CROSS-SLOPE AND SURFACE TYPE INFLUENCE ON MANUAL WHEELCHAIR PROPULSION SYMMETRY

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INTRODUCTION

The bilateral nature of wheelchair propulsion places both upper extremities at risk for pain and overuse injury [1]. Manual wheelchair users likely traverse a variety of surfaces with different texture, hardness, and gradient on a daily basis. Certain surface characteristics such as cross slopes and slippery conditions can cause considerable difficulty for these individuals to efficiently propel their wheelchairs [2, 3].

A cross slope is a transversal slope with respect to the horizon. It is a common design feature for promoting water drainage in daily environment. Base on the Americans with Disabilities Act (ADA) Accessibility Guidelines, the accessible routes to a building including sidewalks, ramps, and parking spaces should have cross slopes no greater than 1:50 (1.15°). Richter et al. found that pushing on a cross slope of 3° and 6° leads to increased loading on the downhill handrim compared to a level surface [2] . Hurd et al. showed there was a significant upper extremity asymmetry for propulsion forces and moments, and the lower arm was exposed to greater propulsion demands on a cross slope of 2° [1].

Several previous studies also addressed the influence of surface texture on wheelchair propulsion. Hurd et al. found that propulsion forces and moments were greatest under the aggregate concrete ground condition compared to the smooth, concrete, tile and carpet flooring [4]. Koontz et al. found that wheelchair users had considerably higher propulsion force and moments during start-up when propelling uphill and rough surfaces such as grass and interlocking pavers [3].

Few studies have discussed the combined influence of cross slopes and surface texture especially slippery conditions on wheelchair propulsion biomechanics and the magnitude of upper extremity asymmetry. The goal of this study is to deepen our knowledge of kinetic characteristics and bilateral demands of propulsion under different surface conditions. The findings of this study are expected to provide evidence for refinement of accessibility guidelines, and contribute to the knowledge base of the influence of upper extremity pathology among manual wheelchair users

METHOD

Participants

The study was conducted during the 2009 National Veteran Wheelchair Games (NVWG) in Spokane, WA. We recruited a convenience sample of 15 manual wheelchair users to participate in the study. Subjects were included if they were between 18 and 70 years old and use a manual wheelchair as a primary means of mobility. To be eligible for participation in the NVWG, all participants underwent a medical examination and obtained clearance from a physician. All participants provided a written informed consent to participate in the study.

Experimental Protocol

Subjects were required to fill a demographics questionnaire and then participate in the study using their own wheelchair. A 16-foot long wood platform with fixtures to adjust the slope angles and cross slope angles was used as the experimental course. Each subject were asked to perform nine trials on the experimental course when it is configured to three types of surfaces (i.e., wood, blind guide, and Teflon drizzled with soapy water) at three different cross slope angles (i.e., 0°, 1°, 2°). The three surfaces simulated the smooth, rough, and slippery road conditions. Subjects were instructed to start propelling their wheelchair from a resting position up to a comfortable pace, pushing in straight line. They were asked to maintain the pace until they reached the designated finish line. Two SMART^{Wheels} were secured on both sides of the subject's wheelchair.

Data Analysis

The selected biomechanical variables analyzed for each trial were peak resultant force, peak wheel torque, push angle, velocity, cadence, number of strokes, and sum of work. We determined the resultant force by calculating the vector sum of the SMART^{Wheel} components (Fx, Fy, Fz) as shown in Equation 1. We used Equation 2 to obtain the work. All the variables were calculated over the push phase of the stroke only. Using the wheel torque, a custom computer algorithm with visual confirmation was used to identify the push phase of each stroke. We removed the first and last stoke from the analysis. The peak resultant force, peak wheel torque, push angle, and velocity were averaged by each stroke. The work was summed over all strokes. A symmetry index for each variable was calculated by dividing the right side (i.e., downhill pushrim) by the left side.

Post processing of all variables in the study was fed into a custom MATLAB program (Version 7.6 R2008a, The Mathworks Inc. MA, USA). Statistics analysis was completed using SPSS statistical software (ver. 15.0, SPSS Inc. IL., USA). Distributions of variables were examined and transformations were made where necessary. Within-condition propulsion symmetry was evaluated with pair-t tests, comparing the values between the right and left sides. Between-condition propulsion symmetry was evaluated for each variable with a two-way repeated-measures analysis of variance where the cross slope angle and the surface condition were the two factors. When significant main effects or interaction effect were found, post hoc pairwise comparisons were performed using the Bonferroni adjustment to evaluate differences between conditions. Differences were determined to be statistically significant at a level of 0.05.

RESULTS

The 15 subjects tested in this study included 9 men and 6 women with an average age of 48 ± 9 years old. Nine of the 15 subjects had a spinal cord injury ranging from L5/S1 to C6/7. Three subjects had multiple sclerosis and three subjects had lower extremity amputation. All subjects were able to complete the protocol.

The resulting biomechanics data are given in Table 1 to Table 6. Within each cross slope and surface condition, we found that the differences in velocity, number of stroke, and cadence between the right and left sides can be neglected under all conditions. The sum of work on the right side was significantly higher than the left side on the cross slope of 1° and 2° for all surface conditions (ps < .020). The average push angle and peak wheel torque on the right side were significantly higher than those on the left side on the cross slope of 2° under the wood (push angle, p=0.014; wheel torque, p=0.019) ,blind guide surfaces (p=0.045; p=0.003 respectively), and approaching significance under the slippery surface (p=0.124; p=0.055 respectively). Although the average peak force on the right pushrim was consistently higher than that on the left pushrim on the cross slope of 1° and 2° for all surface conditions, the differences were not statistically significant.

Between the cross slope and surface conditions, we found that there was a main effect of cross slope on the symmetry index of the peak resultant force (F(2,28)=9.732, p=.001), peak wheel torque (F(2,28)=7.800, p=.002), push angle (F(2,28)=6.838, p=.004), and sum of work (F(2,28)=21.427, p=<.001). Post-hoc analysis indicated that these variables on the cross slope of 2° were significantly different from those on the level condition. There was no main effect of cross slope on the symmetry index of the velocity, number of stroke, and cadence. There was also no main effect of surface condition and no interaction effect on the symmetry index of all variables.

DISCUSSION

This study examined wheelchair propulsion biomechanics especially the symmetry between two upper extremities on a cross slope under surface conditions. The cross slope degrees were selected based on the ADA Accessibility Guidelines. The three surface conditions were selected to simulate some commonly encountered surface conditions by wheelchair users on a daily basis.

All the subjects in this study traveled the same distance, however, the sum of work done on the right side was found significantly greater than that on the left side on the two cross slope conditions, indicating the imbalance of propulsion efforts between the two arms exists on even small-gradient cross slopes. Besides, subjects need to expend more energy with the arm on the downhill side despite arm dominancy. A further examination of the other variables showed that subjects tended to reduce push angle on the left side and increase wheel torque and stroke number on the right side to accommodate the force pulling the wheelchair down the cross slopes. The downhill handrim also tended to bear greater peak resultant forces than the uphill side. However, the differences observed were not statistically significant. One possible reason could be that subjects may choose to regulate the push frequency and amplitude to a greater extent than the propulsion forces on small cross slopes. We also found that the magnitude of propulsion asymmetry in terms of the peak force, peak wheel torque, push angle, and sum of work was dependent on cross slopes, but not on surface conditions. The asymmetry became greater on the cross slope of 2° when compared with the level condition. An interesting phenomenon was observed that subjects had significantly asymmetry stroke number while propelling on slipper and larger cross-slope condition. It is possible that subjects preferred changing stroke number rather than changing push angle and torque to gain more control.

The result of this investigation provides insight into the impact of cross slopes on handrim loading borne by wheelchair users' arms. Assistive Technology Practitioners should be aware that manual wheelchair propulsion is asymmetric with non-negligible magnitudes on even small-gradient cross slopes, which may influence interpretation when using the one side or average value and also the evaluation of their clients on their ability to negotiate cross slopes. However, this study was limited by excluding the weight variable in the analysis. Other limitation of the study was that the sample size was small, only recruited high level athletes and the experimental course was relatively short to yield true steady propulsion states. Future work will focus on larger sample sizes that allow us to compare the impact of cross slopes across different types and levels of diagnoses. Also the protocol could be revised to include more realistic and longer experimental courses.

FIGURE AND TABLES

Table 1: Stroke Number (SN) (M ± SD)

	Cross Slope 0°		
	Right	**Left**	**SI**
Blind	6.20±2.00	6.27±2.22	1.01±0.15
Teflon	6.13±2.75	5.60±1.84	1.07±0.23
Wood	4.93±2.60	4.73±1.87	1.04±0.25
	Cross Slope 1°		
Blind	6.87±2.50	6.47±2.53	1.09±0.19
Teflon	6.73±2.40	6.47±2.17	1.05±0.18
Wood	5.47±2.44	5.33±2.02	1.03±0.28
	Cross Slope 2°		
Blind	7.67±3.31	7.27±3.01	1.07±0.20
Teflon	8.13±3.16*	7.07±2.31*	1.15±0.28
Wood	6.33±2.35	5.67±2.06	1.14±0.27

Table 2: Peak Wheel Torque M_z (Nm) (M ± SD)

	Cross Slope 0°		
	Right	**Left**	**SI**
Blind	21.14±8.13	20.17±6.67	1.06±0.25
Teflon	19.88±7.03	19.69±5.35	1.03±0.32
Wood	21.94±8.37	21.08±7.03	1.09±0.38
	Cross Slope 1°		
Blind	22.82±7.28*	20.19±5.93*	1.14±0.25
Teflon	20.83±7.27	18.71±6.63	1.17±0.41
Wood	23.56±7.32	19.97±6.93	1.25±0.46
	Cross Slope 2°		
Blind	24.60±7.69*	19.00±4.28*	1.31±0.34
Teflon	22.25±8.07	18.73±6.56	1.25±0.48
Wood	24.13±8.43*	19.92±6.77*	1.28±0.50

Table 3: Peak Resultant Force F_R (N) (M ± SD)

	Cross Slope 0°		
	Right	**Left**	**SI**
Blind	106.10±28.66	107.18±29.91	1.01±0.20
Teflon	97.19±26.36	103.23±32.27	0.99±0.28
Wood	105.38±29.87	110.24±35.20	1.00±0.27
	Cross Slope 1°		
Blind	107.03±27.97	103.58±27.31	1.06±0.23
Teflon	102.09±30.11	99.02±35.98	1.13±0.33
Wood	110.76±35.78	104.07±32.84	1.09±0.30

	Cross Slope 2°		
Blind	114.16±28.97	100.94±21.15	1.16±0.29
Teflon	107.74±34.47	99.25±31.59	1.13±0.33
Wood	113.86±32.60	102.98±33.85	1.17±0.39

Table 4: Push Angle (deg) (M ± SD)

	Cross Slope 0°		
	Right	**Left**	**SI**
Blind	73.79±14.53	72.21±15.74	1.03±0.05
Teflon	71.25±15.43	71.30±15.47	1.00±0.09
Wood	74.27±13.63	73.94±13.65	1.02±0.18
	Cross Slope 1°		
Blind	72.41±13.31	70.69±14.86	1.03±0.05
Teflon	68.54±11.08*	65.65±13.20*	1.06±0.08
Wood	74.20±17.15	72.64±19.50	1.04±0.14
	Cross Slope 2°		
Blind	70.19±19.07*	64.18±16.32*	1.10±0.15
Teflon	67.92±12.92	63.56±18.80	1.12±0.23
Wood	71.20±15.98*	65.97±19.48*	1.11±0.15

Table 5: Velocity (deg/s) (M ± SD)

	Cross Slope 0°		
	Right	**Left**	**SI**
Blind	0.82±0.21*	0.80±0.21*	1.03±0.05
Teflon	0.78±0.23	0.76±0.18	1.02±0.15
Wood	0.79±0.11	0.78±0.96	1.01±0.09
	Cross Slope 1°		
Blind	0.78±0.22	0.75±0.17	1.04±0.09
Teflon	0.70±0.17*	0.67±0.15*	1.04±0.04
Wood	0.77±0.14	0.76±0.20	1.04±0.21
	Cross Slope 2°		
Blind	0.69±0.21	0.68±0.17	1.01±0.08
Teflon	0.67±0.19*	0.63±0.17*	1.07±0.10
Wood	0.72±0.23	0.70±0.23	1.04±0.11

Table 6: Cadence (sec^{-1}) (M ± SD)

	Cross Slope 0°		
	Right	**Left**	**SI**
Blind	1.08±0.21	1.08±0.26	1.01±0.09
Teflon	1.26±0.69	1.06±0.26	1.18±0.58
Wood	1.09±0.26	1.12±0.22	0.98±0.15
	Cross Slope 1°		
Blind	1.09±0.22	1.07±0.25	1.04±0.07
Teflon	1.06±0.24	1.02±0.24	1.04±0.08
Wood	1.05±0.22	1.05±0.22	1.01±0.09
	Cross Slope 2°		
Blind	1.06±0.20	1.04±0.21	1.03±0.09
Teflon	1.07±0.20	1.02±0.26	1.06±0.11
Wood	1.05±0.27	1.07±0.29	0.98±0.13

Table 6: Sum of Work (J) (M ±SD)

	Cross Slope 0°		
	Right	**Left**	**SI**
Blind	96.47±35.11	88.69±27.40	1.10±0.28
Teflon	81.58±25.63	79.17±25.45	1.09±0.41
Wood	73.99±26.50	70.14±21.81	1.10±0.41
	Cross Slope 1°		
Blind	111.91±31.67*	85.92±28.64*	1.33±0.26
Teflon	92.34±24.01*	77.39±26.75*	1.28±0.45
Wood	90.59±31.46*	72.03±21.61*	1.29±0.37
	Cross Slope 2°		
Blind	124.73±38.69*	82.97±20.99*	1.53±0.44
Teflon	117.72±40.54*	79.10±33.95*	1.66±0.82
Wood	107.40±34.76*	68.16±17.70*	1.65±0.67

Note: Abbreviation: M, Mean; SD, Standard Deviation; SI, Symmetry Index. *p<.05.

EQUATIONS

$$\text{Resultant Force (FR)} = \sqrt{F_x^2 + F_y^2 + F_z^2} \qquad (1)$$

$$\text{Sum of Work (J)} = \int Mz \; d\theta \qquad (2)$$

ACKNOWLEDGEMENTS

Funding for this research is provided by the United States Architectural Compliance Board (Access Board – TPD-ARC-07-00090). This material does not reflect the views of the Department of Veterans Affairs or the United States Government.

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