Published in final edited form as:

J Electromyogr Kinesiol. 2009 October ; 19(5): 942–947. doi:10.1016/j.jelekin.2008.05.001.

WHEELCHAIR PROPULSION DEMANDS DURING OUTDOOR COMMUNITY AMBULATION

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Abstract

Objective—Quantify manual wheelchair propulsion effort during outdoor community ambulation.

Design—Case series

Subjects—Thirteen individuals (12 with SCI, 1 with spina bifida) who were experienced manual wheelchair users and had no current upper extremity injury or pain complaints.

Methods—Measurements were obtained from instrumented wheelchair rims during steady-state propulsion as subjects traversed outdoor concrete sidewalk terrain that included smooth level, aggregate level, and a ramp with a smooth surface. Propulsion effort was assessed using the average propulsion moment, average instantaneous power, and work for both upper extremities.

Results—Propulsion effort, captured by the propulsion moment, work and power, varied across ground conditions ($p < 0.001$). Propulsion effort was greater as the rolling resistance increased (ie., smooth versus aggregate surfaces) and as the inclination angle progressed from level to inclined surfaces. There were no side-to-side differences across ground conditions for the propulsion moment or work. Power generation was significantly greater on the dominant compared to the non-dominant extremity during the more challenging aggregate surface and ramp conditions.

Conclusions—Propulsion effort varies with demands imposed by different ground conditions. Quantification of wheelchair propulsion demands provides rehabilitations specialists with objective information to guide treatment of patients adapting to manual wheelchair use.

Keywords

wheelchair; propulsion; mobility; rehabilitation; biomechanics

INTRODUCTION

There are approximately 1 ½ million individuals in the United States who utilize manual wheelchairs for community mobility (16). Wheelchair propulsion capacity is an important factor in achieving the highest level of function possible and enabling independent living (8).

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Wheelchair propulsion is, however, highly inefficient and has been associated with high physical strain during daily life (15). Manual wheelchair users are consequently susceptible to fatigue that may impair their mobility, and the ability to complete basic activities of daily living.

Achieving an optimal level of wheelchair propulsion capacity is one of the rehabilitation goals when treating an individual transitioning to manual wheelchair use. Two strategies to achieve this goal include endurance training (23) and propulsion practice (12). Both forms of training may improve wheelchair capacity secondary to greater wheeling efficiency. Several physiological parameters, including peak oxygen uptake, heart rate, peak power output and gross mechanical efficiency may be used to assess wheelchair propulsion efficiency (11). Each of these measures has been shown to improve over the course of early rehabilitation of patients with spinal cord injury (8-10,12). Physiological improvement does not, however, infer a patient's readiness for community wheelchair propulsion. Quantifying wheelchair propulsion effort during real world conditions may assist in the development of rehabilitation programs that prepare patients for ambulation within their natural environment.

Advances in technology have permitted biomechanical investigations of wheelchair propulsion in conditions that capture real-world demands. Few investigations, however, have been performed outside of the laboratory setting. Koontz et al (17) evaluated right-side propulsion kinetics of eleven manual wheelchair users during the initial start-up of wheelchair motion over a variety of indoor and outdoor terrain. The authors reported resultant forces at start-up on each surface were higher than those applied during steady state propulsion on a reference surface. Furthermore, there were significant differences in start-up propulsion biomechanics between the different surfaces. Hurd et al (14) evaluated upper extremity propulsion symmetry of twelve manual wheelchair users over indoor and outdoor terrain, and noted the greatest asymmetry was present during outdoor ambulation. Collectively, these results highlight the importance of evaluating wheelchair propulsion over a range of surfaces. It is unknown, however, what effort is required for manual wheelchair users to traverse variable terrain during the steady-state condition of wheelchair propulsion, the state during which most of community wheelchair ambulation is spent. It is also unknown what influence arm dominance may have on propulsion effort across terrain of varying levels of difficulty.

There is a need to further understand the demands of manual wheelchair propulsion during community ambulation. Such information would advance our knowledge of wheelchair propulsion biomechanics, assist in the development of appropriate therapeutic exercise programs, and provide rehabilitation specialists with objective information to assist in determining whether patients are prepared to return to their home environment. Therefore, the purpose of this study was to evaluate bilateral upper extremity manual wheelchair propulsion demands during routine outdoor community ambulation tasks. We hypothesized more challenging terrain, including aggregate and ramped sidewalk surfaces would require more effort to traverse than smooth, level sidewalk. We further hypothesized the dominant upper extremity contribution to propulsion effort during more challenging conditions would be greater than the non-dominant extremity.

METHODS

Subjects

Thirteen subjects were recruited for study participation. The study sample was comprised of 11 males and 2 females who were on average 43 years old (range=29 to 56 years) with 17 years (SD=9) of experience as a manual wheelchair user (range=1 to 29 years) (Table 1). Twelve of the subjects were wheelchair users secondary to spinal cord injury, and one secondary to spina bifida. All subjects with a spinal cord injury had complete lesions ranging from T2 to L1 (Table 1) sustained as a result of trauma.

Individuals were eligible for the study if they had a minimum of 6 months experience as a manual wheelchair user and had no current upper extremity injury or pain. Exclusion criteria included employment that involved repetitive overhead activities or identification of limited upper extremity motion or muscle strength during physical examination. All participants provided written informed consent approved by the Mayo Clinic Institution Review Board before testing procedures were initiated.

Data Collection

Bilateral kinetic data were collected with two instrumented SmartWheel (Three Rivers Holdings, Inc., Mesa, AZ) rims which were secured to the subject's wheelchair. The SmartWheel is a commercially available, wireless, force-and torque-sensing pushrim that may be used to examine three-dimensional forces, moments, and temporal-spatial characteristics of manual wheelchair propulsion. Application of the SmartWheel rims did not alter individual wheelchair settings. Three-dimensional forces (F_x , F_y , F_z) and moments (M_x , M_y , M_z) were sampled at 240 samples per second during the push phase of wheelchair propulsion for each stroke and subsequently low-pass filtered with an eighth order zero-lag digital Butterworth filter. The SmartWheel coordinate system is defined with x representing forward progression, y representing the axis perpendicular to the floor pointed superiorly, and z pointing out of the wheel along the axle. The precision (2 N) and resolution (0.2 N) of the SmartWheel rims have been documented (6).

The testing was conducted while subjects propelled their wheelchair over community sidewalk terrain. Three different concrete sidewalk conditions were evaluated, including: a) smooth level, b) aggregate (i.e., textured surface) level, and c) 3° ramp (1:19 rise to run) with a smooth surface. Each task was approximately 30 m in length and was completed at the subject's self-selected pace.

Data Management

Three consecutive push cycles from the steady propulsion state within each condition were identified for analysis, with the onset of push defined as $M_z > 0$ and off as $M_z = 0$ (19). Push cycles were identified with a custom computer-algorithm (MatLab, The MathWorks, Inc., Natick, Massachusetts) and visual confirmation, and defined as the propulsion moment (M_z) of the dominant extremity with the smallest average absolute deviation from the median propulsion moment:

$$\frac{1}{n} \sum_{i=1}^n |x_i - \tilde{x}|$$

where

x_i = peak moment for a single push cycle;

$\tilde{x}$ = median peak M_z for entire trial;

and $n = 3$.

Data for the three consecutive push cycles were averaged and the average for each extremity was used for analysis. Upper extremity limb dominance was based on subject self-report. There were no instances in which a subject reported ambidextrousness.

Statistical Analysis

To evaluate propulsion effort the average propulsion moment (M_z), average instantaneous power (Power), and work (Work), were used for analysis (Table 2). Each dependent variable of interest was evaluated with a 2-way ANOVA with 2 repeated factors (condition and extremity). When significant main effects were found for ground conditions, post-hoc tests (Student-Newman-Keuls) were conducted to determine at which level the differences were occurring. Additionally, paired t-tests were performed when a main effect for extremity was identified to evaluate side-to-side differences within each ground condition. Statistical significance was established at $p < 0.05$, and all analyses were performed using commercially available software (SAS 9.1, SAS Institute Inc., Cary, NC).

RESULTS

There was a main effect of ground condition for M_z ($p < 0.001$) and Work ($p < 0.001$). Post-hoc analysis indicated the average propulsion moment (M_z) (Fig. 1A) was significantly different across all ground conditions ($p \leq 0.001$), increasing from smooth level propulsion (Ground Condition Mean, Standard Deviation) (8.5, 2.5), to aggregate level (11.3, 3.3), and ramp conditions (15.2, 3.8). Work (Fig. 1B) was also different across all ground conditions ($p \leq 0.001$), and increased significantly from smooth level propulsion (13.6, 5.4) to aggregate level (18.6, 7.2) and ramp conditions (24.7, 8.1). There was no main effect of extremity for M_z ($p = 0.117$) or Work ($p = 0.121$) across conditions.

Analysis of the propulsion power revealed a main effect of both extremity ($p = 0.041$) and condition ($p = .001$). Across conditions, the dominant extremity propulsion power during smooth level propulsion (48.3, 17.6) was significantly lower than both aggregate level (68.9, 24.1) ($p = 0.007$) and ramp (80.6, 22.1) ($p < 0.001$) conditions. Non-dominant extremity propulsion power across conditions was significantly greater during the ramp condition (65.6, 16.3) than both smooth level (55.6, 22.4) ($p = 0.030$) and aggregate level (55.3, 21.4) ($p = 0.026$) conditions. Within conditions (Fig. 1C), significant side-to-side differences were identified during aggregate level ($p = 0.007$) propulsion, and a trend towards statistical significance during the ramp ($p = 0.059$) condition. There were no side-to-side differences identified within the smooth level ground condition ($p = 0.1812$).

DISCUSSION

The results from this study indicate wheelchair propulsion effort, captured by the propulsion moment, work and power, is variable during outdoor community sidewalk ambulation. Consistent with our hypothesis, propulsion effort was greater as the rolling resistance increased (ie., smooth versus aggregate surfaces) and as the inclination angle progressed from level to inclined surfaces. Although these results are not surprising, this is the first investigation to quantify the effort required to traverse different terrain encountered during outdoor community wheelchair ambulation.

Our hypothesis that the dominant upper extremity contribution to propulsion effort during more challenging conditions would be greater than the non-dominant extremity was partially supported by the data. Bilateral upper extremity contribution to wheelchair propulsion effort did not vary for either the propulsion moment or work performed. The dominant and non-dominant extremities contributed equally to the effort required to propel the wheelchair across the varying terrain as measured by these variables of interest. There was, however, a side-to-side difference in power generation across conditions. The dominant upper extremity power generation was greater than the non-dominant extremity during the more challenging aggregate surface and ramp conditions.

Our findings are consistent with previous work that has reported wheelchair propulsion biomechanics change in response to more challenging wheeling conditions. Laboratory investigations have revealed shoulder joint forces and moments (5,18), and muscle demands (24) are greater during inclined versus level propulsion. Wheelchair users also change their stroke patterns based on surface inclination angle (22). Yet laboratory conditions are limited to ergometer and level tile terrain, and are constrained in their ability to manipulate rolling resistance, propulsion distance, and the inertial effects of propulsion. Thus, laboratory investigations may not accurately capture the wheeling demands manual wheelchair users encounter on a daily basis. The environment in which an individual functions may contribute to the high prevalence of upper extremity pain in manual wheelchair users (21). It is therefore necessary to extend our knowledge of wheelchair propulsion biomechanics in a user's natural surroundings.

Limited work evaluating community wheelchair propulsion has been performed. Koontz et al (17) reported start up wheeling demands were significantly greater than steady-state propulsion across a smooth, level surface. Koontz et al (17) also reported wheeling start-up demands were different across indoor and outdoor terrain. These results, however, were limited to an interval that represents a limited period of wheelchair ambulation: the start-up of wheeling is a period that is limited to the first 3-4 strokes of a given task to initiate motion. Conversely, a significant amount of community wheelchair propulsion time is spent in a steady-state condition (*i.e.*, strokes that are statistically similar). Both intervals of wheelchair propulsion have the potential to impact the development of upper extremity injury among manual wheelchair users. Therefore, we suggest future investigations capture all intervals of wheeling to gain a thorough understanding of how wheelchair propulsion may impact the development of upper extremity injury among this population.

The influence of arm dominance on propulsion biomechanics in manual wheelchair users is poorly understood. Similar to our results, van der Woude et al (25) reported differences in left and right side power production during ergometer testing of elite wheelchair athletes. It was suggested the differences may have been a consequence of hand dominance. Boninger et al (4) and Hurd et al (14) also identified side-to-side differences during wheelchair propulsion, and suggested inaccurate interpretations of propulsion biomechanics may result if the left- and right-sides are assumed to be identical. Conversely, Goosey and Campbell (13) reported no differences in elbow movement patterns during wheelchair propulsion of trained racers. This investigation was limited to a small sample size ($N=7$), though, and may have been underpowered. Alternatively, asymmetry need not be present for all aspects of wheelchair propulsion. Further insight to side-to-side differences during wheelchair propulsion is limited, though, as other investigators have elected to average data for both limbs (1-3) or select only one limb for analysis (20). Results from the current investigation provide support for study designs that evaluate both extremities to gain further insight to the biomechanics of wheelchair propulsion.

For manual wheelchair users, both extremities are at high risk for pain and injury as a consequence of the bilateral demands of propulsion and weight relief. Curtis et al (7) studied the prevalence and intensity of shoulder pain during functional activities in manual wheelchair users, and reported the majority of manual wheelchair users with paraplegia (34%) experienced bilateral upper extremity pain. Although a large number of subjects stated they had pain in only one arm (24%) (7), the incidence of upper extremity pain and injury in manual wheelchair users has not been characterized by limb dominance. Our results indicate there is greater propulsion power generation by the dominant extremity in response to challenging conditions, while the non-dominant extremity does not adapt to terrain demands. These results suggest repeated exposure of high-demand propulsion activities may place the dominant upper extremity at increased risk for injury. Future investigations that evaluate the influence of arm

dominance on injury patterns are necessary, and may contribute to the development of upper extremity injury prevention programs for manual wheelchair users.

Results from this investigation may be used by rehabilitation specialists to individualize the treatment plan for patients transitioning to manual wheelchair ambulation. Specifically, the demands of wheelchair propulsion during outdoor community ambulation have been quantified. By estimating the distances and type of terrain an individual will encounter in their habitual environment, the work volume and average power generation may be calculated. Therapists may then set performance goals in terms of these parameters during wheelchair or upper extremity ergometer training. Furthermore, the rehabilitation team may determine that patients who have not met performance goals at the time of discharge require assistance (ie., caregiver assistance or powered chairs) during community ambulation.

There are limitations to this study. We evaluated propulsion biomechanics during real-world, outdoor conditions. This study design effectively captured an environment manual wheelchair users may encounter on a daily basis. Because testing was conducted outside of the laboratory, however, we were unable to utilize a motion capture system to collect kinematic data. Consequently, trunk and upper extremity motions that may have contributed to alterations in propulsion effort across terrain conditions are unknown. Another potential limitation of this investigation was a study cohort that included subjects with variable level spinal cord lesions, and one individual with spina bifida. Using a diverse sample provides insight to propulsion biomechanics for a spectrum of manual wheelchair users. Propulsion effort may, however, vary by lesion level. Future work that includes larger study samples across spinal cord injury levels may advance our ability to provide individualized treatment and outcome expectations for this population of patients. Finally, we did not perform a quantitative physical examination to identify factors other than terrain that may have contributed to changes in propulsion effort across outdoor terrain. Future investigations that assess physical characteristics such as muscle strength, cardiovascular endurance, and trunk control may provide further insight to factors that influence propulsion biomechanics and enhance rehabilitation program design for the manual wheelchair user.

CONCLUSIONS

Effort during outdoor community wheelchair ambulation varies with demands imposed by different ground conditions. Greater power generation production from the dominant limb occurs during more challenging conditions. These results provide insight to wheelchair propulsion biomechanics. Furthermore, quantification of wheelchair propulsion demands provides rehabilitation specialists with objective information to guide treatment of patients adapting to manual wheelchair use.

ACKNOWLEDGEMENTS

The authors acknowledge Kathie Bernhardt and Diana Hansen for their assistance with subject testing and data processing. All aspects of this study were funded by a grant from the National Institutes of Health (R01HD48781).

Biography

Dr. Hurd is a post-doctoral research fellow in the Motion Analysis Laboratory, Department of Orthopaedics at the Mayo Clinic in Rochester, MN. She received her undergraduate degree (physical therapy) from the University of Missouri-Columbia, and both master and doctoral degrees (biomechanics and movement science) from the University of Delaware. Dr. Hurd is a physical therapy board certified sports specialist. Her research emphasis is neuromuscular contributions to joint stability, and clinically she specializes in sports injuries to the shoulder, knee, and elbow.

Melissa M.B. Morrow is a doctoral student in the Mayo Graduate School at Mayo Clinic. She received her B.S.E. in Biomedical Engineering at Tulane University in 2003. Her doctoral research is focused on the modeling of shoulder biomechanics during wheelchair propulsion.

BIOSKETCH**Kenton R. Kaufman, Ph.D., P.E.**

Kenton Kaufman is the Director of the Biomechanics Laboratory, Professor of Bioengineering, and Consultant in the Departments of Orthopedic Surgery, Physiology and Biomedical Engineering at the Mayo Clinic. He is a registered professional engineer. He received his Ph.D. degree in biomechanical engineering from North Dakota State University in 1988. Dr. Kaufman's research focuses on the biomechanics of human movement. He currently holds several grants from NIH, with projects aimed at improving the mobility of disabled individuals.

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Figure 1 (A-C).

Mean (thick bars) and standard deviation (thin bars) for dominant (D) and non-dominant (ND) extremities for Propulsion Moment (A), Work (B), and Power (C). * = Significant differences ($p < 0.05$).

Figure 1A: Propulsion moment was significantly different across all conditions.

Figure 1B: Work was significantly different across all conditions.

Figure 1C: A side-to-side difference in propulsion power was present during the aggregate level concrete condition, with a trend towards significance during the ramp condition.

Table 1
Subject Characteristics

Subject	Gender	Age (years)	Height (cm)	Weight (kg)	Arm Dominance	Physical Disability	SCI Level	Years as Wheelchair User
1	M	45	178	79	R	SCI	T11	24
2	F	42	163	61	L	SCI	T12	14
3	M	44	183	86	R	SCI	T10	11
4	M	42	175	67	R	SCI	L1	16
5	M	45	180	61	R	SCI	T10	18
6	M	45	170	80	L	SCI	T4	22
7	M	56	170	82	R	SCI	T12	22
8	M	46	180	94	R	SCI	T5	29
9	M	29	152	61	R	SB	NA	29
10	M	42	175	75	R	SCI	T10	5
11	M	35	185	136	R	SCI	L1	1
12	M	45	186	114	R	SCI	T10	26
13	F	40	163	66	L	SCI	T7	7

M=Male
F=Female
R=Right
L=Left
SCI=Spinal Cord Injury
SB=Spina Bifida

Table 2

Variable calculation

<u>Variable</u>	<u>Calculation</u>
Average Propulsion Moment (M_z)	Direct SmartWheel output (Nm)
Work (<i>Work</i>)	$\int M_z d\theta$ (<i>joules</i>)
Average Instantaneous Power (<i>Power</i>)	$\omega * M_z$ (<i>watts</i>)

ω =Angular velocity

$d\theta$ =Angular distance