Impact of Cross Slope and Surface Type on Wheelchair Propulsion

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ABSTRACT

The objective of this study was to evaluate wheelchair propulsion biomechanics under cross-slope degrees and surface types. Testing course consisted of three cross-slopes (0˚, 1˚, and 2˚) and three types of surfaces (Blind-Guide, Teflon, and Wood). We compared biomechanics data using two-way repeated-measures ANOVA. The result showed that the resultant force, torque, and cadence were not significantly different between surface types and cross slope conditions. While self-selected speeds decreased with the increase of cross slope angles (p=0.026) and subjects tended to slow down on the Teflon surface. Push angle had liner decreasing relation with increasing cross slope angles and remained consistently larger among subjects on the Teflon surface. These results indicate that slight cross-slopes, slippery and rough surfaces may not result in significant biomechanics loading on a short duration. However, the difference noted between degrees and surfaces highlight the change of push pattern and decrease propulsion efficiency.

KEYWORDS

Cross-Slope; Surface Type; Kinetic; SmartWheel, Wheelchair Propulsion

BACKGROUND

Cross slope is the slope of a surface perpendicular to one’s path of travel (1). To promote water drainage to the gutter cross slopes are common in built environment, such as roads and sidewalks. According to the specifications of Americans with Disability Accessibility Act (Americans with Disability Act, 2004), the accessible routes to a building, including sidewalks, ramps, and parking spaces should have cross slopes no greater than 1:50. However, to propel manual wheelchair on cross slope, users might need more energy to maintain their lateral balance to counter gravity (1). In Boninger et al. study, they have identified propulsion cadence and magnitude of force might let upper extremities at risk for overuse pathology (2).

Manual wheelchairs are widely used by individuals with mobility impairments to participate in society (3). Certain surface condition characteristics and environments may act as facilitators or barriers to wheelchair users. Richter et al. found that users must push harder and use more pushes on a cross slope (1). Brubaker et al. stated that cross slope condition would cause negative impact on subjects’ propulsion due to the downward turning movement on a two degree cross-slope (4). The type of surface might also affect the propulsion performance. In Hurd et al. study, they noted that greater forces and moments were measured on aggregate concrete compared to tile surface (5). Koontz et al. have also discussed the kinetic performance between different kinds of surface during start-up. They found that users had considerably higher propulsion force and moments to start up while propelling uphill and rough surface (6).

A fairly large body of literature has been performed to gain a better understanding of the propulsion pattern in different environments. However, few studies have discussed the interaction of cross-slope, surface type and slippery surface on wheelchair propulsion. The goal of this study is to deepen our understanding of propulsion characteristics, including force, moment, push angle, push frequency and velocity on different cross slope conditions and types of surface that wheelchair users might encounter during everyday life.

METHOD

Participants

The study was conducted during the National Veteran Wheelchair Games (NVWG) in Spokane, WA, 2009. Subjects were included in the study if they used manual wheelchairs as primary means of mobility and were between the age of 18 and 70 years old. Subjects were excluded if they were unable to tolerate physical activities for two hours. All participants were required to provide written informed consent in the beginning. To be eligible for participation in the NVWG, all participants underwent a medical examination and obtained clearance from a physician.

Experimental Protocol

To begin with the subjects were required to fill a demographics questionnaire and then participate in the study using their own wheelchair. The experimental course consisted of three different surfaces at three different cross-slopes. The surface types were wood, blind guide, and Teflon drizzled with soapy water, which simulated the regular, rough and smooth slippery surface for manual wheelchair users. The three cross-slope positions were zero (level), one and two degrees. The length of the course was 12 feet with a 4 feet extension for user to turn back. Figure 1 shows the mobility course of blind guide. Two SMART$^{\text{Wheel}}$s were secured on either side of the subject's own manual wheelchair. All subjects used either folding or rigid manual wheelchair and the application of the Smart$^{\text{Wheel}}$s did not change the user settings. Subjects were instructed to start propelling their wheelchair from a resting position, four feet away from the mobility course, up to a comfortable pace. Subjects started on a level surface and transitioned to the mobility course through a small ramp. The surface and cross-slope conditions between consecutive subjects were provided in a back-to-back order to minimize the testing time within 2 hours.

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Figure 1 goes here: Test condition

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Kinetic Measurement System

SMART$^{\text{Wheel}}$ (Three Rivers Holding LLC,Phoenix, AZ) is an instrumented wheel that is capable of measuring three dimensional (3-D) forces (Fx, Fy, Fz) and moments (Mx, My, Mz) exerted on the pushrim during wheelchair propulsion at a frequency of 240 Hz. In addition to collecting these variables the device was also used to identify the time instances of the start of push and recovery phases of a stroke.

Data Analysis

The selected biomechanical variables analyzed for each section of the course were resultant force, wheelchair torque, push angle, push frequency and velocity. These biomechanics variables were chosen, as they have been linked to upper-limb injuries among wheelchair users (2). We determined the resultant force by calculating the vector sum of the SMART$^{\text{Wheel}}$ components (Fx, Fy, Fz) as shown in Equation 1. Only the right SMART$^{\text{Wheel}}$ (downhill wheel) was instrumented because the inertial properties of the right devices have found high correlation to the left (1). We calculated all kinetic parameters over the push phase of stroke only and exclude the first and last stoke, which was determined by visually inspection of the wheel torque curves.

Equation 1 goes here

Post processing of all variables in the study was fed into a custom MATLAB (The MathWorks, Inc., Natick, MA) program. Statistics analysis was completed using SPSS (SPSS Inc., Nie, IL) statistical software. Distributions of variables were examined and transformations were made where necessary. Separate two-way repeated-measure ANOVAs were used to compare each variable with the cross-slope condition and surface type as the two factors. Pairwise comparisons with a Bonferroni adjustment were used when significant main effects or interaction effect were found. Differences were determined to be statistically significant at a level of 0.05.

RESULTS

Twelve manual wheelchair users consisting of eight men and four women were analyzed in this study. The average age was 50 ± 10 years old. Nine of the subjects had spinal cord injury that ranged from L5/S1 to C6/7. Two subjects had multiple sclerosis and one subject had lower extremity amputation. Three subjects had disability less than ten years, four subjects between ten to twenty years, and five subjects were over twenty years. All subjects were able to complete the protocol comfortably.

The resulting biomechanics data are given in Table 1 to Table 5. For the peak resultant force, peak wheel torque, and push frequency, there were no main effect on the surface type and cross slope condition, and no interaction effect between the two factors. While looking into the push angle, the data showed no significant main effect on the surface type and no interaction effect, but a significant main effect on the cross slope condition (F (2, 22) = 10.806, p=0.001). Pairwise comparisons indicated the push angle on 2° cross slope was significant lesser than 1° (p= 0.02) and 0° (p<0.001). Data also showed that subjects significantly decreased their propulsion speed with increasing cross slope angles (F (2, 22) = 4.314, p=0.026), and a trend on the main effect of surface type (F (2, 22) = 3.420 p=0.051) with slower speeds on the Teflon surface than on the blind-guide surface.

Tables 1-5 go here

DISCUSSION

The result of this investigation provides insight into the impact of propulsion biomechanics on cross-slope and surface type. In terms of the surface type, Hurd et al. pointed out that forces and moments will increase with ground conditions become more challenging (5). However, in our study we found that the moments and forces were not significantly different on slippery (Teflon) or rough (blind guide) surfaces compared to the wood surface. One of the reasons is that the subjects became more cautious on slippery surfaces and reduced their speeds. An interesting phenomenon was observed by examining the standard deviations in push angles on different surfaces (Table 3). The large standard deviations in push angles on the blind guide and wood surfaces indicate that subjects in this study may have used different propulsion styles, and consistently changed their propulsion style by using larger push angles to compensate for the speed loss under the slippery condition.

We also tested two cross slope conditions (1° and 2°). The two conditions were chosen based on the ADA guideline that no cross slopes should be greater than 1:50 (2% or 1.15°). Although wheelchair users might need more energy to maintain their lateral balance to counter gravity, our results showed that forces, moments, and push frequency were not influenced by the two cross slope conditions. A primary reason could be that the subjects chose to reduce the speeds and push angles on cross slope conditions to gain more accurate control of their wheelchairs and modulate biomechanics loading. Also the cross slope angles were small compared with the study by Richter et al., where they found that wheelchair users must push harder when on cross slopes of 3° and 6° (1). They also found speed and push angle were unaffected by cross slope (1). Overall, our study provides an insight on the relationship between different environment restrictions and wheelchair propulsion strategy. It also confirmed that the maximum cross slope angle defined by the ADA guideline is reasonable for wheelchair users to negotiate when using appropriate strategies. However, when the cross slope becomes steeper, users will have to push harder and the increased loading on the arm could be a risk factor for upper extremity pain or injury.

Results of this study were limited by analyzing only the downhill wheel. Users might change trunk position to keep body upright, and this compensation might cause upper extremity asymmetry and different biomechanics loading at each side. Other limitation of the study was that the sample size was small and may not be representative as they were recruited at the National Veterans Wheelchair Games, Future work will focus on biomechanical analysis using both downhill and uphill wheels and include more subjects.

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FIGURES, EQUATIONS, AND TABLES

Figure 1: Experimental condition

Alternative Text Description for Figure 1:
This figure shows that the subject was tested on the Blind guide surface with 2° Cross slope.

Equation 1: Resultant Force

$$\text{Resultant Force (FR)} = \sqrt{\text{Fx}^2 + \text{Fy}^2 + \text{Fz}^2}$$

Alternative Text Description for Equation 1:
Resultant Force equal the square of three-dimensional forces and then square root the sum value. The SMART$^{\text{Wheel}}$ coordinate system is defined with x representing forward progression, y representing the axis perpendicular to the floor, and z pointing out of the wheel along the axle.

Table 1: Descriptive Statistics of Measured Peak Wheel Torque Differences

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	Peak Wheel Torque Mz (Nm) (Mean ± Standard Deviation)		
	Cross Slope 0°	Cross Slope 1°	Cross Slope 2°
Blind-Guide	20.39±5.61	20.13±6.03	19.39±4.35
Teflon	19.04±7.00	18.80±6.87	18.32±6.75
Wood	20.57±6.96	21.12±7.83	20.67±7.31

Alternative Text Description for Table 1:
This table displays the average of all peak wheel torques over different surface types and cross slope degree.

Table 2: Descriptive Statistics of Measured Peak resultant force Differences
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	Peak resultant force F_R (N) (Mean ± Standard Deviation)		
	Cross Slope 0°	Cross Slope 1°	Cross Slope 2°
Blind-Guide	107.64±21.70	103.73±19.89	103.09±15.66
Teflon	100.19±31.12	98.95±32.46	95.75±27.22
Wood	103.14±28.83	103.99±31.54	102.67±30.64

Alternative Text Description for Table 1:
This table displays the average of all peak resultant forces on different surface types and cross slope degree.

Table 3: Descriptive Statistics of Measured Push Angle Differences
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	Push Angle (deg) (Mean ± Standard Deviation)		
	Cross Slope 0°	Cross Slope 1°	Cross Slope 2°
Blind-Guide	56.27±47.72	54.73±47.21	48.62±43.11
Teflon	70.06±16.48	66.15±14.17	60.56±18.12
Wood	58.85±48.9	55.82±48.63	48.72±50.49

Alternative Text Description for Table 1:
This table displays the average of all push Angles on different surface types and cross slope degree.

Table 4: Descriptive Statistics of Measured Velocity Differences
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	Velocity (deg/s) (Mean ± Standard Deviation)		
	Cross Slope 0°	Cross Slope 1°	Cross Slope 2°
Blind-Guide	0.85±0.20	0.85±0.21	0.77±0.21
Teflon	0.79±0.22	0.73±0.18	0.67±0.20
Wood	0.84±0.19	0.80±0.23	0.75±0.32

Alternative Text Description for Table 1:
This table displays the average of all velocities on different surface types and cross slope degree.

Table 5: Descriptive Statistics of Measured Cadence Differences
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	Cadence (sec^{-1}) (Mean ± Standard Deviation)		
	Cross Slope 0°	Cross Slope 1°	Cross Slope 2°
Blind-Guide	1.13±0.20	1.19±0.24	1.14±0.18
Teflon	1.11±0.20	1.06±0.18	1.09±0.28
Wood	1.10±0.21	1.06±0.22	1.09±0.26

Alternative Text Description for Table 1:
This table displays the average of all cadences on different surface types and cross slope degree.