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THE EFFECT OF STEERING ON THE PHYSIOLOGICAL ENERGY COST OF WHEELCHAIR PROPULSION

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ABSTRACT. Previous studies of the energy cost of wheelchair propulsion have used ergometers or tracks requiring little steering. We have measured minute ventilation ($\dot{V}E$), oxygen consumption ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$) and heart rate (HR) during exercise in a two arm, hand-rim propulsion wheelchair on a treadmill, and on three tracks of increasing tortuosity in eight able-bodied subjects. During propulsion at 0.6 m/sec, $\dot{V}E$, $\dot{V}O_2$, and $\dot{V}CO_2$ were significantly greater on the track with the maximal steering component than on that with the minimal steering component, or on the treadmill with no steering component. Heart rate was significantly higher on the maximal compared to minimal steering component track. Exercise at speeds varying from 0.2 to 1.0 m/sec showed that $\dot{V}O_2$ and $\dot{V}CO_2$ were significantly higher on the medium steering component track than on the treadmill at speeds of 0.6 m/sec and above. We conclude that the effort of steering contributes significantly to the energy cost of wheelchair propulsion particularly at higher speeds.

Key words: energy metabolism, exertion, oxygen consumption, wheelchairs.

Many mechanical factors affect the physiological energy cost of wheelchair propulsion (6) such as position of the drive wheels (7), the gear ratio between the hand operated mechanism and the drive wheels (3), the mechanism of propulsion (12, 13), rolling resistance which depends mainly on tyre and castor pressure (8), and the floor surface (5). Previous studies to determine the energy cost of wheelchair propulsion (2, 5, 7, 12, 13), to evaluate changes in wheelchair design (3), or to compare exercise capabilities in different populations (12) have used either a wheelchair ergometer (2, 3, 11), treadmill (7), or a relatively straight track (5, 13). All these methods involve little or no steering. However, normal wheelchair use requires manoeuvering around obstacles such as furniture or through doors. Observations suggest that steering a wheelchair must consume an appreciable amount of energy since, in a conventional wheelchair which is propelled by using both arms on the hand-rims of the large rear drive wheels, steering is achieved by braking one wheel (or even rotating backwards) while driving the opposite wheel forward. We have therefore studied the effect of steering on the energy cost of wheelchair propulsion using two arm hand-rim propulsion in a conventional wheelchair.

METHODS

Subjects

Eight clinically healthy able-bodied subjects (3 M, 5 F; age 22–43 years; height 1.54–1.81 m; weight 62.3–91.0 kg) were recruited from laboratory staff.

Physiological measurements

The subjects breathed through a two-way valve held in place with a head support (Hans Rudolf 2-way valve model 2 600 and head support). Expired gas was collected in Douglas bags and analysed for expired volume (Tissot spirometer), oxygen (Servomex O_2 analyser Model 570 A), and carbon dioxide (Gould Capnograph Mark III) concentrations. Minute ventilation ($\dot{V}E$ l/min BTPS). Oxygen consumption ($\dot{V}O_2$, l/min STPD) and carbon dioxide output ($\dot{V}CO_2$, l/min STPD), and the respiratory exchange ratio (*R*) were calculated. Heart rate (HR) was recorded using either a Hewlett Packard 78351 A monitor (treadmill studies), or a Polar Electro PE-3 000 monitor (track studies). An Everest and Jennings wheelchair (model 8 AU 25.46.770) was used for the studies. The subjects were familiarised with 2-arm hand-rim wheelchair propulsion under the experimental conditions prior to the study day. Wheelchair tyre pressure was kept at 45 psi for all studies. Ethical permission for the studies was given by the Lothian Health Board Medicine and Clinical Oncology Ethics of Medical Research Sub-Committee. The subjects gave verbal consent to participating in the studies after the nature and purpose had been explained to them.

The effect of steering at 0.6 m/sec

Measurements were made in seven of the normal subjects (3 M, 4 F) seated at rest in the wheelchair, and during exercise in the wheelchair at 0.6 m/sec (1.5 mph) on a level treadmill (Woodway ELG2) which involved no steering component,

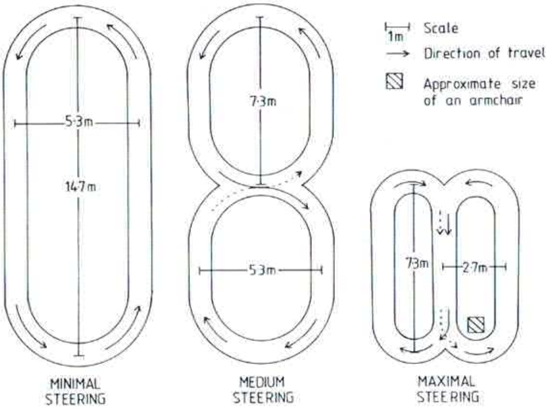

Fig. 1. Scale drawings of the three tracks. The arrows indicate the direction of travel. The angle of the turns on the track with maximal steering were similar to those encountered in everyday life as indicated by the cross-hatched area which represents the approximate size of a domestic armchair.

and on three level tracks of increasing tortuosity (Fig. 1). Steering was eliminated on the treadmill by a guide bar which connected the right castor wheel of the wheelchair to a bar running parallel to the treadmill surface at approximately floor level. The guide bar limited rotational movement of the front castors thus maintaining the direction of the wheelchair on the treadmill without limiting forward or backward movement of the wheelchair. The three tracks were marked out on a wooden floor and were designed to provide minimal, medium and maximal steering components, the last with turning angles equivalent to manoeuvres in the home (Fig. 1). The tracks were also marked at 0.6 metre intervals. To achieve a constant speed of wheelchair propulsion on the tracks, one of the investigators, using a stopwatch, paced between the markers at the required speed of 0.6 m/sec, and the subject was instructed to follow closely behind. The subjects kept the wheelchair within 1 and 3 metres of the investigator during exercise on the tracks. The direction of travel on the tracks with medium and maximal steering components was in a figure-of-eight to ensure similar numbers of right and left hand turns. Minute ventilation, $\dot{V}O_2$, $\dot{V}CO_2$, and R were measured over duplicate 2-min periods after 8 min seated at rest and after 6- min exercise at a constant speed. The mean values were used in subsequent analysis. Heart rate was recorded simultaneously every 5 sec and the mean value over the 2-min study periods was calculated.

The four levels of steering were studied in randomised order, with each study separated by at least 10 min rest. The results were compared using Friedman's non-parametric analysis of variance, with Wilcoxon's critical range method for testing all possible pairs (1).

The effect of steering at different speeds of propulsion

Measurements were made in all eight normal subjects (3 M, 5 F) seated in the wheelchair at rest, and during exercise both on the treadmill with no steering involved, and on the track with the medium steering component (Fig. 1) at 0.2, 0.4, 0.6, 0.8, and 1.0 m/sec. The speed of propulsion increased every 2-min. Minute ventilation, $\dot{V}O_2$, $\dot{V}CO_2$, R, and heart rate were measured over duplicate 2-min periods after 8 min seated at rest and the mean values calculated. On exercise, measurements were made during the second minute at each level of exercise. The order of treadmill and track studies was randomised. The differences between measurements on the treadmill and the track at each speed were compared using Wilcoxon's rank test for paired data.

To validate the Polar Electro PE 3000 monitor, heart rate was measured simultaneously with both heart rate monitors during the studies at rest and on the treadmill. The mean of the 5-sec average value recorded by the PE 3000 monitor during the last minute of rest and at each level of exercise was calculated and compared with the mean of the heart rate recorded every 5 sec by the Hewlett Packard monitor over the same period. Heart rate measured by the two monitors was compared by linear regression.

RESULTS

Validation of the PE 3000 Heart Rate Monitor

Heart rate measured by the two monitors was related by the relationship:

$$\text{HR (PE 3000)} = 0.99 \times \text{HR (Hewlett Packard)} + 0.96 \text{ (beats/min)}$$

with a correlation coefficient of 0.99.

Effects of steering at 0.6 m/sec

At rest, the mean values (±SD) were $\dot{V}E$ 8.0±0.6 l/min, $\dot{V}O_2$ 0.24±0.03 l/min, $\dot{V}CO_2$ 0.22±0.02 l/min, R 0.92±0.06, and HR 70±9 beats/min. Minute ventilation, $\dot{V}O_2$ and $\dot{V}CO_2$ were similar during exercise on the treadmill and on the track with minimal steering, but increased progressively on the tracks with medium and maximal steering components (Fig. 2). These variables were significantly greater on the track with the maximal steering component than on either the track with the minimal steering component ($\dot{V}E$ $p<0.05$; $\dot{V}O_2$ and $\dot{V}CO_2$ $p<0.01$), or the treadmill ($\dot{V}O_2$ $p<0.01$; $\dot{V}E$ and $\dot{V}CO_2$ $p<0.05$). Heart rate tended to be lower on the track involving minimal steering than on the treadmill, but then tended to increase with the amount of steering required (Fig. 2). There was a significant difference between the heart rate on the tracks with minimal and maximal steering components ($p<0.01$). The respiratory exchange ratio R did not differ at any grade of steering.

The effect of steering at different rates of propulsion

At rest, the mean values (±SD) were $\dot{V}E$ 7.4±0.8 l/min, $\dot{V}O_2$ 0.24±0.02 l/min, $\dot{V}CO_2$ 0.20±0.02 l/min, R 0.85±0.05, and HR 72±11 beats/min. All vari-

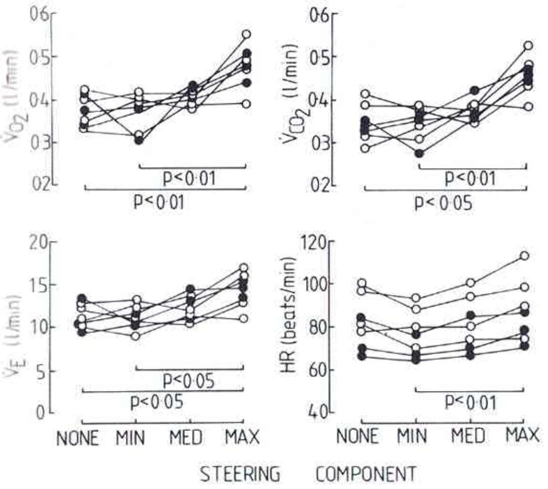

Fig. 2. Oxygen consumption ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$), minute ventilation ($\dot{V}E$), and heart rate (HR) in seven normal subjects (●, males; ○, females) during two arm hand-rim propulsion of a wheelchair on the treadmill with no steering component (none), and the three tracks with minimal (min), medium (med), and maximal (max) steering components. All four variables were similar on the treadmill and the track with minimal steering component, but then rose with increasing steering component.

ables increased progressively with increasing rate of propulsion on both the treadmill and the track (Table I). There was no significant difference between any of the variables during exercise on the treadmill and on the track at speeds of 0.2 and 0.4 m/sec (Fig. 3). At 0.6, 0.8 and 1.0 m/sec, $\dot{V}O_2$ and $\dot{V}CO_2$ were significantly higher during exercise on the track than on the treadmill *($p<0.01$* except for $\dot{V}CO_2$ at 0.6 m/sec where $p<0.02$; Fig. 3). Minute ventilation and HR tended to be higher on the track than on the treadmill at speeds of 0.6 and above, but this was only significant at 1.0 m/sec ($\dot{V}E$, $p<0.01$; HR, $p<0.02$; Fig. 3). There was no difference in *R* between treadmill and track at any speed.

DISCUSSION

In a study of able-bodied subjects, we have shown that $\dot{V}E$, $\dot{V}O_2$, $\dot{V}CO_2$ and HR were significantly higher during exercise in a two-arm hand-rim propulsion wheelchair on a track which involved manoeuvering the wheelchair around sharp turns than on a track which had wide turns, or on a treadmill where steering was eliminated. The differences were significant

Table 1. *Ventilation, gas exchange, and heart rate at five rates of propulsion on the treadmill and on the track with the medium steering component in eight normal subjects*

$\dot{V}O_2$, oxygen consumption (l/min STPD); $\dot{V}CO_2$, carbon dioxide output (l/min STPD); $\dot{V}E$, minute ventilation (l/min BTPS); HR, heart rate (beats/min). Results given as mean ±SD for the eight subjects. Values on the track significantly higher than on the treadmill at the $p<0.02$ (*) or $p<0.01$ (**) levels

	Speed of propulsion (m/sec)				
	0.2	0.4	0.6	0.8	1.0
Treadmill					
$\dot{V}O_2$ (l/min)	0.29	0.36	0.39	0.41	0.47
	±0.03	±0.04	±0.04	±0.07	±0.07
$\dot{V}CO_2$ (l/min)	0.24	0.30	0.34	0.37	0.43
	±0.04	±0.05	±0.07	±0.08	±0.06
$\dot{V}E$ (l/min)	9.19	10.92	11.94	12.84	14.39
	±1.21	±1.76	±2.50	±3.11	±2.02
HR (beats/min)	75	79	83	86	90
	±15	±15	±14	±16	±18
Track					
$\dot{V}O_2$ (l/min)	0.30	0.35	0.46**	0.54**	0.75**
	±0.02	±0.05	±0.05	±0.08	±0.17
$\dot{V}CO_2$ (l/min)	0.25	0.30	0.40*	0.48**	0.75**
	±0.04	±0.06	±0.06	±0.08	±0.19
$\dot{V}E$ (l/min)	9.03	10.25	12.69	15.50	22.83**
	±1.74	±1.31	±1.90	±3.24	±7.60
HR (beats/min)	76	82	87	94	109*
	±12	±13	±13	±14	±18

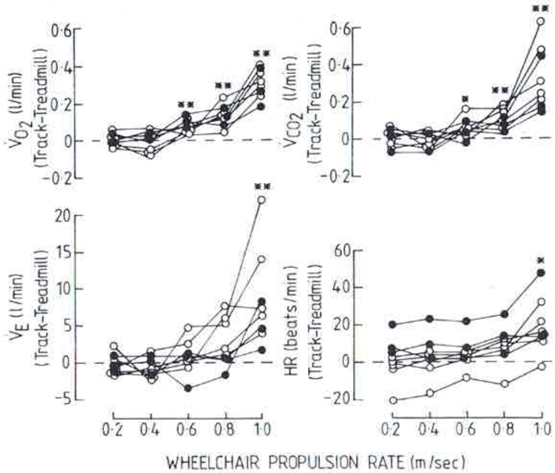

Fig. 3. Differences in oxygen consumption ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$), minute ventilation ($\dot{V}E$), and heart rate (HR) between two arm hand-rim propulsion on the track and on the treadmill at five speeds of propulsion in eight normal subjects (●, males; ○, females). All four variables tended to be higher during exercise on the track than on the treadmill at speeds of 0.6 m/sec and above. Significant differences are indicated as * $p<0.02$, ** $p<0.01$.

at propulsion speeds of 0.6 m/sec (1.5 mph) and above. These results suggest that the effort of steering contributes significantly to the overall energy cost of wheelchair propulsion particularly at higher speeds.

Factors other than steering which may have contributed to the observed differences in energy utilisation must be considered. A treadmill was used to measure the energy cost of propulsion under conditions in which the steering component could be eliminated. The rolling resistance produced by the floor surface is known to affect the energy utilisation required for wheelchair propulsion (4, 5). The surface of treadmill, consisting of a continuous belt of 5.5 cm wide by 1 cm deep rubber slats, will have generated a different rolling resistance than the wooden floor of the tracks. Furthermore, unlike an ordinary floor, the treadmill provides a continuously moving surface. The friction between the moving treadmill belt and the tyres may have helped rotate the wheels of the wheelchair in the direction of travel thus aiding forward propulsion. The effect of these individual factors on the energy cost of wheelchair propulsion is unknown, but the net effect was unimportant since $\dot{V}E$, $\dot{V}O_2$, $\dot{V}CO_2$ and HR were similar on the treadmill and on the track with the minimal steering component. Furthermore, the significant differences seen in $\dot{V}E$, $\dot{V}O_2$, $\dot{V}CO_2$ and HR on the tracks with minimal and maximal steering components, where the floor surface was the same, support the hypothesis that act of steering contributes to the energy cost of propulsion. It is interesting to note that the significant increases which occurred during exercise were on the track with the maximal steering component which simulated most closely the degree of steering encountered in everyday life.

Factors relating to body size (arm length, body weight, seated height) also affect the energy cost of wheelchair propulsion (14). Since the subjects varied in stature the effect of these factors will have differed between them. However, each subject acted as his or her own control and any effect of body size was therefore constant at the various levels of steering.

A change in the direction of propulsion increases the friction between the tyres and floor, and this probably contributed to the increased energy utilisation while manoeuvering the wheelchair. However, steering using two arm hand-rim propulsion of a conventional wheelchair is achieved by braking a wheel with one arm whilst using the contralateral arm to drive the opposite wheel forward. Thus the total work done will be a combination of static (isometric) exercise by the arm involved in braking one wheel, with increased dynamic (isotonic) exercise of the contralateral arm to maintain the same forward speed of propulsion. Since the cardiorespiratory demands of simultaneous static and dynamic exercise have been shown to exceed that of dynamic exercise alone (10), the effect of steering on the energy cost of two arm hand-rim propulsion, as seen in this study, probably reflects the additional static exercise of braking one wheel.

The direct effect of steering on the energy cost of wheelchair propulsion has not been demonstrated previously. Glaser & Collins (4) found that $\dot{V}E$ and $\dot{V}O_2$ were not higher during two arm hand-rim propulsion on a track than when using a wheelchair ergometer set at the same wheel velocity and mechanical power output. However, it is unlikely that steering was a major factor in their studies since they used a 107 metre octagonal course which would provide a degree of steering similar to our track with the minimal steering component (Fig. 1).

In our studies at different rates of propulsion, the effort of steering did not significantly affect gas exchange at speeds below 0.6 m/sec (approximately 1.5 mph), or $\dot{V}E$ and HR at speeds below 1.0 m/sec (approximately 2.5 mph). Observations of the speeds at which recently disabled patients self-propelled their wheelchairs around the wards of the Rehabilitation

Unit showed that the preferred speeds varied between 0.3 and 0.4 m/sec (0.7–0.9 mph). Thus steering would appear to have little effect on energy expenditure at the low speeds at which severely disabled patients normally self-propel their wheelchairs. However, the subjects participating in this study were relatively young (22–43 years) and able-bodied. Sawka and colleagues (12) using a wheelchair ergometer found that the maximal power output and peak $\dot{V}O_2$ reached by healthy subjects aged between 50–60 years was less than half the levels achieved by young adults aged between 20–30 years. Therefore the effort of steering may possibley contribute to energy expenditure even at low speeds of propulsion for disabled middle-aged and elderly people who constitute the majority of wheelchair users.

The steady state exercise conditions used in this study in order to measure gas exchange (9) do not, of course, simulate normal wheelchair usage. In everyday life, most wheelchair users undertake short bursts of activity, and probably compensate for the additional energy requirements of steering by reducing the speed of propulsion. Nevertheless, these results show that the effort of steering does contribute significantly to the overall energy cost of wheelchair propulsion. Thus use of treadmills, wheelchair ergometers, or tracks involving minimal steering for studying the cardiorespiratory responses during wheelchair propulsion, in particular for assessing improvements in wheelchair design, may miss a significant component of the energy cost of self-propulsion.

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