Vibration Exposure of Individuals Using Wheelchairs over Concrete Paver Surfaces

Erik Wolf, M.S.[3,4], Jonathan Pearlman, M.S.[3,4], Rory A. Cooper, Ph.D.[1-4], Shirley G. Fitzgerald, Ph.D.[1,2,4], Annmarie Kelleher, M.S., O.T.R./L, A.T.P.[1,4], Diane M. Collins, Ph.D., O.T.R./L.[1,4], Michael L. Boninger, M.D. [1-4], and Rosemarie Cooper, M.P.T., A.T.P. [1,2,4]

Departments of Rehabilitation Science & Technology[1], Physical Medicine & Rehabilitation[2], and Bioengineering[3]
University of Pittsburgh, Pittsburgh, PA 15261

HUMAN ENGINEERING RESEARCH LABORATORIES[4]
VA Rehabilitation Research and Development Centre
VA Pittsburgh Healthcare System
Pittsburgh, PA, 15206

ADDRESS CORRESPONDENCE TO:

Rory A. Cooper, Ph.D.
Human Engineering Research Laboratories (151-R1)
VA Pittsburgh Healthcare System
7180 Highland Drive
Pittsburgh, PA 15206

TEL: (412) 365-4850
FAX: (412) 365-4858
e-mail: rcooper+@pitt.edu

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Abstract

The vibration exposure produced by traversing nine surfaces was evaluated by having 10 individuals without disabilities propel over them in both a manual and powered wheelchair. 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 only distinguishing characteristic between the surfaces was the height of their bevels and the pattern in which they were installed. **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 bevel ICPI surface in a 90 degree herringbone pattern and a 6mm bevel ICPI surface in a 90 degree herringbone pattern. **Manual Wheelchair Results:** Three surfaces resulted in higher vibration exposure than the standard surface; the 8mm bevel surface in a 90 degree herringbone pattern, and the two 6mm bevel surfaces placed in 90 and 45 degree patterns **Recommendations:** Using smaller bevels 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 bevel or less be used, with a 90 degree herringbone pattern.

KEYWORDS:

Wheelchairs, Vibration, Injury, Sidewalks, Accessible Surface

1. Introduction

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.

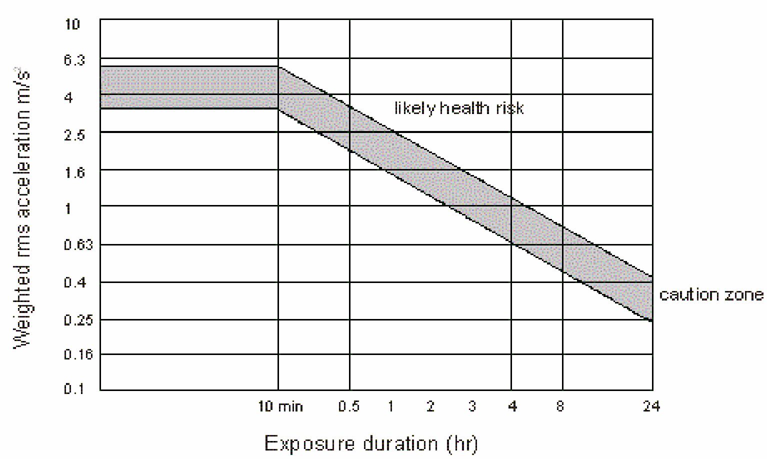


Figure 1 – Limit boundaries of vibration exposure as defined by the ISO-2631 Standard

Previous work evaluated six of the nine sidewalk surfaces used in this study. Wolf *et al.* (11) and Pearlman *et al.* (12) found that surfaces with an 8 mm bevels were not acceptable as pavers for wheelchair access routes, but surfaces with bevels 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 frequency analyses comparing the six sidewalk surfaces (13). They reported that only the 8 mm beveled surface produced significantly higher, and potentially injurious, levels of whole-body vibrations; the other surfaces with 4 mm or smaller bevels could be safely traversed by those using wheelchairs. Further, no significant differences were found in the work required to propel over the ICPI surfaces compared to the poured concrete surface.

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, we performed this study to better understand the vibration exposure experienced by people using both an electric powered and a manual wheelchair as they traversed over selected sidewalk surfaces. 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.

2. Methods

2.1 *Test Surfaces*

We tested nine different types of sidewalk surfaces.

Surfaces 1, 2, and 3

Surfaces 4, 5, and 6

Surfaces 7, 8, and 9

Figure 2 – Photograph of the Nine Surfaces Tested

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). Six sidewalk surfaces were made from interlocking concrete pavement and two of the surfaces were clay brick; all were installed to industry specifications (Figure 3) (14).

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

Figure 3: Specifications of Sidewalks Tested

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^o C and for September was 17.6^o C (15).

2.2 *Test Wheelchairs*

The manual wheelchair (Quickie GP, Sunrise Medical Ltd.) used was a rigid frame design with 127 mm (5”) diameter polyurethane tires, and standard 610 mm (24”) diameter rear wheels (Figure 4).

Figure 4 – 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^{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^{Wheels} attached.

The electric powered wheelchair (Quickie P200, Sunrise Medical Ltd.) used in the study had a rigid frame with 203 mm (8”) front casters, and 254 mm diameter rear wheels (Figure 5).

Figure 5 – 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 (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 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.

2.3 *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.

2.3.1 *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).

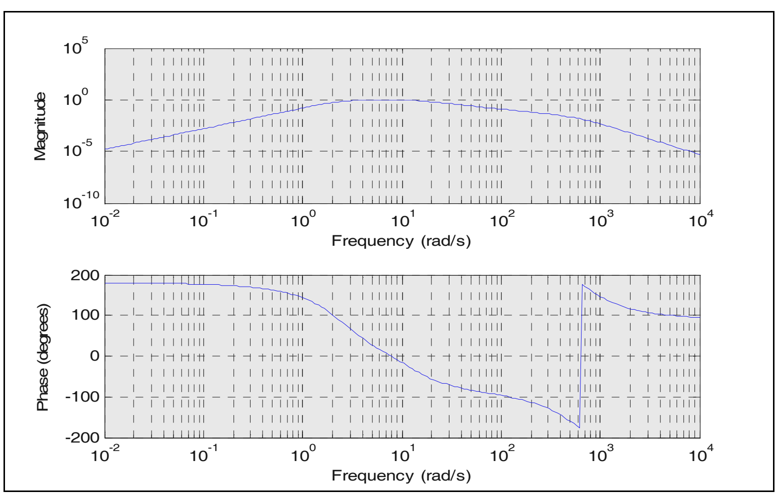
2.4 *Data Reduction*

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.

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

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 6. The fore-aft and the medial-lateral directions use the first weighting scale, while the vertical direction is weighted differently.



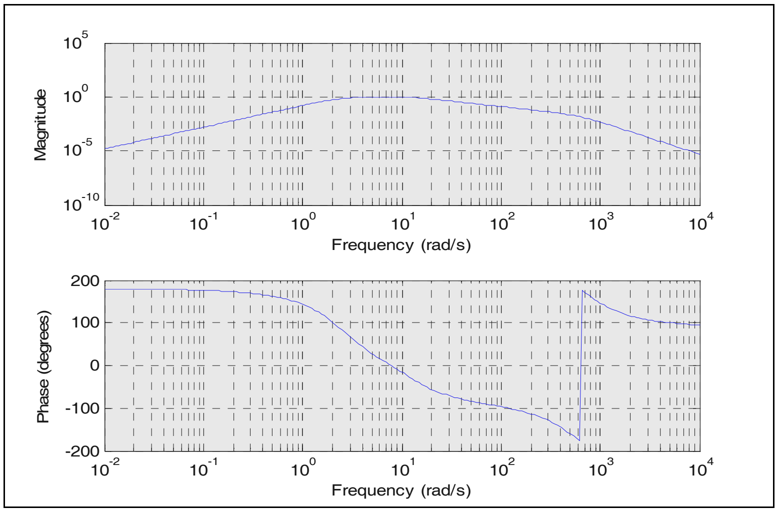


Figure 6 – Frequency weightings for the accelerations. The top weighting is used for the fore-aft and medial-lateral directions and the lower weighting is used for the vertical direction (8).

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.

2.5 *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.

3. Results

3.1 *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). 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 bevel, 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.

3.2 *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 of 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 pattern at 2 m/s had R^2 values of .25, .002, and .016 respectively.

Table 1 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 1 – 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, 0 mm, 90º	13.38	24.31	4.72
3	concrete, 2 mm, 90º	8.53	16.40	3.14
4	concrete, 8 mm, 90º	2.34	2.43	2.31
5	brick, 4 mm, 45º	6.38	15.98	2.52
6	brick, 0 mm, 45º	6.00	12.82	2.03
7	concrete, 6 mm, 90º	4.32	4.81	3.49
8	concrete, 6 mm, 45º	2.46	12.57	2.66
9	concrete, 4 mm, 90º	6.52	11.16	4.44

4. 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 (90deg and 45deg, 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 height bevels, 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.

5. Conclusion

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 ICPI 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 sidewalk surface. A bevel of 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 degreee herringbone pattern is required for the 6mm beveled pavers to maintain safe levels of vibration exposure.

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References

1. Seidel H and Heide R, Long term effects of whole-body vibration: a critical review of the literature, *International Archives of Occupational and Environmental Health*. 1986; 58: 1-26

2. Magnusson M, Pope MH, Wilder DG and Areskoug B. Are occupational drivers at an increased risk for developing musculoskeletal disorders? *SPINE*, 1996; 21: 710-717

3. Fairley T. Predicting the discomfort caused by tractor vibration, *Ergonomics*, 1995; 38: 2091-2106

4. DiGiovine C. Analysis of whole-body vibration during manual wheelchair propulsion using ISO standard 2631, *Proceedings of the annual RESNA conference*, 1999; 242-244

5. Engel P. Aspects of wheelchair seating comfort, *Ergonomics of Manual Wheelchair Propulsion*, 1991; 105-111

6. VanSickle D, Cooper RA, and Boninger ML. Road Loads acting on Manual Wheelchairs, *IEEE Transactions*, 2000; 8: 371-384

7. VanSickle D, Cooper RA, Boninger ML, and DiGiovine CP. Analysis of vibrations induced during wheelchair propulsion, *Journal of Rehabilitation Research and Development*, 2001; 38: 409-421

8. International Standards Organization. Evaluation of Human Exposure to Whole-Body Vibration - Part 1: General Requirements, 1995; *ISO 2631-1*

9. Mansfield N, and Griffin MJ. Difference threshold for automobile seat vibration, *Applied Ergonomics*, 2000; 31: 255-261

10. Lee A, and Salman MA. On the design of active suspension incorporating human sensitivity to vibration, *Optimal Control Applications & Methods*, 1989; 10: 189-195

11. Wolf E, Cooper R, Kelleher A, Fitzgerald S, Ammer W, Assessment of Vibrations During Manual Wheelchair Propulsion Over Selected Sidewalk Surfaces, *Proceedings of the annual RESNA conference*, 2003

12. Pearlman P, Cooper R, Wolf E, Kelleher A, Fitzgerald S, Ammer W, Vibrations During Manual Wheelchair Propulsion Over Selected Sidewalk Surfaces Are Sensitive To Weather-Related Surface Wear, *Proceedings of the annual RESNA conference*, 2004

13. Cooper RA, Wolf E, Fitzgerald S, Kelleher A, Ammer W, Boninger M, Cooper R, Evaluation of Selected Sidewalk Pavement Surfaces, *Journal of Spinal Cord Medicine, In Press*, 2004

14. Interlocking Block Association of Japan. The problem and measures of interlocking block pavement for eyesight or walking disabled people, 1993; 6-24

15. National Weather Service, http://lwf.ncdc.noaa.gov/oa/climate/research/cag3/pa.html, October 27, 2004

16. Asato K, Cooper RA, Robertson RN, and Ster JF. SMART^{Wheels}: Development and testing of a system for measuring manual wheelchair propulsion dynamics, *IEEE Transactions on Biomedical Engineering,* 1993; 40: 1320-1324

17. DiGiovine C, Cooper RA, Wolf EJ, Hosfield J, and Corfman TA. Analysis of vibration and comparison of four wheelchair cushions during manual wheelchair propulsion, *Proceedings of the annual RESNA conference*, 2000; 242-244

18. MATLAB [6.0.1.13], 9-15-2000, Natick, MA, The MathWorks, Inc.

19. Littell RC, Milliken GA, Stroup WW, and Wolfinger RD. SAS System for Mixed Models, Cary, NC: SAS Institute Inc. 1996

20. M.J. Griffin, Handbook of Human Vibrations, Academic Press Inc., San Diego CA 1990 pgs 173-186