VIBRATION EXPOSURE OF INDIVIDUALS USING WHEELCHAIRS OVER CONCRETE PAVER SURFACES

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SUMMARY

According to the International Standards Organization 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. Wheelchair users fit this description perfectly, however little research has been conducted to evaluate the amount of vibration transmitted to a wheelchair user. The vibration exposure was produced by traversing nine pavement surfaces with 10 individuals without disabilities in a manual and powered wheelchair. The surfaces included poured, jointed concrete and concrete and clay pavers with chamfers from 0 to 8 mm wide and two herringbone laying patterns for selected surfaces.

Power wheelchair results: The standard poured concrete surface was used as a norm and compared to the other surfaces. Two surfaces resulted in higher vibration exposure than the standard; an 8mm wide chamfer concrete paver in a 90 degree herringbone pattern and a 6mm wide chamfer pavers 90 degree herringbone pattern. Manual wheelchair results: Three surfaces resulted in higher vibration exposure than the standard surface; the 8mm wide chamfer surface in a 90 degree herringbone pattern, and the two 6mm wide chamfer surfaces placed in 90 and 45 degree patterns. Recommendations: Smaller chamfer widths on pavers exposes individuals using wheelchairs to less vibration. Also, pavers installed in a 90 degree herringbone pattern produced lower vibration exposures. It is recommended that only pavers of 6 mm wide chamfers or less be used with a 90 degree herringbone pattern.

1. INTRODUCTION

On January 10, 2001, the Public Rights-of-Way Access Advisory Committee (PROWAAC) released a report entitled, *Building a True Community* (22). The Committee was commissioned by the United States Architectural and Transportation Barriers Compliance Board, a federal government agency (also known as the Access Board) responsible for issuing accessibility design guidelines for disabled persons. The PROWAAC report proposed a 1.5 m wide pedestrian access route having within it a 1.2 m wide “reduced vibration zone” for new and rehabilitated sidewalks in the public right-of-way. The intent of this zone was to eliminate irregular surface features under users of wheeled mobility devices and under wheelchairs in particular. The PROWAAC report identified surfaces consisting of "individual paving units, bricks or other textured materials" as examples of undesirable surfaces in the pedestrian access route because of the vibration they cause and pain to some users of wheeled mobility aids.

The PROWAAC report identified a need for research on the measurement of the rolling vibration of pedestrian surfaces. A need was expressed for investigations into surface roughness, surface wavelength (vibration), and wheelchair features. In light of the need for research, the Interlocking Concrete Pavement Institute, Brick Industry of America, and the National Concrete Masonry Association jointly funded research in 2002 with the University of Pittsburgh and the United States Veterans Health Administration (VHA) on smoothness of segmental pavements. The results of this study are found in Cooper (21) where six sidewalk surfaces were evaluated. This work is also published by Wolf *et al.* (11) and Pearlman *et al.* (12).

The 2002 study by Cooper (21) tested a poured concrete (jointed) surface, concrete pavers with 0, 2 and 8 mm wide chamfers and clay pavers with 0 and 4 mm wide chamfers. The study found that surfaces with 8 mm wide chamfers were not acceptable as pavers for wheelchair access routes, but surfaces with chamfers of 4 mm or less were considered acceptable when using the poured concrete surface as the norm. Cooper *et al.* produced similar results when performing tests in 2003 with frequency analyses comparing the six sidewalk surfaces (13). They reported that only the 8 mm wide chamfered surface produced significantly higher, and potentially injurious, levels of whole-body vibrations; the other surfaces with 4 mm wide or smaller chamfers could be safely traversed by those using wheelchairs. Further, no significant differences were found in the work required to propel over the segmental pavement surfaces compared to the poured concrete surface.

An objective of the study described in this paper was to install and test three new concrete paver surfaces with 4 and 6 mm wide chamfers in 90 degree and 45 degree patterns. These surfaces were tested with the original six surfaces previously tested in 2002 and 2003. This would provide a more complete spectrum of vibration results from pavers with no chamfers, as well as those with 2, 4, 6, and 8 mm wide chamfers as there was no data from the 2002 and 2003 tests on concrete pavers with 6 mm wide chamfers because they were not tested.

2. VIBRATION EXPOSURE TO WHEELCHAIR USERS

People who use wheelchairs as their primary means of mobility often use their wheelchairs 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 people who use wheelchairs (4-5). Van Sickle *et al.* (6) recorded the forces that resulted from using the American National Standards Institute/Rehabilitation Engineering and Assistive Technology Society of North America (ANSI/RESNA) Standards double drum and curb drop tests, and compared them to the vibrations experienced during ordinary propulsion. Van Sickle *et al.* (7) also demonstrated 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.

The International Standards Organization (ISO) and ANSI (8) developed a Standard for whole-body vibration measurement. This Standard includes the amplitudes of vibrations considered harmful and the associated exposure times for the vibrations ranges that were identified as hazardous. The Standard describes some of the physical effects that can occur from whole-body vibration exposure. Research has found correlations between whole-body vibrations and secondary injuries in the trucking and construction industries (9-10). Seidel *et al.* (1) reported that occupational groups (e.g., tractor, bus, and truck drivers, etc.) exposed to whole-body vibrations near or above the ISO exposure limit had increased risk of secondary musculoskeletal injury.

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 (20). The health guidance caution zone defines the risk for a given time period based on the average amount of vibration experienced by the user. As time progresses, the amount of vibration that someone using a wheelchair can safely tolerate decreases dramatically.

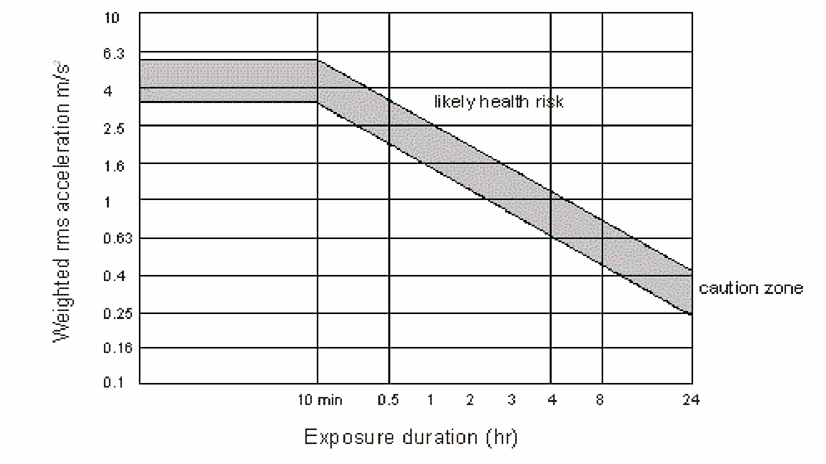

Figure 1. Limit boundaries of vibration exposure as defined by the ISO-2631 standard

Rigorous measurements of vibration exposure due to traversing different sidewalk surfaces—a daily task for most wheelchair users—has not been reported in the literature. If vibration exposure is significant and related to the types of surfaces traversed, this information would be vital in the development of standards for appropriate sidewalks surfaces, and thus would impact regional departments of public works and the manufacturers of sidewalk surfaces. Therefore, this study was performed to better understand the vibration exposure experienced by people using an electric powered and a manual wheelchair as they traversed over a conventional, cast-in-place concrete sidewalk and common segmental clay and concrete surfaces with varying chamfer widths. The study provides support for determining criteria for defining a wheelchair pedestrian access route that does not require excessive propulsive work, or expose people using wheelchairs to potentially harmful vibrations.

3. METHODS

3.1 Test Surfaces

Nine different types of sidewalk surfaces were tested as shown in Figure 2.

Surfaces 1, 2, and 3

Surfaces 4, 5, and 6

Surfaces 7, 8, and 9

Figure 2. Photographs of the nine surfaces tested

All of the sidewalk surfaces were approximately 1.2 m wide and 7.6 m long. One surface was a poured concrete sidewalk with a brush finish to represent the norm (Surface 1). Six sidewalk surfaces were made from interlocking concrete pavement and two of the surfaces were clay brick; all were installed to industry specifications (see Table 1) (14). Surfaces 2, 3, 4, 7, 8 and 9 are concrete pavers with chamfers. Chamfer widths on these pavers are measured from the vertical side of the paver to the horizontal surface. The chamfer widths include an approximate 1 mm ledge or shoulder around the perimeter of the paver and a transition surface approximately 1 mm wide from the top of the chamfer to the horizontal paver wearing surface. Therefore, a 6 mm wide chamfer includes a 1 mm shoulder and a 1 mm transition to the horizontal surface. The actual angles chamfer is 4 mm wide. Surfaces 2 and 6 consisted of concrete pavers and clay pavers without chamfers. Surface 5 was a clay paver with chamfered sides and no shoulder or chamfer-to-surface transition.

Table 1. Specifications for the sidewalk surfaces tested

				Dimension (mm)			
#	Name	Edge Detail	Composition	A	B	C	Pattern Installed
1	Poured concrete (Norm)	Not applicable	Concrete	N/A	N/A	N/A	smooth
2	Holland Paver	Square - no chamfer	Concrete	198	98	60	90°
3	Holland Paver	2 mm chamfer	Concrete	198	98	80	90°
4	Holland Paver	8 mm chamfer	Concrete	198	98	60	90°
5	Whitacre-Greer	4 mm chamfer	Brick	204	102	57	45°
6	Pathway Paver	Square - no chamfer	Brick	204	102	57	45°
7	Holland Paver	6 mm chamfer	Concrete	198	98	60	90°
8	Holland Paver	6 mm chamfer	Concrete	198	98	60	45°
9	Holland Paver	4 mm chamfer	Concrete	198	98	60	90°

Table 2 shows actual, average and standard deviations of four gaps measured randomly from each surface. A gap is the space or joint between the pavers plus the two chamfer widths on facing the joint. Actual joint widths varied between 1.5 and 6 mm and vary depending on the installer.

Table 2. Gaps measurements in mm of the sidewalk surfaces tested

Surface	Material	Chamfer Width	Pattern Angle	#1	#2	#3	#4	Mean	Standard Deviation
1	Cast conc.	n/a	90º	11.79	12.94	13.67	13.3	12.93	0.81
2	Conc. Pavers	0	90º	2.46	1.97	2.3	2.97	2.43	0.42
3	Conc. Pavers	2	90º	5.62	6.21	5.99	6.5	6.08	0.37
4	Conc. Pavers	8	90º	21.7	22.4	21.4	21.2	21.68	0.53
5	Clay pavers	4	45º	10.9	11.26	13.4	11.75	11.83	1.10*
6	Clay pavers	0	45º	1.5	3.7	3.28	1.75	2.56	1.10*
7	Conc. Pavers	6	90º	12.93	13.73	13.27	13.44	13.34	0.33
8	Conc. Pavers	6	45º	17.71	16.54	19.71	17.74	17.93	1.31*
9	Conc. Pavers	4	90º	11.48	10.67	12.96	11.36	11.62	0.96

***** Gap measured in direction of wheel travel

An Interlocking Concrete Pavement Institute (ICPI) certified contractor installed all of the sidewalks. Data were collected in Pittsburgh, Pennsylvania, during June and July of 2004 for the first six surfaces, and during September of 2004 for the additional three surfaces. All surfaces were tested while dry. All of the surfaces were installed outdoors with the same slope of about 1.3 degrees for drainage, and no cross-slope. The approximate temperature during testing for June and July was 19.1° C and for September was 17.6° C (15).

3.2 Test Wheelchairs

The manual wheelchair (Quickie GP, Sunrise Medical Ltd.) used was a rigid frame design with 127 mm diameter polyurethane tires, and standard 610 mm diameter rear wheels (Figure 3).

Figure 3. Setup of the Quickie GP manual wheelchair

The seat width, depth, and backrest height were 406 mm, 458 mm, and 410 mm respectively. The rear axles were placed 45 mm in front of the backrest tubes. SMART$^{\text{Wheels}}$ with solid foam inserts were used as the rear wheels during this study (16). The mass of the manual wheelchair was 15.5 kg with the SMART$^{\text{Wheels}}$ attached.

The electric powered wheelchair (Quickie P200, Sunrise Medical Ltd.) used in the study had a rigid frame with 203 mm front casters, and 254 mm diameter rear wheels (Figure 4).

Figure 4. Setup of the Quickie P200 electric powered wheelchair

The seat width, depth, and backrest height were 406 mm, 415 mm, and 435 mm respectively for the electric powered wheelchair. A standard position-sensing joystick was mounted to the right side armrest, and the manufacturer controller settings were used. All tires were properly inflated to the rated air pressure (0.24 MPa for the caster, and 0.34 MPa for the rear wheels). The approximate mass of the electric powered wheelchair with batteries was 89 kg. The frames of both the manual and the electric powered wheelchairs were made from aircraft quality aluminum. All subjects sat on a 50 mm thick polyurethane foam cushion during all testing.

3.3 Subjects

Ten unimpaired individuals used the same two wheelchairs during data collection: the manual and electric powered wheelchairs previously described. 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 ± 11.2 years, and the range was 22 to 57 years. The average mass of the subjects was 72.8 ± 20.5 kg, with a range of 47 to 107 kg. The average height of the subjects was 170.9 ± 10.8 cm, and the range was 157 to 183 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.

3.3.1 Vibration Exposure during Electric Powered Wheelchair Driving

Subjects were asked to drive the electric powered wheelchair over nine sidewalk surfaces a total of three times each, at two speeds (1 m/s and 2 m/s), for a total of 540 trials (540 = 10 subjects x 9 surfaces x 3 repetitions x 2 speeds). The manual wheelchair was driven at 1 m/s over each of the nine surfaces three times each for a total of 270 trials (270 = 10 subjects x 9 surfaces x 3 repetitions). Speed was verified for each trial using a stopwatch over a known distance. Trials were considered acceptable when the time was within ± 0.5% of the target time. Speed was normalized because of the positive correlation between vibration and speed. Tri-axial accelerations were collected at the footrests and seat, using instrumentation described in a previous study (17). The seat accelerometer was mounted on an aluminum plate (406mm x 406mm x 6mm), and was placed on the seat under the cushion, so the user was not seated on a hard metal surface. The footrest accelerometer was mounted to an aluminum plate and mounted to the footrests (Fig. 4). A custom data-collection program was used to interface with a data acquisition card. The acceleration data were calibrated and converted for analyses in custom software written using Matlab (18).

3.4 Data Reduction

The data reduction consisted of converting each of the three axes of the accelerometers from raw A/D data into acceleration vector data for both the seat and the footrest using calibration constants for each of the accelerometers (K_{acc}). See equation 1.

$$\begin{aligned} a_x &= K_{axc} \times a_x raw \\ a_y &= K_{axc} \times a_y raw \\ a_z &= K_{axc} \times a_z raw \end{aligned} \qquad (1)$$

The subscripts *x, y* and *z* represent the fore-aft, medial-lateral, and superior-inferior directions, respectively. The ISO-2631 Standard defines frequency weightings for accelerations in the time domain for each axis of translation. The plots of these frequency weightings are shown below in Figure 5. The fore-aft and the medial-lateral directions use the first weighting scale, while the vertical direction is weighted differently.

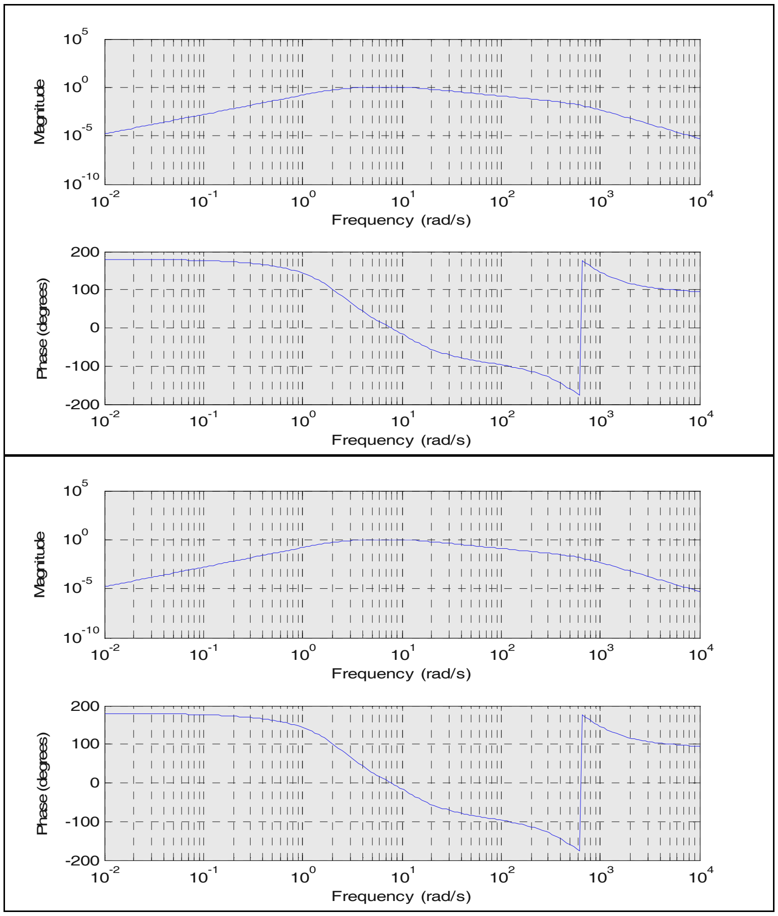

Figure 5. Frequency weightings for the accelerations. The top weighting is used for the fore-aft and medial-lateral directions and the lower weighting is used for the vertical direction (8).

Once the frequency weightings were applied to the accelerations, the root-mean squares were calculated in each direction for the trial. The average root-mean square values in the vertical direction over each of the surfaces were used as the metric of comparison for this study.

3.5 Statistical Analysis

For all variables, distributions were examined for outliers and to determine whether data were normally distributed. For all continuous variables, means and standard deviations were calculated. Analyses were completed using SAS (19). A repeated-measures (repeated: surfaces and subjects) Analysis of variance (ANOVA) was used to determine if differences existed between the main effects of the surfaces, and a Tukey-Kramer post-hoc test was used to determine whether the vibration produced by the surfaces differed significantly. Significance levels were set at $p < 0.05$. Separate models were completed for wheelchair types (manual and power), and separate models were developed for the different speeds of the power wheelchair trials.

4. RESULTS

4.1 Manual Wheelchair Propulsion

Preliminary examination of the data revealed one outlier for one subject due to sharp increases in vibration at the end of the trial (due to popping a “wheelie”). This was removed so as to not skew the data. The comparison of the sidewalk surfaces revealed that, compared to the standard poured concrete surface, (1) Surfaces 3, 5, 6, and 9 did not differ significantly in vibration level produced. Surface 2 was the only surface resulting in significantly lower vibration exposure than Surface 1 (norm), and Surfaces 4, 7, and 8 produced significantly higher vibration exposures.

A linear regression of the data as a whole revealed a positive correlation between the RMS vertical vibration and the surface chamfer, with a slope of 0.0455 and an R^2 value of 0.57. Separate regressions were then run for the 45 degree and 90 degree herringbone-patterned surfaces. The regression for 90 degree patterns had a slope of 0.0517 and an R^2 value of 0.77. The 45 degree regression produced a slope of .04 and an R^2 value of 0.41.

4.2 Electric Powered Wheelchair Driving

At 1 m/s, the RMS accelerations at the seat significantly differed between the sidewalk surfaces ($p=0.004$). The RMS accelerations at the seat for Surfaces 2, 3, and 5 were lower than the standard sidewalk surface, Surfaces 6, 8, and 9 showed no significant differences, and Surfaces 4 and 7 were significantly higher. At 2 m/s RMS of vibration exposure all of the surfaces were significantly lower than that the standard sidewalk surface. A positive correlation at 1m/s with a 90 degree herringbone pattern was found in the power wheelchair trials. The slope was 0.0655 and the R^2 value was 0.83. The other linear regressions demonstrated little or no correlation between vibration levels produced and the bevel sizes. The 45 herringbone pattern at 1 m/s, and the 90 and 45 herringbone patterns at 2 m/s had R^2 values of 0.25, 0.002, and 0.016 respectively.

Table 3 shows displays the time that a wheelchair user would need to travel on each surface to be exposed to a level of vibration that is considered a possible health risk.

Table 3. Comparison to ISO 2631 lower boundary of the Health Guidance Caution Zone

Surface	Material, chamfer width, herringbone pattern angle	Manual Wheelchair	Electric Powered Wheelchair	
		Exposure Limit (hours) at 1 m/s	Exposure Limit (hours) at 1 m/s	Exposure Limit (hours) at 2 m/s
1	Poured concrete	6.77	11.62	1.26
2	Concrete pavers, 0 mm, 90º	13.38	24.31	4.72
3	Concrete pavers, 2 mm, 90º	8.53	16.40	3.14
4	Concrete pavers, 8 mm, 90º	2.34	2.43	2.31
5	Brick pavers, 4 mm, 45º	6.38	15.98	2.52
6	Brick pavers, 0 mm, 45º	6.00	12.82	2.03
7	Concrete pavers, 6 mm, 90º	4.32	4.81	3.49
8	Concrete pavers, 6 mm, 45º	2.46	12.57	2.66
9	Concrete pavers, 4 mm, 90º	6.52	11.16	4.44

5. DISCUSSION

For both the manual wheelchair and the electric powered wheelchair trials, several interlocking concrete surfaces performed as well or better than the sidewalk surface representing the norm.

Surfaces 4, 7 and 8 produced vibration levels that were statistically higher than the standard poured concrete surface in the manual wheelchair trials. The bevel heights of these surfaces were the three highest of the nine tested surfaces, which would explain the findings. Another relevant finding is that Surface 8 produced vibration levels that were statistically higher than Surface 7, suggesting the orientation of the herringbone pattern (90 and 45 degrees, respectively) is an important factor. Consistent results were found between Surfaces 2 and 6, which had the same bevel heights (0 mm), however Surface 6 had a higher vibration output due to its 45 degree pattern orientation. These results lead us to recommend the use of any surface with a bevel height of less than or equal to 6 mm. However, when using the 6mm width chamfers, the pavers should only be placed in a 90 degree herringbone pattern.

The linear regression model of the bevels versus the vibration levels produced with the 90 degree herringbone-patterned surfaces revealed a reasonably good fit, as the vibration level produced increases with the bevel heights. The 45 degree pattern was not as good a fit, but this result may be due to insufficient data. If additional 45 degree herringbone-patterned surfaces had been available for testing, the regression might have provided a better fit.

Results from the electric powered wheelchair were similar to those of the manual chair at the 1 m/s speed. Only Surfaces 4 and 7 produced vibration levels statistically higher than the standard Surface 1. However, at 2 m/s all of the surfaces produced vibration levels that were statistically lower than the standard sidewalk surface. The higher speed of the chair and its reaction to the sharp peak vibrations caused by the spaces in the sidewalk may explain the results obtained from the 2 m/s trials. Another possible explanation may be due to the fore-aft acceleration of the chair itself as it approached a constant velocity. At the 2 m/s rate of speed, the surfaces were not long enough for the chair to reach constant velocity for the entire trial.

The linear regression of the power wheelchair data was consistent with the manual chair data only at the 1 m/s speed. The regression had a similar slope to its best-fit line, and the R^2 value was slightly better than that of the manual chair. Results from the 2 m/s regression demonstrated a poor linear relationship; this is thought to be due to the limited number of surfaces tested with a 45 degree herringbone pattern, and also the high accelerations in the fore-aft direction (as discussed above which might have significantly affected the vibration measurements in the vertical direction.

6. CONCLUSIONS

In the report, entitled "Building a True Community: Final Report of the Public Rights-of-Way Access Committee", produced by the U. S. Access Board, Section X02.1.6.1 Advisory 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." Based on the manual and power wheelchair results of this study, use of selected concrete and clay pavers would be acceptable for any route traveled by individuals using wheelchair. The results are as good as, and in some cases better, than that of a standard cast-in-place concrete sidewalk surface. A chamfer width less than or equal to 6mm must be used for routes used by individuals using wheelchairs. Furthermore, a 90 degree herringbone pattern is preferred over the 45 degree pattern, while the 90 degree herringbone pattern is required for the 6mm wide chamfered pavers to maintain safe levels of vibration exposure.

In 2002, the U.S. Access Board did not advance the PROWAAC's recommendation for a reduced vibration zone for wheelchairs in sidewalks in a draft accessibility design guidelines for the public right-of-way. Initial draft guidelines published by the Access Board in 2002 for public comment identified the need for further research on the relationship between surface roughness and wheeled mobility aids, including possible measurement protocols for the pedestrian access route. Therefore, a quantitative requirement for surface smoothness was not included. Final draft guidelines were published in November 2005 and will likely be adopted as design guidelines in 2007 or 2008. These design guidelines reference this research in the preamble and caution against the use of cobbles or other surfaces the cause excess vibrations in wheelchair users. This research was presented to the Access Board has provided a rationale for including segmental pavers with in the pedestrian access route.

7. ACKNOWLEDGEMENTS

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