 in the "Combined" column. These data are based on the duration of exposure recorded by the VDL. On average, participants spent an average of 13.07 ± 3.85 hours per day seated on their WC during the 2 weeks of data collection.

In the second week of data collection, in the community environment, there were cases where no activity was recorded for entire days. It was assumed that participants used a backup WC those days. Although information about ownership of a backup WC was not recorded in this study, Tolerico *et al.*[25] found that 83% of the subjects in their study, who were also veterans participating in national events, owned a backup WC; and that 38% of them used their backup WC at least once a week. They included inactive days in their analysis, as did we; because it was assumed that these patterns of activities are representative of day-to-day life.[25]

VDVs estimations for the seat surface and $x$-axis of the backrest were included in the analysis since computation of crest factor for the first nine participants of the study revealed crest factor values greater than 9 (mean = 19.86, SD = 9.38, $n = 9$). Only vibration exposure levels measured in $z$ and $x$ directions of the seat surface were combined as they were seen as comparable (i.e. the lowest vibration at any axis was at least 30% and sometimes was the same as the vibration in another axis of measurement).

After checking for assumptions of multivariate normality and homogeneity of covariance matrices for MANOVA analysis, the Pillai statistic indicated that no significant differences existed on mobility characteristics (distance, speed, and accumulative driving time), vibration level exposures, or duration of exposure based on the effect of LBP presence or type of WC frame. No significant interaction effects were found either. A summary of these data is shown in Tables 1 and 2. An additional analysis on the sub-group with SCI showed similar results.

Significant differences were found for mobility characteristics (distance, speed, and accumulative driving time) and vibration levels based on the effect of the environment: $V = 0.48$, $F(3,\ 27) = 8.31$, $P < 0.001$; and $V = 0.704$, $F(4,\ 27) = 16.09$, $P < 0.001$; respectively, based on the Pillai statistic. Subsequent univariate pairwise comparisons on dependent variables, with a Sidak correction, revealed that participants traveled greater distances (mean = 3324.32, SE = 241.33), and accumulated longer periods of movement (mean = 68.47, SE = 4.34) at national event settings than they did in their home environments (mean = 1883.73, SE = 172.72, for distance, and mean = 43.53, SE = 3.78, for accumulated continued movement time), $t\ (34) = -4.75$, $P < 0.001$, $r = 0.63$; and $t\ (34) = -4.46$, $P = 0.001$, $r = 0.61$, respectively. Similarly, in their home environment setting, $a_{\mathrm{v}}$ (median = 0.72) and $\mathrm{VDV_v}$ (median = 14.91), measured at the seat, were significantly lower than at the national event environment (median = 0.85, for $a_{\mathrm{v}}$ and median = 16.79, for $\mathrm{VDV_v}$), $z = -4.346$, $P < 0.001$, $r = -0.73$, and $z = -3.88$, $P < 0.05$, $r = -0.65$, respectively. Likewise, $a_{\mathrm{rms}}$ (mean = 0.52, SE = 0.02) and VDV (mean = 11.07, SE = 0.51), measured at the $x$-axis of the backrest, were significantly lower in their home environment than at the national event environment (mean = 0.58, SE = 0.02, for $a_{\mathrm{rms}}$, and mean = 12.77, SE = 0.38, for VDV), $t\ (35) = -5.40$, $P < 0.001$, $r = 0.68$, and $t\ (35) = -4.88$, $P < 0.001$, $r = 0.64$, respectively. When duration of exposures were compared based on environment settings, no significant differences were found $T = 0$, $P > 0.05$, $r = -0.03$.

### Evaluation of vibration exposure levels based on their risk to health

ISO 2631-1 has established a health guidance caution zone to evaluate the effects of vibration on health. According to these guidelines, for a 13-hour duration of vibration exposure (i.e. the average duration of vibration exposure to participants in this study) the maximum weighted acceleration exposures ($a_{\mathrm{rms}}$ or $a_{\mathrm{v}}$) for a potential effect on health (lower bound of the zone) is 0.34 m/second$^2$, and to be likely (upper bound of the zone) is 0.68 m/second$^2$. The estimated VDV corresponding to the lower and upper bounds are 8.5 m/second$^{1.75}$ and 17 m/second$^{1.75}$, respectively. An analysis of vibration exposure at the home and national event environment, revealed that *all the participants were exposed to vibration at the seat surface ($\mathrm{VDV_v}$ and $a_{\mathrm{v}}$) that was within or above the health caution zone specified in ISO 2631-1* (see Table 3). However, vibration exposure at the national event environment tended to be higher. Ninety-seven percent of $a_{\mathrm{v}}$ measurements were above the health caution zone. Participants' exposure to vibration measured at the $x$-axis of the backrest was lower and tended to be localized within the health caution zone in comparison to exposure measured at the seat. Table 3 shows how vibration exposures at the seat and at the $x$-axis of the backrest were distributed in the health caution zone specified in ISO 2631-1.

**Table 1 Comparison of mobility characteristics and vibration exposure levels (mean ± SD) to participants according to presence of self-reported LBP in the past month**

| | No LBP group ($n = 19$) | LBP group ($n = 18$) | Combined ($n = 37$) |
|---|---|---|---|
| Mobility characteristics | | | |
| Max distance of continued movement (m) | 251.0 ± 151.1 | 200.4 ± 87.9 | 226.4 ± 125.4 |
| Max period of continued movement (min) | 3.8 ± 1.9 | 3.0 ± 0.9 | 3.4 ± 1.5 |
| Distance (m) | 2,931.2 ± 1041.1 | 2,324.2 ± 690.1 | 2,635.9 ± 928.1 |
| Speed (m/second) | 0.74 ± 0.15 | 0.71 ± 0.16 | 0.73 ± 0.16 |
| Accumulated movement time (minutes) | 64.2 ± 18.2 | 50.1 ± 15.3 | 57.3 ± 18.1 |
| Seat vibration measurements | | | |
| $a_v$ (m/second$^2$) | 0.81 ± 0.13 | 0.85 ± 0.21 | 0.83 ± 0.17 |
| VDV$_v$ (m/second$^{1.75}$) | 17.27 ± 3.39 | 17.26 ± 3.15 | 17.26 ± 3.23 |
| $x$-Axis backrest vibration measurements | | | |
| $a_{rms}$ (m/second$^2$) | 0.54 ± 0.11 | 0.57 ± 0.14 | 0.55 ± 0.13 |
| VDV (m/second$^{1.75}$) | 12.44 ± 2.77 | 11.66 ± 1.85 | 12.06 ± 2.37 |
| Duration of exposure (hours) | 16.69 ± 3.88 | 12.41 ± 3.82 | 13.07 ± 3.85 |

Max, maximum.

Figure 2 shows vibration exposure levels, in $a_v$ and VDV$_v$, recorded at the seat surface of the WC during the two weeks of data collection. It can be seen in this plot that the all the participants were exposed to vibration levels within and above the health caution zone established by the ISO 2631-1.

## Discussion

By attaching custom VDLs and MDLs, we were able to objectively measure some of the risk factors to health of WC users in real-world environments for extended periods of time and without interfering with the person's activities. Measuring mobility characteristics and vibration levels at the WC frame during day-to-day living instead of during laboratory trials gives the opportunity to evaluate real conditions to which WC users are exposed to, such as vibrations induced when traveling over surfaces in the home and community. It also provides the opportunity to assess current strategies being adopted to reduce vibration transmission such as WC with suspension systems added. The preliminary scanning of vibration level exposures revealed crest factors greater than 9, which indicates that the measured vibrations contain high-peak accelerations. These data support previous findings of a short field trial carried out to investigate the loads applied on manual WCs by road characteristics.[12, 13] These studies suggest that WC and riders are exposed to infrequent but high-magnitude vertical loads. Because of the presence of this acceleration peaks, VDV$_v$ and VDV measures at the seat surface ($z$ and $x$ axis) and at the backrest ($x$ axis) were included. These results also have implications on suspension design, which should be able to dampen these large accelerations.

Our results indicate that *100% of the subjects were exposed to vibration loads at the seat surface that were either within or above the health-caution zone* established by the ISO2631-1 standards. This result demonstrates how critical the need is for developing and implementing vibration-dampening strategies to prevent spine

**Table 2 Comparison of mobility characteristics and vibration exposure levels (mean ± SD) to participants according to type of WC frame (folding, rigid, and suspension)**

| | Folding ($n = 9$) | Rigid ($n = 20$) | Suspension ($n = 8$) |
|---|---|---|---|
| Mobility characteristics | | | |
| Max distance of continued movement (m) | 315.4 ± 197.2 | 196.3 ± 69.4 | 201.3 ± 99.2 |
| Max period of continued movement (min) | 4.7 ± 2.3 | 3.1 ± 0.8 | 2.8 ± 1.0 |
| Distance (m) | 2,863.0 ± 649.5 | 2,445.1 ± 810.3 | 2,857.5 ± 1392.8 |
| Speed (m/second) | 0.7 ± 0.2 | 0.7 ± 0.1 | 0.7 ± 0.2 |
| Accumulated movement time (minutes) | 64.7 ± 15.1 | 54.0 ± 18.1 | 57.3 ± 20.7 |
| Seat vibration measurements | | | |
| $a_v$ (m/second$^2$) | 0.87 ± 0.14 | 0.82 ± 0.18 | 0.82 ± 0.20 |
| VDV$_v$ (m/second$^{1.75}$) | 16.99 ± 2.60 | 17.27 ± 3.43 | 17.57 ± 3.70 |
| x-Axis backrest vibration measurements | | | |
| $a_{rms}$ (m/second$^2$) | 0.60 ± 0.13 | 0.53 ± 0.11 | 0.58 ± 0.16 |
| VDV (m/second$^{1.75}$) | 12.20 ± 1.59 | 11.97 ± 2.55 | 12.11 ± 2.87 |

Max, maximum.

**Table 3 Frequency of vibration exposure levels for participants on the Health Caution Zone**

| | | Health Caution Zone | |
|---|---|---|---|
| | Below (home/competition) (%) | Within (home/competition) (%) | Above (home/competition) (%) |
| Seat vibration | | | |
| $a_v$ (m/second$^2$) | 0.0/0.0 | 30.6/2.8 | 69.4/97.2 |
| VDV$_v$ (m/second$^{1.75}$) | 0.0/0.0 | 66.7/54.0 | 33.3/46.0 |
| x-Axis backrest vibration | | | |
| $a_{rms}$ (m/second$^2$) | 2.8/0.0 | 80.6/78.4 | 16.7/21.6 |
| VDV (m/second$^{1.75}$) | 16.7/0.0 | 77.8/94.6 | 5.6/5.4 |

Vibration exposure levels are based on acceleration measurements at the home environment (second week of data collection).

injuries among WC users. Nearly 31% of the participants were exposed to vibration levels ($a_v$) at the seat that were within the health caution zone (above 0.34 m/second$^2$ and below 0.68 m/second$^2$, for this specific exposure time) whereas the rest were exposed to vibration levels that were even higher than the health caution zone upper boundary (above 0.68 m/second$^2$). Regarding VDV$_v$, 67% of the time subjects were within the health caution zone (above 8.5 m/second$^{1.75}$ and below 17 m/second$^{1.75}$) and the remainder of the time the subjects were exposed to levels above the health caution zone (i.e. vibration doses greater than 17 m/second$^{1.75}$). *These results show that WC users are at high risk of spine injuries because of the WBV levels they are exposed to, and thus reducing this risk should be a very high priority.*

Although most of the investigations performed in the past have suggested that WC users are exposed to WBV that contribute to LBP,[9] none have actually quantified vibration levels in a real-world environment for significant amounts of time. VanSickle *et al.*[13] indicated that vibration during WC propulsion exceed the fatigue-decrease proficiency boundary established in ISO 2631-1 at the seat of the WC during simulated course roads and a short field test. WBV exposures that exceed ISO 2631-1 standards have been positively correlated with LBP, herniated disc, degeneration of the spine, and other musculoskeletal disorders in motor vehicle drivers—more so for prolonged periods of exposure.[4, 5] Vibration levels at the seat found in this study (0.82 ± 0.20 m/second$^2$, all subjects during 2-week of data collection) are comparable to those induced by an interlocking concrete surface with 8-mm bevels (0.80 m/second$^2$) and higher that those induced by standard poured concrete (0.47 m/second$^2$) that were measured in another study.[22]

Vibration levels at the anterior-posterior axis ($x$ axis) of the backrest also exceed ISO 2631-1 standards. The number of participants who exceeded the lower safety vibration threshold established by ISO was similar when measured with $a_{rms}$ and with VDV. 80% and 78% of the participants exceeded this boundary when

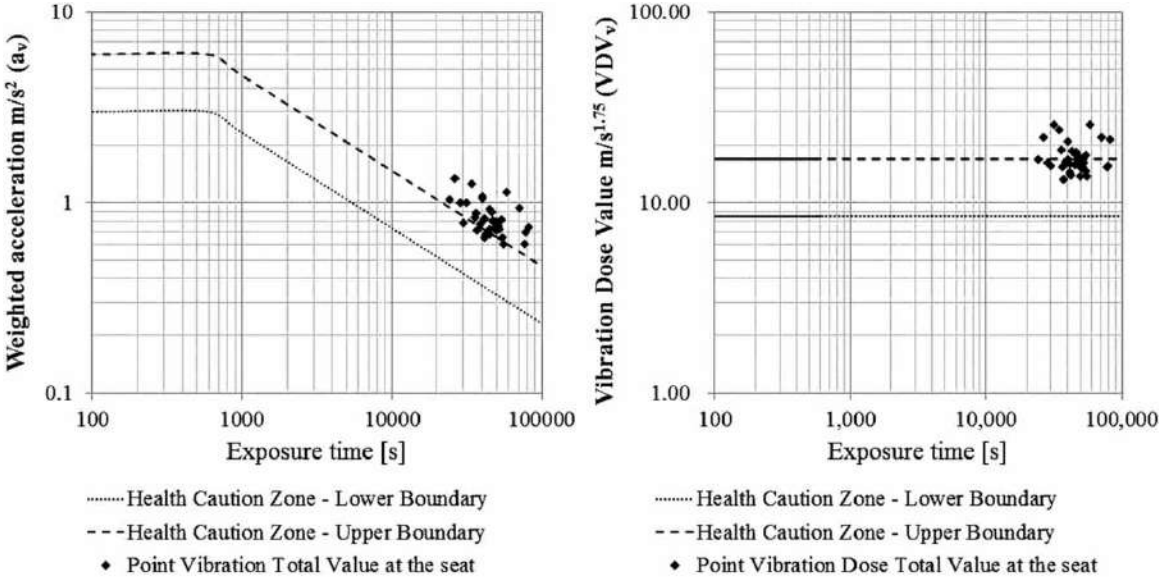

**Figure 2 Average daily point vibration total value ($a_v$) and point vibration dose total value (VDV$_v$) at the seat of two weeks of data collection for all the participants compared to the acceptable threshold-limits for WBV exposure established by ISO 2631-1.**

vibration was measured with $a_{\mathrm{rms}}$ and VDV respectively. At the seat, $a_v$ measured differed from $\mathrm{VDV}_v$, since the second is a measurement more sensitive to high-acceleration peaks than $a_v$. Because vibration values measured at the seat combined $x$ and $z$ directions of acceleration, it is not surprising that for the seat measurements $a_v$ and $\mathrm{VDV}_v$ differed whereas they were similar for the backrest which only included the anterior-posterior axis of vibration. It has been suggested that acceleration measured at the anterior–posterior axis is mostly composed by voluntary motion of the user during the propulsion activity, which is repetitive and continuous along the day, whereas the vertical acceleration component of the vibration measured at the seat surface is better explained by a few high-peak acceleration events.[13]

Vibration levels were found to be significantly higher at the national event setting than in the home environments. This finding may be explained by the fact that participants were more active at the national event settings. Results showed that participants traveled significantly farther, faster, and were active for more hours per day in these environments. Other studies have found similar results.[25, 26] Although not reported in this study, significant differences were found in vibration levels when comparing the types of national competition settings. Events that included more outdoor competition activities had higher vibration levels induced. Studies have shown that different paver surfaces induce significantly different levels of vibration during manual WC propulsion.[22] The fact that no significant differences were found on vibration levels among LBP groups may be explained by the observation that all the participants propelled their WC (regardless of pain) on similar surfaces at similar speeds during the first week at the national event.

An investigation of the vibration exposure based upon different types of WC frame revealed that suspension systems added to WC do not significantly reduce the amount of vibration measured at the frame. These results are similar to previous studies carried out on suspension WC that showed that adding suspension to manual and power WC does not necessarily reduce the amount of WBV transmitted to the user.[20, 21] However, the fact that suspension WC did not produce a significant reduction in vibration measured in this study has to be taken with caution, since the number of participants with suspension WC recruited in this study was small (only three participants had suspension on the frame, and the other five included in this category had suspension in the casters). Although not significant, vibration measured in rigid and suspension WC was lower than those measured on a folding frame. Other studies' results have suggested that some WC with suspension have similar vibration-dampening performance to rigid frames WC without suspension.[20, 21] The reduction of vibration observed here may be produced by the caster suspension. Caster suspensions have shown some reduction on vibration levels in other studies.[20] WC suspensions are not the only way to reduce vibration level exposure to WC users. WC cushions have also been identified as a means to decrease vibration exposure. In this study, vibration levels were measured below the seat cushion without correcting for the transmissibility of the cushion material. However, other studies investigating WC cushions' dampening characteristics have shown that cushions are not effective in reducing vibration transmitted to the riders and in some cases they amplify them,[2, 14, 15, 17, 18] suggesting that our findings may be a lower-bound on the actual exposure to the body.

Individuals in this study remained in their WC for an average of 13.07 ± 3.85 hours per day. Long periods of exposure time is one of most important contributing factors for risk of spine injury, and WC users are seated in their WC for even longer periods of time than other occupational groups at risk, for whom the literature reports an average of 8-hour exposure.

Because of the accumulative effect of vibration, the risks associated with vibration for this amount of time is higher and therefore the vibration level threshold is lower than for 8 hour exposures to vibration. It is important to mention that caution should be taken when considering time duration as exposure duration, since it represents seated and not propelling time. Therefore, this time may overestimate real exposure duration when WC users are propelling their WC. Seated time includes times in which the WC users are actually not moving and may underestimate vibration levels. Although the way exposure duration was measured may be a worst-case scenario, this approach allows capturing vibration exposure data also when the WC riders are not actually propelling their WC but are exposed to vibration, as for example, during car and bus rides.

LBP prevalence in this study supports prior evidence that LBP prevalence is higher in WC users than in the general working population.[10, 27] LBP prevalence among participants was nearly 48.6%. Other studies investigating LBP prevalence in WC users have reported higher rates of LBP: between 61 and 63%.[28, 29] This difference may be explained by the difference between the studies' participants. Subjects in this study were WC users participating in the VA WC events who were in an appropriate physical and mental condition to travel and participate, thereby under-representing those who stayed home because of severe pain.[9]

In general, a high LBP prevalence may suggests that WC users are highly exposed to contributing factors such as prolonged sitting. The results of this study show that almost 50% of the participants spend more than 12 hours in their WC, which was confirmed by our VDL results. This result is not surprising since WC riders rely on their WC to perform most part of their activities throughout the day. Periods of rest between seated times may be recommended since excessive time seated cannot be avoided. Other risk factors to LBP such as amount of time in seated position, working with hands above shoulder level, heavy object lifting, and weight bearing should also be explored.

One limitation of this study was the design of the seat sensors used to detect occupancy in a manual WC. During the national events, there were a large variety of WC frames and cushions. These factors affected the performance of the seat sensors because these were designed for evenly distributed pressures along the surface. Future generations of VDL will require a different occupancy sensor design able to accommodate a wide variety of seat and cushion characteristics. A sensor that detects motion and log time stamps when the WC user is actually moving would be desirable, for example the MDL.

## Conclusions

WC users are exposed to vibration levels that exceed the ISO 2631-1 health caution zone. This level of vibration has been shown to have an effect on the spine, increasing the risk of deformities, LBP, and other types of musculoskeletal disorders. The use of suspension systems did not show a reduction of vibration and high-peak accelerations transmitted to WC users. Future suspension systems and/or cushions should be designed with vibration-dampening capabilities without impeding propulsion.[12]

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