

# Effects of side slope on wheelchair performance<sup>†</sup>

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**Abstract**—Compensation for the downhill turning moment of a wheelchair on a 2-degree side slope results in a retarding force approximately equal to the rolling drag of a wheelchair on a level surface. The total drag force on the wheelchair while transversing a sloping surface is, therefore, roughly double the rolling drag. In contrast, the net energy cost of propulsion on this side slope is only 30 percent greater than for a level surface. Side slope propulsion is managed by “dragging” the uphill rim while pushing the downhill rim. Although this results in increased mechanical efficiency through greater use of a smaller muscle mass, it is more difficult and tiring for the wheelchair user.

## INTRODUCTION

The relative ease (or difficulty) in propelling a wheelchair with handrims is dependent on several factors: namely, the weight, physical dimensions, and materials of the wheelchair, the physical dimensions and capacities of the user, the compatibility of wheelchair and user dimensions, and external factors such as the texture, hardness, and slope of the surface on which the wheelchair is operated. All these factors have been elaborated to some degree by a number of investigators. Despite impressive efforts by various investigators to quantify the effects of these different factors, there remain a substantial number of significant problems. Much of the difficulty in improving wheelchair performance is a result of

the interaction of the variables mentioned above and the fact that improvement of one factor often results in undesired changes in other factors.

One nearly universal problem is the downhill turning tendency on sloping surfaces. This results from the characteristic mass distribution of a wheelchair and its occupant relative to the wheel orientation and the fact that nearly all outdoor, improved surfaces (e.g., streets and sidewalks) are sloped for drainage. It is arguable whether this phenomenon is the most significant problem in wheelchair mobility; however, it was identified as such in a national report on technology for the handicapped (1). While most wheelchair users and others familiar with problems of wheelchair mobility would likely agree that this is a problem of significance, very little has been accomplished beyond identification of this effect as a problem.

## THE PROBLEM

The purpose of the present investigation was to identify and quantify the factors affecting direction stability of manual wheelchairs on uneven and sloping surfaces and to recommend potential means of controlling wheelchairs.

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\* “Technical Notes” are published in the *Journal* as a means of exchanging information concerning an investigator’s use of a particular scientific instrumentation or procedure, which might further the course of research. While these original notes are subject to peer review and represent an important contribution to the research literature, they lack controlled comparison studies and are thus different from “scientific articles.”

**TABLE 1**

Drag and propulsion data for standard and sport wheelchairs on level and sloped surfaces.

	0 Degrees				2 Degrees			
	standard		sport		standard		sport	
Speed, km/hr	3	4	3	4	3	4	3	4
Drag, N	7.60	7.96	6.62	6.98	15.97	15.29	14.70	13.48
Power, W	6.38	8.85	5.51	7.76	13.31	16.99	12.25	14.97
Strokes/min	41	44	41	45	42	47	42	46
Heart rate	88	91	89	86	103	106	96	100
VO <sub>2</sub> net, L/min	0.24	0.30	0.21	0.28	0.34	0.37	0.27	0.35
Energy cost, W	83.7	104.63	73.24	97.66	118.59	129.05	94.17	122.07
Mech. Eff., %	7.62	8.45	7.52	7.95	11.22	13.17	12.61	12.26
VO <sub>2</sub> /distance, L/km	4.8	4.5	4.2	4.2	6.2	5.55	5.4	5.25

\* VO<sub>2</sub> rest = 0.19 L/min; heart rate rest = 69 beats/min

## METHODS

Drag forces were determined for two different wheelchairs at 3 and 4 km/hr on a motorized treadmill with the bed level and with the bed inclined laterally at 2 degrees. These measurements were determined with the chairs tethered to a load cell attached to the front frame of the treadmill. The measurements were made with the test subject seated in the wheelchairs. The wheelchairs were "steered" for the slope condition by having the subject apply a resistive force to the uphill handrim.

Each of the above conditions was repeated with the subject propelling the wheelchairs at the pace set by the treadmill. The subject's oxygen consumption, heart rate, and stroke rate were determined while he propelled the wheelchairs. The exercise bouts were conducted over 5-minute periods with the measurements determined for the fourth and fifth minutes.

The subject was an athletic 20-year old male paraplegic (T12, L1). The wheelchairs used were a standard model with the rear axle located on the rear vertical frame member and a sport model with adjustable axle. The axle position used for the latter model was 2.5 inches in front of the rear vertical frame member. This wheelchair also had a 3-degree camber in each drive wheel.

A static analysis of the 2-degree slope condition was made to determine the downhill turning moment to provide a basis for comparison with the results of the drag tests.

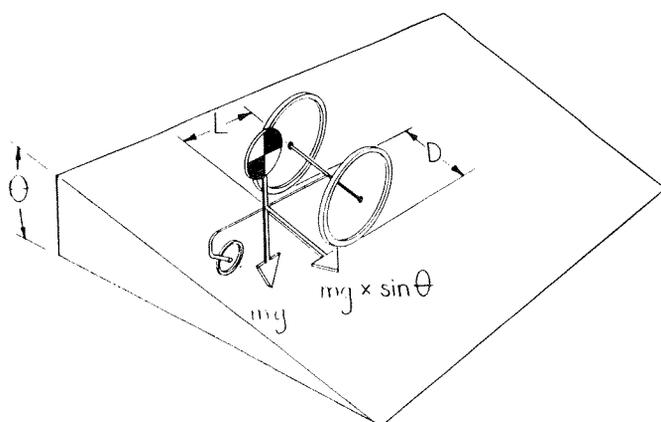
## RESULTS

The results from the drag tests and exercise tests are presented in Table 1. An inspection of this table reveals

that drag was approximately 12 percent higher for the standard wheelchair. Drag was higher for the 4 km/hr condition on the level surface, but was higher for the 3 km/hr condition on the sloped surface for both models. Further inspection of Table 1 reveals that the drag was roughly two times as large for both chairs at both speeds on the sloped surface as it was on the level surface.

The physiological effort required for the various conditions is reflected by the respective oxygen consumptions and heart rates. Both of these values were ordinarily consistent with the power requirements determined for the different conditions; however, it can be seen that the oxygen consumption increased by only about 30 percent from the level condition to the slope condition, whereas the power required to propel the wheelchairs increased more than 100 percent with respect to these conditions. These differences correspond necessarily with the mechanical efficiencies for the various conditions since the percent efficiency is based on the ratio of power required to energy cost. According to this definition, efficiency of propulsion on the sloped surface is higher. When efficiency is interpreted as the ratio of net oxygen consumption (or energy cost) to distance traveled, it can be seen that propulsion on the level surface is more efficient.

The factors that produce the downhill turning effect are identified in Figure 1. These factors include the slope ( $\theta$ ), the moment arm of the center of gravity (c.g.) about the downhill wheel ( $l$ ), the mass of the wheelchair and occupant ( $m$ ) and the distance between the wheels at the surface ( $d$ ). Therefore, downhill turning moment =  $mg l \sin \theta$ , and drag on uphill wheel =  $(mg l \sin \theta)/d$ . If  $l = 0.15$  meters,  $m = 80$  kg,  $d = 0.56$  meters, and  $\theta = 2$  degrees, then downhill turning moment = 4.1 Nm, and, required drag for uphill wheel = 7.3 N.



**FIGURE 1.**  
Static analysis of downhill turning moment.

The drag for a wheelchair with the above dimensions on a 2-degree slope would be the sum of the rolling drag and the drag necessary to counter the downhill turning moment (i.e., rolling drag + 7.3 N).

The respective differences in drag determined for the level and 2-degree slope conditions are presented in Table 2. It can be seen that the average difference for the four conditions is 7.57 N. It can also be seen that the differences are less for the 4 km/hr condition for both wheelchairs.

## DISCUSSION

An increase in drag due to the side slope was anticipated; however, the magnitude of this increase was somewhat surprising. The correspondence of the experimental results with the predicted value based on static analysis would appear to confirm the accuracy of these measurements. The higher drag values at the 3 km/hr speed for the slope condition is attributed to more frequent and higher amplitude oscillations from the line of progression. This was evident from the analog recordings of the forces with respect to the different speed conditions and was also consistent with subjective observations.

The higher mechanical efficiency obtained for the side-slope conditions may be attributed to the more favorable conditions with respect to the force-velocity relationship of the muscles and also to the fact that only one arm was used for propulsion. The significance of the latter is in part a result of having only one arm active in the recovery phase. The recovery phase typically accounts for 75 percent of the stroke time and consumes

**TABLE 2.**  
Differences in drag forces between level and slope conditions

Speed N	Standard WC		Sport WC		Average
	3	4	3	4	
	8.37	7.33	8.05	6.50	7.57

metabolic energy but does not produce any work. This explanation is reinforced by the fact that the stroke frequency was nearly constant for all test conditions.

When the ratio of energy cost to distance traveled is used as the efficiency criterion, it can be seen that propulsion on the level surface is more "efficient." This measure of efficiency is also consistent with the perceived effort by the subject for the different conditions.

It is evident from both the static analysis and the experimental results that the downhill turning moment and, correspondingly, the power requirement are decreased by moving the rear axle position closer to the center of gravity and increasing the effective wheel width dimension with camber.

Two potential design solutions to eliminate the side slope effect are the center-of-gravity (c.g.) wheelchair (c.g. positioned over the drive axle with casters in front and back) and "steerable" casters. Although a properly balanced c.g. wheelchair eliminates side-slope effect, it also eliminates the directional stability or tracking tendency of the wheelchair and, therefore, requires nearly constant steering corrections. An acceptable "steering" mechanism for casters would not require manual control or it would be self-defeating. This effectively reduces the options to a weight shift mechanism.

Two different concepts based on weight shift to control the casters are under consideration at the University of Virginia Rehabilitation Engineering Center. A design by McLaurin and Stapleton which utilizes a novel suspension mechanism on a three-wheel undercarriage has been developed to the prototype stage. This design works quite well but would be difficult to adapt to a four-wheel configuration. ■

## REFERENCE

- BROWN JW, REDDEN MR: *A Research Agenda on Science and Technology for the Handicapped*. AAAS, 1979, (Report No. 79-9-15).