
Impact Attenuation and Efficiency Characteristics of a Flexible Wheelchair Handrim

W. Mark Richter, Adam P. Karpinski, Russell Rodriguez, and Peter W. Axelson

Manual wheelchair users are at considerable risk for developing upper extremity overuse injuries. Novel ergonomic handrim designs hold promise to reduce physical demand on the wheelchair user. In this study, a flexible handrim design was evaluated to assess its effects on impact attenuation and the oxygen cost of propulsion. The flexible handrim was found to reduce the peak rate of loading by 10.2%, 9.5%, and 10.0% for low-, moderate-, and high-impact levels. Oxygen cost of propulsion was assessed through submaximal propulsion on a belt-driven treadmill using a population of wheelchair users. On average, the flexible handrim was found to reduce the oxygen cost of propulsion by 13% ($p = .039$). Use of the flexible handrim may help reduce the likelihood of developing secondary upper limb impairments related to impact loading or propulsion-induced fatigue. **Key words:** *efficiency, flexible, flexrim, handrim, impact, propulsion, wheelchair*

Manual wheelchair users are at considerable risk of developing upper extremity overuse injuries.¹⁻³ Repetitive impact loading is one factor that has been associated with the development of such injuries.⁴ The use of a compliant handrim, one that can absorb impact loading, has been suggested as a preventive measure to protect the user's upper extremities.⁵ A flexible handrim (FlexRim; Spinergy, San Diego, CA) has recently become commercially available that combines compliance to reduce impact and a high-friction grip surface to reduce grip exertion during propulsion (**Figure 1**).

This flexible handrim has been shown to reduce peak and overall forearm muscle exertion during propulsion over a variety of propulsion conditions.⁶ It also has been shown to result in more powerful pushes, so users spend less time pushing and more time coasting.⁷ Although these results are compelling, there are unanswered questions

related to its performance. What effect does the flexible handrim have on the metabolic cost of propulsion? Surely there must be some energy absorbed by the handrim that is not fully transferred to the wheels during the push. Despite findings that forearm muscle activation was reduced, there still exists the possibility that other musculature might be

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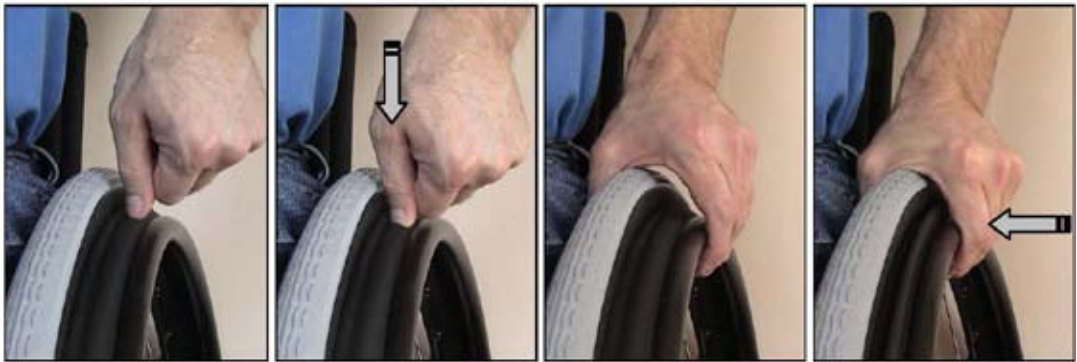


Figure 1. The flexible handrim allows local deformation under the hand and general movement of the tubular handrim relative to the wheel.

more active. However, if there is a net reduction in muscle activation during propulsion, then one would expect a reduction in the oxygen cost of propulsion.

How much does the flexible handrim reduce impact loading? Because subjects pushed harder when using the flexible handrim,^{7,8} it was not clear how much of the impact was being absorbed during the push. To answer this question, a method by which controlled impact can be administered to the flexible handrim is needed.

The purpose of this study was to provide insight into these questions by evaluating the impact attenuation characteristics of the flexible handrim and by assessing any effects the flexible handrim may have on the oxygen cost of propulsion.

Methods

Substudy: impact attenuation

An impact fixture was developed that can repeatedly simulate an impact between the hand and the handrim. The fixture, shown in **Figure 2**, consists of a weighted arm that

is free to pivot about the shoulder joint. The arm is held at a prescribed height by a pin. Once the pin is released, the arm drops and the hand impacts the handrim. The forearm is split and held together by two commercially available load cells (Transducer Techniques, Temecula, CA). The load cells were monitored by a data acquisition system (National Instruments, Austin, TX) with a logging frequency of 1000 Hz.

The initial impact fixture was equipped with a rigid hand segment. With a fully rigid hand, the level of impact loading with a standard handrim was considerably higher than what is typically found during propulsion. To achieve more typical levels of impact loading, a semi-compliant hand was developed. A flexible silicone mold of a human hand was created with the hand postured similar to that seen just before impacting the handrim. Then a porous hand segment core was inserted into the mold and 40 Shore-A durometer urethane was poured around it. Once cured, the hand resembled the look and feel of the palm of the hand and thumb (**Figure 3**). Three impact loading levels were created based on previously published values for propulsion on a

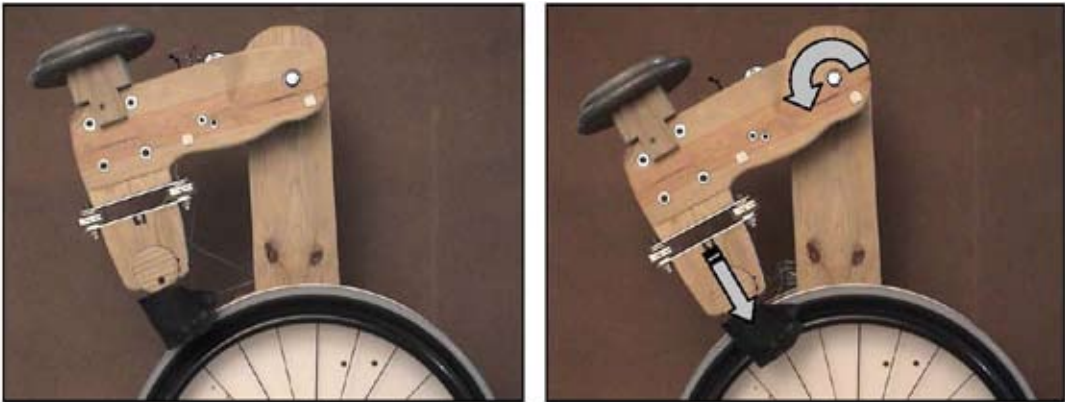


Figure 2. The impact fixture used in this study included a weighted arm that rotated about a fixed shoulder joint. Load cells embedded in the forearm were used to measure the reaction forces at impact.

variety of level and uphill conditions.⁸ Impact levels of approximately 900 N/s, 1600 N/s, and 2000 N/s were created by adjusting the initial height of the arm to different locations. The added weight to the arm remained fixed at 6.8 kg.

Testing was done on a standard uncoated tubular aluminum handrim (Sun Metal Products, Warsaw, IN) and the flexible han-

drim. Both handrims were mounted to the same model of wheel (Sun Metal Products, Warsaw, IN), with comparable spoke tension. Testing order was randomized. Each handrim was mounted into the fixture and subjected to 20 impacts, while impact loading was recorded. Impacts were generated through release of the pin that allowed the arm to drop and strike the handrim. This



Figure 3. The hand interface of the impact fixture used in this study was molded to the shape of a human hand postured similar to that seen just prior to impact with the handrim.

process was repeated for each impact level, for a total of six handrim/impact level conditions.

Reaction forces from each of the two load cells were summed into a single net reaction force. Rate of loading of the resultant force was calculated based on a discrete difference between adjacent data points divided by the time between samples. The peak rate of loading was identified from each impact event. Descriptive statistics were calculated for peak rate of loading for each of the impact level and handrim conditions. Differences in peak rate of loading between the standard handrim and the flexible handrim were assessed using an analysis of variance followed by a Bonferroni post hoc adjusted *t* test. Differences were determined to be statistically significant for $p < .05$. All statistical tests were completed using SPSS statistical software (SPSS, Inc., Chicago, IL).

Substudy: oxygen cost of propulsion

Institutional review board approval (Western IRB, Olympia, WA) of the protocol was received prior to recruiting subjects for the study. A convenience population of manual wheelchair users was recruited to participate in the study from an internal database of potential and experienced test subjects. Inclusion requirements included: (a) use of a manual wheelchair as the primary means of mobility, (b) comfortable propelling a wheelchair continuously for periods of up to 5 minutes, and (c) no medical conditions that might be aggravated by wheelchair propulsion or moderate exercise periods. All subjects read and signed the IRB-approved consent form prior to participation.

Subjects were asked about their wheelchair experience, disability, and age. Sub-

jects were fitted with a metabolic mask and a nose clip. Fit of the mask was tested to ensure respiration gases were channeled properly. A portable metabolic testing system with telemetry (VO2000; Medgraphics, St. Paul, MN) was attached to the posterior aspect of the wheelchair backrest (replacing any backpacks). The metabolic system was then calibrated using the AutoCal function. The metabolic mask was connected to the metabolic system using the low-flow Pneumotach. Subjects were asked to close their eyes and sit still in silence for a period of 10 minutes while their resting metabolic demand was measured.

While sitting in their wheelchairs, subjects were loaded onto a large multigrade belt-driven treadmill. Pushing on a treadmill provides a controlled propulsion environment where the inertial properties of propulsion are preserved. Subjects became acclimated to the treadmill by pushing at a variety of speeds and grades and then chose their comfortable speed for a 2-degree grade. The acclimation period was completed using a standard uncoated tubular aluminum handrim (Sun Metal Products). A hand-held force gauge (Transducer Techniques) was used to determine the force required to support (drag) each subject passively sitting in the wheelchair on the treadmill on a 2° grade and at their self-selected speed.

The testing order of the handrims was randomized. Subjects then pushed at their self-selected speeds for 4 minutes. Metabolic data were collected over the entire propulsion bout. After a 15-minute rest period, subjects repeated the propulsion bout using the untested pair of handrims.

The metabolic instrumentation added 1.7 kg to the weight of the wheelchair. Respiratory volume was measured using a bi-di-

Table 1. Impact attenuation results

Impact level	Impact (N/s) standard handrim	Impact (N/s) flexible handrim	Decrease with flexible handrim (N/s)	<i>p</i>
Low	871 (64)	782 (66)	89	.000
Moderate	1611 (73)	1458 (57)	153	.000
High	1956 (63)	1760 (44)	196	.000

Note: Standard deviations are given in parentheses.

rectional pitot tube with an accuracy of 3% of absolute volume. Oxygen was measured using a galvanic fuel cell with a range of 0%–96% and an accuracy of 0.1%. Carbon dioxide was measured using a nondispersive infrared sensor with a range of 0%–10% and an accuracy of 0.2%. Measurements were internally averaged over 10-second intervals and transmitted wirelessly to a lab computer, which acquired and stored the data.

Power output for each subject was determined by the product of the drag force and the treadmill belt speed. Resting metabolic measures were averaged over the last 2 minutes of the rest period. Metabolic measures during propulsion were averaged over the final minute of propulsion. The net oxygen consumption resulting from propulsion was determined by subtracting the resting values from the propulsion values for each subject. Oxygen cost was then determined by normalizing each subject's oxygen consumption by total distance propelled, resulting in units of liters of oxygen required per meter travelled.

Descriptive statistics were calculated for continuous subject characteristics and oxygen cost. Differences in oxygen cost between the standard handrim and the flexible handrim were assessed using a repeated measures two-tailed *t* test. Differences were determined to be statistically significant for

$p < .05$. All statistical tests were completed using SPSS statistical software.

Results

Impact attenuation

Results of the impact testing are given in **Table 1**. Statistically significant reductions in impact loading were found for the flexible handrim in each of the three loading conditions. The percent reductions in impact loading for the low-, moderate-, and high-impact levels were 10.2%, 9.5%, and 10.0%, respectively. The average reduction over all three impact conditions was 9.9%.

Oxygen cost of propulsion

Eighteen manual wheelchair users gave written consent and participated in the study. Subject characteristics of age, gender, disability, weight, wheelchair experience, and disability level are summarized in **Table 2**. All of the subjects were able to comfortably complete the protocol. The average self-selected speed over all three grades was 0.87 m/s ($SD = 0.20$), and the average power output over all three grades was 31.4 W ($SD = 12.9$).

The resting oxygen consumption for the population was 0.34 L/min ($SD = 0.16$). The average oxygen consumption for the

Table 2. Subject characteristics

Number of subjects	18
Age, years	35.7 (11.3)
Wheelchair use, years	12.5 (6.8)
Gender	12 male, 6 female
Weight, kg	63.5 (10.1)
Injury/condition	16 SCI, 2 spina bifida
Injury level	L1 – T6

Note: Standard deviations are given in parentheses.

population was 0.88 L/min ($SD = 0.28$) and 0.81 L/min ($SD = 0.29$) for the standard uncoated and flexible handrims, respectively. The resulting oxygen cost of propulsion for the standard handrim was 10.4 L/km ($SD = 3.8$) and 9.0 L/km ($SD = 4.0$) for the flexible handrim. These differences were found to be statistically significant ($p = .039$) and represent a 13% decrease in the average oxygen cost of propulsion for the group.

Discussion

Manual wheelchair propulsion is the primary mode of locomotion for millions of people around the world. There are over a million wheelchair users in the United States alone.⁹ Over half of those wheelchair users are estimated to have developed an upper limb overuse injury.^{1-3,10-14} The consequences of such injuries can be significant, including decreased quality of life due to pain, decreased mobility, shoulder and wrist surgeries, and the eventual need for a powered wheelchair.¹

Impact attenuation

As was previously mentioned, impact loading is one of the factors that has been associated with the development of upper

extremity overuse injuries.⁴ The flexible handrim was found to consistently reduce impact loading across each of the impact conditions. These results imply that when a user impacts the flexible handrim, approximately 10% of that impact is absorbed. One of the limitations of this study was that impact attenuation was quantified using an impact fixture rather than during actual propulsion. Although it is likely that the flexible handrim will reduce impact loading during propulsion, it is also likely that results will vary by individual. The impact fixture was designed to approximate the shape and posture of a hand impacting the handrim. However, variability in hand size, shape, and posture across wheelchair users may affect the degree to which impact is absorbed.

Oxygen cost of propulsion

Pushing while fatigued is also considered to be a risk factor in the development of upper extremity injuries. The concerns with pushing while fatigued are the following: (a) the muscles stabilizing the shoulder joint may be compromised and therefore not able to prevent the humeral head from translating superiorly in the glenohumeral joint, and (b) users tend to alter their propulsion technique when fatigued, pushing with higher forces on the handrim.^{15,16} Decreasing the oxygen cost of propulsion may serve to delay the onset of propulsion-induced fatigue and therefore may also serve to reduce the risk of developing upper limb injuries.

The flexible handrim was found to significantly decrease the oxygen cost of propulsion for this group of wheelchair users and this test condition. This group was made up of those with spinal cord injury and full arm and hand function. This subject population

was also fairly young, with an average age of 36 years. It is unclear how individuals with tetraplegia or persons with a disability who are aging will be affected by use of the flexible handrim. None of the test subjects had previous experience using the flexible handrims and they all had experience using the standard tubular handrim. Having a limited time to become acclimated to the flexible handrims is expected to limit rather than accentuate the differences in oxygen cost. As such, the current results could be conservative compared to testing after a substantial usage period.

There is evidence in the literature to support the belief that increasing the size of the handrim as well as improving its frictional characteristics have the potential to reduce metabolic demand during propulsion. The flexible handrim presents improvements to both of these characteristics. Van der Linden et al found that pushing on a wheelchair ergometer with larger tubing handrims (25 x 30 mm oval) slightly but statistically improved gross mechanical efficiency over the standard 18-mm diameter tubing.¹⁷ Because the surface characteristics of the two handrims were the same, the researchers concluded that the grip posture with larger tubing must have improved the biomechanical advantage of the hand, thereby decreasing finger flexor

activity. Richter et al found that pushing on a treadmill with a high-friction vinyl-coated handrim decreased oxygen consumption over that required with a standard handrim by 9%.¹⁸

Conclusion

In this study, a flexible handrim design was shown to reduce impact loading on an impact fixture and reduce the oxygen cost of steady-state, submaximal wheelchair propulsion for a population of wheelchair users. Use of a flexible handrim may benefit wheelchair users by protecting their upper extremities from the damaging effects of repetitive impact loading during propulsion. Additionally, the decreased oxygen cost of propulsion may serve to delay the onset of propulsion-induced fatigue and therefore decrease the likelihood of developing fatigue-related injuries.

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