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Low-impact wheelchair propulsion: Achievable and acceptable

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Abstract—Incidence of upper-limb overuse injuries among the manual wheelchair population has been found to be associated with hand-rim loading characteristics such as impact and peak loading on the hand rim during propulsion. One proposed method to reduce impact and peak loading is the use of a compliant hand rim, one that can displace relative to the wheel when impacted by the hand. A Variable Compliance Hand-Rim Prototype (VCHP) was designed and used to experimentally optimize the level of compliance through subjective and qualitative propulsion outcome measures. Seventeen manual wheelchair users participated in the study. Subjects propelled their wheelchairs using the VCHP set to each of three compliance levels through a maneuverability test course, as well as on a range of grade conditions using a wheelchair treadmill. Biomechanical measures such as peak hand-rim force, rate of loading at impact, and metabolic demand were assessed during treadmill propulsion bouts. No adverse biomechanical side effects to compliance were found. As compliance was increased, user acceptance decreased. All the subjects found the lowest level of compliance (C1) to be acceptable. Use of the C1 hand rim resulted in significant reductions in the peak rate of rise in the hand-rim force on the 6% and 8% grades and significant reductions in the average rate of loading for the 2%, 4%, and 6% grades. This study showed that low-impact wheelchair propulsion is both achievable and acceptable to users.

Key words: biomechanics, compliance, hand rim, low impact, propulsion, pushrim, spinal cord injury, rehabilitation, repetitive stress injuries, wheelchair.

INTRODUCTION

The manual wheelchair user controls the wheelchair with the hand rims. Hand rims enable the wheelchair user to propel forward, turn, perform wheelies, and brake. Since wheelchair users rely on their upper limbs for mobility, pain and injuries to an upper limb can severely impact function and independence. Unfortunately, a high occurrence of upper-limb injuries exists in the manual wheelchair user population. In a study of 239 manual wheelchair users, Sie et al. found that 64 percent of patients with paraplegia reported upper-limb pain [1]. Dalyan et al. found that 59 percent of 130 manual wheelchair users experienced upper-limb pain [2], and Gellman et al. reported the same in 68 percent of 84 manual wheelchair users [3]. Results of these studies suggest that over half the wheelchair user population experiences some form of upper-limb pain.

Abbreviations: ANOVA = analysis of variance, C1 = compliance level 1, C2 = compliance level 2, C3 = compliance level 3, CTF = contribution of tangential force, DOF = degrees of freedom, HR = heart rate, aROR = average rate of rise, pROR = peak rate of rise, SD = standard deviation, VCHP = Variable Compliance Hand Rim Prototype, VO_2 = oxygen consumption.

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Wheelchair propulsion biomechanics research has grown out of the need to better understand the demands on the wheelchair user during propulsion and to find methods to optimize wheelchair locomotion. Research efforts are being made to determine the etiology of secondary upper-limb injuries in the wheelchair user population. The general characteristics of the forces applied to the hand rim during propulsion, shown in **Figure 1** and described by Boninger et al., include a rapid rate of loading in the beginning of the push, leading to an impact spike, and followed by a more gradual application and release of force [4]. The impact spike on the hand rim is at least partially the result of the hand driving radially into the hand rim. The hand has been shown to impact the hand rim at a speed of approximately 40 percent of the total hand velocity [5]. Incidence of both wrist and shoulder injuries have been associated with characteristics of the hand-rim force profile, including the peak force, the peak rate at which the force is applied, and the frequency of pushes [6–8]. Results from these studies suggest that reducing the peak forces and rate of loading on the hand rim during propulsion may reduce the likelihood of developing secondary upper-limb injuries.

One proposed solution to reducing impact loading is the use of a compliant hand rim (U.S. Patent 6,120,047). A compliant hand rim is a hand rim that is able to displace relative to the wheelchair wheel when impacted by the hand during propulsion (**Figure 2**). Pilot studies investigating hand-rim compliance have found that impact loading can be reduced by approximately 30 percent [9]. However, a trade-off was found to exist between hand-rim compliance and user acceptance [10]. As compliance was increased, impact was reduced but, unfortunately, so was user acceptance. Clearly, a hand rim that reduces impact but is not used will not help prevent repetitive stress injuries in the wheelchair user population. Results from these pilot studies suggested that an optimal compliance might exist at which impact is reduced and user acceptance is preserved. This study investigated hand-rim compliance within the range of those values previously studied and determined whether such an optimal level exists. In addition to impact attenuation and user acceptance, other potentially adverse side effects such as an increase in metabolic demand or push frequency were also investigated.

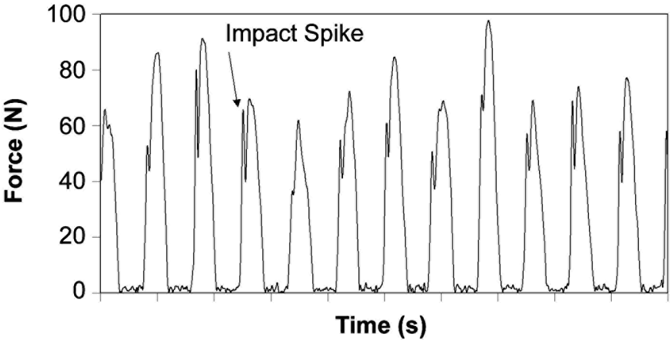

Figure 1.
Force measured at hand rim during push generally consists of rapid rate of initial loading leading up to impact spike, followed by more gradual loading and unloading.

METHODS

Variable Compliance Hand-Rim Prototype

We developed a Variable Compliance Hand-Rim Prototype (VCHP) to study the effect of compliance on propulsion ergonomics and user acceptance. As shown in **Figure 3**, the VCHP involved coupling the hand rim to the wheel through three compliant disk housings. Modified tabs welded onto the hand rim are allowed to move in

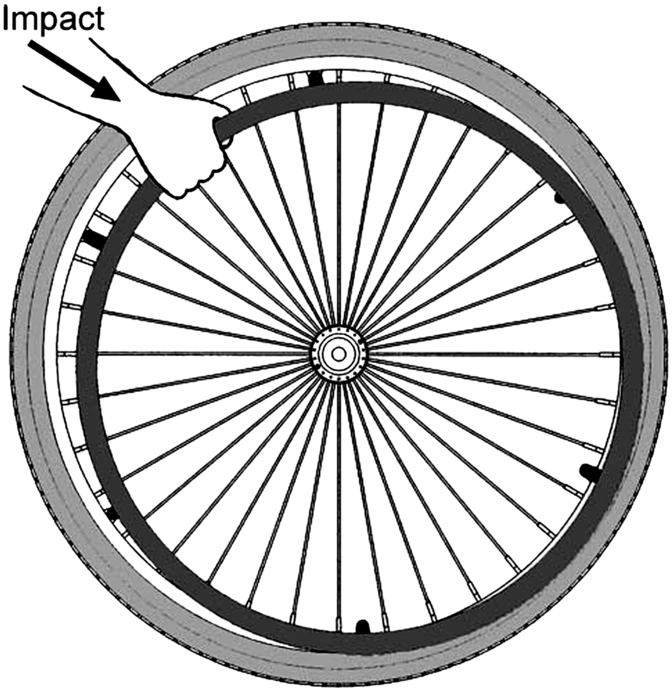

Figure 2.
Compliant hand rim is able to displace relative to wheelchair wheel when impacted by hand to reduce impact loading.

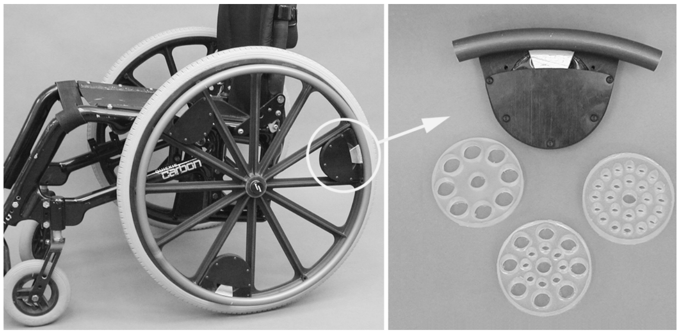

Figure 3.
Variable Compliance Hand-Rim Prototype (VCHP) was developed to study effect of compliance on propulsion ergonomics and user acceptance.

the plane of the wheel inside the housings. At the distal end of each tab is a peg, which passes through the center of the disk. As the hand rim is loaded, the disk is compressed inside the housing. One can vary compliance by changing the durometer of the disk material or by changing the void concentration. The amount of displacement is limited by the size of the housing opening, 1.91 cm. The lateral positioning of the hand rim is the same as it is for a standard rigid hand rim, also 1.91 cm. The compliant disks were developed with the use of a two-part room temperature thermoset urethane (Synair, Chattanooga, TN).

We characterized hand-rim compliance by measuring the response to static loading. Eight loading levels were applied to the hand rim and the resulting displacement measured. The compliance characterization setup consisted of a rigid attachment for the wheel, a coil-spring wound cable linear potentiometer (UniMeasure, Corvallis, OR) to measure hand-rim displacement, and a 1 degree of freedom (DOF) load cell (Transducer Techniques, Temecula, CA) to quantify the applied load. The resulting load/displacement data from each set of disks were then graphed as a scatter plot. A least-squares linear regression trendline was fitted to the data and the corresponding coefficient of determination (R^2) calculated. We set a target R^2 value of 0.98 to ensure a highly linear hand-rim response. Disks were iteratively evaluated and redesigned until three evenly distributed linear response designs were achieved.

Subjects

We submitted the study protocol and gained approval by the Western Institutional Review Board (Olympia, WA) before recruiting or involving any human subjects. Twenty full-time wheelchair users were randomly recruited from an internal subject database to participate in the study. All subjects were prescreened for compliance with inclusion criteria and health risks associated with completion of the protocol. Subjects read and signed an approved consent form before participating in the study. To be included in the study, the subjects had to (1) use a manual wheelchair as their primary means of mobility, (2) have full function of their upper limbs, (3) be comfortable propelling their wheelchair continuously for periods of up to 5 min, (4) use a wheelchair equipped with 24 in. or 25 in. quick-release rear wheels, (5) have no medical conditions that could be aggravated by wheelchair propulsion, and (6) have no cognitive or behavioral impairment.

Usability and Acceptance Testing

The primary goal of the usability and acceptance portion of the study was to determine at what level of compliance the users felt the hand rim was too soft. Wheelchair users were weighed in their own wheelchairs and then asked to transfer from their wheelchairs so their wheels could be replaced with VCHP test wheels. Subject wheelchairs were weighed and the resulting subject body weight determined by subtraction from the total weight.

Subjects were then asked to propel their wheelchairs through a mobility activity test course using the VCHP test wheels. The VCHP was initially set to the rigid setting. The test course consisted of seven activities, including negotiating a slalom course, level sprint, pushing and maneuvering on carpet, curved downhill path, and curved uphill path. The slalom course consisted of four pylons spaced 1.25 m apart. The level sprint was 20 m long and performed on an asphalt surface. The curved uphill path was 10 m long. The average grade of the curved path was 8.5 percent, with a minimum of 4 percent and a maximum of 12.3 percent. The average cross-slope of the curved path was 4.5 percent, with a minimum of 0.3 percent and a maximum of 9.6 percent.

After activities were completed with the VCHP set to the rigid setting, the compliance was increased to compliance level 1 (C1) and subjects were asked to repeat the test course. After completing the test course at C1, subjects were asked whether the hand rim felt too soft. If subjects responded that it was not too soft, then the compliance was increased to compliance level 2 (C2) and the process was repeated. If C2 was not too soft, then it was increased to compliance level 3 (C3) and repeated. C3 was the most compliant setting evaluated. Subject responses were collected and compared with a histogram. We also cross-evaluated results to investigate a relationship between compliance preference and subject body weight. Since heavier subjects will likely propel with greater forces and since hand-rim displacement is related to applied forces, heavier subjects were expected to prefer a less compliant level than lighter subjects.

Controlled Propulsion Testing

Subjects were asked to transfer from their wheelchairs and the VCHP test wheels were replaced with a propulsiometer on the right side and a "dummy" propulsiometer on the left side. A propulsiometer is an instrumented wheelchair wheel developed by Beneficial Designs (Nashville, TN), capable of measuring the dynamic hand-rim loading and wheel angle during propulsion. Hand-rim loading is measured with a 6 DOF load cell mounted at the center of the wheel (ATI Industrial Automation, Apex, NC). Wheel angle is measured with an absolute inclinometer (U.S. Digital, Vancouver, WA). Since straight propulsion requires the user to apply approximately equal forces to each wheel to maintain a straight path, only one instrumented wheel is required. The dummy propulsiometer is a propulsiometer with the instrumentation replaced with an equivalent weight. This ensures that the wheels are symmetrically balanced and geometrically similar.

Subjects then transferred back into their wheelchairs and were loaded onto an oversized multigrade research treadmill. Lap belts secured subjects to their wheelchairs, and the wheelchair was connected to a securement system. Subjects were fitted with a heart-rate (HR) monitor chest strap (Polar, Kempele, Finland) and a portable metabolic gas analyzer (AeroSport KB1-C, St. Paul, MN). The metabolic unit was battery-powered and transferred data wirelessly to the data collection computer. A Hans Rudolph mask fitted to each subject ensured an airtight seal around the face. The autocalibration feature of the metabolic unit was used before each testing session.

Subjects propelled their wheelchairs on the treadmill for up to 5 min continuously using each hand-rim condition (rigid, C1, C2, and C3) in a randomized order. Each propulsion bout on the treadmill consisted of a ramping profile with four grade/speed combinations. The grade/speed combinations were chosen to represent a range of environmental conditions that wheelchair users encounter during daily mobility activities. The treadmill profile for the rigid and C3 hand-rim conditions included the following stages: (1) 2 percent grade at 0.94 m/s for 2 min, (2) 4 percent grade at 0.49 m/s for 1 min, (3) 6 percent grade at 0.31 m/s for 1 min, and, finally, (4) 8 percent grade at 0.22 m/s for 1 min. The grade speed conditions were the same for the C1 and C2 hand-rim conditions, but the time was reduced such that 20 pushes on each grade were completed. The reduced propulsion time for the C1 and C2 hand-rim conditions ensured that subjects did not become fatigued. Subjects had a 15 min rest period between propulsion bouts.

Hand-rim kinetics and wheel kinematics were measured before the trial and during propulsion for the last minute of each grade. Hand-rim kinetics were measured at 480 Hz and filtered with the use of a fourth-order Butterworth digital filter with a 20 Hz cutoff frequency [11]. Metabolic and HR measurements were made during the entire 5 min trial. Data from the metabolic gas analyzer were averaged over 20 s intervals and then transmitted to a data collection computer. HR was averaged over a 5 s interval, stored on the receiver watch, and then transferred to a data collection computer after each trial. The experimental setup for the propulsion testing is shown in **Figure 4**.

Data Analysis

We wrote a data processing program using MATLAB (The MathWorks, Natick, MA) to analyze and store the results of each trial. Signal offsets were removed from the propulsiometer data, with data collected before each trial began. Kinetic data were converted to three-dimensional forces and moments with the load cell calibration matrix. The resulting kinetic and kinematic data were divided into push and recovery phases by identification of the initiation and termination of significant nonzero forces or moments applied to the hand rim. We skipped the first five pushes at each grade to allow for the effects of transitioning to that grade to reach steady state. The next 15 pushes were used in our analysis.

The resulting force and moment vector were rotated from a wheel fixed reference frame to an inertial laboratory reference frame with the use of the wheel angle. The most accurate and stable method of determining the radial and tangential components of force on the hand rim is to rotate the reference frame by the hub to hand marker angle [12]. Since this study did not include measurement of hand kinematics, we did not use this method. The force components could be calculated with the equation

$$F_t = M_z / R_h \quad ,$$

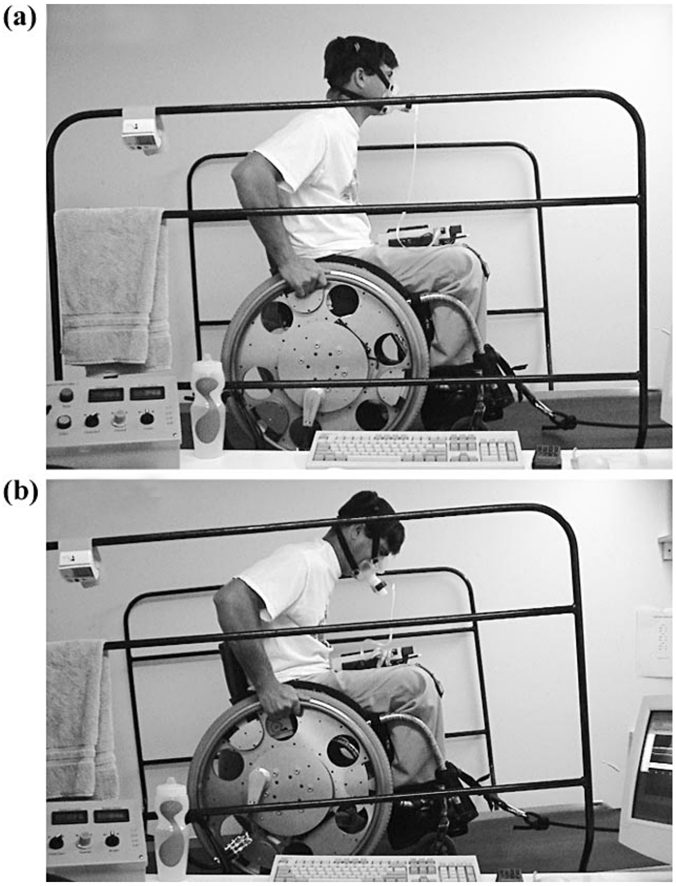

Figure 4.
Experimental setup for propulsion performance testing on treadmill. Subjects propelled wheelchairs with addition of propulsiometer test wheels to measure dynamic hand-rim kinetics and wheel kinematics. Propulsion bouts included grades from **(a)** 2 percent to **(b)** 8 percent.

where F_t is the tangential component of force, M_z is the total moment applied about the axle, and R_h is the radius of the hand rim. However, this equation assumes that the contribution of the hand moment to the wheel moment is negligible. This assumption is likely an oversimplification and has not been tested for propulsion on grades, which is likely to affect propulsion technique. Consequently, the resultant in-plane force was used instead of the individual radial and tangential components in this analysis. However, to evaluate the effect of grade on the contribution of tangential force (CTF), we calculated CTF using the established relationship

$$\mathrm{CTF} = F_t^2 / F^2 \qquad ,$$

where F_t is the tangential force component, as just described and F is the total force applied to the hand rim. CTF was averaged during the push phase over each of the 15 push trials. Peak forces and moments for each push were averaged across each propulsion condition, for the resultant force applied to the hand rim F, the force applied to the hand rim in the plane of the wheel F_{xy}, and moment applied to the hand rim about the wheel axle axis M_z.

Metabolic data were averaged over the last 40 s of each grade condition. Before metabolic data is used, subjects propelled for 2 min, 20 s, until they reached steady state. Since the power output at each grade condition was expected to be reasonably similar across grades (speed drops as grade is increased) and the subjects had already reached steady state for the 2 percent grade condition, the time allowance for the subjects to reach steady state at each of the grades above the 2 percent condition was reduced to 20 s. The specific metabolic measures targeted included HR, oxygen consumption (VO_2), and ventilation. Power output was calculated with the average torque applied to the hand rim and the average angular velocity of the wheels during each grade condition. We then doubled the power output to account for an equal torque applied to the nonmeasurement wheel.

Push angle was determined for each push by the wheel angle subtended during the push phase. Push time was defined as the time elapsed during the push phase and recovery time as the time between pushes. The push frequency was defined as the inverse of the sum of the push and recovery times for each push. Timing metrics were averaged over each 15-push trial.

Rate of Loading

Several different approaches exist to characterizing the rate of loading during the push. Boninger et al. used the peak rate of rise (pROR) of the force during the push (**Figure 5(a)**) [6]. In previous studies, we have also used the average rate of loading over the first 10 percent of the push to characterize the beginning or impact phase of the push [9]. The pROR of the force represents the rate of loading at one instant during the push, which may or may not coincide with the impact phase. Use of the average rate of loading over the first 10 percent also has limitations. Ten percent of the push was chosen, since it corresponded approximately with the location of the impact peak. However, the location of the impact peak can vary outside of the 10 percent value, thereby introducing uncertainty into the outcome measure.

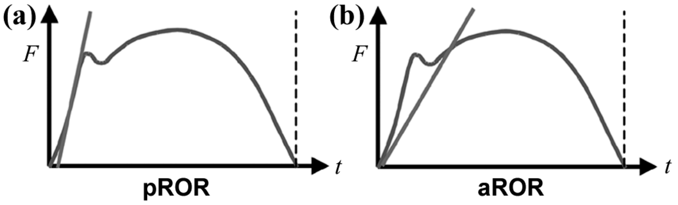

Figure 5.
(a) Peak rate of rise (pROR) of force is maximum instantaneous loading rate. **(b)** Average rate of rise (aROR) averages *positive* slope values during push and can be used to resolve existence of impact spike.

We designed a new metric to improve our ability to characterize the rate of loading during propulsion. The average rate of rise (aROR) of the force (**Figure 5(b)**) is the average of the *positive* force rate values over the push. Unlike an average slope calculation, the aROR is path-dependent and therefore capable of resolving the influence of impact spikes during propulsion.

Statistical Analysis

We compared resulting propulsion outcomes measures using a two-way analysis of variance (ANOVA) with repeated measures on compliance to determine if statistically significant differences existed between the hand rim conditions. A Bonferroni post hoc *t*-test detected which compliant conditions differed from the rigid (control) condition. We set the statistical significance level to 0.05, and corrected it to account for the multiple comparisons ($k = 3$), resulting in a significance level of $p < 0.017$.

RESULTS

VCHP

We explored and characterized a wide variety of compliant disk patterns and properties. The most compliant disk design with a linear response was found to displace 1.42 cm for a 177.9 N applied load. Based on subjective evaluations of lesser compliant disks, the lower compliance bound was set to 0.66 cm of displacement for the same load. A mid-compliance level of 0.94 cm of displacement for a 177.9 N load was also chosen. The three chosen compliance levels, named C1, C2, and C3, corresponded to compliances of 266.2 N/cm, 190.9 N/cm, and 125.2 N/cm, respectively. The VCHP was equipped to emulate a rigid hand rim by pinning the center peg to the housing.

Subjects

Of the 20 subjects recruited, 17 participated in the study, 10 male and 7 female. The three subjects who did not participate cancelled because of schedule conflicts. The average age of the subjects was 37 years ± 12 standard deviation (SD). The average years of wheelchair use was 14 ± 10 SD. Sixteen of the subjects had a spinal cord injury and one had spina bifida. The average subject weighed 60.8 kg ± 16.8 SD. All subjects were able to comfortably complete the protocol without signs of fatigue.

Usability and Acceptance

The results of the usability and acceptance study are given in **Figure 6**. None of the subjects felt that use of the compliant hand rims compromised their ability to maneuver or control the wheelchair. None of the subjects felt C1 was too soft. Twenty-nine percent of the subjects felt the C2 was too soft. Forty-seven percent of the subjects felt the C3 was too soft. And 24 percent of the subjects felt the hand rim could be even softer than the C3. The average weight of the subjects with a tolerance limit of C2 was 79.5 kg ± 26.6 SD; C3, 72.8 kg ± 10.34 SD; and >C3, 69.2 kg ± 14.7 SD.

Push Angle and Timing

The push angle and frequency relationships for each of the hand-rim conditions on the four grades are given in **Figure 7**. Only one hand-rim condition, C1, exhibited a statistical difference from the rigid hand rim (designated by an *). Subjects pushed, on average, an additional 3.5° when using the C1 hand rim on the 2 percent grade than when using the rigid hand rim—a 4.1 percent increase.

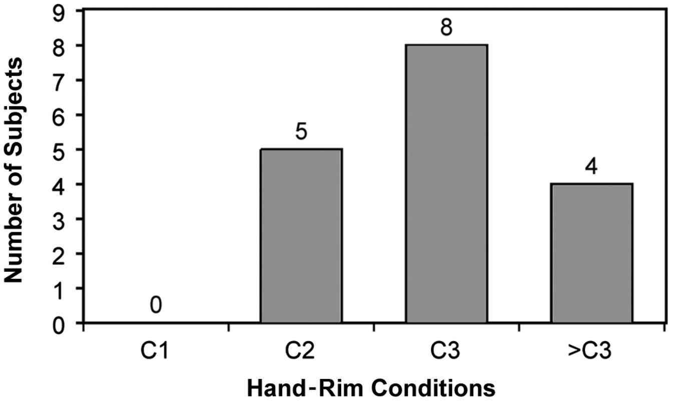

Figure 6.
Subject responses as to when compliance level became too soft.

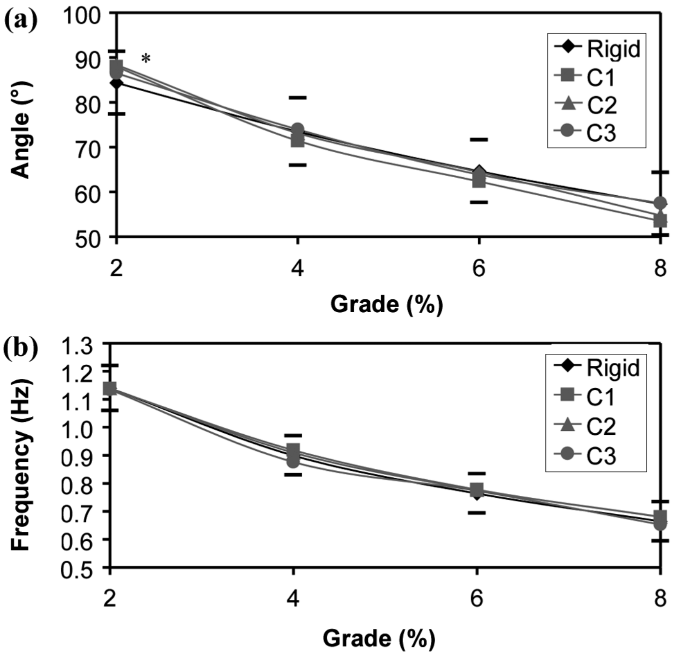

Figure 7.
(a) Push angle and **(b)** push frequency for each hand-rim condition on each of four grades. Standard deviation error bars are given for rigid hand rim. *Statistical difference from rigid hand rim.

Subjects' push frequency decreased from 1.14 Hz on the 2 percent grade to 0.66 Hz on the 8 percent grade when they were using the rigid hand rim.

Push angle, push frequency, and recovery time tended to decrease with increasing grade. Push time tended to increase with increasing grade. The push angle for the rigid hand rim was reduced from 84.4° on the 2 percent grade to 57.5° on the 8 percent grade. The decrease in push angle is likely the result of a more forward trunk and head posture of the subjects on the steeper slopes, required to maintain rearward stability.

The push time and recovery time relationships are given in **Figure 8**. One hand-rim condition was found to be statistically different from the rigid hand rim for one of the grade conditions. The C2 hand rim resulted in a 31.6 percent reduced recovery time on the 8 percent grade compared with the rigid hand rim.

Push time (**Figure 8(a)**) increased from 0.51 s on the 2 percent grade to 1.3 s on the 8 percent grade when the rigid hand rim was used. According to the protocol, the propulsion speed was reduced from 0.94 m/s on the 2 percent grade to 0.22 m/s on the 8 percent grade. The increase in push time is likely related to the increased time allowed by the slower propulsion speed. Recovery time decreased with increasing grade. When subjects used the rigid hand rim, the average recovery time (**Figure 8(b)**) was 0.38 s on the 2 percent grade and reduced by 29 percent to 0.27 s on the 8 percent grade.

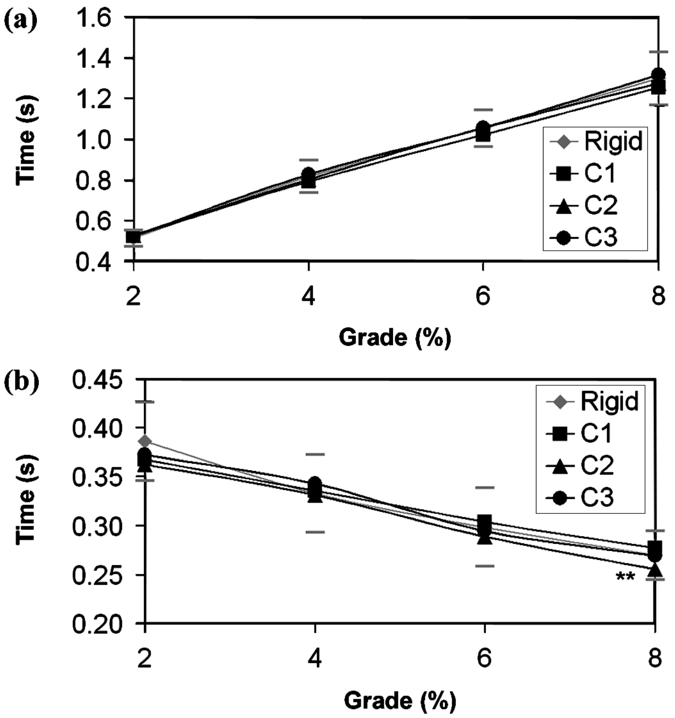

Figure 8.
(a) Push time and **(b)** recovery time for each hand-rim condition on each of four grades. Standard deviation error bars are given for rigid hand rim.

Peak Kinetics and CTF Characteristics

The peak resultant and in-plane resultant force relationships for each of the hand-rim conditions on the four grades are given in **Figure 9**. No statistically significant differences were found between the rigid hand rim and any of the compliant hand-rim conditions. The general trend for all the hand-rim conditions is an increasing peak hand-rim force as the grade is increased. The peak force during propulsion with the rigid hand rim was, on average, 21 percent higher on the 8 percent grade than on the 2 percent grade. The in-plane force values are just slightly less than the resultant force values, indicating that the lateral force component is minimal during propulsion.

The resulting peak wheel moment and estimated CTF for each hand-rim condition on each of the four grades are shown in **Figure 10**. None of the compliant hand rims were found to differ statistically from the rigid hand rim.

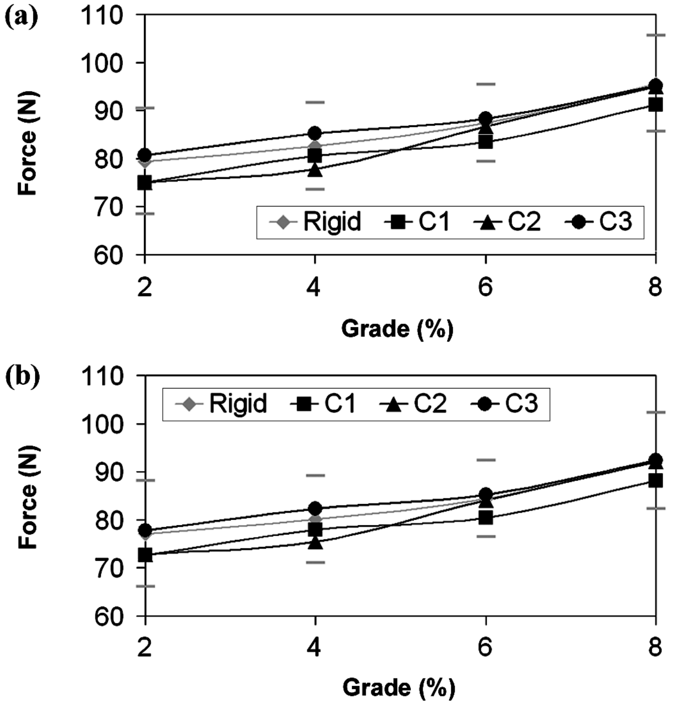

Figure 9.
(a) Peak resultant force and **(b)** peak in-plane resultant force for each hand-rim condition on each of four grades. Standard deviation error bars are given for rigid hand rim. No difference was found to be statistically significant.

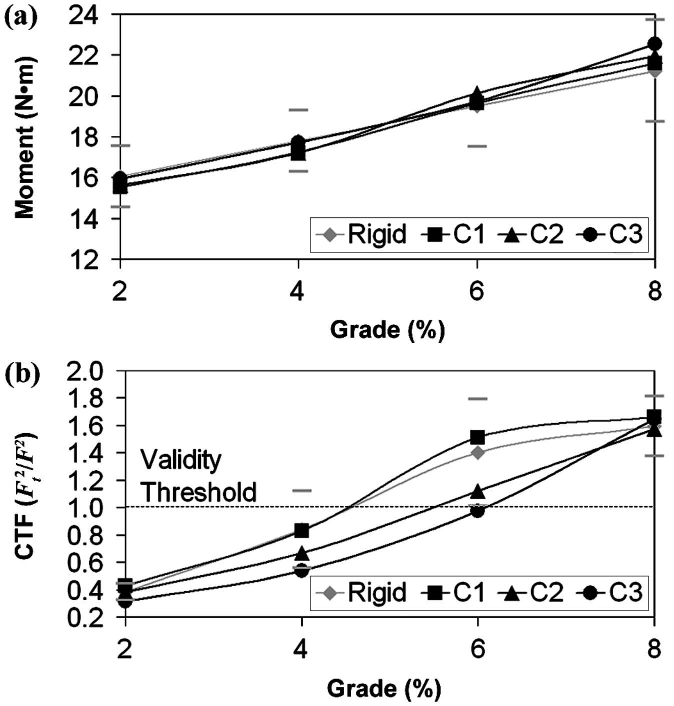

Figure 10.
(a) Peak wheel moment and **(b)** contribution of tangential force (CTF) for each hand-rim condition on each of four grades. Standard deviation error bars are given for rigid hand rim. No difference was found to be statistically significant.

A relationship is clear between increasing grade and increasing wheel moment. Additionally, negligible variation in peak moment exists for any of the compliant hand rims. A 37.5 percent increase in the overall peak moment for the rigid hand rim is seen when the grade is increased from 2 percent to 8 percent. The CTF (**Figure 10(b)**) shows an increasing trend for increasing grades. A validity threshold is shown at a value of 1.0. Since the CTF is defined as the percentage of the applied force in the tangential direction, the value cannot theoretically exceed 100 percent, or 1.0.

Rate of Loading and Impact Attenuation

The pROR of the resultant and in-plane resultant forces for each hand rim on increasing grades are shown in **Figure 11**. The C1 hand rim was found to be statistically lower than the rigid hand rim on the 6 percent and 8 percent grades. C1 was found to reduce pROR by 15.9 percent on the 6 percent grade and by 22.9 percent on the 8 percent grade. The C3 hand rim was found to reduce pROR by 13.7 percent on the 8 percent grade.

The general trend for all the hand-rim conditions is a slight decrease in pROR on the 4 percent grade from the 2 percent grade and then increasing pROR for the 6 percent and 8 percent grades. No appreciable differences in pROR were seen for any of the compliant hand rims on the 2 percent grade. The complaint hand rims begin to appear to differentiate from the rigid hand rim on the 4 percent grade and then continue to spread through to the 8 percent grade. The pROR of the resultant force increased by 18.5 percent from the 2 percent grade to the 8 percent grade, which is comparable with the 21 percent increase in the peak resultant force for the 8 percent grade.

The aROR of the resultant and in-plane resultant force for each hand rim on increasing grades are shown in **Figure 12**. All three compliant hand rims were found to be statistically different than the rigid hand rim on the 2 percent, 4 percent, and 6 percent grades. The most apparent characteristic found in both the graphs is the distinct difference between the rigid hand rim and each of the compliant hand rims. Unlike the pROR, which increased with increasing grade, aROR decreased by 39.7

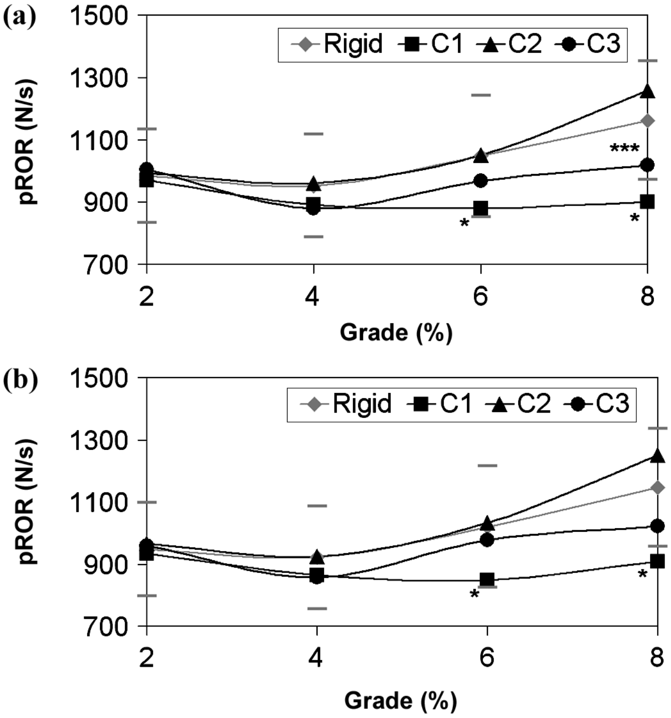

Figure 11.
Peak rate of rise (pROR) for **(a)** resultant and **(b)** in-plane resultant force for each hand-rim condition on each of four grades. Standard deviation error bars given for rigid hand rim. Statistical differences delineated by *C1 and ***C3 = $p < 0.017$.

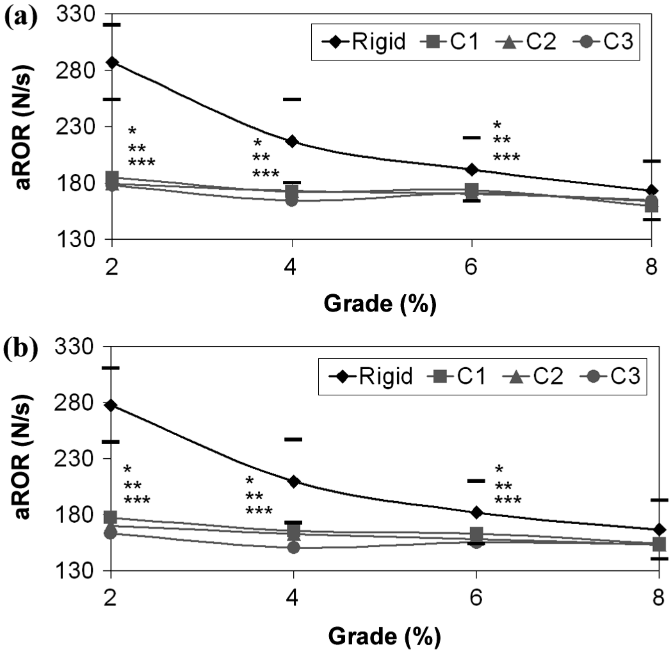

Figure 12.
Average rate of rise (aROR) for **(a)** resultant and **(b)** in-plane resultant force for each hand-rim condition on each of four grades. Standard deviation error bars given for rigid hand rim. Statistical differences delineated by *C1, **C2, and ***C3 = $p < 0.017$.

percent from the 2 percent grade to the 8 percent grade for the rigid hand rim. The aROR for each of the compliant hand rims remained relatively constant across the increasing grades and was consistently less than the rigid hand rim. Since the aROR is sensitive to impact spikes, the clear and statistically significant reduction between the rigid and compliant hand rims was very likely due to impact spike attenuation.

Metabolic Demand

The metabolic demand outcome measures for the rigid and C3 hand rims are given in **Figure 13**. None of the differences between the C3 and the rigid hand rim were found to be statistically significant. Metabolic demand was fairly constant across grade conditions. Power output for grade conditions were found to be 28.06 ± 7.62 W on the 2 percent grade, 23.72 ± 5.94 W on the 4 percent grade, 22.02 ± 6.68 W on the 6 percent grade, and 20.62 ± 5.84 W on the 8 percent grade.

DISCUSSION

Usability and Acceptance

User acceptance of assistive technology is very important and will likely determine its eventual usefulness. The results of this portion of the study suggest that most, if not all, wheelchair users would be tolerant of hand-rim compliance at C1, and approximately 70 percent of users would be tolerant of compliance at the C2 level. Many of the subjects commented that the addition of compliance felt more comfortable and took the “edge” off the pressure in their hand during propulsion. When asked if they would use a compliant hand rim within their tolerance limit, all subjects responded that they would.

We evaluated the relationship between the weight of the user and their compliance tolerance using a Pearson product-moment correlation. We expected that heavier subjects would prefer a lower compliance, since they would typically apply larger forces on the hand rims than a lighter subject. The resulting R^2 value was 0.06, suggesting that such a relationship is unlikely.

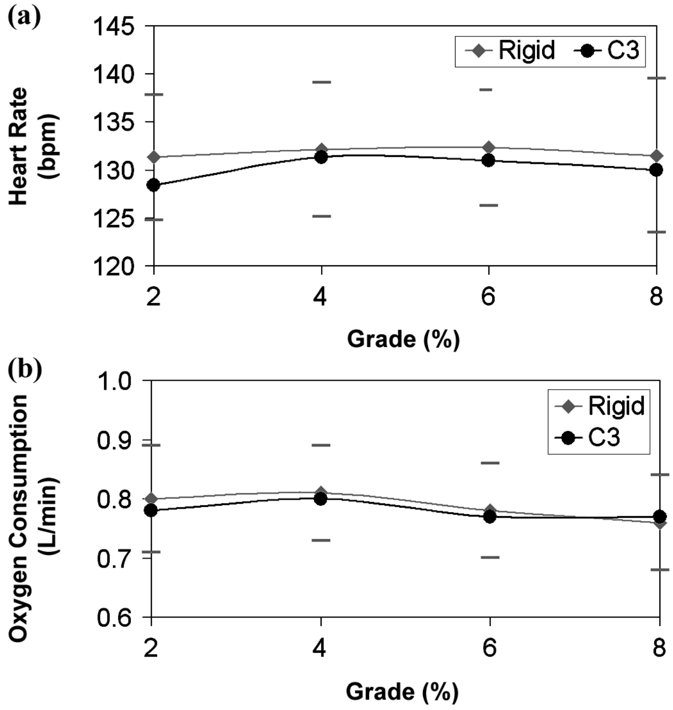

Figure 13.
(a) Heart rate and **(b)** oxygen consumption for rigid and C3 hand-rim conditions on each of four grades. Standard deviation error bars given for rigid hand rim. No difference was found to be statistically significant.

Push Angle and Timing

The results using the compliant hand rims closely followed the pattern found for the rigid hand rim, strongly suggesting that push frequency is not affected by moderate hand-rim compliance. This is an important consideration, because push frequency has been associated with the development of wrist injury and should be kept to a minimum to reduce upper-limb exposure to repetitive loading [13].

Veeger et al. studied propulsion timing and technique on a treadmill at different speeds and grades using five male wheelchair athletes [14]. While the conditions were not exactly the same as those used in this study, one condition combination was similar enough to compare with the results found in the current study. The push angle results between the two studies were very similar. However, the push timing parameters were quite different. Subjects in the Veeger et al. study pushed less often and spent less time pushing and more time coasting than the subjects in our study. Since wheelchair athletes were used in the Veeger et al. study, as opposed to a balanced spectrum of everyday wheelchair users in this study, the differences may have been due to a more aggressive propulsion technique.

Peak Kinetics and CTF Characteristics

While no significant differences were found, peak forces for the compliant hand rims were generally equal to or slightly less than the rigid hand rim. This result might be expected, since the peak force generally occurs well within the push, after the initial impact. Once the compliant hand rim has displaced during impact, it will remain displaced for the rest of the push. The only way the peak reaction force on the wheel can be reduced is by further hand-rim displacement, which requires increasingly larger applied forces to occur.

As previously mentioned, the CTF is defined as the percentage of the applied force aligned in the tangential direction and therefore it cannot theoretically exceed 100 percent, or 1.0. While the compliant hand-rim values were not found to differ significantly from the rigid hand rim, the values of CTF for the rigid hand rim exceed 1.0 for the 6 percent and 8 percent grades. On the 2 percent grade CTF was found to be 0.38 for the rigid hand rim. For similar simulated resistance and speed conditions, Boninger et al. in a study of 34 manual wheelchair users on a dynamometer found the CTF (referred to in that paper as the mechanical effective force, [MEF] to be 0.26 [6]. We believe that the discrepancy between these results is due to the differences in propulsion environments and tolerances on propulsion velocity.

The underlying assumption in the calculation of CTF is that the hand moment is negligible and can be ignored. While researchers have found the net hand moment to be negligible for simulated level propulsion [15–16], the contribution of the hand moment when propelling up an incline on varying grades has not been studied, and hence its limitations have not been identified. Clearly, from the results of this study, the hand moment becomes much more influential on steeper grades and the hand moment is contributing to the moment about the wheel.

Rate of Loading and Impact Attenuation

The primary objective of hand-rim compliance is to reduce impact loading. The pROR is a particularly important metric, since it has been associated with incidence of repetitive stress injuries [6]. In general, the compliant hand rims resulted in an equal to or decreased pROR when compared with the rigid hand rim. The decreased pROR was statistically significant for the C1 hand rim on the 6 percent grade and with the C1 and C3 hand rims on the 8 percent grade. When viewed from an impact physics perspective, the introduction of compliance should consistently reduce the pROR of the reaction force. However, this requires the impact velocity of the arm to be the same when propelling with the various hand rims. From previous studies, we have learned that users may adapt to compliant hand rims by impacting the hand rim with an even greater initial hand velocity [5]. The increased impact velocity may improve propulsion efficiency, or it may simply be a way to compensate for the hand-rim displacement.

The second measure of impact loading, the aROR, was dramatically reduced when subjects were using the compliant hand rims. The aROR is a measure that is sensitive to the presence or absence of an impact spike. A reduced aROR equates to a reduced impact spike. The aROR was reduced by over 30 percent on the 2 percent grade, over 20 percent on the 4 percent grade, and approximately 10 percent on the 6 percent grade for all the compliant hand rims. An example of what a decrease in aROR looks like on a hand-rim force profile is shown in **Figure 14**. One subject generated the force profiles shown while propelling on the 2 percent grade. The force profile in **Figure 14(a)** on the top was generated with the use of the rigid hand rim. The impact spikes are a consistent feature of the profile. **Figure 14(b)** was generated with the use of the C1 hand rim. Notice that the impact spikes are eliminated or substantially reduced. Two individual push profiles of approximately equal force magnitude were isolated from each of the 10 s force profiles and compared (**Figure 14(c)**). This overlay comparison sheds light on the process of impact attenuation. The transient impact spike found with the use of the rigid hand rim has been mechanically filtered by the C1 compliant hand rim. Evidence of the impact spike still exists in the C1 profile; however, it is subtler.

Metabolic Demand

Neither HR nor VO_2 were found to differ between the compliant and rigid hand-rim conditions. In general, with the exception of the 8 percent grade, the results suggest that if a difference did exist, use of the C3 hand rim would reduce metabolic demand relative to the rigid hand rim rather than increase it. These results were found to be consistent with those predicted by our dynamic propulsion model for similar levels of compliance [17].

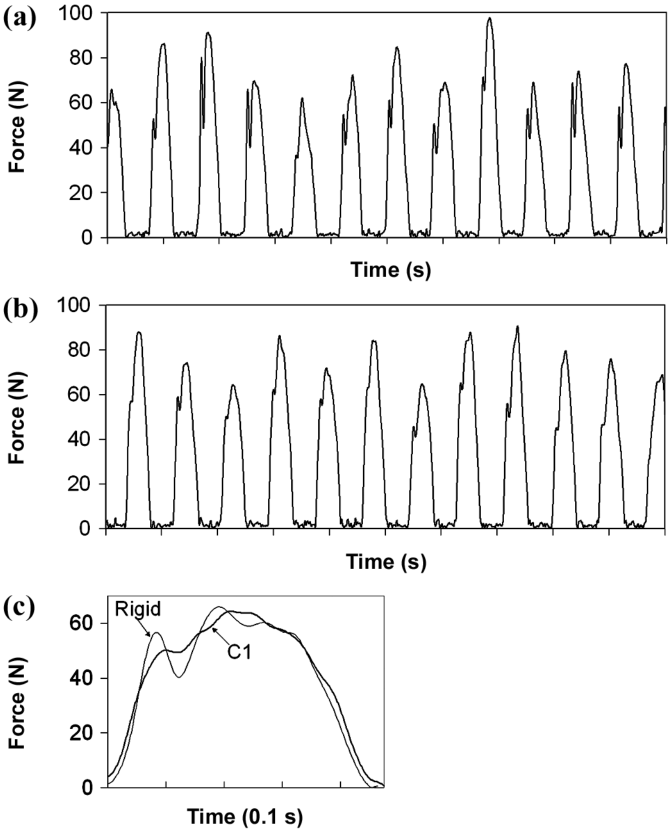

Figure 14.
Comparison of resultant hand-rim force profile for one subject using **(a)** rigid (note impact spikes) and **(b)** C1 hand rims (noticeably reduced impact spikes). **(c)** Single-push overlay comparison.

While metabolic measures did not vary appreciably across grades, the power output did. We had hoped that the power output would be nearly constant across grade conditions. Our primary reason for maintaining a nearly constant power output was to minimize the time required to reach metabolic steady state on each grade. The average power output was greatest for the 2 percent grade and decreased with increasing grade. If power output had increased with increasing grade, the resulting metabolic metrics may have been presteady state. However, since power output decreased with increasing grade, the problem was not reaching steady state, but recovering as the power output dropped to the next level. The expected effect of the decreasing power stages is an averaging of the current and previous grade results, effectively applying a moving average to the results. Future investigations should either ensure a constant power output or test the varying grade conditions separately.

Generally Optimal Compliance

A generally optimal compliance can be defined as one in which user acceptance is maximized, impact loading is minimized, and no adverse side effects occur. C1 was found to be acceptable by 100 percent of the study participants. It outperformed the C2 and C3 hand rims in reducing the pROR and achieved comparable performance in reducing the aROR. No adverse side effects were found for any of the compliant hand rims. As a result, the C1 hand rim is believed to represent a generally optimal level of compliance.

Limitations

While a generally optimal compliance was determined with which impact was attenuated and user acceptance was preserved, an absolutely optimal compliance has not been determined. A lighter wheelchair user likely will not require the same level of compliance as a heavier user. The research approach of this study could be used to further tune the level of compliance for specific users.

The nature of the impact spike on the hand-rim force curve is still not well understood. Although the impact spikes appear as spikes when viewed from a distance, when we zoom in on a single push (as shown in **Figure 14**), the spikes are far more rounded. In addition, the location of the impact peak is well within the push progression. These qualitative characteristics suggest that the impact spike may not be solely related to the impact of the hand, but rather a combination of an impact spike and an impulse transient; or, in other words, part of what we call the impact spike may simply be a discontinuity in the push. If the case is that some portion of the impact spike is a useful attribute of propulsion, then the level of compliance should be set such that it only attenuates the impact.

CONCLUSION

A variable-compliance wheelchair hand rim was evaluated for its potential to reduce impact loading during propulsion. Reducing impact loading is important, since it has been associated with the incidence of repetitive stress injuries [6]. In addition to impact loading, other effects, including user acceptance, push frequency, peak force, and metabolic demand, were also assessed. A generally optimal compliance level (C1) was determined whereby impact was reduced, user acceptance was maximized, and no adverse side effects were found. Since the testing protocol used in this study included a broad range of real-world usage scenarios, performance of a compliant hand rim is expected to be the same in the field as it was found to be in the laboratory environment. This study has shown that low-impact wheelchair propulsion is both achievable and acceptable to users. We hope that the results of this project will lead to a hand-rim design that will prevent or delay the development of upper-limb injuries.

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