USING THE ABSORBED POWER METHOD TO EVALUATE EFFECTIVENESS OF SELECTED SEAT CUSHIONS DURING MANUAL WHEELCHAIR PROPULSION

by

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Although wheelchair users are constantly subjected to oscillatory and shock vibrations not much research has been conducted to assess the whole-body vibrations experienced by wheelchair users. Studies that have been published have only involved the testing of manual wheelchairs not interventions such as suspension or seating systems.

The purpose of this study was to determine if selected wheelchair cushions reduce the amount of harmful whole-body vibrations transferred to wheelchair users and, if the absorbed power method a good measure of evaluating the whole-body vibrations.

Thirty-two participants, who use a wheelchair as their primary mode of mobility, partook in this study. Four of the most commonly prescribed wheelchair cushions were selected. Participants were asked to propel their wheelchair over a simulated activities of daily living (ADL) obstacle course while acceleration and force data was collected.

A repeated measures ANOVA showed no significant differences between the different cushions for the total averaged absorbed power (p = .190), the 50 mm curb drop (p = .234), or the rumble strip (p = .143). A repeated measures ANOVA for the peak curb drop absorbed power revealed a significant difference in the cushions (p = .043).

The cushions that appeared to perform the best in this testing appear to be the Invacare Pindot and the Varilite Solo. Not only did those cushions appear to have the lowest values much of the time but did not display the highest values. Absorbed power appears to be just as effective at determining the effects of vibrations in the time domain as the prescribed methods of the ISO 2631 standard.

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1.0 BACKGROUND

1.1 HARMFUL EFFECTS OF WHOLE-BODY VIBRATION

Prolonged exposure to whole-body vibrations can cause harmful physiological responses in areas of the body such as the cardiovascular system, musculoskeletal system, and the central nervous system (1). These reactions predominantly occur in the musculoskeletal system, specifically leading to spinal deformities, herniated discs, and chronic low back pain (2-4).

Multiple studies have shown a correlation between whole body vibrations and injuries in the trucking, construction, and farming industries (5-9). Mehta et al revealed that in a study of vibrations during tractor operation, the measured vibrations exceeded the ISO levels at 4 and 8 hours of operation (10). Magnusson et al revealed in 1996 that in a questionnaire 60% of bus drivers, and 56% of truck drivers reported low back pain, and bus drivers reported an average of 18 missed days of work per year due to low back pain (11).

Low back pain represents one of the most socio-economically draining injuries present in the work force (12-14). Pope et al revealed that it has been estimated that low back pain is the leading cause of disability payments in the workplace and the second leading cause of missed work in the industrial setting (15). Nishiyama et al displayed that there have been improvements in reducing the amount of vibrations transmitted to tractor drivers through the advancement of technology and simple additions of suspension systems, although these systems are not yet ideal (16).

1.2 EVALUATION OF VARIABLES EFFECTING WHOLE-BODY VIBRATION

The effects of different seating systems, i.e. suspension and cushion selection, as well as postures in the seated and standing positions have also been examined for effects due to vibration stimuli (17-23). In two consecutive studies, Ebe et al attempted to determine both qualitative and quantitative models to assess seat discomfort (24-25). In the first study they determined that overall seat discomfort is affected by both static and dynamic parameters as well as the magnitude of the exposed vibrations. In the later study, it was determined that a prediction of the overall comfort of a seat cushion could be determined by using two variables; cushion stiffness and vibration dose value.

Pope et al examined the effects of posture on exposure of vibration to a seated subject. It was determined that when subjects were forced to maintain an erect posture (i.e. back of the head, posterior peak of the thoracic spine, and the midpoint between the posterior superior iliac spines were collinear), they experience a higher level of whole-body vibration than if maintaining a personalized relaxed posture or any posture where they maintained their highest level of comfort (26).

Lee et al attempted to reduce the amount of whole-body vibrations that are transmitted to humans by modeling the addition of active suspension to a car seat. The addition of these different suspension systems resulted in a maximum reduction of 20% of the accelerations in the frequency range at which humans are most susceptible (27).

1.3 STANDARDS OF WHOLE-BODY VIBRATION

Almost every major country incorporates some type national standard that includes whole-body vibration (1). Furthermore, there is an international standard dealing with the evaluation of human exposure to whole-body vibration: ISO 2631-1 (28). The standard mainly includes the evaluation of whole-body vibrations on a seated, standing or recumbent human body. It details the methods that should be used to measure whole-body vibrations as well as analyzing the vibrations in the .5 – 80 Hz range, althought it states that the frequencies between 4-15 Hz are the most important regarding injury in humans, using weighting factors applicable to the most damaging frequencies of the human body. Griefahn et al conducted a study attempting to validate the ISO 2631-1 standard that was re-released in 1997. They concluded that in the evaluation of single-axis vibrations on humans the standard is in agreement with their results, however they recommend a revision of the standard in reference to studies with multi-axis evaluations because their results showed an underestimation of the frequency weighted vibrations in the lateral direction above 1.6 Hz, which includes the frequencies most critical in whole-body vibrations on humans (29).

1.4 WHOLE-BODY VIBRATION AND WHEELCHAIR USE

Although wheelchair users are constantly subjected to oscillatory and shock vibrations little research has been conducted to assess the vibrations experienced by wheelchair users and the attempts to reduce the whole-body vibrations that occur. VanSickle et al showed that differences existed in the forces and moments exerted on a manual wheelchair when testing on a simulated road course and during a home trial as compared to the ANSI/RESNA standards testing. These results seem valid because the ANSI/RESNA tests are designed to accelerate testing for the life of the wheelchair (30). DiGiovine et al examined the relationship between lightweight and ultra-lightweight wheelchairs and perceived ride comfort while traversing an ADL course. Results showed that an ultra-lightweight wheelchair was rated highest, however it appeared that results were also based on factors such as wheelchair setup and user's personal preferences (31). DiGiovine et al examined the relationship between the seating system selected for a manual wheelchair and the vibrations experienced by the user, showing a difference in vibration levels for different seating systems (32). Wolf et al concluded that suspension manual wheelchairs could reduce the transmission of shock vibrations to wheelchair users but results were mixed in response to oscillatory vibrations. This result was possibly due to the fact that the testing was done on a double drum machine and that the suspension wheelchairs that utilized elastomer shock absorbers were not specifically tuned for the user, a 75 kg Hybrid III test dummy (33).

Wheelchairs that can reduce the amount of vibrations transmitted to the user present a useful solution to harmful whole-body shocks and vibrations. Whole-body vibrations must be minimized to reduce an individual's vulnerability to secondary injuries, such as low-back pain and disc degeneration.

The addition of suspension to a wheelchair has been implemented in recent years by many of the major wheelchair companies. Cooper et al have shown that the addition of suspension caster forks do reduce the amount of vibrations experienced in the natural frequencies of humans (4-15 Hz) where vibrations have been shown to cause the most frequent injuries. The development of suspension wheelchairs needs to be improved in order to enhance the quality of life of wheelchair users and reduce secondary injuries (34).

1.5 ABSORBED POWER AS A MEASURE OF VIBRATION EFFECTS

Absorbed power can be a very potent measure when analyzing the transmission of vibrations to human subjects. The absorbed power is a measure of the energy absorbed by the subject due to the external forces applied to the system of measurement, in this case a wheelchair. However not much vibration research has been conducted that employs the absorbed power method, especially in relation to wheelchair users. Mansfield et al showed that subjects experience the greatest absorbed power at the 5 Hz frequency with increasing effects as the vibration is increased in proportion to the square of the experienced vibrations. They also discovered that the frequency weighting applied to other whole-body vibration measures (i.e. from the ISO 2631 standard) was not necessarily appropriate when analyzing vibrations using the absorbed power method (35). Lundstrom et al observed the greatest absorbed power in the 4-6 Hz range and that the level of absorbed power increased ten fold when the acceleration was tripled (36), showing a continuity with the results in the study by Mansfield. Lundstrom also recommends that a good way to evaluate the effectiveness of the absorbed power method is conduct a study using a questionnaire where drivers evaluate perceived comfort while whole-body vibrations are measured and absorbed power is analyzed.

2.0 RESEARCH QUESTION

The problem being examined in this study is two fold: Do selected wheelchair cushions reduce the amount of harmful whole-body vibrations transferred to the wheelchair user more than other selected cushions, and, is the absorbed power method a good measure of evaluating the whole-body vibrations that are transmitted to wheelchair users.

3.0 METHODS

3.1 PARTICIPANTS

Thirty-two participants, who use a wheelchair as their primary mode of mobility, partook in this study. Descriptives of the participants (i.e. gender, age, weight, and height) are listed in **Table 1**. Twenty-six of the participants had a spinal cord injury, four had spina bifida, and two had multiple sclerosis. Before any testing began, each of the participants was informed of the risks and benefits of the study as well as all of the procedures involved in the testing.

Table 1 Participant Statistics

	Age (yrs.)		Weight (kg)		Height (cm)	
	Mean	St Dev	Mean	St Dev	Mean	St Dev
Female (n=10)	38.1	7.2	61.3	11.2	153.2	11.9
Male (n=22)	41.5	9.5	85.3	12.8	177.3*	11.2*
Total (n=32)	40.4	8.9	77.5	16.0	170.2*	16.3*

*The height of one participant was not available.

3.2 TESTING PROTOCOL

All of the testing was conducted with the subject using their own wheelchair. Of the 32 wheelchairs tested, 30 of them classified as ultra-lightweight wheelchairs while the remaining two were classified as lightweight wheelchairs. 19 of the 32 wheelchairs were folding while the remaining wheelchairs were rigid. Four cushions and four back supports were selected, which represented four each of the most commonly prescribed seat cushions and back supports currently available at the time. The seat cushions and back supports were purchased through the Department of Veterans Affairs (VA) so that off the shelf items would be used for testing. Multiple sizes of each of the back supports and cushions were purchased to insure a good fit for any wheelchair user who participated in this study. This study however only examined the effects of the cushions of transmitted vibration. Each participant tested five conditions during the course of testing; all four seat cushions as well as their own seat cushion. Any marks on the cushions identifying any company name were covered so as to avoid any bias. The cushions and used in this study are listed in **Table 2**.

Table 2 Description of the Seat Cushions

No.	Abbreviation	Manufacturer	Model	Description
1	PDCM	Invacare / Pin-dot	Comfort-mate	Contoured Foam
2	VS	Varilite	Solo	Air Bladder with a Foam Base
3	JA	Sunrise Medical / Jay	Active	Viscoelastic Material with a Foam Base
4	RLP	Roho	Low-Profile	Air

The testing order was randomized using MATLAB (37). A multitude of sizes were available to fit each individual's wheelchair. The seat cushions are shown in **Figure 1**.

Figure 1 The seat cushions without covers: (clockwise from the upper left corner) the Varilite Solo, the Sunrise Medical / Jay Active, the Invacare / Pin-Dot Comfort-Mate, and the Roho Low Profile

Three trials were conducted for each of the cushions examined. Between each set of three trials the participant was allowed to rest while the cushion was changed and the data were checked. Participants were asked to propel their wheelchair over a simulated activities of daily living (ADL) obstacle course, described previously by DiGiovine et al (31). Before collecting any data, participants were asked to propel over the course three times to become acclimated and avoid any adverse effects. The nine obstacles, that made up the simulated activities of daily living obstacle course, were small, medium and large sinusoidal bumps (2.5 cm, 5.1 cm and 7.7 cm), a 5.0 degree ramp, a 50 mm curb drop, carpeting, truncated dome bumps (a.k.a. dimple strip), a simulated door threshold (1.6 cm high), and unidirectional bumps (a.k.a. rumble strip). Each participant traversed the course at a self-selected speed. The obstacles were selected based upon various types and levels of vibrations that a wheelchair user might experience in any given day.

3.3 DATA COLLECTION

Instrumentation was attached to the participant's own wheelchair to collect force and moment data from the casters, and propulsion wheels as well as acceleration data from the wheelchair seat (**Figure 2**).

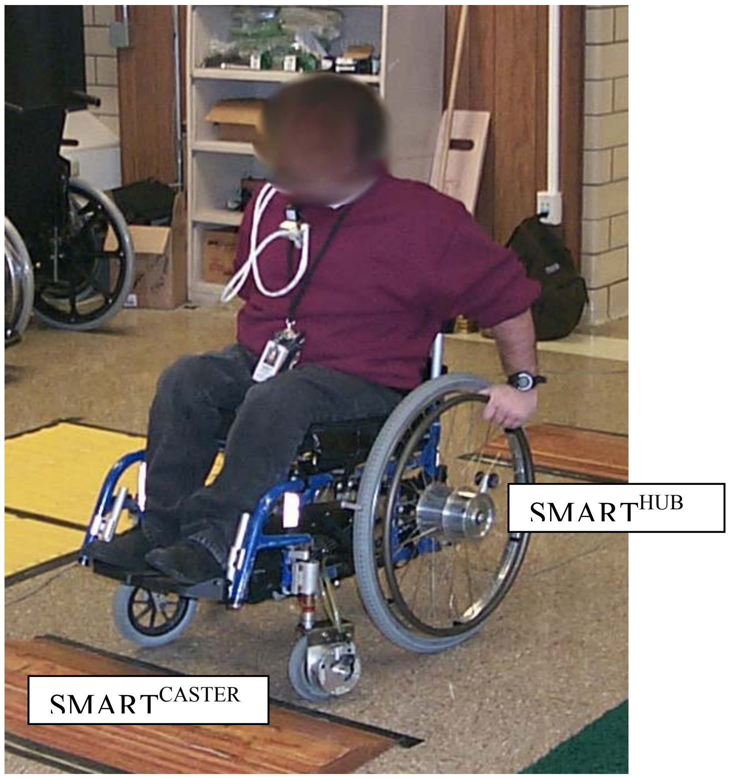

Figure 2 Participant in the testing setup propelling over the ADL course

Additionally, acceleration data was collected from the participant through the use of a bite bar. All data were collected at 200 Hz.

To collect the forces and from the caster and the hub of the wheelchair, two devices, the $SMART^{HUB}$ and $SMART^{CASTER}$, were used. The explanation and calibration methods of these devices are previously described by VanSickle et al [30]. Both the $SMART^{HUB}$ and $SMART^{CASTER}$ are comprised of a core four-beam system each of which is instrumented with strain-gauges. The forces and moments at the hub and caster can be calculated by applying the calibration constants to the raw voltages obtained from the strain-gauges. Accelerations were measured at the seat of the participant's wheelchair and the head of the participant through the use of two tri-axial accelerometers. Again, the accelerations at the seat and head can be acquired by applying the calibration constants to the raw data collected from the accelerometers.

3.4 DATA ANALYSIS

Absorbed power is a measure of transmitted energy to a human, in this case a seated participant in a wheelchair. Absorbed power was calculated along the direction defined by the vertical beam of the $SMART^{HUB}$ using Equation. 1 (see Appendix for more detailed calculations).

$$P_{ABS} = \left\langle F(t)_{ABS} * V(t)_{ABS} \right\rangle \quad [1]$$

This measure was chosen based both on its simplicity of calculation and the relevance to the causation of secondary injuries due to wheelchair propulsion. The calculated variable is directed along the spinal column of the participant making it a valid estimation of the transferred power that the spine experiences during wheelchair propulsion over obstacles. The forces were determined from the $SMART^{HUB}$ and the $SMART^{CASTER}$. Total force ($F(t)_{ABS}$) was then calculated by multiplying the sum of the forces from each component by two, assuming symmetry of the wheelchair forces while traversing the each of the obstacles.

The velocity was calculated by numerically integrating in MATLAB, the calculated acceleration with the initial condition that the initial velocity was zero.

3.5 STATISTICS

Three variables were examined in this study. These were the mean absorbed power over the entire course, the mean absorbed power while descending the curb drop, and the mean absorbed power while traversing the rumble strip. The later two of these three variables represent specific types of harmful whole-body vibrations that wheelchair users experience commonly; shock vibrations and oscillatory vibrations.

The values were collected for the three trials that the participant completed and an average value was assigned to the cushion that the participant used for that particular trial (i.e. one of the four selected cushions or the subject's own cushion).

To examine if differences existed between the absorbed power exhibited by each of the cushions, a repeated measures ANOVA, with a p-value of 0.05 was used. This statistical method was chosen because each of the participants used each of the selected cushions. One of the major advantages of the repeated measures design is that the variability within subjects is perpetually negligible. The sex, age, and weight for example will not change significantly for any particular subject. This allows for the effects of the different treatments, in this case the different selected cushions. A disadvantage of the repeated measures design is a learning effect that the participant experiences from repeating the same test over and over again with different treatments. An attempt was made to reduce this bias by instructing the participants to try to propel with the same selected speed during each trial. It is also for this reason that the subjects were instructed to initially propel over the course three times to become familiarized with the course. Average and standard deviation of time to complete the course for all subjects was 44 s. with a standard deviation of 14 s.

4.0 RESULTS

The average absorbed power was evaluated for the entire activities of daily living course, the 50 mm curb decent, and the rumble strip as shown in **Figures 3, 4, and 5**. It was assumed that the transferred energy would be applied at the point of contact between the subject and the cushion and in the direction of the applied forces and velocities used to calculate the absorbed power.

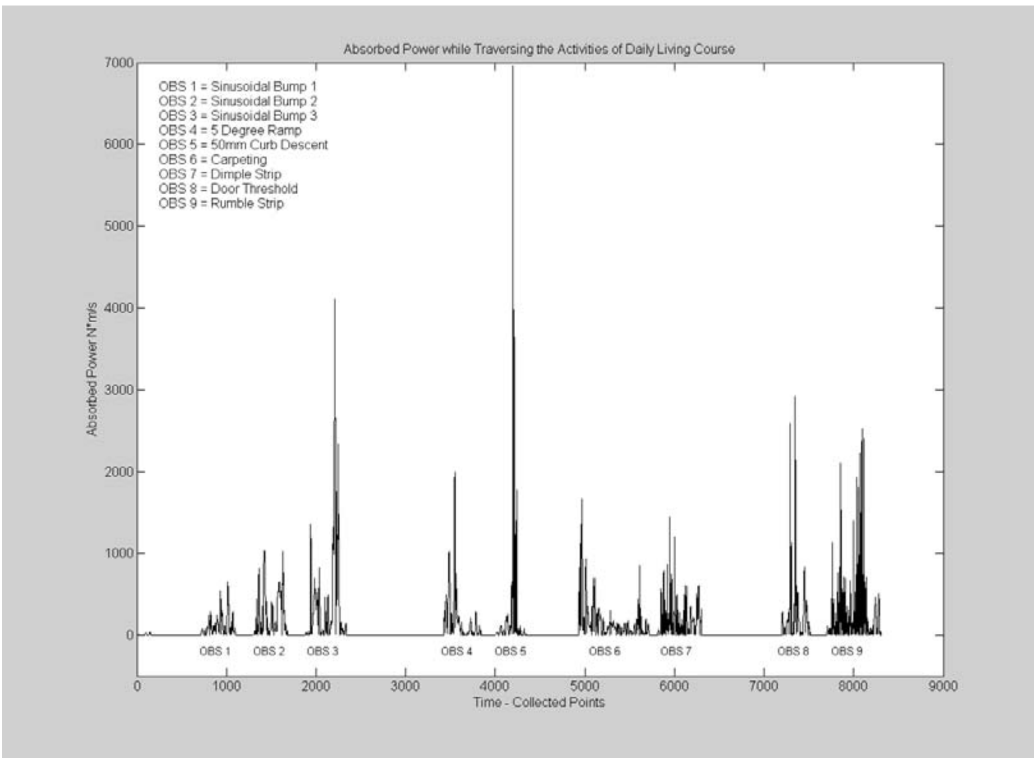

Figure 3 Graph showing the absorbed power for a subject traversing the activities of daily living course

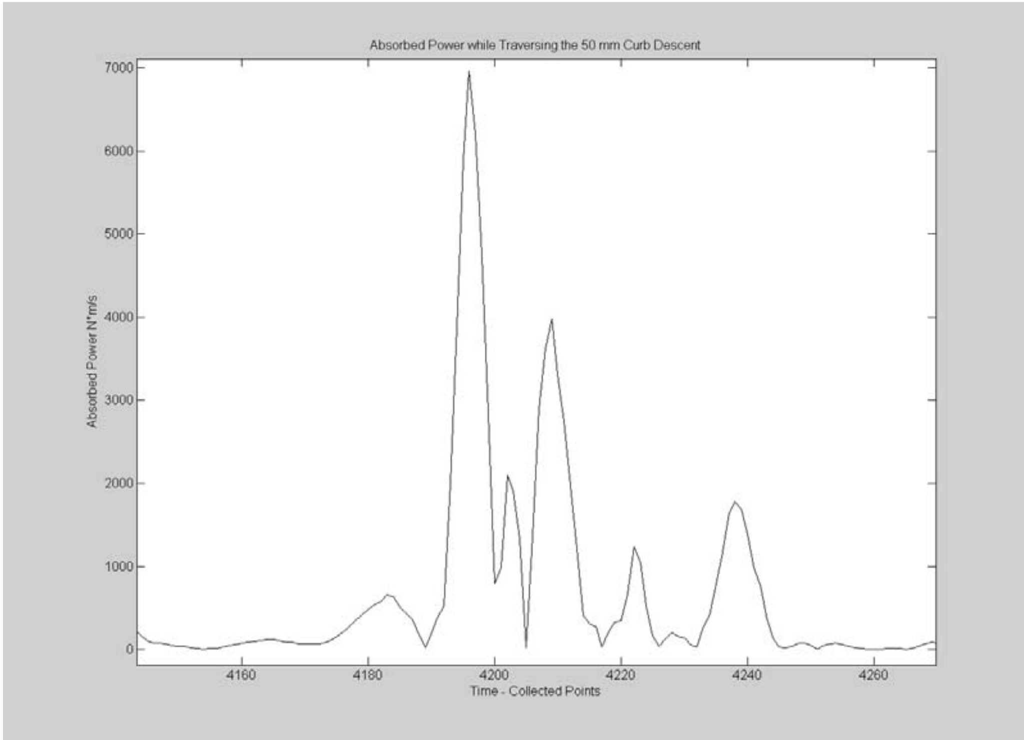

Figure 4 Absorbed power for a subject traversing the 50 mm curb descent

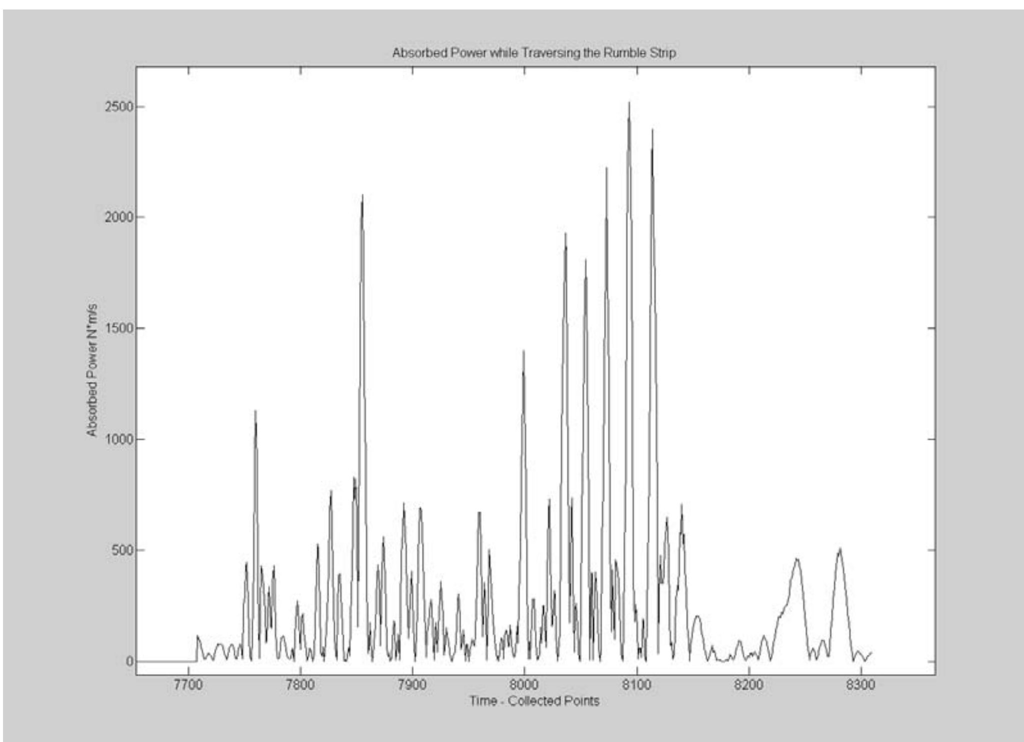

Figure 5 Absorbed power for a subject traversing the rumble strip

The repeated measures ANOVA showed no significant differences between the different cushions for the total average absorbed power (p = 0.286), or the 50 mm curb drop (p = 0.169), however the rumble strip showed significance with (p = 0.25).

Within the repeated measures test Mauchly's test of Sphericity proved to show significance (p = .009). Therefore the Huynh-Fedlt epsilon measure was used to account for the significant difference in Mauchly's test. The reason that this particular epsilon measure was used (as opposed to the Greenhouse-Geisser measure) was the number of subjects used in the testing. However, upon review all results would have remained non-significantly different if either or neither of the corrections were applied. Statistics also showed that the between subject effects were significantly different (p < .05), which is to be expected since each of the participants had different personal measurements (i.e. height, weight, etc.).

Table 3 Average values and standard deviations for each of the measured cushions while traversing the entire ADL, the curb drop and the rumble strip

Cushion	Total Mean AP $\frac{N*m}{s}$	Curb Drop Mean AP $\frac{N*m}{s}$	Rumble Strip Mean AP $\frac{N*m}{s}$
Pindot	206.30±97.83	597.49±264.14	275.57±147.74
Varilite	198.83±92.32	569.53±321.18	252.16±135.36
Jay 2	212.36±101.71	665.54±403.34	304.46±182.71
Roho	211.27±106.57	671.91±419.89	272.27±157.16

Visually it appears that that the Varilite Solo produces the lowest absorbed powers for each of the measured variables. The Jay 2 and the Roho Low Profile transfer the most absorbed power over the entire course, while the Jay 2 appears to transfer the most power while traversing the rumble strip. It seems that Roho Low Profile and the Jay 2 transfer significantly higher amounts of absorbed power when descending the 50 mm curb drop however these results are not significantly different primarily due to the high level of standard deviation in the measure.

These results are mostly consistent when examining how often each of the cushions produces the least or highest measure for any of the given variables. The highest measures for the total course was recorded by the Roho Low Profile and for the 50 mm curb drop, and the rumble strip the Jay 2 (for both the curb descent and the rumble strip) (**Table 4**).

Table 4 The number of times each cushion recorded the highest or lowest value in each of the tests

LOWEST			
Cushion	Total	Curb	Rumble
Pindot	9	10	11
Varilite	9	9	11
Jay 2	6	5	2
Roho	6	6	6

HIGHEST			
Cushion	Total	Curb	Rumble
Pindot	3	6	6
Varilite	8	5	5
Jay 2	9	13	13
Roho	10	6	6

The lowest values were recorded by Invacare Pin-dot for the curb descent and the Varilite Solo and the Pin-dot for the rumble strip. The Varilite Solo was slightly behind in each of the cases while it maintained the lowest average values for each of the measured variables. Again, this is believed to be caused by the high standard deviations in the measurements.

4.1 PEAK ABSORBED POWER

The peak absorbed power was analyzed for the curb descent for each of the subjects and again a repeated measures ANOVA was evaluated. The average values and standard deviations can be seen in **Table 5** and the lowest and highest recorded cushions can be found in **Table 6**. The repeated measures ANOVA revealed a significant difference in the cushions (p = .043).

Table 5 Average absorbed power values and standard deviations for each of the measured cushions while traversing the entire ADL, the curb drop and the rumble strip and peak values for the curb descent

Cushion	Mean AP $\frac{N*m}{s}$	CD Mean AP $\frac{N*m}{s}$	Curb Drop Peak AP $\frac{N*m}{s}$	RS Mean AP $\frac{N*m}{s}$
Pindot	206.30±97.83	597.49±264.14	8358±3616	275.57±147.74
Varilite	198.83±92.32	569.53±321.18	9132±4040	252.16±135.36
Jay 2	212.36±101.7	665.54±403.34	10181±5434	304.46±182.71
Roho	211.27±106.5	671.91±419.89	10451±5491	272.27±157.16

Table 6 The number of times each cushion recorded the highest or lowest value in each of the tests including the new curb drop peak variable

LOWEST				
Cushion	Total	Curb	Curb Peak	Rumble
Pindot	9	10	14	11
Varilite	9	9	5	11
Jay 2	6	5	5	2
Roho	6	6	6	6

HIGHEST				
Cushion	Total	Curb	Curb Peak	Rumble
Pindot	3	6	3	6
Varilite	8	5	5	5
Jay 2	9	13	11	13
Roho	10	6	11	6

The Invacare Pindot, overall, recorded the lowest values for the peak absorbed power while traversing the curb drop.

A non-parametric Chi-squared test was run based on the ranked data. Results showed that for both the lowest and highest ranked values significant differences existed with a p-value of $p = 0.017$ for both tests. Results also showed that the Invacare Pindot recorded the lowest absorbed power the most times and the highest absorbed power the least amount of times, while the Jay 2 was the exact opposite recording the lowest absorbed power least and the highest absorbed power the most.

4.2 ABSORBED POWER AND PARTICIPANT SPEED

Because velocity is a component of the absorbed power calculation, speed is an important characteristic to account for when evaluating the absorbed power. Participants were instructed to attempt to maintain a uniform speed each time they traversed the ADL course, however this is not always possible. To determine if speed was a variant factor when calculating absorbed power, the data for the rumble strip was time normalized. Statistical analysis was conducted similar to the original tests but with the new data. Results from this data yielded a p-value of $p = 0.173$. Recalling the p-value from the previous data ($p = 0.25$) it is evident that the time is a factor when traversing obstacles that cause oscillatory vibrations to the wheelchair user. Among participants the average time to traverse the rumble strip was 3.04 seconds with an average standard deviation of .237 seconds. Standard deviations among individual participant trials ranged from 6.19 – 154.5. This variance in the time for the subject to negotiate the rumble strip may be the cause for the change from the non-normalized data.

5.0 DISCUSSION

Recently, more research is being conducted that evaluates specific interventions that might possibly reduce the amount of vibrations caused to wheelchair users. Two recent studies examined the influence of suspension on the reduction of vibrations in manual wheelchairs. Wolf et al examined the effects of suspension manual wheelchairs while descending three different curb heights and using the absorbed power method (40). The results showed no significant differences in the reduction of the energy absorbed between the suspension chairs tested and the cross brace wheelchairs. Kwarciak conducted the same experiment, however examined the suspension wheelchairs versus the cross brace wheelchairs using the traditional methods of vibration analysis outlined in the ISO 2631 standard (28,39). Again, no significant differences were found between the suspension manual wheelchairs and the cross brace wheelchairs. They concluded that the reason for the lack of significant difference might have been a shortcoming in the design of the suspension wheelchairs, claiming that the orientation of the suspension element is crucial when the wheelchair is exposed to the shock vibrations.

DiGiovine et al have conducted two studies, discussing the effects of seat cushions and back supports and their use in controlling the exposure of whole-body vibration (41,42). The two papers deal respectively with the vibration exposure on individuals without a disability and individuals who use their wheelchair as a primary means of mobility. Their data analysis included the use of the ISO 2631 standard (28), and the evaluation of the seating systems in both the time domain and the frequency domain. Results for the first study (i.e. individuals without a disability) showed that for vertical transmission of vibrations in the time domain the Varilite Solo tended to display the lowest transmission with the Jay 2 cushion close behind. Results in the frequency domain showed that the Jay 2 transmitted significantly higher vibrations in the range where humans are most susceptible (4-12 Hz). Results of the second study (individuals who use a wheelchair as their primary mode of mobility) showed no significant differences between the cushions while traversing the entire course. The Varilite Solo experience higher transmitted vertical vibrations while negotiating the dimple strip. In the frequency domain no significant differences were observed when examining the max frequency amplitude. However when examining the proportional bandwith transfer function, (which is the transmissibility of vibrations from the seat to the head in the frequency domain broken into one-third octaves), differences existed for vertical vibrations where the Jay 2 was less effective while traversing all obstacles.

Overall, in comparison with the experiments done by DiGiovine et al, absorbed power appears to be just as effective at determining the effects of vibrations in the time domain as the prescribed methods of the ISO 2631 standard. However the absorbed power method is has benefits and downfalls. The measurement of absorbed power does not require the use of a bite bar by the participant because it measures the amount of energy absorbed at the user/cushion interface. This results in the participant being more comfortable and possibly less data bias from participant heterogeneity. One downfall of the absorbed power method is that the value achieved mostly reflects the amount of energy experienced at the point of contact. Therefore for ailments such as low back pain absorbed power might be a good evaluator but for other symptoms of whole-body vibrations such as headaches, motion sickness, and muscle pain in the extremities it might not reflect so well. For this instance however the variable in the study was a difference in wheelchair cushions. Therefore it seems viable that the measure would be acceptable.

The cushions that appeared to perform the best in this testing were the Invacare Pindot and the Varilite Solo. Not only did those cushions appear to have the lowest values much of the time but also, did not display the highest values. On average these two cushions appeared to have the lowest values of absorbed power for each of the variables measured.

5.1 APPLICATION TO CLINICAL CUSHION SELECTION

The ultimate goal of this study and the data obtained from it is to aid in the selection of cushions for wheelchair users. Based on the results, an absorbed power analysis in the clinical setting might be used as a cushion selection criteria for a wheelchair user. The main complication with this is the specific instrumentation (i.e. the SMART^{HUB} and the SMART^{CASTER}) used to collect the data in this study. However based on the similarity to the previous work of DiGiovine et al, it may be suggested that specific vibration values are examined when selecting a cushion. The collection and analysis of this data could be quickly computed with simple instrumentation and driving tasks for both manual and power wheelchair users.

5.2 FREQUENCY WEIGHTING AND ABSORBED POWER

The ISO 2631 standard utilizes a frequency weighting on the measured vibrations when analyzing whole-body vibration data. The reason for this weighting is that the vibrations experienced in the 4-15 Hz range have been shown to cause more damage (28). The frequency weighting curve diagramed in ISO 2631 normalizes the acceleration data. It is not for certain if frequency weighting is necessary when using the absorbed power method. Lunstrom et al suggests that amounts of absorbed energy could be harmful regardless of frequency (36). The opinion held by Mansfield et al varies in that they believe that a frequency weighing is necessary for absorbed power measurements but that it is different from the ISO 2631 frequency weighting for vibrations (35). More research needs to be conducted to determine if frequency weighting for the absorbed power measure is necessary or if a new weighting curve, different from the one in ISO 2631, needs to be created.

5.3 LIMITATIONS

The main limitation of the stated results is that each individual wheelchair user is different and demands different types of functionality and support from their seat cushions. This is one of the major reasons why so many different types of cushions exist. Wheelchair users require pressure relief, support, and comfort from their cushions not to mention whole-body vibration relief.

Another parameter that was not considered in the study was variation in speed for each of the participants. Each of the subjects served as their own control, however although the participants were instructed to attempt to maintain a constant speed throughout the course of testing that was not always constant. A method of correcting this issue is to simply place the subject on a vibrating plate and record the data in that fashion. However the trade off is that the real world whole-body vibrations would not be experienced as they are in the simulated road course used.

Men and women were grouped together in this study and not considered separately. Lunstrom et al revealed that the absorbed power experienced by women and men are different and may require different exposure guidelines when dealing with whole-body vibration exposure on either men or women.

5.4 FUTURE WORK

Currently the ISO 2631 standard dealing with the evaluation and analysis of whole-body vibration and its effect on humans does not consider absorbed power as a variable to assess the damage that can occur from these vibrations. More controlled work, dealing specifically with a correlation of absorbed power and vibration with no covariates, needs to be conducted in order for the methods to be added to a standard.

Lunstrom et al showed that the absorbed power that a participant experiences is related to the frequency of the exposed vibrations (36). This study did not deal with the investigation of absorbed power in the frequency domain. This could present useful information that may show a larger benefit of the absorbed power method and a more distinct difference in the cushions examined.

6.0 CONCLUSION

There has been a limited amount of research done on the effects of whole-body vibrations on wheelchair users although it has been shown that they experience shocks and vibrations at and above the normal exposure limit (43). It has also been shown that people exposed to similar whole-body vibrations (i.e. construction, truck and bus drivers, etc.) experience harmful injuries from these vibrations including disk degeneration, spinal deformation, and low-back pain (5-11).

Although some research has been done on the development of interventions for wheelchair users to reduce whole-body vibrations, such as suspension wheelchairs, manufacturing using vibration absorbing materials (i.e. titanium), and the development of more advanced seating systems, more research needs to be conducted to determine how to maximize these advances in wheelchair development.

APPENDIX A

Mathematical Formulation of the Absorbed Power

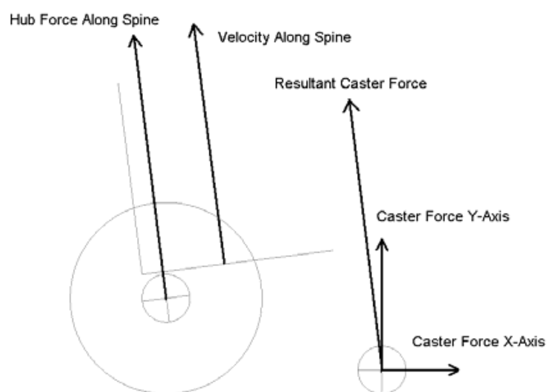

Figure 6 Calculation of the Absorbed Power: The resultant forces from the caster and the hub are multiplied by the velocity along the spine, which yields the absorbed power.

Using calibration constants, the raw voltages from the accelerometers and the SMART^{HUB} and the SMART^{CASTER} are converted to accelerations and forces and moments respectively.

$$V_{spine} = \int_0^t a_{spine} \bullet dt \qquad [1]$$

Equation 1 – derivation of velocity at the seat along the spine from the acceleration

$$CF_{res} = Fx \bullet \cos(90-\alpha) + Fy \bullet \cos(\alpha) \; ; \; \alpha = seat\ angle \qquad [2]$$

Equation 2 – calculation of the caster force in the direction of the spine

$$AP_{spine} = V_{spine} \bullet \left(2 \bullet CF_{spine} \bullet HF_{spine}\right) \qquad [3]$$

Equation 3 – The absorbed power along the spine is calculated using the velocity along the spine and the forces from the caster and the hub.

APPENDIX B

```
%This MATLAB Program defines the calculation of the absorbed power for one
%subject trial.  Absorbed Power was calculated for all [18] subject trials.
%The calculations are the same for each individual trial.

s=input('Seat angle for subject              ');

s_rad=s*2*3.14159/360;

%Loads the data from one subject trial
x1=xlsread('ad25_011n.xls');
load ad25_011_marker.xls;

%Determine the total Absorbed Power for one
%subject trial over the entire ADL course
power1=((x1(1:max(ad25_011_marker),2)+x1(1:max(ad25_011_marker),7))*2)...
    *(x1(1:max(ad25_011_marker),13)*cos(s_rad));
figure(1)
stem(total_power);

%Find Curb Descent ABS POW-----------------------------------

power_cd1=power1(ad25_011_marker(10):ad25_011_marker(11));
figure(2)
stem(total_power_cd)

%Find Rumble Strip AB POW------------------------------------------

power_rs1=power1(ad25_011_marker(18):ad25_011_marker(19));
figure(3)
stem(total_power_rs)

save totalabspower.xls total_power -ascii -tabs;
save totalabspowercurbdescent.xls total_power_cd -ascii -tabs;
save totalabspowerrumblestrip.xls total_power_rs -ascii -tabs;

%----------------
```

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