ORIGINAL ARTICLE

Consequences of a Cross Slope on Wheelchair Handrim Biomechanics

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ABSTRACT. Richter WM, Rodriguez R, Woods KR, Axelson PW. Consequences of a cross slope on wheelchair handrim biomechanics. Arch Phys Med Rehabil 2007;88:76-80.

Objective: To test the hypothesis that pushing on a cross slope leads to increased handrim loading compared with that found on a level surface.

Design: Case series.

Setting: Biomechanics laboratory.

Participants: Twenty-six manual wheelchair users.

Intervention: Subjects pushed their own wheelchairs on a research treadmill set to level, 3°, and 6° cross slopes. Propulsion speed was self-selected for each cross-slope condition. Handrim biomechanics were measured for the downhill wheel, using an instrumented wheelchair wheel and a motion capture system.

Main Outcome Measures: Speed, peak kinetics (force, rate of loading, torque), push angle, cadence, push distance, and power output were averaged over a 20-push set for each subject and each cross-slope condition. Outcomes were compared across cross slopes using a repeated-measures analysis of variance.

Results: Push angle and cadence were unaffected by cross slope. A trend of decreasing self-selected speeds with increasing cross slope was not significant. There were considerable increases in the peak kinetic measures, with the axial moment increasing by a factor of 1.8 on the 6° cross slope ($P=.000$). More pushes were required to cover the same distance when on a cross slope ($P<.034$). The power required for propulsion increased by a factor of 2.3 on the 6° cross slope ($P=.000$).

Conclusions: Users must push harder when on a cross slope. This increased loading is borne by the users' arms, which are at risk for overuse injuries. Exposure to biomechanic loading can be reduced by avoiding cross slopes when possible.

Key Words: Environment; Rehabilitation; Wheelchairs.

A CROSS SLOPE IS THE SLOPE of a surface perpendicular to one's path of travel. Cross slopes can be found in most built environments, such as roads, parking lots, and sidewalks. Roads are typically convex in shape (known as road crown) to promote water drainage to the gutters. Similarly, sidewalks are built with some degree of cross slope to channel water to the gutter. As a result, someone traveling along a road or sidewalk will likely encounter a cross slope. Cross slopes can range from subtle to significant. Parking lots, bike paths, and other paved surfaces often follow the general shape of the surrounding terrain, which, depending on the direction of travel, can result in significant cross slopes.

Cross slopes can be a considerable hindrance to wheelchair users, because the wheelchair tends to turn downhill in the direction of the cross slope. With the wheelchair on a cross slope, there is a force pulling the wheelchair down the slope. The rear wheels resist this lateral force but the front casters are free to rotate about the caster stem, allowing the front of the wheelchair to turn down the slope. This downhill turning tendency is about the midpoint of a line connecting the contact points of the 2 rear wheels and the support surface.

The Americans with Disabilities Act (ADA) specifies that accessible routes to a building, including sidewalks, ramps, and accessible parking spaces have cross slopes no greater than 1.1° (1:50).[1] Actual conditions for these routes may vary because the ADA allows for a construction tolerance that is "subject to conventional building industry tolerances for field conditions." These guidelines only apply to an accessible route into a building. Much of the built environment does not fall into this category and therefore is not subject to these guidelines. The U.S. Department of Transportation (DOT) Best Practices Design Guideline for sidewalks and trails recommends that sidewalks be limited to a 1.1° cross slope.[2] For nonpaved access routes such as trails, a steeper cross slope is generally necessary for adequate drainage, so the DOT guidelines recommend a cross slope limit of 2.9° (5%). The DOT guidelines, however, are recommendations, not requirements, so compliance is optional.

Brubaker et al[3] studied metabolic demand for a single manual wheelchair user pushing at 3 and 4km/h for periods of 5 minutes. The subject completed propulsion bouts on a level treadmill and with the treadmill leaning at a 2° cross slope. The subject consistently had a higher oxygen consumption when pushing on the cross slope. The average cost of propulsion was found to be 4.4L/km on the level surface and 5.6L/km on the 2° cross slope, corresponding to a 27.3% increase in metabolic demand. The subject's cadence was only slightly affected, with an average of 42.8 pushes/min on level and 44.3 pushes/min on the cross slope. The researchers provided a static analysis of a wheelchair on a cross slope. The downhill moment (M_d) acting to pull the wheelchair down the hill can be minimized by reducing the total weight of the wheelchair and user or by moving the seat closer to the rear axle, which will also make the wheelchair more "tippy" to the rear.

Research studies to date have not investigated the biomechanic loading associated with pushing a wheelchair along a cross slope. It is important to quantify the loading on the user's upper limbs, as various characteristics of loading have been associated with the development of upper limb repetitive stress injuries (eg, peak force on the handrim, rate of handrim load-

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ing, push cadence),[4-8] which are estimated to affect over half the manual wheelchair user population.[9-13] Variables of particular interest include the magnitude of the forces applied to the hand-
rim, the rate of application of those handrim forces, push angle, and cadence. The purpose of this study was to test the hypothesis that pushing on a cross slope leads to increased loading on the downhill handrim compared with that found on a level surface.

METHODS

Participants

After receiving institutional review board (IRB) approval, we recruited a convenience sample of 25 manual wheelchair users to participate in the study. A population of at least 20 subjects is a required threshold for consideration by some research compendiums.[14] Study inclusion requirements were: (1) primary use of a manual wheelchair for mobility, (2) comfort pushing for up to 2 minutes, (3) use of a wheelchair with 61-cm (24-in) diameter rear wheels, and (4) no medical conditions that propulsion might aggravate. All subjects were required to read and sign IRB-approved consent forms prior to their participation.

Experimental Protocol

Subjects transferred out of their wheelchairs and their rear wheels were replaced with propulsiometer test wheels. Only the right propulsiometer (downhill wheel) was instrumented. The inertial properties of the right propulsiometer matched those of the left. Subjects then transferred back into their wheelchairs and pushed onto a platform where they were weighed using digital postal scales under each wheel.

Subjects loaded onto a large multigrade research treadmill and were fitted with a safety system. The safety system was comprised of rope and repelling hardware. A spotter at the front of the treadmill controls the rope slack to allow the wheelchair freedom of movement while preserving the ability to quickly secure it if necessary. Subjects became acclimated to the treadmill by pushing at a variety of speeds for level, 3°, and 6° cross slopes and then choosing their comfortable speeds. After a 5-minute rest period, subjects completed a single propulsion bout of 35 pushes on 1 of the 3 cross-slope conditions at their self-selected comfortable speeds. The order of the cross-slope conditions was randomized. During each propulsion bout, biomechanics on the downhill handrim were measured using the propulsiometer. After a 5-minute rest period, subjects repeated the process for the next cross-slope condition, until all 3 conditions were completed.

Instrumentation

The propulsiometer is an instrumented wheel that measures the dynamic 3-dimensional forces and moments applied to the handrim during propulsion. Kinetic measures are made using a commercially available 6–degree-of-freedom load cell.[a] The load cell is mounted at the center of the wheel. The handrim is coupled to the wheel through the load cell. The handrim plane is aligned with the load cell, thereby ensuring equivalency between loads applied to the handrim and those measured at the load cell. Measurements are transferred from the load cell to a data collection computer wirelessly. Kinetics were measured at 200Hz and filtered using a fourth-order Butterworth digital filter with a 20-Hz cutoff frequency.[15] Dynamic offset was removed from each channel and the calibration matrix applied in post-processing. This process results in conditioned force and torque outputs.[16]

We measured wheel kinematics using an active-marker motion capture system.[b] Markers located on the propulsiometer were used to resolve wheel angle. Motion capture markers were activated using a wireless transceiver. An external trigger was used to ensure the kinematic data collection was synchronized with the kinetic data collection. The sampling rate of the motion capture system was set to 100Hz. The data were filtered using a fourth-order Butterworth digital filter with a 10-Hz cutoff frequency.[17] The effective sampling rate of the kinematic data was then increased to match the kinetic data (200Hz) by applying a cubic spline to each channel measured.

Data Reduction

We determined front to rear weight distribution using the net weight on the front casters (W_C) divided by the total weight (W). The horizontal location of the center of gravity (L_{CG}) was determined using a moment balance about the rear wheel contact point:

$$(W_C/W) \cdot L_{WB}$$

where L_{WB} is the length of the wheelbase with the casters in the trailing position. The static downhill moment (M_d) for each condition was then determined by

$$W \cdot \sin(\theta) \cdot L_{CG}$$

with θ representing the cross-slope angle. This downhill turning tendency is about the midpoint of a line connecting the contact points of the 2 rear wheels and the support surface.

We used the last 20 pushes from each propulsion bout in the analysis.[18] The resultant force on the handrim was defined as the vector sum of the 3 local force components. Pushes were identified by working from within the push outward using a search algorithm. The initiation or termination of the push was identified when either the force reached zero or the rate of change of the force reached zero. The rate of change condition catches occasions when the force does not fully reach zero (drift, noise, or inertial loading). Push identifiers were visually inspected on a graph prior to accepting the results. For each push analyzed, the peak force, peak rate of loading, peak moment about the wheel axle, push angle, cycle time, coast time, and power output were all determined. Peak force was defined as the maximum force magnitude applied to the handrim during the push. Peak rate of loading was defined as the maximum positive rate of change in handrim force. Power output was defined as the product of axial moment (torque about the wheel rotation axis) and the change in wheel angle. Individual push characteristics were then averaged over each 20-push set. Cadence was calculated as the inverse of the average cycle time. Net distance traveled per push was determined by dividing treadmill belt speed by cadence. Data reduction was automated using custom programs developed in Matlab.[c]

Statistical Analyses

We calculated descriptive statistics for the biomechanic outcomes for each of the cross-slope conditions, as well as for subject characteristics. The data were tested for normality using a Kolmogorov-Smirnov test. Cross-slope conditions were compared using an analysis of variance for the continuous dependent variables, including all the biomechanic outcomes as well as propulsion speed. Bonferroni post hoc tests were used to assess the statistical strength of differences between cross-slope conditions. Linear regressions were performed for each of the kinetic outcomes and the downhill moment. We determined 95% confidence intervals for each of the kinetic regression coefficients. Differences were determined to be sta-

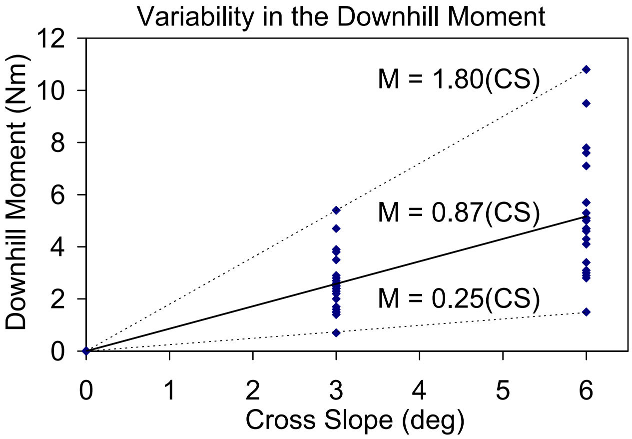

Fig 1. The downhill moment on the wheelchair (M) varied across users. On average, the moment is increased by 0.87Nm/deg of cross slope (CS). However, that relationship varied from 0.25 to 1.80Nm/deg of cross slope across the population.

tistically significant for P less than .05. Correlations were tested between peak handrim force and both total weight as well as percentage of weight over the rear wheels. All statistical tests were completed using SPSS statistical software.[d]

RESULTS

Twenty-six manual wheelchair users gave written consent and participated in the study (1 additional subject learned of the study and volunteered to participate). Twenty-four of the subjects had a spinal cord injury at or below the T6 level. Two of the subjects had spina bifida. All subjects were able to comfortably complete the protocol. The average age ± standard deviation (SD) of the subjects was 36±11 years old. Subjects had an average of 17±11 years of wheelchair experience. Seven of the 26 subjects were women.

Downhill Moment

The total weight of the wheelchair and user ± SD was 88.5±15.7kg. The percentage of the total weight located over the rear wheels was found to be 84.4%±6.4%. Wheelbase length was 37.3±3.5cm. The downhill moment resulting from the 3° slope was calculated to be 2.6±1.1Nm. Similarly, the downhill moment on the 6° cross slope was calculated to be 5.2±2.1Nm. The data were found to be normally distributed (significant at >.19). The resulting scatterplot and linear regression for the downhill moment is shown in figure 1. In general, the downhill moment was found to increase by .87Nm/deg of cross slope (R=.84, P<.001). Despite the strength of the regression, there was considerable variability across this subject population. Downhill moments ranged from 0.25 to 1.80Nm/deg of cross slope.

Handrim Biomechanics

The resulting handrim biomechanics are given in table 1. The data were found to be normally distributed (significant at >.18). While not statistically significant, subjects tended to slow down slightly in response to cross slopes. Peak kinetic measures all showed statistically significant increases with increasing cross slope. The peak handrim force, rate of loading, and axial moment increased by a factor of 1.4, 1.3, and 1.8, respectively, on the 6° cross slope (P=.000, P=.000, P=.000). The sharp increase in axial moment is illustrated for a single subject in figure 2. The time scales are equal for both these graphs. Push angle and cadence were unaffected by cross slope. Distance traveled in the forward direction per push decreased with cross slope (P=.034, P=.000). On average, subjects needed to push an extra 80 pushes/km on the 3° cross slope and 110 pushes/km on the 6° cross slope.

The coast time decreased consistently from .43 seconds on level to .35 seconds on the 6° cross slope (P=.042, P=.000). A decreasing coast time results in less time for the user to prepare for the next push. Power output required for the downhill wheel increased substantially with increasing cross slope. Power output required for the 3° and 6° cross slopes were on average 1.6 and 2.3 times greater than the power required on the level setting (P=.000, P=.000).

Correlations between cross slope and each of the kinetic outcomes yielded statistically significant relationships. Pearson correlation coefficients and linear regression coefficients are given in table 2. The peak handrim force and rate of loading were found to increase by an average of 3.9N and 51N/s, respectively, for each degree of cross slope (P=.000, P=.018). Similarly, axial moments were found to increase by an average of 1.3Nm/deg of cross slope (P=.000).

Correlations between peak handrim force and total weight were significant for 3° (R=.56, P=.004) and 6° grades (R=.63, P=.001). However, correlations between peak handrim force and the percentage of weight over the rear wheels for the 3° (R=.19, P=.383) and the 6° grades (R=.25, P=.243) were not found to be statistically significant.

DISCUSSION

This study represents the first investigation of wheelchair propulsion biomechanics on a cross slope. As was expected, handrim loading increases with cross slope. Increases in kinetic measures were found to be linearly related to the degree of cross slope, within the range tested. Push angle was not affected by cross slope. Push angle was expected to decrease slightly due to postural changes. With the wheelchair on a cross slope, the user will tend to lean into the hill so that his torso remains vertical. This accommodation places the downhill handrim further away from the user, effectively similar to raising the seat height, which has been shown to decrease push angle.[19] Kinematic adaptations to a cross slope were outside the scope of this study but will be addressed in future work.

Table 1: Handrim Biomechanics Measured at the Downhill Wheel for Level, 3° Cross-Slope, and 6° Cross-Slope Conditions

Condition	Speed (m/s)	F_R* (N)	dF_R dt* (N/s)	M_z* (Nm)	Push Angle (deg)	Cadence (min^{-1})	Distance* (m/push)	Coast* (s)	P_O* (W)
Level	1.16±0.22	53.4±15.4	1026±346	8.8±2.6	106.3±19.0	67.8±15.6	1.06±0.30	0.43±0.16	4.7±2.4
3° cross slope	1.12±0.27	62.8±17.0	1218±449	12.1±3.5	105.9±17.3	69.0±13.8	0.98±0.26	0.38±0.13	7.3±3.5
6° cross slope	1.07±0.27	77.0±17.1	1382±510	16.7±4.7	107.2±19.3	70.2±14.4	0.95±0.31	0.35±0.14	10.9±4.2

NOTE. Values are mean ± SD. All variables except for speed, push angle, and cadence differed statistically between cross-slope conditions (*P<.05).
Abbreviations: dF_R dt, peak rate of loading; F_R, peak resultant force; M_z, peak axial moment; P_O, power output.

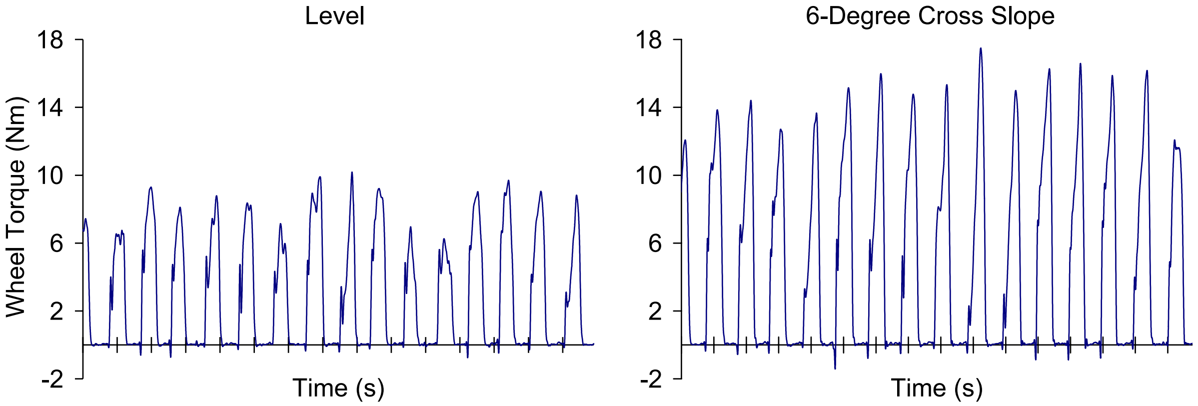

Fig 2. **Axial moment applied to wheel for a single subject on the level and 6° cross-slope conditions. Cadence remains similar while the magnitude increases sharply.**

Cadence was also unaffected by cross slope. With both push angle and cadence remaining constant, the distance traveled per push was also expected to remain constant. Nevertheless, the net distance traveled per push was found to significantly decrease with cross slope. This was likely due to the wheelchair curving up and down the cross slope with every push. It may be that the wheelchair does travel a similar distance per push, but, since the path is curved, the net displacement along the length of the treadmill is reduced. As a result, wheelchair users will not only have to push harder when on a cross slope but will also need to increase their number of pushes to cover the same distance.

For a single subject, Brubaker et al[3] found propulsion cadence on a level treadmill to be 42 pushes/min at an average speed of .97m/s. This cadence is much lower than the 68 pushes/min found as a group average in this study. The average speed of 1.16m/s in this study was also faster, which may account for the differences in cadence. In reviewing individual cadence values, 5 subjects were found to have cadences below 52 pushes/min and 1 subject pushed at 44 pushes/min. There was considerable variability across subjects, with 1 subject pushing at 99 pushes/min, reinforcing the need to test a population of wheelchair users.

The downhill moment is the source of increased biomechanic loading when pushing on a cross slope. As shown in figure 1, the magnitude of that moment increases with cross slope and was found to vary from subject to subject. If this moment were to be reduced for any individual, biomechanic loading on that person would also be expected to be reduced. One way to reduce the magnitude of the downhill moment is to reduce the cross-slope angle. Although every effort should be made to reduce the magnitudes of cross slopes in the built environment, a certain amount of cross slope is necessary to facilitate water drainage.

Table 2: Linear Regression Results for Each of the Kinetic Outcomes

Kinetic Outcomes	Pearson r*	A*	B*
F_R	0.51	3.9 (±1.6)	52.6 (±6.1)
dF_Rdt	0.28	51 (±42)	1039 (±162)
M_z	0.66	1.31 (±0.36)	8.60 (±1.37)

NOTE. Coefficients are given for the linear relationship $Ax + B$, where A is the slope, B is the intercept, and x is cross slope in degrees. The 95% confidence interval is given in parentheses for each coefficient of the linear relationship. All coefficients were statistically significant (*$P<.02$).
Abbreviations: see table 1.

In this study, peak handrim forces were found to be correlated with total weight. Based on these results, achieving a healthy body weight and using a lightweight wheelchair should reduce peak handrim forces when on a cross slope. The effect of weight distribution on handrim force was not directly measured in this study. Moving the seat as far back as comfortably possible (or axle forward) is expected to reduce the downhill moment. However, peak handrim force was not found to be correlated with weight distribution in this study. While the results of this study do not support adjusting the seat to the rear, they also do not invalidate the potential benefits. Further research is needed to properly examine the role of wheelchair setup on cross-slope performance.

Wheel camber has 2 presumed benefits when on a cross slope: increased lateral stability and a decreased axial moment required to overcome the tendency to turn down into the cross slope.[3] These benefits were not addressed in this study. The disadvantage of wheel camber is that it makes the wheelchair wider, so accessibility is reduced. Further research in this area is needed, so that a cost to benefit analysis of wheel camber can be made.

Study Limitations

Results of this study were limited by investigating only the downhill wheel. Most of our test subjects tended to brake rather than push with the uphill wheel when on a cross slope. However, this was not formally tested and warrants further investigation. We brought 1 subject back in and repeated the experiment with the treadmill tilted to both sides, such that both the uphill and downhill wheels were measured. When on the 3° cross slope, the braking torque applied to the uphill handrim was 8.3% of the forward torque applied to the downhill handrim. The braking torque dramatically increased to 38.6% when on the 6° cross slope, reinforcing the need to study this aspect of propulsion.

Other limitations of the study were: including only 3 cross-slope conditions, using a relatively small sample size, and the use of a treadmill rather than directly studying over-ground propulsion. Future studies on cross slope are needed to better understand how this propulsion environment affects the manual wheelchair user.

CONCLUSIONS

Cross slopes can be a considerable hindrance to wheelchair users, because the wheelchair tends to turn down into the cross slope. Despite this, cross slopes are a part of everyday propulsion environments and are often necessary to facilitate water drainage. To continue moving straight ahead when on a cross slope, users must push harder on the downhill handrim. This increased loading is borne by the users' arms, which are at risk for overuse injuries. Exposure to biomechanic loading can be reduced by avoiding cross slopes when possible.

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Suppliers

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