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Influence of Varying Level Terrain on Wheelchair Propulsion Biomechanics

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Abstract

Objective—To evaluate manual wheelchair propulsion across level ground conditions that are encountered during everyday life.

Design—Subjects included 14 individuals (13 with spinal cord injury [SCI], 1 with spina bifida) who were experienced manual wheelchair users and had no current upper extremity injury or pain complaints. Subjects propelled their wheelchairs at a self-selected speed across four different level ground conditions, including smooth and aggregate concrete and tile and carpet flooring. Temporal and kinetic measurements were obtained bilaterally from instrumented wheelchair rims during the steady-state phase of propulsion.

Results—There were no side-to-side differences for any of the temporal or kinetic variables. Propulsion velocity and pushrim contact time were consistent across ground conditions. Propulsion frequency was significantly greater during both concrete conditions than either tile or carpet ground conditions. Forces and moments were greatest during the aggregate concrete ground condition and lowest during propulsion across tile flooring.

Conclusions—The rolling resistance of level surface terrain significantly impacts wheelchair propulsion biomechanics. Identification of environmental conditions that may contribute to upper extremity pathology is a step toward injury prevention and maintenance of functional abilities for the manual wheelchair user. These results may be used to assist with home and community terrain design to minimize the demands associated with wheelchair propulsion.

Keywords

Wheelchair; Mobility; Rehabilitation

More than 1.5 million individuals in the United States use manual wheelchairs for community mobility.¹ This mode of ambulation places significant demand on the upper extremities secondary to the forceful, repetitive nature of wheelchair propulsion. Consequently, both upper extremities are at risk for overuse pathology. Among spinal cord injured individuals who are manual wheelchair users, the shoulder is the most common injury site. The prevalence of shoulder pain has been reported between 31 and 73% for this population.^{2–5} Neither surgical⁶ nor nonoperative⁷ treatment of shoulder injuries in persons with spinal cord injury reliably restores premorbid function. The treatment ineffectiveness

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may be explained, in part, by the fact that primary contributing factors to upper limb pain including wheelchair propulsion cannot be avoided.⁷ Injury prevention may, therefore, be a more effective strategy to address the pain and compromised daily function frequently encountered by manual wheelchair users.

Investigation of wheelchair propulsion biomechanics is one mechanism to gain insight to factors that may contribute to upper extremity pathology.⁸ Based on the results of their multicenter trial, Boninger et al.⁹ identified propulsion cadence and magnitude of force as risk factors for upper extremity injury in manual wheelchair users. The authors suggested altering propulsion recovery patterns, using the lightest wheelchair possible, and limiting patient weight gain as injury prevention strategies.⁹ These studies were performed, however, while subjects were secured to a wheelchair dynamometer that simulated propulsion over smooth, level tile flooring. The impact of environment on wheeling biomechanics and injury risk were not evaluated.

Few investigators have evaluated wheelchair propulsion outside of the laboratory setting. Koontz et al.¹⁰ measured right upper extremity propulsion kinetics as subjects traversed terrain that included grass, concrete, carpet, tile, wood, and ramped surfaces. The investigators reported kinetic values during the start-up phase of wheeling were significantly different across ground conditions, and when compared with steady-state propulsion across smooth, level concrete. Temporal-distance differences were also identified during ramp and grass terrain propulsion compared with the other ground conditions. Koontz et al.¹⁰ stated that these results highlight the importance of evaluating wheelchair propulsion over a range of surfaces. The investigation was limited, however, to an analysis of propulsion technique for only one extremity during the start-up phase of wheeling. A bilateral upper extremity analysis during the steady-state interval of wheeling would further elucidate the impact of terrain on wheelchair propulsion patterns.

Determining the impact of level wheeling terrain on propulsion biomechanics may contribute to additional injury prevention strategies for manual wheelchair users. Therefore, the purpose of this study was to evaluate manual wheelchair propulsion across ground conditions that are encountered during everyday life. Using instrumented wheelchair rims, we evaluated bilateral temporal and kinetic characteristics of wheelchair propulsion as the subject traversed level aggregate concrete, smooth concrete, carpet, and tile surfaces. We hypothesized propulsion forces, moments, and contact time would be greater, and velocity and cadence lower during propulsion across uneven terrain (i.e., aggregate concrete) compared with smooth terrain (tile flooring), and that kinetic and temporal values measured during carpet and smooth concrete ground conditions would be intermediate to aggregate concrete and tile terrain. Side-to-side differences between extremities have included greater power production from the dominant limb during manual wheelchair propulsion across outdoor terrain.¹¹ Therefore, we also hypothesized there would be significant differences between extremities for kinetic variables, with forces and moments measured for the dominant upper extremity to be significantly higher than the nondominant extremity.

METHODS

Subjects

Fourteen subjects between the ages of 18 and 65 were recruited for study participation. Study inclusion criteria included a minimum of 6 mos experience as a manual wheelchair user, and no current upper extremity injury or pain. Individuals were excluded from participation if their occupation involved repetitive overhead activities or limited upper extremity motion or muscle strength was identified during physical examination. All

participants provided written informed consent approved by the Mayo Clinic Institutional Review Board before testing procedures were initiated.

Data Collection

Two SmartWheel rims (Three Rivers Holdings, Inc., Mesa, AZ) were attached to the subject's wheelchair before testing. All subjects used either ultralightweight or lightweight manual wheelchairs, and application of the SmartWheel rims did not alter individual wheelchair settings. The SmartWheel is a commercially available, wireless, force- and torque-sensing pushrim that may be used to examine three-dimensional forces (F_x , F_y , F_z), moments (M_x , M_y , M_z), and temporal-spatial characteristics of manual wheelchair propulsion. 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.¹²

All testing entailed manual wheelchair propulsion over level terrain. Ground conditions included smooth concrete, aggregate concrete, low-pile carpet, and tile surfaces. Smooth and aggregate concrete propulsion tasks were performed over outdoor community sidewalk sections each approximately 30 m in length. The level carpet and tile tasks were located indoors, and were both 10 m long. Subjects performed one trial each of the outdoor level concrete tasks, and three trials each for the indoor carpet and tile conditions. All activities were performed at the subject's self-selected pace.

Data Management

Bilateral kinetic data collected from the SmartWheel rims were sampled at 240 Hz and subsequently low-pass filtered with an eighth order zero-lag digital Butterworth filter.¹² Kinetic data were normalized to subject mass and height to facilitate between-subject comparisons. All variables of interest were evaluated during the push phase of wheelchair propulsion for each stroke. Three consecutive, representative push cycles from the steady propulsion state within each propulsion task were identified for analysis, with the onset of push defined as $M_z > 0$ and $M_z = 0$ as off.¹³ Selection criteria were 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 $n = 3$.

Push cycles of interest were identified with a custom computer-algorithm (MatLab, The Math-Works, Inc., Natick, MA) with visual confirmation. Data for the three consecutive push cycles were averaged, and the average for each extremity was used for analysis. When multiple trials were performed for a given task, the trials were averaged for analysis.

Statistical Analysis

Kinetic and temporal-spatial variables were identified as variables of interest to evaluate manual wheelchair propulsion (Table 1). Each dependent variable was evaluated with a two-

way analysis of variance with two repeated factors (ground condition and extremity). When significant main effects were identified, post hoc tests (Student-Newman-Keuls) were conducted to determine at which level the differences were occurring. 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

Subjects were on average 43 yrs old (range = 29–56 yrs) and had an average of 16 yrs (SD = 9) of experience as a manual wheelchair user (range = 1–29 yrs) (Table 2). The 14 subjects comprising the study sample included 12 men and 2 women. Thirteen of the subjects were wheelchair users secondary to spinal cord injury, and one was secondary to spina bifida.

There were no side-to-side differences for any of the temporal (velocity, $P = 0.307$; contact, $P = 0.112$; push frequency, $P = 0.229$) or kinetic (propulsion moment, $P = 0.475$; total force, $P = 0.194$; tangential force, $P = 0.707$; radial force, $P = 0.127$) variables (Table 3). The dominant and nondominant extremities were, therefore, combined for statistical analysis of the variables of interest across ground conditions.

Among the temporal variables only push frequency was significantly different across ground conditions ($P = 0.045$). Post hoc analysis indicated push frequency during both aggregate and smooth sidewalk conditions was significantly greater than carpet and tile conditions (Fig. 1C). There were no differences across ground conditions for either propulsion velocity ($P = 0.159$) (Fig. 1A) or contact time ($P = 0.154$) (Fig. 1B).

All kinetic variables were significantly different across ground conditions (propulsion moment, $P < 0.001$; total force, $P < 0.001$; tangential force, $P < 0.001$; radial force, $P < 0.001$). In each instance, the moment and forces measured during aggregate concrete wheelchair propulsion were significantly greater than smooth concrete, carpet, and tile ground conditions (Fig. 2A–D). The propulsion moment and forces were also significantly greater during concrete and carpet ground condition than the tile condition (Fig. 2A–D).

DISCUSSION

The results of this investigation provide insight into the impact of real-world terrain on wheelchair propulsion biomechanics. As we predicted, propulsion forces and moments varied across terrain. Kinetic values were highest during propulsion across aggregate concrete, ranging from 37 to 50% greater than propulsion across the tiled floor surface and from 20 to 25% greater than the smooth concrete and carpeted surfaces. Temporal characteristics of wheelchair propulsion across varying terrain were in partial agreement with our hypothesis. We expected propulsion cadence to be significantly higher during aggregate concrete vs. tile ground conditions. Inconsistent with our hypothesis, however, wheelchair velocity and rim contact time were consistent across each ground condition. We were also incorrect in anticipating significant differences in wheelchair propulsion based on arm dominance, as there were no side-to-side differences for any kinetic or temporal variables.

As ground conditions become more challenging, manual wheelchair users must push with adequate force to overcome the demands of the environment. Significantly, higher pushrim forces and moments have been reported during wheelchair propulsion on inclined (8%)¹⁴ and cross-sloped (3 degrees and 6 degrees)¹⁵ dynamometer surfaces compared with level propulsion. Unlike the current investigation, these studies evaluated the influence of gravity (i.e., surface angle) on propulsion biomechanics. In our study, surface angle, and subject and

wheelchair weight were constant across conditions, and self-selected wheelchair velocity did not change as a consequence of terrain. The differences in propulsion biomechanics we measured may, therefore, be attributed to the rolling resistance created by each surface. Tile surfaces have a lower rolling resistance than carpet flooring,¹⁶ as the carpeted floor is generally softer and results in greater deformation and dissipation of energy at the wheel-floor interface.¹⁶ This is in agreement with our finding of higher pushrim forces and moments necessary to overcome the greater rolling resistance of carpet compared with tile terrain. Interestingly, we measured the highest pushrim forces and moments during the aggregate concrete ground condition. The surface irregularities such as those found in aggregate concrete can increase rolling resistance through greater contact pressure, and increase the energy required to overcome the surface irregularities.¹⁷ This suggests that, among the terrain we evaluated, uneven concrete was the most demanding (i.e., greatest rolling resistance) wheeling environment. Advantages to using uneven concrete and carpet for construction of sidewalk and flooring include better traction and a lower slip risk. However, the higher demands of these terrain imposed on the manual wheelchair user may serve as an impetus to implement alternative terrain during sidewalk and building construction in the future. Future studies that evaluate additional level terrain may assist with additional decisions regarding ground construction and the impact on manual wheelchair users.

There were no side-to-side differences in wheelchair propulsion for any of the temporal or kinetic variables of interest. Overall, the influence of arm dominance on wheelchair propulsion biomechanics is poorly understood. In previous studies, investigators have elected to average data for both limbs^{18–20} or have selected only one limb⁸ for analysis. A significant correlation between right- and left-side values has been cited as rationale for not evaluating wheelchair propulsion as a bilateral task.^{8,18–20} Other investigations have, however, reported side-to-side differences in power production^{11,21} and stroke patterns²² during wheelchair propulsion. We have recently measured bilateral power production across varying level and inclined terrain, and found that as the terrain became more challenging, the power produced by the dominant extremity was greater than the nondominant extremity.¹¹ Perhaps propulsion across level terrain was not challenging enough to elicit differences between extremities. Alternatively, the absence of differences between extremities may be a result of evaluating uninjured subjects. Injured individuals may be more likely to exhibit asymmetrical propulsion patterns. Or, the presence of asymmetry may be a risk factor for future injury. Despite the absence of side-to-side differences in this study, we agree with Boninger et al.,²² who stated that inaccurate interpretations of propulsion biomechanics may result if the left- and right-sides are assumed to be identical. Furthermore, we suggest future study designs incorporate evaluation of both extremities to gain further insight into the biomechanics of wheelchair propulsion of injured and uninjured subjects.

Injury prevention strategies for manual wheelchair users have been suggested. After a review of their multicenter trial, Boninger et al.²² identified cadence, force, and the hand pattern during recovery as specific aspects of propulsion that may relate to injury. Boninger et al.²² suggested a circular propulsive stroke in which the hand falls below the pushrim during recovery is conducive to injury prevention by promoting longer pushrim contact time and a lower push frequency. Because lower propulsion forces are associated with lower rolling resistance, Boninger et al.²² also suggested using the lightest wheelchair possible and encouraging subjects to minimize weight gain as strategies to minimize rolling resistance. A notable limitation of Boninger's multicenter trial was that all testing was conducted on a level wheelchair dynamometer. The investigators could not identify environmental conditions that may serve as injury risk factors. Studies that have evaluated the impact of wheeling surface have suggested avoiding inclined¹⁴ and cross-sloped terrain,¹⁵ as well as rapid starts and stops¹⁰ to limit excessive pushrim forces and thereby lower injury risk.

Consistent with these studies, our results implicate environmental demands as an injury risk factor. This is the first time, however, propulsion biomechanics have been reported to be significantly different during steady-state propulsion as a consequence of level terrain. These results should be considered by manual wheelchair users when they are free to choose their propulsion environment, and by investigators who are designing studies with the purpose of evaluating propulsion biomechanics.

There are limitations to this study. Our investigation included a single testing session of manual wheelchair users who were free of upper extremity injury. Long-term, prospective trials that evaluate both injury rates and wheeling environment will be necessary to validate the role of level terrain as an injury risk factor for manual wheelchair users. We evaluated propulsion biomechanics during real-world conditions, including indoor hallway and outdoor sidewalk terrain. This study design effectively captured ground conditions manual wheelchair users may encounter on a daily basis. Because testing was conducted outside of the laboratory, however, we were unable to use a motion capture system to collect kinematic data. Consequently, trunk and upper extremity motions that may have contributed to the altered kinetics across terrain conditions are unknown. Perhaps, with advancements in technology, future studies will capture both forms of data as the manual wheelchair user interacts with their natural environment. In the absence of such advancements, inclusion of varied terrain rather than tiled floor or wheelchair dynamometer conditions within the laboratory may be useful in determining how each joint and specific pathology risk are affected by changing wheeling surface. Finally, we did not measure the rolling resistance of the different ground conditions. We are, therefore, unable to quantify the demands of each surface, or determine the nature of the relationship between level terrain rolling resistance (e.g., linear, exponential, etc.) and propulsion biomechanics.

We were able to help elucidate the relationship between wheeling environment and biomechanics by testing subjects during the demands of real-world propulsion, and outside of the laboratory. These results emphasize the importance of considering terrain as a significant component in studies designed to evaluate wheelchair propulsion. Inclusion of additional environmental conditions that may contribute to upper extremity pathology is a step toward injury prevention and maintenance of functional abilities for the manual wheelchair user. Results from this study have demonstrated that wheelchair propulsion over aggregate concrete is the most physically demanding task for wheelchair users. These results may be used to assist with home and community terrain design to minimize the demands associated with wheelchair propulsion.

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FIGURE 1. Mean (thick vertical bars) and standard deviation (thin vertical bars) across ground conditions for temporal variables, velocity (A), contact time (B), and push frequency (C). Statistically significant different conditions ($P < 0.05$) are identified by lower case letters.

FIGURE 2.

Mean (thick vertical bars) and standard deviation (thin vertical bars) across ground conditions for kinetic variables, propulsion moment (A), total force (B), tangential force (C), and radial force (D). Statistically significant different conditions ($P < 0.05$) are identified by lower case letters.

TABLE 1

Variables of interest

Variable	Calculation
Average propulsion moment (Mz)	Direct output (Nm)
Average total force (F _{tot})	$\sqrt{F_x^2 + F_y^2 + F_z^2}$ (N)
Average tangential force (F _{tan})	Mz/r (N)
Average radial force (F _{rad})	$\sqrt{F_x^2 + F_y^2 + F_{tan}^2}$ (N)
Velocity (Vel)	Direct output (m/sec)
Push frequency (PushFreq)	Direct output (pushes/sec)
Length of push cycle (contact)	Mz onset-off (sec)

r, wheelchair rim radius; *F*, force.

TABLE 2

Subject characteristics

Subject	Gender	Age (yrs)	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
14	M	45	180	28	L	SCI	T12	1

M, male; F, female; R, right; L, left; SCI, spinal cord injury; SB, spina bifida.

TABLE 3

Mean (standard deviation) for dominant (D) and nondominant (ND) extremities across conditions

	<u>Aggregate Concrete</u>		<u>Smooth Concrete</u>		<u>Carpet</u>		<u>Tile</u>	
	D	ND	D	ND	D	ND	D	ND
Temporal variables								
Velocity	1.4 (0.3)	1.4 (0.3)	1.5 (0.3)	1.5 (0.2)	1.5 (0.3)	1.5 (0.3)	1.5 (0.3)	1.5 (0.3)
Contact time	0.3 (0.07)	0.3 (0.07)	0.3 (0.1)	0.3 (0.07)	0.3 (0.07)	0.3 (0.07)	0.3 (0.07)	0.3 (0.07)
Push frequency	1.1 (0.2)	1.1 (0.2)	1.1 (0.2)	1.1 (0.2)	1.0 (0.2)	1.0 (0.2)	1.0 (0.3)	1.0 (0.3)
Kinetic variables								
Mz	13.2 (5.1)	10.8 (2.7)	7.8 (2.3)	9.0 (2.4)	9.7 (3.3)	9.6 (3.4)	6.5 (2.2)	6.7 (2.5)
Total force	0.8 (0.2)	0.8 (0.2)	0.6 (0.2)	0.6 (0.2)	0.7 (0.1)	0.6 (0.1)	0.5 (0.1)	0.5 (0.1)
Tangential force	0.6 (0.1)	0.5 (0.2)	0.4 (0.2)	0.5 (0.1)	0.5 (0.08)	0.5 (0.1)	0.3 (0.1)	0.3 (0.1)
Radial force	0.5 (0.2)	0.5 (0.1)	0.5 (0.2)	0.4 (0.2)	0.4 (0.09)	0.4 (0.1)	0.3 (0.1)	0.3 (0.1)

Mz, propulsion moment.