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Comparison of wheelchair wheels in terms of vibration and spasticity in people with spinal cord injury

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Abstract—A wheelchair undergoes vibrations while traveling over obstacles and uneven surfaces, resulting in whole body vibration of the person sitting in the wheelchair. According to clinicians, people with spinal cord injury (SCI) report that vibration evokes spasticity. The relatively new Spinergy wheelchair wheels (Spinergy, Inc; San Diego, California) are claimed to absorb more road shock then conventional steel-spoked wheelchair wheels. If this claim is true, this wheel might also reduce spasticity in people with SCI. We hypothesized that Spinergy wheels would absorb vibration, reduce perceived spasticity, and improve comfort in individuals with SCI more than standard steel-spoked wheels. To test this hypothesis, 22 nondisabled subjects performed a passive ramp test so that we could more closely examine the dampening characteristics of the Spinergy versus traditional wheels. Furthermore, 13 subjects with SCI performed an obstacle test with both wheel types. Vibrations were measured with accelerometers, and spasticity and comfort were assessed with subject-reported visual analog scales. The results of the study showed that, within the current experimental setup, the Spinergy wheels neither reduced vibration or perceived spasticity nor improved comfort in people with SCI more than the conventional steel-spoked wheels.

Key words: obstacles, rehabilitation, spasticity, spinal cord injury, Spinergy, steel-spoked, vibration, visual analog scale, wheelchair wheels, whole-body vibration.

INTRODUCTION

The number of people using a wheelchair is estimated at 2.2 million in the United States, 750,000 in the United Kingdom, and 152,400 in the Netherlands [1]. These individuals spend a large part of their life in their wheelchair, so their quality of life depends highly on the quality and comfort of the wheelchair. A wheelchair vibrates while traveling over obstacles and uneven surfaces, resulting in whole-body vibration (WBV) of the person sitting in the wheelchair. WBV can result in decreased comfort, interference with activities, impaired

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Abbreviations: ANOVA = analysis of variance, EMG = electromyography, ISO = International Organization for Standardization, MAS = Modified Ashworth Scale, PSD = power spectral density, RMS = root-mean-square, SCI = spinal cord injury, SD = standard deviation, VAS = visual analog scale, VDV = vibration dose value, WBV = whole-body vibration.

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health, pain, and motion sickness [2]. According to clinicians from the GF Strong Rehabilitation Centre in Vancouver (British Columbia, Canada), people with spinal cord injury (SCI) have reported that rough surfaces and obstacles, such as bumps in sidewalks or rumble carpets, illicit spasms. However, in the literature, no research has been conducted to support these reports.

Spasticity and neuropathic pain can result after an SCI. Spasticity is defined as "a velocity dependent increase in the tonic stretch reflex (muscle tone) with exaggerated tendon reflexes, resulting from the hyper excitability of the stretch reflex, as one component of the upper motor neuron syndrome" [3]. The exact mechanisms underlying the development of spasticity are not fully understood [4–5]. Among individuals with SCI, 65 to 78 percent have symptoms of spasticity [4].

Spinergy wheelchair wheels (Spinergy, Inc; San Diego, California) are relatively new on the market. These wheels have specialized features, including a triple-cavity rim, an alloy hub with one-piece construction, and carbon-fiber spokes that originate from the hub (reverse spoking). Spinergy claims that as a result of these specialized features, the wheels absorb 25 percent more road shock than conventional steel-spoked wheels [6]. If true, this energy absorption would be highly advantageous in long-term wheelchair use and would suggest that these wheels could decrease the discomfort caused by WBV. More specifically, they might reduce spasticity caused by WBV in individuals with SCI. In a previous study, Hughes et al. compared Spinergy wheelchair wheels with standard steel-spoke wheelchair wheels in terms of energy expenditure and user comfort [7]. They found that the Spinergy wheels provided a more comfortable ride but did not significantly affect energy expenditure. They suggested that the increased comfort may have important implications for patient management of pain and spasticity.

The first purpose of this study was to verify Spinergy's claim that its wheelchair wheels absorb 25 percent more road vibration than other conventional wheelchair wheel designs. The second purpose was to assess whether Spinergy wheelchair wheels, as compared with standard steel-spoked wheelchair wheels, reduce spasticity triggered by wheeling over rough surfaces and obstacles and improve the comfort level of individuals with SCI. Our hypothesis was that the Spinergy wheels would absorb vibration, reduce spasticity triggered by wheeling over rough surfaces and obstacles, and increase subjective comfort more than the conventional steel-spoked wheels.

MATERIALS AND METHODS

Part 1: Vibration

The first part of the study addressed the single question of whether the Spinergy wheels absorb more vibration than conventional steel-spoke wheels. The experiment consisted of a standardized coast-down test in which 22 nondisabled subjects rolled down a ramp from a fixed height in an experimental wheelchair while we evaluated vibration. We chose the coast-down test for the first part of the study to provide a method of standardization for velocity, since vibration is velocity dependent. We chose nondisabled subjects instead of subjects with SCI since we were not assessing any specific factors related to SCI. Appropriate university ethics and hospital review certificates were obtained before data collection.

Subjects

Twenty-two nondisabled subjects participated (12 men, 10 women), roughly the same number that participated in Hughes et al.'s study [7]. The mean ± standard deviation (SD) weight of these subjects was 71.5 ± 11.5 kg. They had no previous experience with wheeling in a wheelchair. After giving informed consent, the subjects started the experiment. Subjects were randomized to begin with either steel-spoked or Spinergy wheels.

Wheelchair

All subjects used the same wheelchair, a 15 kg Invacare A4 wheelchair (Elyria, Ohio) that was lent by the GF Strong Rehabilitation Centre. Tire pressure was kept at 100 psi. The position of the axle remained constant for all subjects. Steel-spoked wheels were painted black to look like Spinergy wheels, and Spinergy stickers were removed. The only obviously visible difference between the two wheel types was the number of spokes.

Measurement of Vibration

Vibration was measured with two Mechworks MDS 203 two-dimensional accelerometers (Waterloo, Ontario, Canada). One accelerometer was mounted on the main axle and the other on the footplate. Both accelerometers measured accelerations in the fore-and-aft direction (x) and the vertical direction (y) (**Figure 1**). The accelerometers were placed in a fixed position on the wheelchair. The axle accelerometer was secured with a bolt (**Figure 1(b)**). The footplate accelerometer was firmly secured to the best of our capabilities (**Figure 1(a)**). Horizontal positioning of the accelerometers was ensured with a level. With this setup,

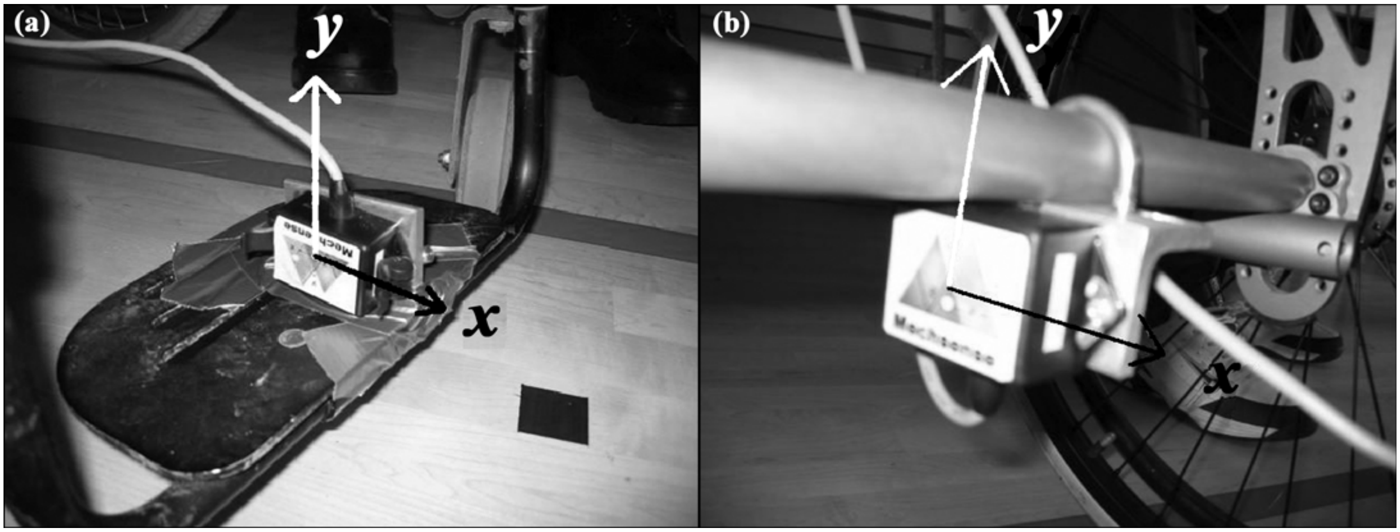

Figure 1.
Accelerometers attached to wheelchair **(a)** footplate and **(b)** axle to measure vibration in fore-and-aft (*x*) and vertical (*y*) directions.

all acceleration data were in reference to the wheelchair. The accelerometer has a built-in converter that converts the analog signal to digital. The accelerometers were directly attached to a laptop. Data were collected at 1,000 Hz. The footplate was chosen because, according to Wolf et al. [8], vibration to the limbs can cause musculoskeletal damage and discomfort. Furthermore, clinical observations suggest that the initiation of spasticity is due to foot stimulation and a possible stretch reflex reaction that trigger rapid firing of the gastrocnemius.

Procedures

In this first part of the study, the subjects sat passively in the wheelchair and rolled down a ramp with a slope of 8° after being released by the researcher. At the bottom of the ramp, the wheelchair and subject rolled over a small speed bump (0.025 m high × 0.080 m long) that caused vibration (**Figure 2**). The accelerometers were started when the researcher released the wheelchair and stopped when the wheelchair and subject had rolled over the speed bump. The researcher walked behind the wheelchair, holding the laptop that collected the accelerometer data. Since speed affects vibration [2], we examined two different speeds to validate our measurements. Starting 1.65 and 2.00 m from the speed bump led to estimated mean speeds at impact of 0.8 and 1.2 m/s, respectively. These velocities fall within typical wheeling speeds [9]. Each subject performed four test runs: two types of wheelchair wheels at two different velocities.

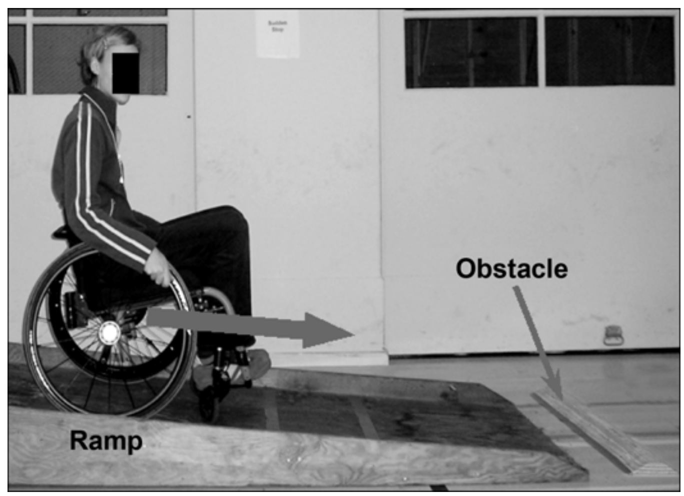

Figure 2.
Researcher sitting in experimental wheelchair on ramp. Obstacle was placed further from ramp than shown here.

Data Analysis and Statistics

The vibration signals from the accelerometers were analyzed with MATLAB (version 7.2, The MathWorks, Inc; Natick, Massachusetts). Zero measurements were subtracted from the acceleration data to eliminate noise. Peak acceleration and root-mean-square (RMS) values were calculated in MATLAB. RMS is a measure of the magnitude of vibration and is the square root of the average of the squares of a set of numbers (here, the acceleration) [2].

The formula for RMS is stated in the **Equation**, where *x* is the separate data points and *N* is the number of data points.

$$x_{\text{RMS}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2} = \sqrt{\frac{x_1^2 + x_2^2 + \cdots + x_N^2}{N}}\ .$$

Three types of comparisons were made: (1) wheel type (Spinergy vs steel-spoked), (2) speed (fast vs slow), and (3) sensor placement (axle vs footplate). The first comparison addressed the research question, while the other two comparisons validated the vibration analysis. Two repeated measures analyses of variance (ANOVAs) were conducted in SPSS (SPSS, Inc; Chicago, Illinois) for the ramp test: one with the RMS values and one with the peak accelerations. The three main factors of the repeated measures ANOVA were wheel type (Spinergy vs steel-spoked), sensor placement (axle vs footplate), and speed (fast vs slow).

To compare the two wheels in terms of frequency, we obtained a power spectral density (PSD) analysis from every signal by using fast Fourier transform analysis. The PSD (range 0–500 Hz) was divided into bins of 2 Hz each, after which the maximum amplitude within each bin was taken as a measure of peak power. Subsequently, an ANOVA was conducted with MATLAB for every 2 Hz bin to compare the peak power between the two wheels, with speed as the second experimental variable. Significance for all statistics was set to $p < 0.05$.

Part 2: Vibration and Spasticity

The second part of the study evaluated whether, compared with steel-spoked wheels, Spinergy wheels reduce vibration-induced spasticity in individuals with SCI. This evaluation was made during a test in which 13 subjects with SCI wheeled over nine individual obstacles in their own wheelchairs but using the two different types of wheels. The vibrations of the two different wheel types were again compared.

Subjects

Thirteen subjects with SCI participated (10 men, 3 women); their mean ± SD age was 46.2 ± 11.2 years. The aim was to include 20 persons, similar to the study by Hughes et al. [7]. **Table 1** shows the main characteristics of the study participants.

The inclusion criteria for the subjects were—

- Age between 16 and 65 years.
- SCI below seventh cervical level.
- Spasticity of at least Modified Ashworth Scale (MAS) grade 1 or Spasm Frequency Scale grade 1 for at least 1 year.
- Independent manual wheelchair use with sufficient strength to wheel over the obstacles.
- No changes to current wheelchair setup for at least 6 months.

Table 1.
Main characteristics of study participants.

Subject	Sex	Age (yr)	Lesion Level	Complete vs Incomplete Injury	Modified Ashworth Scale	
					Quadriceps (Left/Right Leg)	Gastrocnemius (Left/Right Leg)
1	M	50	T3–4	Complete	0/0	0/2
2	F	30	T11	?	0/0	0/0
3	M	30	T5–6	Complete	0/0	2/2
4	M	46	T4	Complete	0/0	1/1
5	M	52	T3	Complete	4/4	1/1
6	M	54	C5	?	1/0	1/0
7	M	58	T5–6	Complete	4/3	4/4
8	F	38	T5	Complete	1/1	3/3
9	M	48	C7	Incomplete	3/3	3/3
10	M	60	T4–5	?	0/0	3/3
11	F	33	T8	Complete	1/1	2/1
12	M	39	C6–7	?	0/0	2/2
13	M	62	T12	Incomplete	0/0	1/1

? = data unavailable, C = cervical, F = female, M = male, T = thoracic.

- Ability to understand the instructions and give informed consent.

The exclusion criterion was—

- Any history of cardiovascular disease that would inhibit performance or make participation unsafe for the subject.

Once we determined that the subjects met the inclusion criteria, informed consent forms were completed. To understand the subjects' baseline level of spasticity, a rehabilitation physician completed the MAS [10].

Appropriate university ethics and hospital review certificates were obtained before data collection. Subjects were recruited from the outpatient Spinal Cord Injury Program at the GF Strong Rehabilitation Centre. Subjects received a modest honorarium for their participation in the study.

Wheelchairs

Subjects used their own wheelchairs and were provided either a smooth or plastic-coated handrim on the experimental wheels to ensure their normal wheeling style. Characteristics of the subjects' personal wheelchairs are shown in **Table 2**.

The two wheel types were randomized. The Primo (Primo Wheelchair Tires, Inc; Philadelphia, Pennsylvania) v-track tires used were inflated to 100 psi. Subjects were randomized to either start with the Spinergy or steel-spoked wheels.

Measurement of Vibration

We measured vibration using the same protocol outlined for the first part of the study.

Measurement of Spasticity and Comfort

Immediately after each trial, the subjects used visual analog scales (VASs) to answer questions about the severity of their spasticity and their level of comfort during the trial, as suggested by Platz et al. [11]. The extremes for the spasticity VAS were "no spasms" and "worst it could be," and for the comfort VAS, "extreme discomfort" and "extreme comfort." After the subjects completed all nine trials, they completed five VASs about their overall assessment of the wheels (comfort, spasticity, support and stability, maneuverability, and comfort of hand on pushrim).

Procedures

The obstacles in the test were similar to those used in the obstacle course previously described and validated by DiGiovine et al. [12]. The obstacle test consisted of a set of nine obstacles that resembled as much as possible real-life obstacles that people come across in their daily lives. We also used this course for our previous study with the Spinergy wheels (Hughes et al. [7]). In contrast to this previous study, subjects in the current study wheeled over each obstacle individually, instead of in one continuous loop, to better control for velocity, since vibration is velocity dependent [2]. The nine obstacles are listed in **Table 3**. The obstacle test setup is shown in **Figure 3**.

Table 2.
Characteristics of subjects' personal wheelchairs.

Subject	Brand & Model	Wheel Type	Special Components
1	Top End Terminator Ti	Steel-spoked	Roho cushion
2	Invacare A4	Sunrims, solid tires	Triad
3	Quickie R2	Steel-spoked	Jay 2 cushion
4	Quickie 2 (folding chair)	Sunrims (steel-spoked)	Jay 2 cushion
5	Invacare Top End	Spinergy	Roho cushion
6	Action A4	?	No
7	Invacare A4	Sunrims	Roho
8	Shadow	Sunrims (steel-spoked)	Roho cushion
9	Quickie TI (titanium)	Quickie Sunrims (steel-spoked)	Stimulite cushion
10	Quickie TI (titanium)	Quickie	Ride cushion
11	Quickie 2 (folding chair)	Pneumatic	?
12	Top End Action	Sunrims (steel-spoked)	Not applicable
13	Top End Terminator	Sunrims (steel-spoked)	Roho cushion

? = data unavailable.

Table 3.
Description of obstacles that subjects wheeled over during obstacle test.

Obstacle	Dimensions
Rumble Strip	13 foam lines (0.015 m × 0.025 m cross section) oriented perpendicular to driving direction under 1.70 m-long hard rubber coat.
Carpet	1.20 m long × 0.01 m thick.
Dimple Strip	1.20 m long × 0.01 m thick.
Threshold	0.08 m long × 0.015 m high.
Ramp	0.80 m long × 0.08 m high before drop.
Speed Bump	
Small	0.08 m long × 0.025 m high, beveled.
Medium	0.24 m long × 0.05 m high, beveled.
Large	0.38 m long × 0.075 m high, beveled.
Floor	5.20 m long.

Figure 3.
Different obstacles used to evaluate vibration, spasticity, and comfort.

Once the first set of wheels was mounted to the subject's own wheelchair, the subject was asked to wheel over each obstacle. The obstacles were placed in the center of a gymnasium. The subject started behind a line on one end of the gymnasium, wheeled 2.6 m, went over the obstacle, and continued wheeling until crossing a line at the other end. This sequence represented one trial. To calculate average velocity, we used a stopwatch to measure the time the subject took to complete the trial. This process was repeated for the second set of wheels. The sequence of the obstacles was also randomized. The subjects had to complete 18 trials: nine different obstacles with two different types of wheels.

Data Analysis and Statistics

The VASs on spasticity, comfort, and overall rating of the wheels and the average trial velocity were analyzed with a paired-samples *t*-test in SPSS to compare the two different wheel types at each obstacle. The vibration signals from the accelerometers were analyzed in the same way as in the first part of the study, except that the third factor in the repeated measures ANOVA was obstacle instead of speed. We used subjects as their own controls by using a within-subject comparison. Significance for all statistics was set to $p < 0.05$.

RESULTS

Part 1: Vibration

All 22 nondisabled subjects completed the ramp test. **Figure 4** shows a typical example of the acceleration signal and its power spectrum. All data are presented as mean ± standard deviation unless otherwise indicated.

Wheel Types

No significant differences were found between the two wheel types for peak acceleration (Spinergy: 2.84 ± 1.16 *g*, steel-spoked: 2.81 ± 1.09 *g*), RMS (Spinergy: 0.33 ± 0.10, steel-spoked: 0.33 ± 0.10), or peak power.

Validation of Vibration Analysis

Over the whole data set (data from the different wheel types combined), significant differences were found for peak acceleration between the different positions of the accelerometers (footplate: 3.41 ± 1.01 *g*, axle: 2.24 ± 0.90 *g*, $p < 0.001$) and the different speeds (fast: 3.07 ± 1.11 *g*, slow: 2.59 ± 1.09 *g*, $p < 0.001$). Similar significant differences were found for RMS between the positions of the accelerometers (footplate: 0.40 ± 0.09, axle: 0.26 ± 0.05, $p < 0.001$)

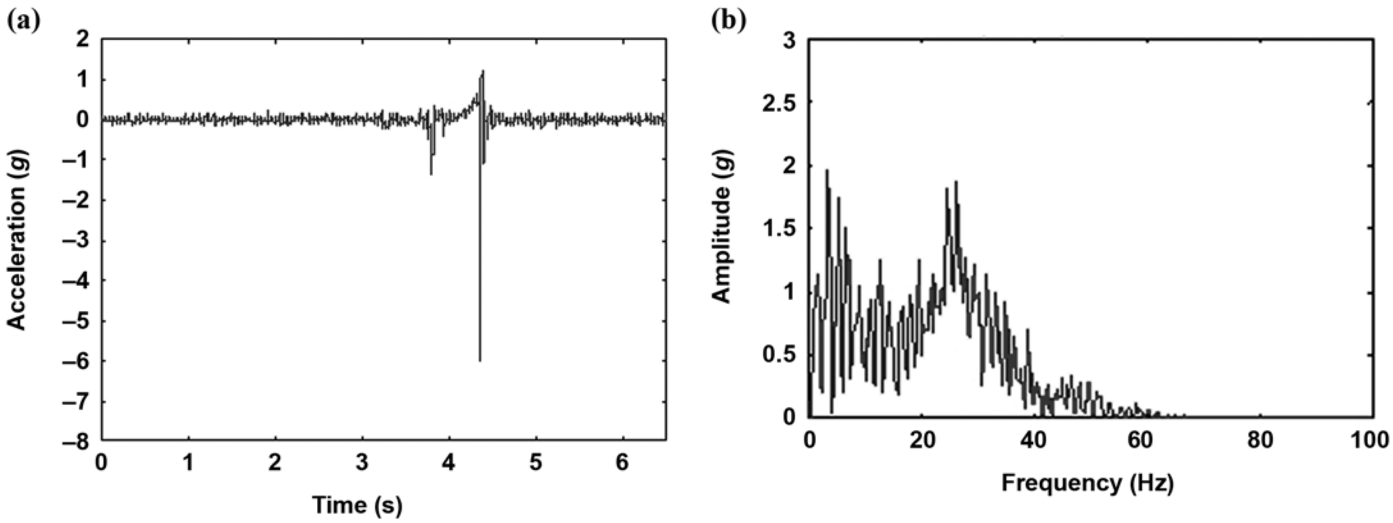

Figure 4.
(a) Typical example of acceleration signal when subject is going over medium speed bump and **(b)** its measured power spectrum. Acceleration is in *y*-direction at the axle.

and the speeds (fast: 0.35 ± 0.09, slow: 0.31 ± 0.09, $p < 0.001$). Peak accelerations and RMS values were higher at the footplate than at the axle and were higher at the higher velocity.

Part 2: Vibration and Spasticity

All subjects completed the obstacle course. One subject did not feel comfortable wheeling over the ramp; hence, $n = 12$ for the ramp (obstacle 4) and $n = 13$ for the other obstacles. Average speed did not differ significantly between the two wheel types.

Wheel Types

No significant differences were found between the two wheel types for peak acceleration (Spinergy: 2.41 ± 2.33 *g*, steel-spoked: 2.26 ± 2.20 *g*), RMS (Spinergy: 0.20 ± 0.14, steel-spoked: 0.19 ± 0.13), or peak power.

Validation of Vibration Analysis

Over the whole data set (data from the different wheel types combined), significant differences were found between the different positions of the accelerometers for peak acceleration (footplate: 2.76 ± 2.39 *g*, axle: 1.90 ± 2.03 *g*, $p < 0.001$) and RMS (footplate: 0.40 ± 0.09, axle: 0.26 ± 0.05, $p < 0.001$). The peak accelerations and RMS values were higher for the footplate.

Spasticity and Comfort

The VAS on spasticity was not significantly different between the different wheel types for any of the obstacles (**Figure 5**). The VAS on comfort also did not significantly differ between the Spinergy and steel-spoked wheels for any of the obstacles.

Overall Assessment

The VASs on overall assessment of the wheels did not show any significant differences between the Spinergy and steel-spoked wheels.

DISCUSSION

Vibration

For both parts of the study, no significant differences were found between the Spinergy and steel-spoked wheels in peak acceleration, RMS, or peak power. For peak power, only a few significant differences were found between the power bins over the whole frequency spectrum, but they were not consistent across the conditions. Significant differences were found between the two speeds and the two positions of the accelerometers in the first part of the study. The higher speed led to higher peak accelerations. This result was expected, since reaching

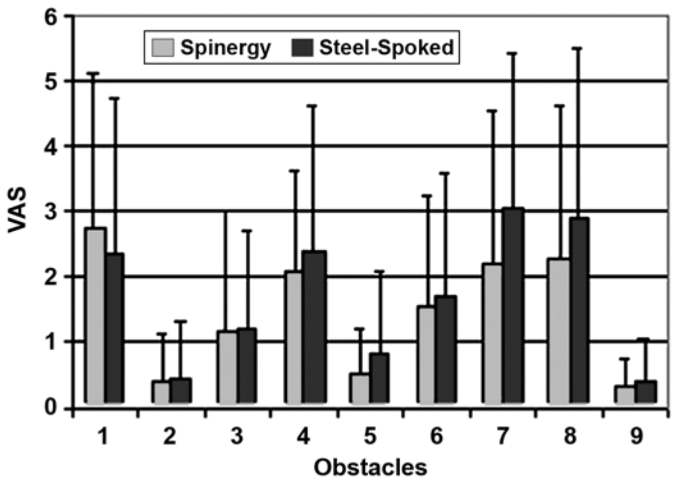

Figure 5.
Subjective spasticity ratings (mean ± standard deviation) measured with 0–10 visual analog scale (VAS). Subjects with spinal cord injury wheeled over obstacles in own wheelchair and either Spinergy or steel-spoked wheels. Obstacles: 1 = rumble strip, 2 = carpet, 3 = door threshold, 4 = ramp, 5 = dimple strip, 6 = small speed bump, 7 = medium speed bump, 8 = large speed bump, 9 = floor.

the speed bump at a higher speed would logically result in higher acceleration peaks. The footplate peak accelerations were significantly higher than the axle peak accelerations. This result was also expected, since the mass at the footplate to which the force (shock) is being applied is significantly lower than at the axle, resulting in higher peak accelerations. Furthermore, smaller caster size at the footplate will result in higher accelerations and deformation of the tires, tubes, and rims, and the spokes on the rear wheels act to dampen accelerations transmitted in the rear of the wheelchair. The results for velocity and position of the accelerometer met all theoretical expectations, thus validating the experimental approach and technique for the evaluation of vibration exposure.

For the frequency analysis, grouping the frequency ranges and assigning them to one of the two wheel types would have been preferable. Cooper et al. [13] and DiGiovine et al. [14] compared frequency in wheelchair research by dividing the frequency range into octaves and subsequently comparing within each octave. The downside of this kind of analysis is that octaves are of different lengths, which makes interpreting the results difficult. VanSickle et al. divided the frequency range into equal bins of 3.125 Hz [15]. Griffin provided proportional bandwidth analysis (octaves) and constant bandwidth analysis as options for frequency analysis [2]. For nondisabled people in a sitting position, 4 to 12 Hz has been determined to be the most dangerous WBV frequency range [2]. However, no research-based values are available for people with SCI and spasticity. Therefore, we chose a constant bandwidth analysis. For the same reason, we did not apply the frequency weightings specified by the International Organization for Standardization (ISO) 2631-1 [16] when calculating RMS. These weightings are based on different sensitivity of the body to vibration in each axis, something that has not been researched in people with SCI. Another reason we did not apply the frequency weightings was the placement of the accelerometers: they were not placed exactly in line with the axes of the body, as ISO 2631-1 prescribes [16]. Future research should be directed toward the question of which frequency ranges trigger spasticity and/or create discomfort or health risks among people with SCI. Subsequently, future research should focus on developing a wheelchair that specifically targets those frequencies for vibration dampening.

In a wheelchair study with a similar obstacle course [14], accelerations were analyzed by means of a vibration dose value (VDV). The VDV is a cumulative measure of the vibration absorbed by a person over a certain time period [2]. The focus of this study was not cumulative vibration and shocks; thus, the VDV was not useful for our analysis. VanSickle et al. [15] and DiGiovine et al. [14] used a bite-bar to measure transmissibility of vibrations onto the body. Since the current study was focused on vibration exposure on the wheelchair rather than absorption of vibration in the body, we chose not to measure vibration transmission. It could be that Spinergy wheelchair wheels reduce transmissibility of vibrations from the wheelchair onto the body. This possible effect requires further research with a somewhat differently designed study and different outcome measures.

We recognized that different speeds might generate different vibrations, thereby making the results dependent on the rate of propulsion [14]. As a result, we chose the method used in the first part of the study to control for velocity. Since subjects served as their own controls, we believed we could reasonably compare the two types of wheels without speed being a confounder.

Spinergy claims on its Web site that its fiber spokes act as vibration and shock dampeners—25 percent more absorbent than steel [6]. It could be that the material itself (PBO fiber) does reduce vibrations by 25 percent but that this effect cannot be extrapolated to the vibration characteristics of an entire wheelchair wheel.

Spasticity and Comfort

The spasticity and comfort results are in line with the vibration results; no differences in vibration exposure were seen between the wheel types, so an effect on spasticity and/or comfort would not be expected given the hypothesized relation among these phenomena in SCI.

The VASs showed no significant difference between the wheels on either spasticity or comfort. The results in the graph (**Figure 5**) indicate a trend toward steel-spoked wheels being rated as higher in terms of spasticity for eight of the nine obstacles ($p = 0.06$). However, because of the large variability in the data, this trend did not reach significance. With a larger sample size, a significant trend might have been attained. The VAS results on comfort did not confirm the results of Hughes et al. [7]. In a similar study also comparing Spinergy versus steel-spoked wheels on energy efficiency, Hughes et al. found Spinergy wheels to be preferred over steel-spoked wheels in terms of comfort [7]. The difference in the results could be explained by the fact that Hughes et al. [7] used the obstacle course previously described by DiGiovine et al. [12], in which the subjects wheeled consecutively over all the obstacles in one trial. Therefore, subjects had to maneuver the wheelchair between the obstacles (make turns, brake, accelerate, and decelerate), unlike in the current study. Spinergy wheels may be more comfortable in terms of general wheelchair use and maneuverability; however, we are not able to confirm this hypothesis.

Some subjects had severe visible spasms during the transfers, but these kinds of spasms were not observed during the wheeling tests. The obstacle course may not have sufficiently simulated the experiences individuals have in the community. Also, one must consider that, up to now, no objective measurements for spasticity were suitable for this kind of study [17]. The VAS might have failed to detect a difference in spasticity because of its subjective nature. Wewers and Lowe mention that the necessary conditions for reliability and validity of the VAS remain unresolved [18]. Despite the fact that no articles were found in which the VAS was used as a measure of spasticity, we chose the method for lack of finding a better one. In a study by Lingjærde and Foreland [19], the VAS showed excellent test-retest reliability and high validity while measuring depression. In their review on clinical scales for the measurement of spasticity, Platz et al. mentioned that the VAS as a self-report scale on spasticity might add valuable information [11]. A better understanding of the syndrome of spasticity and the development of a valid, reliable assessment tool are needed [4]. In future research, electromyography (EMG) could provide a more objective measurement [17,20]. The downside of EMG is that subjects will have to deal with wires that can obstruct wheeling and functioning.

Some discussion has occurred regarding the reliability and validity of the MAS [21–22]. Bakheit et al. suggested that the MAS measures muscle hypertonia rather than spasticity [23]. Furthermore, Blackburn et al. concluded that when assessing muscle tone, the MAS yields reliable measurements but only for a single examiner [10]. In our study, the same physician performed the MAS for every measurement. Since no other reliable and valid objective assessment tools exist to measure spasticity [17], the MAS was the best alternative.

Protocol

One change we made from the previous DiGiovine et al. [12] and Hughes et al. [7] studies was to separate out each obstacle in the second part of the study (i.e., one trial represented one obstacle instead of an obstacle course). We included this change to ensure that the previous obstacle had no influence on the outcome of the next obstacle and so that we could individually evaluate each obstacle. In addition, this change in protocol attempted to standardize speed, a limitation of the setup in DiGiovine et al. [12]. We did not find that Spinergy wheels, compared with standard steel-spoked wheels, had beneficial effects with respect to vibration, spasticity, and comfort. Factors such as weight of the wheels (Spinergy wheels are lighter than steel-spoked wheels) could make Spinergy wheels preferable.

Limitations

Most of the subjects in our study had fairly well-managed spasticity, which may have limited the effect of the vibrations. Most subjects used some kind of medication to inhibit their spasticity, usually baclofen or Lyrica. For ethical reasons, we could not ask them to stop their medication. Even though the medication does not completely take away all spasms, it may have affected our results. It would be interesting to test those subjects who have more difficulties managing their spasticity and see whether the Spinergy wheels offer more comfort, as seen in the previous study [7].

Completely controlling for velocity is difficult. In the second part of the study, speed was not completely standardized like it was in the first part. We attempted to standardize velocity by adjusting the protocol of DiGiovine et al. [14]. Instead of wheeling over all the obstacles at once, subjects wheeled over one obstacle at a time. The average velocity was calculated per obstacle and was not significantly different between the wheels. We found that subjects used different wheeling strategies over the obstacles, especially the big speed bump. Some did a "wheelie" (wheeling on hind wheels), while others went over the bump slowly on four wheels. The difference in strategy could have affected the outcome measures.

In the first part of the study, the nondisabled subjects used one experimental wheelchair, while in the second part, the subjects with SCI used their own wheelchairs, causing an extra dimension of variation. However, since comparisons were made within subjects, this variation was assumed to not be a confounder.

One aim of this study was to stay close to real-life situations. The downside of this approach is that several variables could have had a confounding effect on the results. Such variables include the subjects' height, weight, and technique while wheeling over the obstacles. To understand whether specific frequencies trigger spasms, we need a more standardized approach; this approach might include the creation of a vibrating plate [24] with variable vibration frequencies for subjects to sit on, as well as the use of EMG of the leg muscles to measure the response to the vibration, rather than relying only on subjective feedback. A study without people sitting in the wheelchair would enhance standardization of the vibration analysis, for example, use of a double drum comprised of a little bump [13]. For the measurement of the effect of wheelchair vibration on spasticity, standardization would be enhanced if people with SCI were to sit in their wheelchair on a standardized vibration stimulator.

CONCLUSIONS

We can conclude that under the current standardized conditions, the Spinergy wheelchair wheels, as compared with the standard steel-spoked wheelchair wheels, neither absorb more vibration at the footplate or the axle nor reduce perceived spasticity or improve comfort in individuals with SCI wheeling over rough surfaces and obstacles.

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