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 (VE), oxygen consumption (VO₂), carbon dioxide output (VCO₂) 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, VE, VO₂ and VCO₂ 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 VO₂ and VCO₂ 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 caster pressure (8), and the floor surface (3). 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 maneuvering 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 bracing 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 2600 and head support). Expired gas was collected in Douglas bags and analysed for expired volume (Tissot spirometer), oxygen (Servomex O₂ analyser Model 570 A), and carbon dioxide (Gould Capnomatograph Mark III) concentrations. Minute ventilation (VE) (lit/min BTPS), oxygen consumption (VO₂) (lit/min BTPS) and carbon dioxide output (VCO₂) (lit/min BTPS), and the respiratory exchange ratio (R) were calculated. Heart rate (HR) was recorded using either a Hewlett Packard 7133A monitor (treadmill studies), or a Polar Electro P6-3000 monitor (track studies). An Everest and Jennings wheelchair (model 8 AU 25.48-770) 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 was similar to those encountered in everyday life as indicated by the circumscribed 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 caster 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 casters 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 maneuvers in the home (Fig. 1). The tracks were also marked at 0.6 meter 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 meter/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, VO₂, VCO₂, and R were measured over duplicate 2-minute 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-minute 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 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, VO₂, VCO₂, R, and heart rate were measured over duplicate 2-minute 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 3 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:

HR (PE 3000) = 0.99 × HR (Hewlett Packard) + 0.96 (beats/min)

with a correlation coefficient of 0.99.

Effects of steering at 0.6 m/sec

At rest, the mean values (± SD) were VE 8.0 ± 0.6 l/min, VO₂ 0.24 ± 0.03 l/min, VCO₂ 0.02 ± 0.02 l/min, R 0.92 ± 0.06, and HR 70.9 ± 9.6 beats/min. Minute ventilation, VO₂, and VCO₂ 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 (VE p < 0.05; VO₂ and VCO₂ p < 0.01), or the treadmill (VO₂ p < 0.01; VE and VCO₂ 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 VE 7.4 ± 0.8 l/min, VO₂ 0.24 ± 0.02 l/min, VCO₂ 0.20 ± 0.02 l/min, R 0.85 ± 0.05, and HR 72.1 ± 11 beats/min. All variables increased progressively with increasing rate of propulsion on both the treadmill and the track (Table 1). 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, VO₂ and VCO₂ were significantly higher during exercise on the track than on the treadmill (p < 0.01 except for VCO₂ 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 (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 VE, VO₂, VCO₂, and HR were significantly higher during exercise in a two-arm hand-propulsion wheelchair on a track which involved maneuvering 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.
and on three level tracks of increasing tortuosity (Fig. 1). Steering was eliminated on the treadmill by a guide bar which connected the right caster 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 casters 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 out 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, VO₂, VCO₂, 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 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, VO₂, VCO₂, R, and heart rate were measured over duplicate 2-min periods after 8 min seated at rest and the mean values were 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 sum 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 3 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:

HR (PE 3000) = 0.99 × HR (Hewlett Packard) + 0.96 (beats/min)

with a correlation coefficient of 0.99.

Effects of steering at 0.6 m/sec

At rest, the mean values (±SD) were VE 8.0 ± 0.6 l/min, VO₂ 0.24 ± 0.03 l/min, VCO₂ 0.22 ± 0.02 l/min, R 0.92 ± 0.06, and HR 70.9 ± 8.3 beats/min. Minute ventilation, VO₂ and VCO₂ 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 (VE: p<0.05; VO₂ and VCO₂: p<0.01), or the treadmill (VO₂: p<0.01; VE and VCO₂: 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

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Table 1. Fentanyl, 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

<table>
<thead>
<tr>
<th>Speed of propulsion (m/sec)</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treadmill VO₂ (l/min)</td>
<td>0.29</td>
<td>0.30</td>
<td>0.39</td>
<td>0.41</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>±0.03</td>
<td>±0.04</td>
<td>±0.06</td>
<td>±0.07</td>
<td>±0.09</td>
</tr>
<tr>
<td>Treadmill VCO₂ (l/min)</td>
<td>0.24</td>
<td>0.30</td>
<td>0.34</td>
<td>0.37</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>±0.04</td>
<td>±0.05</td>
<td>±0.07</td>
<td>±0.08</td>
<td>±0.06</td>
</tr>
<tr>
<td>Treadmill VE (l/min)</td>
<td>9.19</td>
<td>10.92</td>
<td>11.84</td>
<td>12.84</td>
<td>14.39</td>
</tr>
<tr>
<td></td>
<td>±1.21</td>
<td>±1.76</td>
<td>±2.56</td>
<td>±3.11</td>
<td>±2.02</td>
</tr>
<tr>
<td>Track HR (beats/min)</td>
<td>75</td>
<td>79</td>
<td>83</td>
<td>86</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>±5</td>
<td>±7</td>
<td>±14</td>
<td>±16</td>
<td>±18</td>
</tr>
<tr>
<td>Track VO₂ (l/min)</td>
<td>0.30</td>
<td>0.35</td>
<td>0.46**</td>
<td>0.54**</td>
<td>0.75**</td>
</tr>
<tr>
<td></td>
<td>±0.02</td>
<td>±0.05</td>
<td>±0.05</td>
<td>±0.08</td>
<td>±0.17</td>
</tr>
<tr>
<td>Track VCO₂ (l/min)</td>
<td>0.25</td>
<td>0.30</td>
<td>0.40**</td>
<td>0.48**</td>
<td>0.55**</td>
</tr>
<tr>
<td></td>
<td>±0.04</td>
<td>±0.06</td>
<td>±0.06</td>
<td>±0.08</td>
<td>±0.19</td>
</tr>
<tr>
<td>Track VE (l/min)</td>
<td>9.03</td>
<td>10.23</td>
<td>12.69</td>
<td>15.50</td>
<td>22.83**</td>
</tr>
<tr>
<td></td>
<td>±1.74</td>
<td>±1.31</td>
<td>±1.90</td>
<td>±3.24</td>
<td>±2.60</td>
</tr>
<tr>
<td>Track HR (beats/min)</td>
<td>76</td>
<td>82</td>
<td>87</td>
<td>94</td>
<td>109**</td>
</tr>
<tr>
<td></td>
<td>±12</td>
<td>±13</td>
<td>±14</td>
<td>±14</td>
<td>±18</td>
</tr>
</tbody>
</table>
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 utilization 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 the treadmill, consisting of a continuous belt of 5.5 cm wide by 1 cm deep rubber slats, would 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 VE, VO₂, VCO₂ and HR were similar on the treadmill and on the track with the minimal steering component.

Furthermore, the significant differences seen in VE, VO₂, VCO₂ and HR on the tracks with minimal and maximal steering

ACKNOWLEDGEMENTS

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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 tires and floor, and this probably contributed to the increased energy utilisation when maneuvering 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 (isometric) 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 VE and VO₂ 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 VE 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 VO₂ reached by healthy subjects aged between 50-60 years was less than the levels achieved by young adults aged between 20-30 years. Therefore the effort of steering may possibly 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 handrim, 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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