# EVALUATION OF SELECTED SIDEWALK PAVEMENT SURFACES

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**Funding**: This study was partially funded by a consortium of the Interlocking Concrete Pavement Institute (ICPI), Brick Industry Association (BIA) and the National Concrete Masonry Association (NCMA). In addition, funding was provided by the VA Rehabilitation Research and Development Service, Veterans Health Administration, U.S. Department of Veterans Affairs (F2181C), and the U.S. Department of Education, National Institute on Disability and Rehabilitation Research (NIDRR) Rehabilitation Engineering Research Center on Wheeled Mobility (H133E990001).

## Abstract

**Objective**: The purpose of this study was to conduct an evaluation of the vibration exposure during electric powered wheelchair driving and manual wheelchair propulsion over selected sidewalk surfaces. The mechanical energy requirements for manual wheelchair propulsion were also examined.

**Participants and Design**: Ten unimpaired individuals gave written informed consent to participate in this study. A single-site engineering evaluation of vibration exposure and energy requirements for selected sidewalk surfaces was conducted. This study was designed to investigate some of the issues raised in the report, entitled "Building a True Community: Final Report of the Public Rights-of-Way Access Advisory Committee", produced by the U.S. Access Board. In Section X02.1.6.1 Advisory, the report includes the statement "Individual paving units, bricks or other textured materials are examples of surfaces that are undesirable in the pedestrian access route because of the vibration that they cause. They may, however, be used in the portions of the public sidewalk that do not contain the pedestrian access route. The purpose of the visually uniform surface is to provide uniformity in color along the pedestrian access route as a way finding cue for person with low vision." One surface was a poured concrete sidewalk with a brush finish to represent the norm (Surface 1). Three sidewalk surfaces were made from interlocking concrete pavement installed to industry specifications. Surfaces 2, 3, and 4 were made of concrete pavers of varying bevels and placed in a 90 degree herringbone pattern.  Surfaces 5, and 6 were clay pavers and placed in a 45 degree herringbone pattern with 4 mm beveled edges and squared edges, respectively. The interlocking concrete pavement surfaces were constructed of blocks with squared edges (Surface 2), 2 mm (1/16") beveled edges (Surface 3), and 8 mm (5/16") beveled edges (Surface 4), respectively.

**Setting**: A rehabilitation engineering research and development center.

**Main Outcome Measures**: Power of the acceleration per octave, mechanical work to propel over surfaces, peak acceleration, frequency at which peak acceleration occurs.

**Results**: For both the manual and electric powered wheelchair, at 1 m/s, significant differences were found in peak accelerations between the seat and footrest ($p<0.0001$) and between the sidewalk surfaces ($p=0.004$). The peak accelerations at the seat for surfaces 2, 5 and 6 were lower than the standard sidewalk surface. Similar results in the peak accelerations were found with the electric powered wheelchair at 2 m/s. Results from the mixed model indicated that the sidewalk resulted in significantly higher ($p<0.0001$) vibration for most of the octaves examined.

**Discussion**: The greatest risk for injury due to shock and vibration exposure is when the frequency is near the natural frequency of seated humans. The natural frequency of seated humans is between 4 Hz and 12 Hz.  The sidewalk surface resulted in higher or no difference in power per octave in throughout most of natural frequency range of seated humans. The work required to propel over the surfaces tested were not statistically significantly different. This is probably because the surfaces all had similar grade and no cross-slope. Besides

appearance and construction concept, the only substantive distinguishing characteristic was surface roughness due to the joints. Comparison to ISO 2631, shows that at 1 m/s all surfaces, but surfaces 4 and 5 exceed the exposure limit after greater than eight hours of driving an electric powered wheelchair. It is unlikely that wheelchair users will spend more than eight hours driving over sidewalk surfaces at a given stretch.

**Conclusion**: When treating the poured concrete sidewalk as the normative standard, the 2, 3, 5 and 6 surfaces compared most favorably in terms of shock and vibration exposure whereas surface 4 produced mixed results. Surfaces 2, 3, 5 and 6 yielded results that were similar to the poured concrete sidewalk, and should be considered acceptable as a pedestrian access route for wheelchair users, surface 4 requires further study.

# INTRODUCTION

People who use wheelchairs as their primary means of mobility often make use of their wheelchair's throughout the course of the entire day. While propelling a wheelchair, users encounter obstacles such as bumps, curb descents, and uneven driving surfaces. These obstacles cause vibrations on the wheelchair and in turn, the wheelchair user, which through extended exposure can cause low-back pain, disc degeneration and other harmful effects to the body (1-3). To date, little research has been conducted to assess the vibrations experienced by wheelchair users (4-5). Van Sickle *et al* recorded the forces when using the ANSI/RESNA standards double drum and curb drop tests and compared them to the road loads during ordinary propulsion (6). Van Sickle *et al* also showed that wheelchair propulsion produces vibration loads that exceed the ISO 2631-1 standards at the seat of the wheelchair as well as the head of the user (19). The International Standards Organization (ISO) and the American National Standards Institute developed a standard for whole-body vibration measurement. It includes the amplitudes of vibrations that are considered harmful and the exposure times for vibrations to be dangerous. The standard also discusses some of the physical effects that can occur from whole-body vibration exposure (16). DiGiovine *et al* showed that users prefer ultra-light wheelchairs to lightweight wheelchairs while traversing a simulated road course in higher comfort level and better ergonomics (7). DiGiovine *et al* examined the relationship between the seating systems for manual wheelchairs and the vibrations experienced, showing differences in how seating systems transmit or dampen vibrations (8). Based on the exposure magnitudes of vibrations defined in the ISO-2631 standard, wheelchair companies added suspension to their wheelchairs to reduce the level of vibrations that are transmitted to wheelchair users. Wolf *et al* concluded that, on average, suspension manual wheelchairs do reduce the transmission of shock vibrations to wheelchair users, but are not yet optimal in their design (9).

Studies have shown correlations between whole-body vibrations and secondary injuries in the trucking and construction industries (10-11). Seidel et al reported that occupational groups (i.e. tractor, bus, truck drivers etc.) who were exposed to whole-body vibrations near or above the ISO exposure limit had increased risk of secondary musculo-skeletal injury (20). Other studies have examined the effects of posture (in seated as well as standing positions) and its relation to secondary injuries due to vibration exposure. Suspension additions to heavy machinery and seating system alterations have also been examined (12-13). Pope *et al* (14) revealed in a review of studies that occupational environments subject workers to high vibration levels possibly resulting in low-back pain and other musculo-skeletal back injuries. Nishiyama *et al* have shown that over the course of 20 years technological improvements have been made to reduce the amount of vibrations transmitted drivers through the addition of suspension to the seating systems mainly through the replacement of steel springs with air dampeners (15).

The boundaries in ISO-2631 are based on cumulative root-mean-square (RMS) amplitude over a single day specified for frequencies between 1 Hz and 80 Hz. No allowance is made for the effect of recovery periods within a given day. There are three boundaries defined in ISO-2631. These boundaries are, in increasing order of exposure, the "reduced comfort boundary", the "fatigue-decreased performance boundary", and the "exposure limit boundary." The "fatigue-decreased performance" boundary is used as a baseline and the other two boundaries are determined by direct scaling. The "exposure limit boundary" is defined to be 6 dB (2 x) greater in magnitude than the "fatigue-decreased performance boundary", and the "reduced comfort boundary" is defined as 10 dB less. The resonant frequencies of the human body are used as a basis for determining the level of exposure allowed. The frequencies where the lowest longitudinal vibration exposure is allowed are for the range from 4 Hz to 8 Hz, which is the resonant frequency of the human body in the seated position. The boundaries for transverse vibration are lowest for the range of 1 Hz to 2 Hz.

Recently many wheelchair companies have attempted to reduce the amount of vibrations transferred to users by adding suspension to their chairs. Cooper et al have shown that in the natural frequency of humans (4-15 Hz) the addition of suspension caster forks do reduce the amount of vibrations transferred to the user (17). Wolf *et al* has shown that suspension manual wheelchairs are approaching significance in reducing the amount of shock vibrations transmitted to wheelchair users during curb descents (21). Kwarciak *et al* revealed that although suspension manual wheelchairs visually reduce shock vibrations the chairs are not yet ideal, possibly due to the orientation of the suspension elements (22).

This purpose of this study was to record vibrations while traversing selected sidewalk surfaces in an electric powered wheelchair, and a manual wheelchair. This study also examined the work to cross each surface in a manual wheelchair. The study should provide support for determining the criteria for defining a wheelchair pedestrian access route that does not require excessive propulsive work, or expose wheelchair users to potentially harmful vibrations.

## METHODS

### *Test Surfaces*

We tested six different types of sidewalk surfaces, see **Figure 1**. All of the sidewalk surfaces were approximately four feet wide and 25 feet long. One surface was a poured concrete sidewalk with a brush finish to represent the norm (Surface 1). Three sidewalk surfaces were made from interlocking concrete pavement installed to industry specifications (23). All of the interlocking concrete pavement surfaces were installed with a 90-degree herringbone pattern. The interlocking concrete pavement surfaces were constructed of blocks with squared edges (Surface 2), 2 mm (1/16") beveled edges (Surface 3), and 8 mm (5/16") beveled edges (Surface 4), respectively, see **Figure 2**. Two sidewalk surfaces were constructed of fired clay bricks. Both brick sidewalks used a 45-degree herringbone pattern (Surfaces 5 and 6). An Interlocking Concrete Pavement Institute (ICPI) certified contractor constructed all of the sidewalks. Test was performed within one month of installation of the sidewalks. Data were collected in Pittsburgh, Pennsylvania during April and May of 2002. The precipitation was average for this time period however all surfaces were tested while dry. All of the surfaces were installed outdoors side-by-side with the same slope of about 1.3 degrees, and no-cross slope. The approximate temperature was $19^{o}$ C during testing.

### *Test Wheelchairs*

The manual wheelchair (Quickie GP, Sunrise Medical Ltd.) was a rigid frame design with 127 mm (5”) diameter polyurethane tires, and standard 610 mm (24”) diameter rear wheels, see **Figure 3**. The seat width was 406 mm, the seat depth was 458 mm, and the backrest height was 410 mm. The rear axles were placed 45 mm in front of the backrest tubes. The SMART$^{\text{Wheels}}$ were used as the rear wheels during this study (24). SMART$^{\text{Wheels}}$ use solid foam inserts. The approximate mass of the manual wheelchair was 15.5 kg with the SMART$^{\text{Wheels}}$ attached. The electric powered wheelchair (Quickie P200, Sunrise Medical Ltd.) had a rigid frame with 203 mm (8”) front casters, and 254 mm diameter rear wheels, see **Figure 4**. The seat width was 406 mm, the seat depth was 415 mm, and the backrest height was 435 mm for the electric powered wheelchair. A standard position-sensing joystick was mounted to the right side armrest, and the manufacturer default controller settings were used. All tires were properly inflated to the rated air pressure (36 PSI for the caster, and 50 PSI for the rear wheels). The approximate mass of the electric powered wheelchair with batteries was 89 kg. The frames of both the manual wheelchair and the electric powered wheelchair were made from aircraft quality aluminum. All subjects sat on a 50 mm thick linear polyurethane cushion during all testing.

### *Subjects*

Ten unimpaired individuals used a wheelchair during data collection. All subjects provided written informed consent prior to participating in the study. Five men and five women were included in the study sample. The mean ± SD age of the subjects was 32.5 ± 10.0 years, and the range was 23 to 55 years. The mean ± SD mass of the subjects was 71.1 ± 18.9 kg, and the range was 47 to 104 kg. The mean ± SD height of the subjects was 170 ± 11.2 cm, and the range was 157 to 187 cm. Subjects self-reported to be free from any shoulder pain that would prevent them from propelling a manual wheelchair, and had no reported history of cardiopulmonary disease.

### *Part 1. Vibration Exposure during Electric Powered Wheelchair Driving*

Subjects were asked to drive the test electric powered wheelchair over six sidewalk surfaces a total of three times each at two speeds (1 m/s and 2 m/s) for a total of 360 trials (360 = 10 subjects x 6 surfaces x 3 repetitions x 2 speeds). Speed was verified for each trial using a stopwatch over a known distance. Trials were considered acceptable when the time was within 0.1 s of the target time. Tri-axial accelerations were collected at the footrests and seat, using instrumentation described in a previous study (8). A custom data-collection program was used to interface with a data acquisition card. The acceleration data were calibrated and converted for analysis in custom software written using Matlab.

### *Part 2. Vibration Exposure and Mechanical Work during Manual Wheelchair Propulsion*

Subjects propelled the test manual wheelchair at 1 m/s and the pushrim propulsive moments were recorded using a SMART$^{\text{Wheel}}$ (24). The data from the SMART$^{\text{Wheel}}$ will be used to calculate the mechanical work exerted by the users in order to traverse each of the test sidewalk surfaces. Subjects traversed each surface three times for a total of 180 trials (180 trials = 10 subjects x 6 surfaces x 3 repetitions). The SMART$^{\text{Wheel}}$ has been accepted as a measurement tool for the ASTM PS 83-97/F1951 Standard on Playground Surface Accessibility.

### *Data Reduction*

The data reduction consisted of converting each of the three axes of the accelerometers into a resultant acceleration vector (a) for both the seat and the footrest, see equation (1).

$$a(n) = \left\| a(n)_x^2 + a(n)_y^2 + a(n)_z^2 \right\| \qquad (1)$$

Where the subscripts x, y and z represent the fore-aft, medial-lateral, and superior-inferior directions, respectively, and the variable n represents an individual sample. To reduce the noise in the signal it was processed using an autocorrelation sequence, see equation (2), where m is the lag index.

$$\hat{r}_{xx}(m) = \frac{1}{N - |m|} \sum_{n=0}^{N-|m|-1} x(n) * x(n + |m|) \qquad (2)$$

The resultant autocorrelation vectors for both the seat and the footrest was conditioned using a Hamming Window (W(n)), see equation (3).

$$W(k) = .54 \pm .46 \cos\left(\frac{2\pi k}{N}\right) \qquad k = -\frac{N}{2} \cdots, -1, 0, 1, \cdots \frac{N}{2} \qquad (3)$$

In equation (3), N represents the number of samples, and k is an index. The conditioned acceleration data were then entered into a Fast Fourier Transform (FFT) algorithm to determine their respective frequency spectra, see equation (4).

$$A(K+1) = \sum_{n=0}^{N-1} a(n+1) \times e^{-j(2\pi/N)} \qquad (4)$$

The variable A represents the resultant acceleration in the frequency domain, K is the frequency index of each sample, j is $\sqrt{-1}$. The power spectral density (PSD) is a means of showing how the power of the acceleration is distributed over frequency. The PSD was divided into the frequency octaves for human vibration exposure, see equation (5).

$$f_2 = (2^{1/3}) \times f_1 \qquad (5)$$

The PSD for each octave was determined by integrating the signal over the length of the octave being measured. The area under the curve at each octave was used as a measure of the total vibration power per octave.

### *Statistical Analysis*

For all variables, distributions were examined for outliers and to determine whether data was normally distributed. For all continuous variables, means and standard deviations were calculated. Mixed models were developed for the peak seat and foot accelerations, seat and foot frequencies, and the mechanical work. Mixed model analysis was used because both fixed and random effects are incorporated into the model. Analyses were completed using SAS. (25) Significance level was set at 0.05. For all models, both seat and foot accelerations were included in the model simultaneously. For the seat and foot frequencies, the mixed models were completed for average power per octave to determine differences between surfaces and accelerations. Separate models were completed for wheelchair types (manual and power), and for the power wheelchairs, separate models developed for the different speeds. Mechanical work was determined through use of the SMART$^{\text{Wheel}}$ and averaging the right and left sides of the work value. Vibration data were also compared to ISO 2631.

## RESULTS

### *Part 1 – Electric Powered Wheelchair Driving*

The peak accelerations recorded at the seats and footrests and the frequencies at which they occurred are reported in **Table 1**. At 1 m/s, significant differences were found in peak accelerations between the seat and footrest ($p<0.0001$) and between the sidewalk surfaces ($p=0.004$). The peak accelerations at the seat for surfaces 2, 5 and 6 were lower than the standard sidewalk surface, with surface 4 being significantly higher. The same pattern of results were found at the foot accelerations. Similar results were seen for 2 m/s, with significant differences ($p<0.0001$) found between the seat and foot accelerations. Borderline significance ($p=0.049$) was found between surfaces, with surface 4 having higher peak amplitude for both speeds and at the footrest and seat. There were significant differences ($p<0.001$) in the peak accelerations when comparing the peak seat accelerations between the manual and electric powered wheelchairs at both 1 m/s and 2 m/s, with higher peaks found in manual wheelchairs. There were also significant differences ($p=0.02$) in the frequencies at which the peak accelerations occurred for the manual wheelchair and the power wheelchair at the faster speed. The frequency at which it occurred was higher in the power wheelchair.

**Table 2** shows the mean values for the footrest and seat vibrations. As can be seen, at 1 m/s, the majority of mean values for the sidewalk were higher than the mean values for other surfaces for all octaves for both seat and footrest vibrations. Results from the mixed model indicated that the sidewalk resulted in significantly higher ($p<0.0001$) vibration for most of the octaves examined (1.6-2 Hz, 2-2.5 Hz, 2.5-3.15 Hz, 3.15-4 Hz, 6.3-8 Hz). For octaves 5-6.3 Hz and 8-10 Hz, the sidewalk and surface 4 were similar in vibration, with the other surfaces having significantly lower vibration. At 2 m/s, no differences in the vibration were recorded for octaves 1.6-2 Hz, 2-2.5 Hz, 2.5-3.15 Hz. Mean values for both seat and footrest were highest for the sidewalk and at several octaves lowest for surface 4 at 2 m/s, with other surfaces being very similar in vibration. Results from the model indicate that the standard sidewalk recorded significantly ($p<0.001$) higher vibration values per octave than other surfaces for the octaves examined. Interestingly, for several of the octaves, surface 4 recorded the lowest vibration at 2 m/s, although the differences were not statistically significant.

**Figures 5, 6, and 7** show ensemble average curves of the seat accelerations for while driving the manual and electric powered wheelchairs over the six sidewalk superimposed over the curves for exposure limits defined in ISO 2631. **Table 3** shows the time to exceed the ISO 2631 exposure limits for the surfaces tested.

***Part 2 – Manual Wheelchair Propulsion***

For peak accelerations in manual wheelchairs, significant differences were found between the seat and foot accelerations ($p<0.0001$) and surfaces ($p<0.0001$). All surfaces were significantly different ($p=0.001$) than the standard sidewalk, with surfaces 2, 3, 5, 6 having lower peak vibrations and surface 4 having higher peak vibrations than a standard sidewalk, see **Table 1**.

The results of comparing the vibration power in each octave between the selected surfaces are presented in **Table 2**. Similar results were found with both foot and seat accelerations. For the octaves between 2 Hz – 12.5 Hz the vibration power for all surfaces were equal to or significantly lower than the standard sidewalk, with exception of surface 4. Surface 4 had higher vibrations in all octaves in comparison to the standard sidewalk. For octaves, 2.5-3.15 Hz, 4-5 Hz, 5-6.3 Hz, 10-12.5 Hz, and 12.5-16 Hz these differences were significant. For surfaces 2, 3, 5 and 6, the differences were significantly lower than the standard sidewalk for octaves 1.6-2 Hz, 2-2.5 Hz, 3.15-4 Hz, 4-5 Hz, and 6.3-8 Hz. **Table 4** shows that for all surfaces, no significant differences were found for the work to propel over the sidewalks.

## DISCUSSION

The greatest risk for injury due to shock and vibration exposure is when the frequency is near the natural frequency of seated humans (5). The natural frequency of seated humans is between 4 Hz and 12 Hz (10). At the natural frequency, shock and vibration induced in the body is amplified, thus increasing the risk of injury. It is desirable to either reduce the amplitude or power of the shock and vibration or to shift it in frequency so that it is outside the range of natural frequencies of humans. In our study, the peak frequencies occurred in the 2-11 Hz range. The electric powered wheelchair (EPW) tended to record seat vibrations higher than the manual wheelchair, and the EPW average data for the frequency at which the peak occurs were within the natural frequency range of seated humans for all surfaces. Surfaces 1, 2 and 6 tended to transmit peak accelerations lower than the natural frequency range of humans when using the manual wheelchair.

The power per octave is a good measure of vibration or repeated shock exposure, whereas the peak acceleration is closely related to infrequent shock exposure. Our analysis of the power per octave showed that surfaces 2, 3, 5 and 6 induced lower values for both the seat and footrest vibrations than surface 1 across a broad range of frequencies at 1 m/s for both manual and power wheelchairs. The power per octave was similar for surface 4 in the 5-6.3 Hz and 8-10 Hz octaves. At 2 m/s, there were no significant differences in the power per octave for any of the surfaces. The sidewalk surface resulted in higher or no difference in power per octave throughout most of natural frequency range of seated humans. This would indicate that all of the surfaces, with the exception of surface 4 should be considered accessible from a vibration exposure perspective when using a standard poured concrete surface (surface 1) as a reference.

The work required to propel over the surfaces tested were not statistically significantly different. This is probably because the surfaces all had similar grade and no cross-slope. Besides appearance and construction concept, the only substantive distinguishing characteristic was surface roughness due to the bevels and joints. It is likely that materials or constructions with greater differences in surface roughness may yield differences in the work required to propel over them.

Comparison to ISO 2631, shows that at 1 m/s all surfaces, but surfaces 4 and 5 exceed the exposure limit after greater than eight hours of driving an electric powered wheelchair. It is unlikely that wheelchair users will spend more than eight hours driving over sidewalk surfaces on a given day. This preposition is support by studies on the driving habits of wheelchair users (26, 27). Data from driving the electric powered wheelchair at 2 m/s were less promising. All of the surfaces, including the poured concrete sidewalk, induced whole-body vibrations that exceeded the limit after less than three hours of exposure. This is something that needs to be studied further, and may require changes to wheelchair designs to improve vibration suppression.

Future studies need to examine a broader range of sidewalk surfaces. It is also important to examine the surfaces after they had been aged due to exposure to the elements. Studies also need to be conducted using experienced wheelchair users as subjects. A wheelchair user would need to sit on their personal cushion in order to avoid injury. The different cushions could confound the vibration and shock results. Muscle function and spasticity may influence results as well. A standardized wheelchair could be used in future studies; however, the study of subjects in their personal wheelchairs would provide results that could be appropriately generalized. This would naturally require a larger sample of participants.

## CONCLUSION

The report, entitled “Building a True Community: Final Report of the Public Rights-of-Way Access Advisory Committee”, produced by the U. S. Access Board. In Section X02.1.6.1 Advisory, the report includes the statement “Individual paving units, bricks or other textured materials are examples of surfaces that are undesirable in the pedestrian access route because of the vibration that they cause. They may, however, be used in the portions of the public sidewalk that do not contain the pedestrian access route. The purpose of the visually uniform surface is to provide uniformity in color along the pedestrian access route as a way finding cue for person with low vision.” When treating the poured concrete sidewalk as the normative standard, the 2, 3, 5 and 6 surfaces compared most favorably in terms of shock and vibration exposure whereas surface 4 produced mixed results. Surfaces 2, 3, 5 and 6 yielded results that were similar to the poured concrete sidewalk, and should be considered acceptable as a pedestrian access route for wheelchair users.

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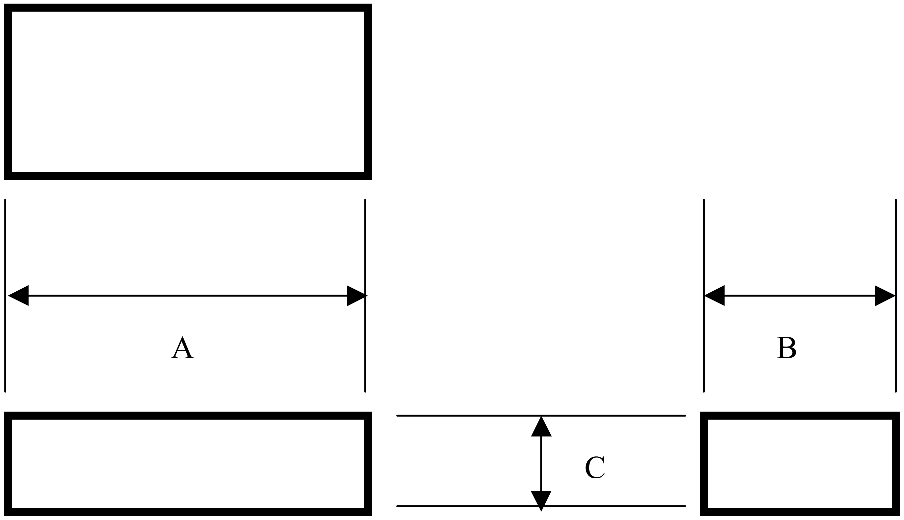
Figure 1. Photograph of surfaces and experimental set-up.

| | | | | Dimension (mm) | | |
|---|---|---|---|---|---|---|
| **#** | **Paver Name** | **Edge Detail** | **Composition** | **A** | **B** | **C** |
| 2 | Holland Paver | Square - no chamfer | Concrete | 198 | 98 | 60 |
| 3 | Holland Paver | 2 mm chamfer | Concrete | 198 | 98 | 80 |
| 4 | Holland Paver | 8 mm chamfer | Concrete | 198 | 98 | 60 |
| 5 | Whitacre-Greer | 4 mm chamfer | Clay | 204 | 102 | 57 |
| 6 | Pathway Paver | Square - no chamfer | Clay | 204 | 102 | 57 |



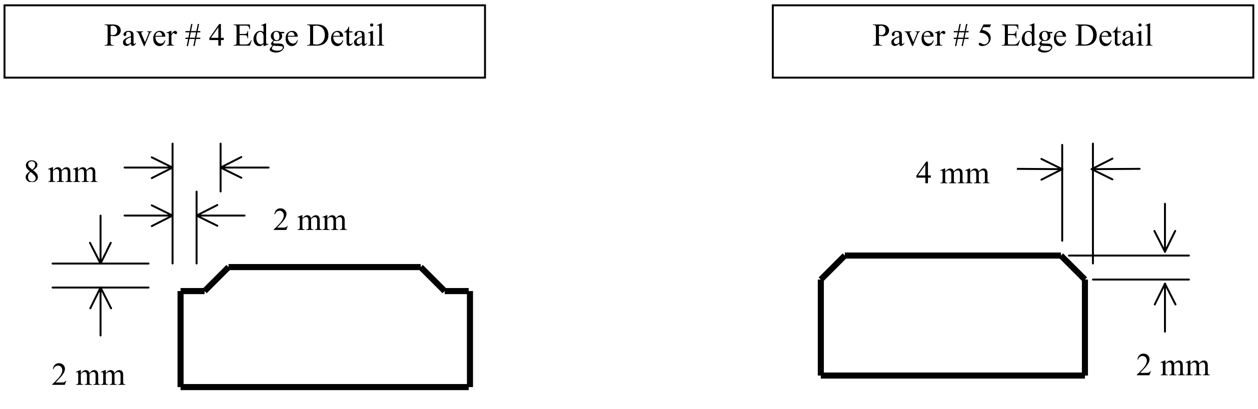


Figure 2. Critical dimensions of the concrete and clay paving tiles used to construct test surfaces.

Figure 3. Manual wheelchair with accelerometers at the footrest and seat, and the SMART$^{wheel}$

Figure 4. Electric powered wheelchair with accelerometers at the footrest and seat

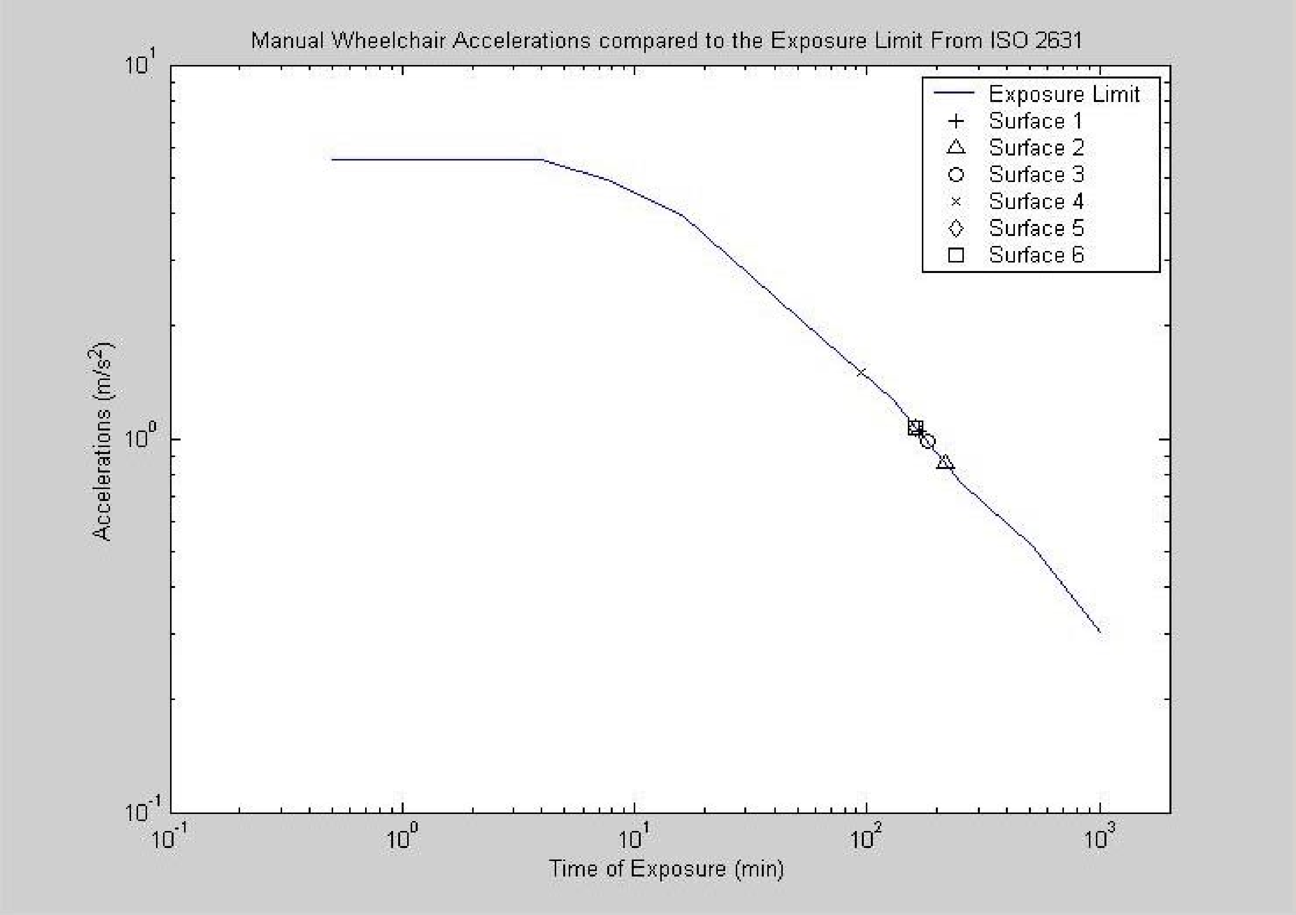


Figure 5. Seat accelerations compared to exposure limit from ISO 2631 for manual powered wheelchair at 1 m/s.

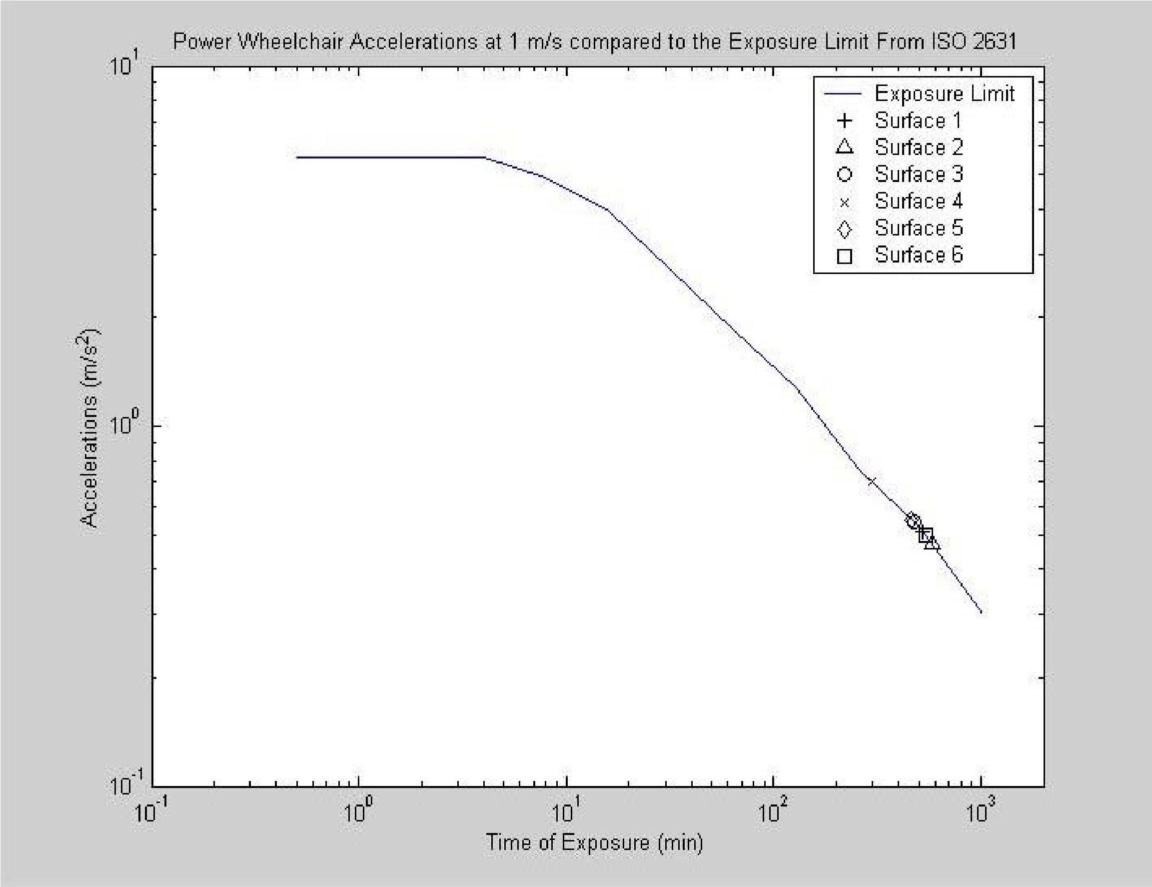


Figure 6. Seat accelerations compared to exposure limit from ISO 2631 for electric powered wheelchair at 1 m/s.

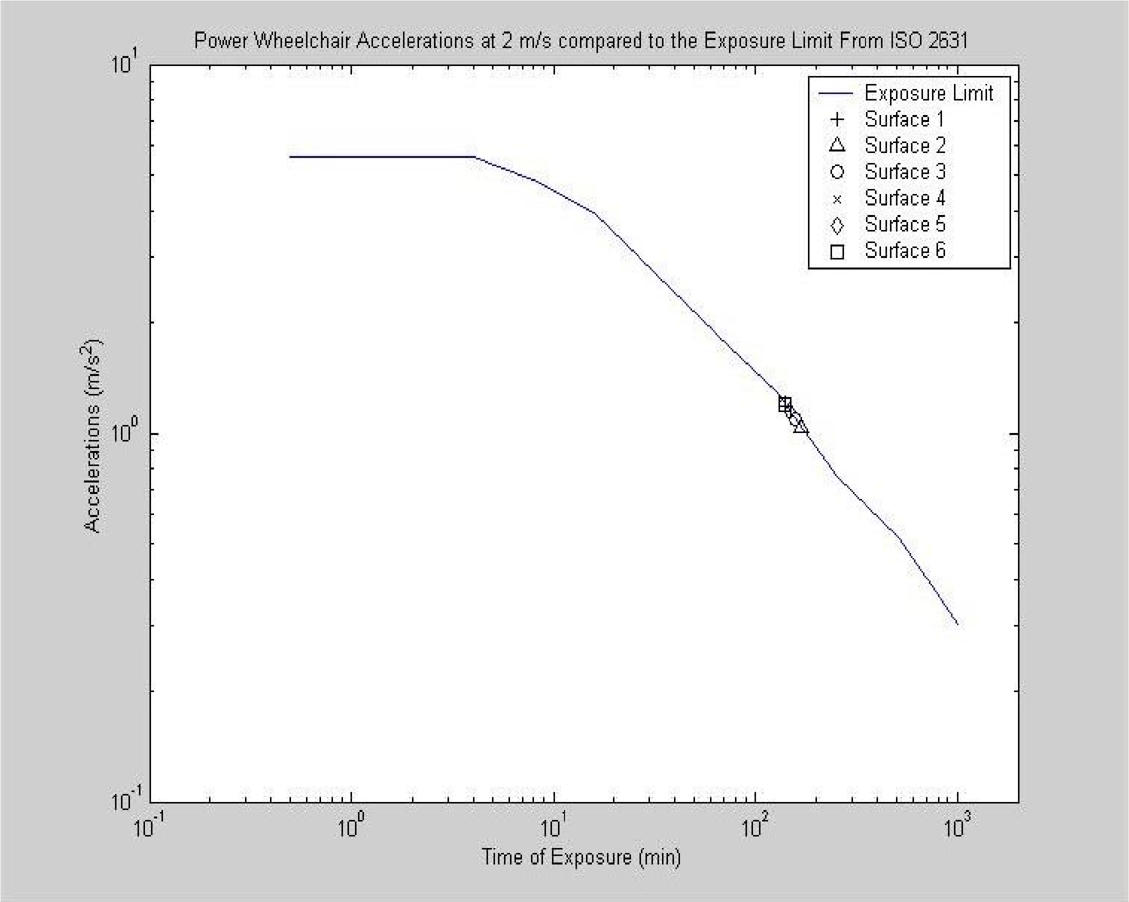


Figure 7. Seat accelerations compared to exposure limit from ISO 2631 for electric powered wheelchair at 2 m/s.

Table 1. Peak accelerations in $m/s^2$, and the frequencies in Hz, at which they occur of foot and seat for manual and power wheelchairs over selected surfaces.

| | | Seat | Frequency | Foot | Frequency |
|---|---|---|---|---|---|
| Surface 1 | Manual | 13.41±3.13 | 2.51±1.25 | 35.36±7.34 | 2.21±0.68 |
| | Power WC, 1 m/s | 2.34±0.43 | 7.55±11.16 | 4.36±2.13 | 4.54±6.03 |
| | Power WC, 2 m/s | 5.16±0.91 | 6.13±7.06 | 8.82±3.80 | 10.47±12.56 |
| Surface 2 | Manual | 5.30±2.16 | 3.70±1.3 | 13.98±4.67 | 5.46±6.82 |
| | Power WC, 1 m/s | 2.01±0.48 | 8.6±9.99 | 3.17±0.81 | 5.31±5.54 |
| | Power WC, 2 m/s | 4.04±1.02 | 8.18±9.81 | 6.67±2.00 | 11.76±11.89 |
| Surface 3 | Manual | 8.35±4.15 | 4.11±4.87 | 19.47±7.20 | 8.13±8.83 |
| | Power WC, 1 m/s | 2.41±0.61 | 5.03±9.84 | 3.44±0.94 | 7.86±8.58 |
| | Power WC, 2 m/s | 4.64±0.83 | 6.2±6.55 | 7.71±1.94 | 11.98±12.17 |
| Surface 4 | Manual | 18.22±2.10 | 10.14±9.79 | 40.98±3.94 | 12.29±9.78 |
| | Power WC, 1 m/s | 2.77±0.65 | 10.54±14.73 | 4.98±2.30 | 11.27±9.01 |
| | Power WC, 2 m/s | 5.34±1.33 | 7.28±9.37 | 10.15±4.75 | 23.52±17.32 |
| Surface 5 | Manual | 9.56±3.75 | 6.04±5.79 | 24.43±5.39 | 10.3±6.21 |
| | Power WC, 1 m/s | 2.19±0.61 | 4.38±5.34 | 3.86±1.20 | 7.9±6.78 |
| | Power WC, 2 m/s | 4.94±1.38 | 11.1±20.51 | 8.34±3.31 | 10.66±13.84 |
| Surface 6 | Manual | 8.00±2.40 | 2.72±1.73 | 23.78±6.29 | 4.29±4.25 |
| | Power WC, 1 m/s | 1.99±0.32 | 6.18±8.86 | 3.33±0.95 | 6.43±7.56 |
| | Power WC, 2 m/s | 4.72±0.93 | 5.75±6.68 | 7.75±2.43 | 7.89±8.28 |

Table 2. Power per octave over surfaces at the footrest

| | Wheelchair | 2.5-3.15 Hz | 4-5 Hz | 6.3-8 Hz | 10-12.5 Hz | 16-20 Hz | 25-31.5 Hz | 40-50 Hz | 63-80 Hz | 100-125 Hz |
|---|---|---|---|---|---|---|---|---|---|---|
| Surface 1 | Manual | 186.4±124.2 | 460.3±147.8 | 235.2±128.5 | 402.8±259.3 | 338.2±241.8 | 504.7±255.1 | 407.7±153.9 | 254.3±117.3 | 211.1±130.1 |
| | Power, 1 m/s | 3.1±4.6 | 4.8±7.6 | 1.8±2.2 | 4.2±5.8 | 3.8±4.2 | 9.6±9.8 | 5.7±7.5 | 3.6±2.4 | 4.1±1.3 |
| | Power, 2 m/s | 0.0±0.0 | 0.0±0.0 | 0.0±0.0 | 12.9±19.4 | 12.7±20.2 | 3.6±3.8 | 23.1±29.6 | 11.4±12.5 | 26.3±22.8 |
| Surface 2 | Manual | 9.9±10.7 | 40.9±47.7 | 30.7±32.2 | 45.2±71.4 | 43.0±54.9 | 45.0±65.7 | 48.5±53.4 | 48.3±49.3 | 57.1±44.8 |
| | Power, 1 m/s | 0.4±0.3 | 1.0±1.1 | 0.4±0.3 | 1.5±0.7 | 1.1±0.7 | 2.1±0.7 | 2.1±1.2 | 2.2±1.6 | 1.3±0.4 |
| | Power, 2 m/s | 0.0±0.0 | 0.0±0.0 | 0.0±0.0 | 3.4±6.0 | 3.4±5.6 | 1.8±1.4 | 6.8±5.7 | 5.9±6.3 | 18.3±21.5 |
| Surface 3 | Manual | 17.1±20.2 | 67.7±67.0 | 84.0±95.3 | 76.9±94.4 | 44.0±55.5 | 186.4±232.9 | 99.2±111.0 | 88.3±120.2 | 114.7±77.7 |
| | Power, 1 m/s | 0.8±0.8 | 1.0±0.9 | 0.9±0.8 | 1.4±0.9 | 1.4±0.9 | 5.8±6.0 | 2.4±1.7 | 1.8±0.9 | 3.1±1.5 |
| | Power, 2 m/s | 0.0±0.0 | 0.0±0.0 | 0.0±0.0 | 3.6±3.0 | 4.0±3.7 | 5.6±1.9 | 8.4±6.5 | 9.9±7.2 | 37.2±50.7 |
| Surface 4 | Manual | 192.5±173.4 | 464.7±337.3 | 459.4±310.6 | 316.4±308.4 | 167.9±160.0 | 1388.3±697.8 | 475.1±293.6 | 319.0±182.7 | 723.0±451.0 |
| | Power, 1 m/s | 1.1±1.2 | 1.8±1.5 | 0.9±0.5 | 2.7±1.8 | 2.8±1.6 | 13.7±4.3 | 3.2±2.1 | 3.8±2.6 | 6.0±4.1 |
| | Power, 2 m/s | 0.0±0.0 | 0.0±0.0 | 0.0±0.0 | 2.8±3.1 | 2.7±2.5 | 2.8±1.7 | 5.9±3.5 | 7.0±6.5 | 60.7±78.2 |
| Surface 5 | Manual | 55.2±38.1 | 124.0±70.4 | 102.6±76.6 | 75.7±79.6 | 44.2±31.6 | 56.2±72.9 | 58.1±54.7 | 72.4±57.6 | 107.7±57.3 |
| | Power, 1 m/s | 0.4±0.3 | 0.5±0.3 | 0.6±0.5 | 1.3±1.0 | 0.9±0.4 | 7.9±2.5 | 2.0±0.9 | 1.3±0.4 | 3.2±3.7 |
| | Power, 2 m/s | 0.0±0.0 | 0.0±0.0 | 0.0±0.0 | 5.3±5.6 | 4.3±5.7 | 2.7±2.0 | 7.6±4.3 | 7.2±4.8 | 26.8±42.7 |
| Surface 6 | Manual | 60.7±46.8 | 118.0±75.0 | 102.8±74.3 | 103.3±88.1 | 101.6±70.7 | 106.5±70.9 | 162.9±110.8 | 161.8±92.4 | 142.5±70.4 |
| | Power, 1 m/s | 1.0±1.0 | 1.0±1.1 | 0.5±0.3 | 1.4±1.4 | 1.5±1.1 | 3.9±1.2 | 3.1±2.4 | 2.2±1.1 | 3.2±2.3 |
| | Power, 2 m/s | 0.0±0.0 | 0.0±0.0 | 0.0±0.0 | 8.0±7.8 | 7.8±7.6 | 2.4±1.5 | 11.1±8.1 | 8.7±5.9 | 14.1±14.0 |

Table 2. Power per octave over surfaces at the seat

| | Wheelchair | 2.5-3.15 Hz | 4-5 Hz | 6.3-8 Hz | 10-12.5 Hz | 16-20 Hz | 25-31.5 Hz | 40-50 Hz | 63-80 Hz | 100-125 Hz |
|---|---|---|---|---|---|---|---|---|---|---|
| Surface 1 | Manual | 17.1±16.9 | 40.4±16.5 | 24.6±16.7 | 35.8±25.2 | 30.9±17.5 | 50.0±31.2 | 38.6±14.9 | 27.5±7.9 | 23.8±10.0 |
| | Power, 1 m/s | 0.6±0.3 | 0.8±0.7 | 0.4±0.3 | 1.1±0.6 | 0.8±0.4 | 2.5±2.3 | 1.6±1.1 | 1.0±0.4 | 2.1±1.3 |
| | Power, 2 m/s | 0.0±0.0 | 0.0±0.0 | 0.0±0.0 | 7.8±8.7 | 7.6±8.4 | 3.2±2.1 | 10.7±9.5 | 4.9±4.2 | 9.6±7.5 |
| Surface 2 | Manual | 2.7±4.2 | 7.3±6.0 | 6.4±5.7 | 8.9±7.4 | 8.0±5.4 | 9.0±7.9 | 6.7±3.1 | 7.1±4.4 | 7.8±7.7 |
| | Power, 1 m/s | 0.1±0.1 | 0.3±0.3 | 0.3±0.2 | 0.6±0.5 | 0.4±0.2 | 1.4±1.2 | 0.6±0.4 | 0.9±0.4 | 1.0±0.5 |
| | Power, 2 m/s | 0.0±0.0 | 0.0±0.0 | 0.0±0.0 | 3.0±5.6 | 2.5±4.3 | 1.5±1.2 | 3.5±2.9 | 2.1±2.7 | 5.1±3.0 |
| Surface 3 | Manual | 4.1±6.2 | 11.2±10.4 | 10.6±10.2 | 13.5±14.8 | 9.6±10.6 | 23.6±31.1 | 14.9±18.9 | 18.1±32.4 | 16.0±15.1 |
| | Power, 1 m/s | 0.3±0.2 | 0.3±0.2 | 0.3±0.2 | 0.6±0.3 | 0.6±0.3 | 2.9±2.9 | 1.0±0.8 | 0.9±0.4 | 1.1±0.7 |
| | Power, 2 m/s | 0.0±0.0 | 0.0±0.0 | 0.0±0.0 | 3.2±3.3 | 3.5±3.8 | 2.1±1.2 | 4.6±3.1 | 3.0±2.9 | 5.7±5.3 |
| Surface 4 | Manual | 33.3±31.6 | 78.4±60.4 | 72.1±63.3 | 44.4±51.0 | 16.7±10.5 | 147.0±66.3 | 60.8±37.8 | 40.5±24.4 | 75.0±47.6 |
| | Power, 1 m/s | 0.4±0.3 | 0.6±0.4 | 0.4±0.3 | 1.1±0.9 | 0.9±0.5 | 5.2±4.6 | 1.2±0.5 | 1.0±0.3 | 1.6±0.7 |
| | Power, 2 m/s | 0.0±0.0 | 0.0±0.0 | 0.0±0.0 | 1.3±1.2 | 1.3±1.24 | 1.7±1.4 | 2.5±1.6 | 2.6±2.0 | 9.5±7.6 |
| Surface 5 | Manual | 7.6±4.9 | 19.1±13.3 | 18.0±20.8 | 13.5±24.1 | 6.1±3.2 | 10.8±14.1 | 9.4±7.8 | 9.9±9.8 | 12.7±9.5 |
| | Power, 1 m/s | 0.2±0.2 | 0.2±0.1 | 0.3±0.2 | 0.4±0.2 | 0.4±0.3 | 2.7±4.1 | 0.8±0.4 | 0.7±0.2 | 1.1±0.3 |
| | Power, 2 m/s | 0.0±0.0 | 0.0±0.0 | 0.0±0.0 | 2.8±3.6 | 2.9±3.4 | 2.2±1.0 | 4.0±2.1 | 2.3±2.0 | 6.0±4.3 |
| Surface 6 | Manual | 7.0±8.4 | 14.5±11.8 | 12.9±9.6 | 12.6±14.8 | 9.2±3.7 | 9.9±6.2 | 10.9±5.0 | 11.9±5.4 | 12.9±8.6 |
| | Power, 1 m/s | 0.3±0.3 | 0.4±0.3 | 0.3±0.2 | 0.6±0.3 | 0.4±0.2 | 1.3±1.4 | 0.8±0.4 | 0.8±0.3 | 1.3±0.7 |
| | Power, 2 m/s | 0.0±0.0 | 0.0±0.0 | 0.0±0.0 | 5.4±5.8 | 5.4±5.8 | 2.9±1.3 | 4.7±4.7 | 3.7±2.0 | 5.7±5.1 |

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Table 3. Comparison to ISO 2631 exposure limits.

| | Manual Wheelchair | Electric Powered Wheelchair | |
|---|---|---|---|
| Surface | Exposure Limit (hours) at 1 m/s | Exposure Limit (hours) at 1 m/s | Exposure Limit (hours) at 2 m/s |
| 1 | 2.8 | 8.7 | 2.4 |
| 2 | 3.6 | 9.7 | 2.8 |
| 3 | 3.0 | 8.0 | 2.6 |
| 4 | 1.6 | 5.0 | 2.2 |
| 5 | 2.7 | 7.7 | 2.5 |
| 6 | 2.7 | 9.0 | 2.3 |

Table 4. Average work in N•m, for propulsion over surfaces at 1 m/s for manual wheelchair.

| Surface | Mean ± Std dev. |
|---|---|
| 1 | 3.33±0.80 |
| 2 | 3.28±0.83 |
| 3 | 3.25±0.67 |
| 4 | 3.29±0.73 |
| 5 | 3.23±0.73 |
| 6 | 3.30±0.78 |