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A Technical Note

Dynamic characteristics of a sport wheelchair

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Abstract—A single subject performed 36 coast-down trials on a hardwood floor in a sport model wheelchair with velocity ranging from 1.28 to 5.31 m/s (4.6 to 19.1 km/h). A portable computer attached to the wheelchair was used to record the time to the nearest 0.001-second of each half-revolution of a rear wheel. The deceleration during each trial was determined with an average coefficient of variation of 2.6 percent from linear regression of velocity versus time values. A significant relationship (r=0.97) between deceleration and the square of the velocity was noted in an analysis of the values from the 36 trials. Total drag force and power was calculated as a function of wheelchair velocity from this relationship, indicating that the power output needed to propel the wheelchair increased as a function of the velocity cubed. It is speculated that this noted exponential increase in the energy cost of wheelchair propulsion at higher speeds was due mainly to an increase in air drag.

Key words: *kinetics of propulsion, portable computers, sport wheelchairs, velocity, wheelchair athletes.*

INTRODUCTION

Voigt and Bahn (6) have previously determined the power requirements of propelling a standard wheelchair at speeds of up to 1.1 m/s (4 km/h), and for inclines up to 4 degrees with loads of 30, 50, and 70 kg in the wheelchair. Their nomogram, based on this data and the efficiency of wheelchair propulsion, provides a convenient estimate of the energy cost of wheelchair locomotion. In a more recent similar study (5), the effect of velocity (0.55 to 1.39 m/s) and inclination (0- to 3-degree slope) on power output was reported for a group of wheelchair sportsmen who used their own sport wheelchairs. The low maximal speeds in these studies, however, do not include the high speeds attained by wheelchair athletes in a number of sports. The effect of body position on the decrease in velocity of racing wheelchairs on an indoor track at speeds of up to 6 m/s was studied (3), but the measured velocity decreases were not converted into drag force or power loss values.

Other studies of high-speed wheelchair locomotion have generally focused on a kinematic description of the motion of body segments using cinematographic techniques, although the rolling resistance of the rear wheels at speeds up to 2.8 m/s (10 km/h) has been studied (4), and the air drag for a standard wheelchair and occupant has been reported for wind speeds up to 9 m/s (32.4 km/h) (1). There is limited kinetic information about the high-speed wheelchair locomotion found in a number of wheelchair sports.

The purpose of this paper is to report the total drag force and power of a sport model wheelchair on a hardwood gymnasium floor over the range of velocities normally experienced during wheelchair basketball. This information will provide some estimate of the energy requirements for propelling a sport model wheelchair on similar surfaces, and permit comparisons with past and future studies of the energy cost of wheelchair locomotion under different test conditions.

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METHODS

A commercially available sport wheelchair (Kusching of America, Champion 3000 model) commonly used by athletes for basketball, tennis, or other court games was used in this study. The wheelchair was instrumented with a magnetic switch from a cycle computer. Two magnets were mounted on the spokes of one of the rear wheels, 180 degrees apart. The switch was wired into the parallel port of a portable computer (Toshiba T1000) attached to the back of the wheelchair behind the lower back support. This placement permitted easy access to the computer, while attempting to minimize the exposed frontal area and air drag due to the computer. The computer was programmed to read and store the time to the nearest 0.001 second of each switch closure; the time for each half-revolution of the rear wheel was recorded for later processing and analysis. Details of the subject and wheelchair are contained in **Table 1**.

To determine the effect of wheelchair velocity on total drag forces and power loss, a single subject performed 36 trials involving a coast-down period at different velocities on a hardwood gymnasium floor. Each trial consisted of accelerating the wheelchair to different velocities, and then allowing the wheelchair to coast down within the limits of the length of the gymnasium. The direction of travel across the floor was reversed on alternate trials to cancel out any effect of a slope in the floor. In order to achieve velocities high enough to span actual values of a wheelchair basketball player, an assistant was used to accelerate the wheelchair prior to the coast-down period during some trials. The subject maintained an erect sitting position during the coast-down phase, with the arms held comfortably out to the side to avoid contact with the wheels and provide a standardized body position.

Table 1.
Characteristics of subject and wheelchair.

Subject's mass	76.1 kg
Wheelchair's mass	11.4 kg
Computer and attachments	3.5 kg
m (Total mass)	91.0 kg
rw (Radius of rear wheel)	.306 m
rc (Radius of front caster)—Make: Supreme Court	.06 m
lw (Moment of inertia of 2 rear wheels)	.2638 kg · m^2
lc (Moment of inertia of 2 front casters)	.0010 kg · m^2
Tires: Gray Rubber (24 x 13/8 in)—Make: Cheng Shin inflated to 450 KPa (65 psi)	
Rear wheel toe-in	0°
Rear wheel camber	6°

Table 2.
Velocity versus time correlation and regression analysis—raw data.

Trial	Correlation Coefficient	Avg. Velocity (m/s)	Acceleration (m/s/s)	SE est. (m/s/s)	Coef. of Variation (%)
1	−.9786	2.61	−.0864	.0041	4.7
2	−.9862	2.61	−.0900	.0040	4.4
3	−.9638	2.96	−.1032	.0101	9.8
4	−.9800	2.86	−.0971	.0049	5.0
5	−.9752	2.91	−.1026	.0062	6.0
6	−.9248	2.84	−.0902	.0112	12.4
$\bar{X}$	−.9681	2.80	−.0949	.0068	7.1
S.D.	.0225	.15	.0071	.0031	3.3

The linear velocity of the wheelchair was calculated for each recorded time interval which represented the linear displacement equivalent to one-half the circumference of the rear wheel (0.958 m), based on a measured diameter of 61 cm. The coast-down portion of each trial involved a distance of about 20 m; approximately the same number of consecutive wheelchair velocity determinations were obtained in each trial. Each velocity was considered to be the instantaneous velocity at the mid-point of the time interval that the displacement occurred. The average acceleration during the coast-down period of each trial was determined from linear regression analysis of the velocity versus time data.

The error associated with this method of determining the coast-down acceleration was determined in a preliminary analysis of the first six trials. **Figure 1** presents the velocity versus time plot for a complete trial (Trial 1), showing the initial acceleration (0 to 6 seconds), coast-down period (6 to 13 seconds), and the final stopping phase (13 to 15 seconds). An initial linear regression analysis of the raw data (indicated by "X" and a dotted line in **Figure 1**) during the coast-down period for each of the first six trials was carried out, and the results of these analyses are shown in **Table 2.** The coefficient of variation for the acceleration value in each trial averaged 7.1 percent, with a range of 4.4 to 12.4 percent. Visual inspection of the data (as in **Figure 1**) indicated an alternating high and low

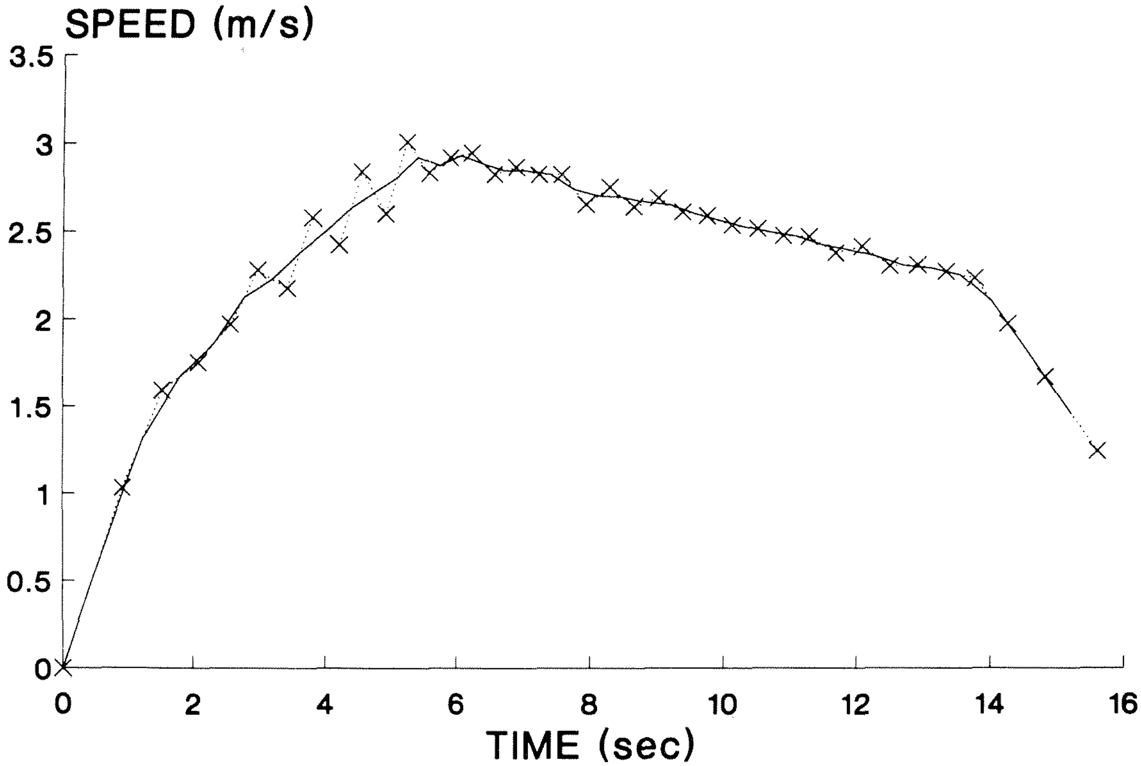

Figure 1.
Velocity versus time curve for trial (X · · · , raw data; ——— , smoothed data).

variation of the velocity values during even relatively smooth portions of the coast-down period. Since this variation would reflect error in placing the two magnets exactly 180 degrees from each other on the wheel, a moving average of every two velocity values was calculated to eliminate this problem. This recalculation is equivalent to calculating a velocity value for each complete revolution of the wheel, which is updated at each one-half revolution. The solid line in **Figure 1** is a plot of these smoothed velocity values. **Table 3** presents the results of the regression analyses for the smoothed data. The average coefficient of variation in determining the acceleration was reduced to 2.8 percent, with the highest coefficient being 4.9 percent. The smoothing technique was thus applied to the data for all 36 trials, and the linear correlations within a trial between velocity and time ranged from 0.95 to 0.99. The average coefficient of variation in estimating the coast-down acceleration was 2.6 percent (range 1.0 to 8.2 percent).

Table 3.
Velocity versus time correlation and regression analysis—smoothed data.

Trial	Correlation Coefficient	Avg. Velocity (m/s)	Acceleration (m/s/s)	SE est. (m/s/s)	Coef. of Variation (%)
1	−.9947	2.63	−.0865	.0020	2.3
2	−.9984	2.63	−.0901	.0014	1.6
3	−.9905	2.97	−.1055	.0052	4.9
4	−.9941	2.88	−.0982	.0027	2.7
5	−.9935	2.93	−.1041	.0032	3.1
6	−.9967	2.86	−.0920	.0022	2.4
$\bar{X}$	−.9946	2.82	−.0961	.0028	2.8
S.D.	.0027	.15	.0078	.0013	1.1

The acceleration and average velocity of the 36 trials were then subjected to regression analysis to obtain a mathematical relationship between acceleration and the square of velocity. The total drag force and power loss as a function of velocity were then calculated from this relationship using the following equations, where "a" is the acceleration: the values for the other symbols are contained in **Table 1**.

$$\text{Total drag force (N)} = ma + (lw \times a/r_w)/r_w + (lc \times a/r_c)/r_c$$

$$\text{Power (w)} = \text{Total drag force (N)} \times \text{velocity (m/s)}$$

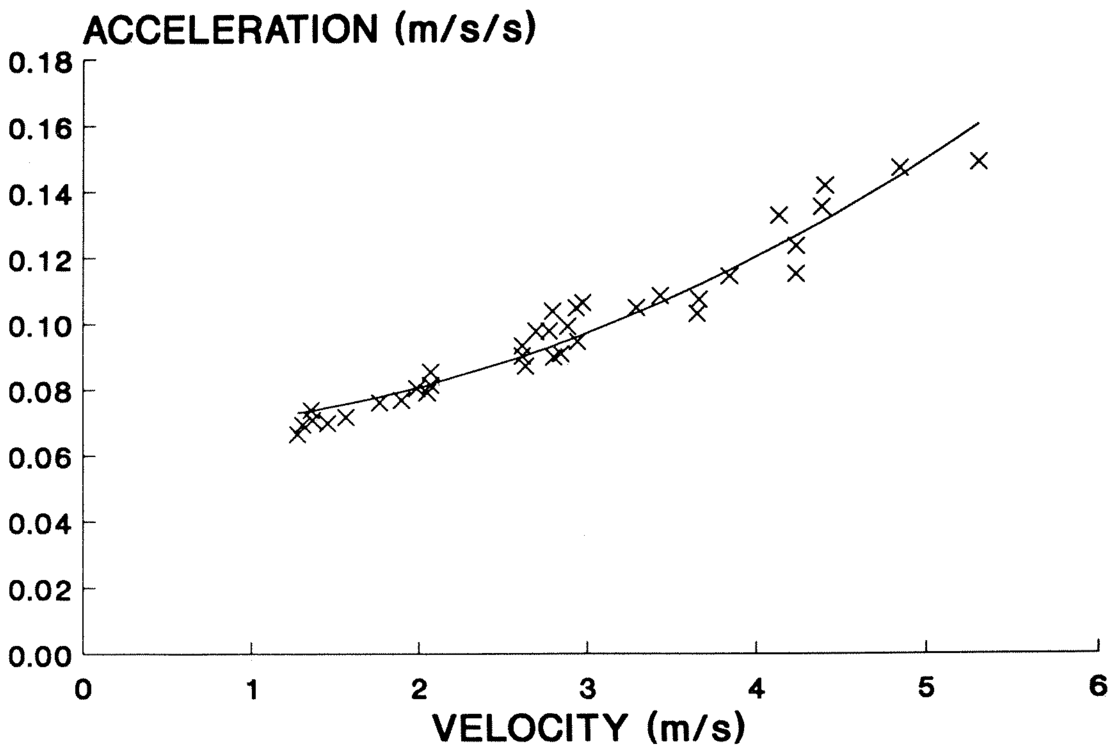

Figure 2.
Regression line and individual data points (X) for acceleration versus wheelchair velocity relationship.

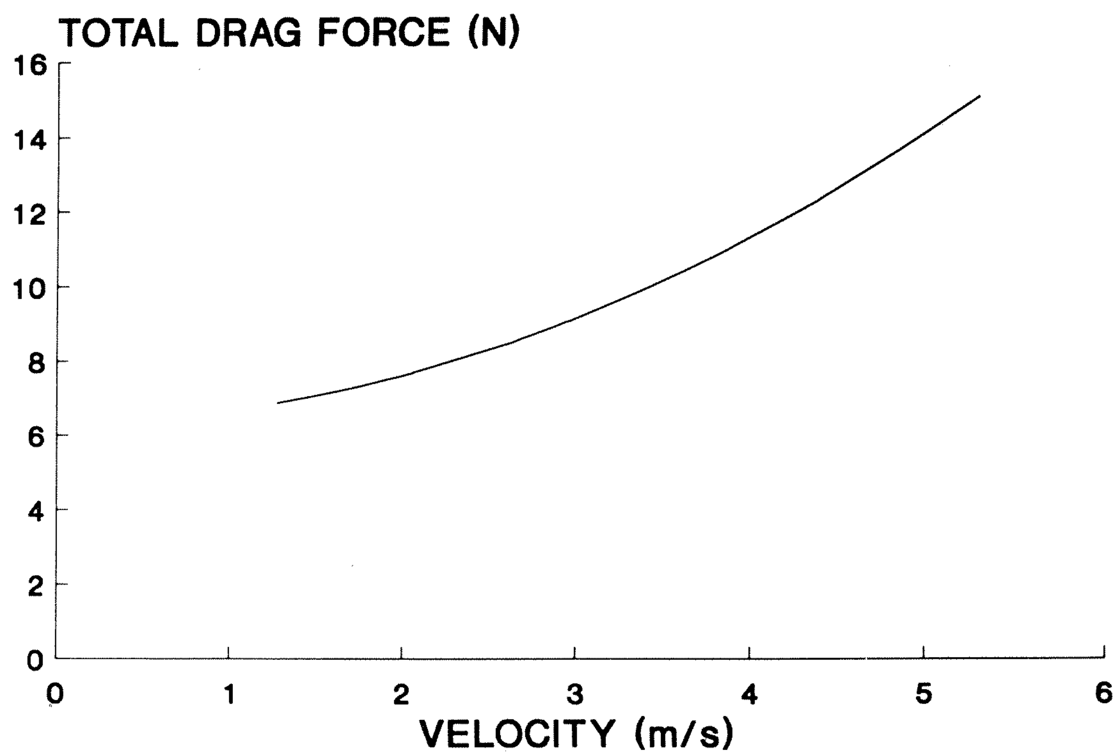

Figure 3.
Calculated total drag force versus wheelchair velocity.

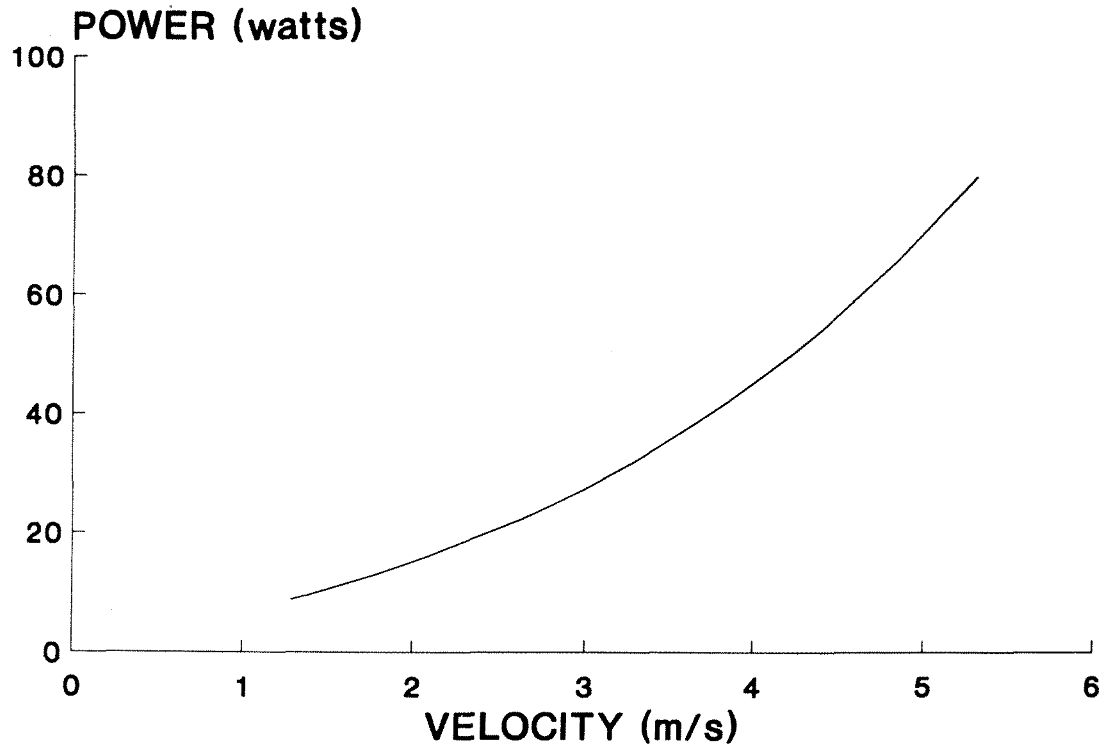

Figure 4.
Calculated power versus wheelchair velocity.

RESULTS

A significant ($p < 0.05$) linear correlation ($r = 0.97$) was found between the wheelchair deceleration values and the square of average coast-down velocity in the 36 trials. **Figure 2** presents a plot of the acceleration versus velocity data points and the regression line for this relationship. The average coast-down velocity ranged from 1.28 to 5.31 m/s (4.6 to 19.1 km/h), and the regression line in **Figure 2** has not been extrapolated beyond this range. The regression equation, acceleration (m/s/s) = $0.0675 + 0.0033 \times \text{velocity}^2$, may be used to estimate values outside the range of the recorded data. **Figure 3** and **Figure 4** are plots of the calculated total drag force and power versus velocity, respectively, based on the regression equation and previously noted formulas.

DISCUSSION

The use of an on-board portable computer to record serial time measurements of each half-revolution of a rear wheel provided a simple and relatively inexpensive method for accurate determination of the deceleration during the coast-down trials in this study. The analysis of the effect of wheelchair velocity on this deceleration, with subsequent calculation of drag force and power loss, serves as an example of possible uses of this basic recording technique. The influence of other factors such as tire pressure, ground surface, body weight, etc., on the kinetics of wheelchair propulsion could also be studied under laboratory or field conditions. Detailed kinematic and kinetic data of a patient's locomotor activity or a wheelchair athlete's performance in a race are also plausible applications of this basic recording technique.

A value of 7.4 W was calculated as the power required for propelling a sport model wheelchair at a speed of 1.1 m/s (4 km/h) with a laden weight of about 80 kg (subject plus computer and attachments) on a hardwood floor. This is well below a 12 W value obtained using Voigt and Bahn's nomogram (6), and reflects the advantage of a sport model wheelchair over earlier, heavier models and/or tire, surface, or other differences between the two studies. An estimated power output value for sport model wheelchairs of about 7.5 W at a speed of 1.11 m/s (4 km/h) from another study (5) is in close agreement with the present value, but differences in body mass and ground surface (treadmill belt versus hardwood floor) between the two studies prohibit further comparison of this similarity.

The general finding in this study of a significant relationship between wheelchair deceleration and velocity squared (which includes velocities approaching those obtained in wheelchair racing), means that the power drain and muscular power input will increase in relation to the cube of the velocity increase. This is consistent with the analysis of wheelchair racing results by Coutts and Schutz (2) in which it was noted that the 1984 fastest sprint racing speed of 6.43 m/s was not a great deal higher than the fastest 5,000 m speed of 5.75 m/s. Based on a cubic relationship between speed and power, this 12 percent increase in average racing speed from long distance to sprint events would require a 40 percent increase in power input by the athlete.

While determination of the factors responsible for this exponential increase in power loss with increasing velocity is beyond the scope of this study, it can be speculated that air drag is the main factor responsible for this noted increase. This suggestion is based on the relatively low values and relative linear increase in power loss due to rolling resistance as determined for similar pneumatic tires inflated to a lower pressure of 45 psi for speeds of up to 2.8 m/s (10 km/h) (4), and the relatively high and similar exponential increase in air drag, expressed as power, for a wheelchair and occupant (1).

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