Pushing Economy and Propulsion Technique of Wheelchair Racers at Three Speeds

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Pushing economy and wheelchair propulsion technique were examined for 8 wheelchair racers on a motorized treadmill at 6.0, 6.5, and 7.0 m/s. Kinematic data for the sagittal view were collected by a video camera for two-dimensional analysis. Adaptations to speed changes occurred, initially by a decrease in cycle time and an increase in cycle rate, and later by an increase in the flexion of the elbow. At each speed there were large variations in pushing economy between individuals. The relationship between pushing economy and selected kinematic variables revealed that at 6.0, 6.5, and 7.0 m/s, economy was associated with (a) the lighter athletes \( r = .89, .86, .83 \), (b) a greater range of elbow movement \( r = -.85, -.65, -.63 \), and (c) a lower push rate \( r = .73, .81, .63 \), respectively. Effects of lesion level and wheelchair design may be more important in explaining differences in pushing economy than differences in propulsion technique.

Morgan, Martin, and Krahenbuhl (1989) have suggested that running economy (submaximal oxygen consumption) is a good predictor of long distance running performance, and changes in economy during running at a given speed are likely to lead to changes in performance (Cavanagh, 1990). Compared to the volume of studies on running economy, relatively few investigations have directly examined pushing economy. Pushing economy is defined as the energy cost (oxygen uptake) of wheelchair propulsion at a constant fixed speed (Lakomy & Williams, 1996).

It has been clearly shown that running economy is linked to the mechanics of running style (Bransford & Howley, 1977; Cavanagh, 1990; Cavanagh & Williams, 1982; Daniels, 1985; Morgan et al., 1989). For the wheelchair racer, far less research is available to provide insight into how variables related to propulsion mechanics affect pushing economy (Goosey, Campbell, & Fowler, 1996; Jones, Baldini, Cooper, Robertson, & Widman, 1992).

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Many researchers have examined wheelchair design features such as seat height, handrim size, and camber (Masse, Lamontagne, & O’Riain, 1992; Veeger, Woude, & Rozendal, 1988; Veeger, Woude, & Rozendal, 1989; Woude, Veeger, Rozendal, Ingen Schenau, Rooth, & Nierop, 1988). These variables that affect wheelchair propulsion style have an effect on the cardiorespiratory responses during wheelchair ergometry. For example, Woude and coworkers (1988) reported a 10% rise in VO₂ during wheelchair propulsion with large handrims of 0.56 m, compared with the smallest handrim size of 0.30 to 0.35 m. Veeger et al. (1988) also found that smaller handrims (0.31 m) are associated with reduced cardiorespiratory stress. Similar to findings of Woude and coworkers (1988), Veeger et al. (1988) reported a 10 to 15% difference in oxygen cost between the 0.31 m handrims and the 0.56 m handrims. It was also noted that, as the handrim increased in size, there was a significant effect on the movement pattern of the upper arm in both the sagittal and frontal planes of motion (Veeger et al., 1988; Woude et al., 1988). Both these studies employed a “Speedy Wheely” standard wheelchair at speeds ranging from 0.83 m/s to 4.17 m/s. In contrast, the typical race speeds reported at the 1995 World Athletics Championships in Sweden, for 800 m and 1500 m events ranged from 6.60 m/s to 7.60 m/s. Little information is available concerning propulsion technique at these propulsion speeds, a problem that this study addresses.

More recently, both the physiological and biomechanical aspects of wheelchair racers have been reported at realistic race speeds (Campbell, 1992; Campbell & Goosey, 1996; Goosey, Campbell, & Fowler, 1996; Jones et al., 1992; Lakomy et al., 1987; Wang, Deutsch, Morse, Hedrick, & Milikan, 1995). From a physiological perspective, Lakomy et al. (1987) found large variations between wheelchair racers in pushing economy; this intraindividual variation was greater than that generally reported for running economy. Campbell (1992) stated that the differences found in pushing economy may partly be explained by differences in propulsion technique. From a biomechanical perspective, Wang et al. (1995) described the 3D kinematic patterns of wheelchair propulsion across four speed conditions, 90, 70, 50, and 30% of the peak speed for each subject. The speeds examined ranged from approximately 2.8 m/s to 8.3 m/s, but were different for each athlete. They concluded that, as speed increased, the drive phase was performed faster. The range of the push-angle remained constant, and greater forward lean also occurred. Wang et al. (1995), however, did not investigate cardiorespiratory responses.

The relationship between economy and specific descriptors of wheelchair propulsion in the racing population has been reported by only one group of researchers in the form of an abstract (Jones et al., 1992). These individuals examined pushing economy and wheelchair propulsion technique at speeds up to 6.25 m/s in male wheelchair racers. Ten athletes were selected from 15 and divided into two groups, (5 most economical and 5 least economical). Jones et al. (1992) reported that the economical group (a) had less head and trunk velocity with more elbow and wrist velocity at the strike and release, (b) released the wheel with a straighter arm and higher wrist velocity, and (c) stroked less frequently with less time in contact with the rim. Thus, Jones et al. (1992) does provide some evidence that the mechanics of wheelchair propulsion influence oxygen consumption. However, with so few studies in this area, there is a need to increase the understanding concerning pushing economy and propulsion technique of wheelchair racers. This may ultimately aid the performance of these athletes, as some researchers have suggested the importance of the relationship between pushing economy and en-
durance performance (Campbell, 1992; Campbell, Williams, & Lakomy, 1995; Cooper, 1992).

The purpose of the present study was (a) to describe kinematic patterns at a range of wheelchair propulsion speeds, (b) to examine pushing economy at a range of speeds, and (c) to determine relationships between wheelchair propulsion mechanics and pushing economy.

Method

Subjects

Eight paraplegic wheelchair athletes (7 male and 1 female), aged 30 ± 8 years with a body mass of 68.0 ± 11.3 kg, volunteered to participate in this study. All athletes trained for and competed at a national level for endurance events, and six of the athletes competed at international level. The physical and physiological data of the athletes are shown in Table 1. The inclusion of the female athlete with the male athletes was based on the following assumptions: (a) that large variability in oxygen consumption exists between athletes at a given speed (Campbell, 1992), (b) large variability in pushing techniques also exist between and within groups regardless of gender (Goosey, Campbell, & Fowler, 1997), (c) although senior male athletes outperform senior female athletes, there is great similarity between athletes of different gender in terms of the arm movement pattern (Goosey et al., 1997), and (d) the female (Subject 1) was an experienced and well-trained endurance athlete.

Exercise Test Protocol

Each athlete completed a five-stage incremental exercise that included speeds of 6.0, 6.5, and 7.0 m/s at an incline of 0.7% on a motorized treadmill (Woodway ELG2; speed range 0 to 9.5 m/s; gradient range 0 to 22%) adapted for racing wheelchairs (Campbell & Williams, 1996; Goosey, Campbell, & Fowler, 1995). Each subject was fully familiarized with the testing procedures on the motorized treadmill, using his or her own racing chair.

The use of the athlete’s own racing chair is an important issue when examining pushing economy and wheelchair propulsion techniques. Two major components are involved in wheelchair racing: the athlete and the chair. In reality the chair cannot be separated from the athlete; therefore, they should be considered as one integrated unit (Woude et al., 1992). Researchers have demonstrated that changes in wheelchair design can influence energy costs (Woude, Veeger, & Rozendal, 1989). However, in our opinion, when a standardized chair is used in research, athletes may alter their wheeling style to adjust to a test chair. From a practical standpoint, racing wheelchairs and their components are determined largely by the athlete’s personnel preference (Higgs, 1983). Through training, athletes become tuned to their own chair. Therefore, we believe that athletes should use their own racing chairs when participating in research. All wheelchairs were fitted with 0.70 m (diameter) spoked wheels with the handrim sizes varying from 0.37 m to 0.39 m.

Technique Analysis

Two-dimensional analysis was used; a stationary Panasonic F15 video camera was positioned perpendicular to the treadmill and recorded the sagittal view. It was
assumed that wheelchair propulsion movements of both upper extremities were symmetrical (Sanderson & Sommer, 1985; Wang et al. 1995). The left side of each athlete was analyzed, following the same method reported by Goosey et al. (1997). Each sequence was digitized manually at a sampling frequency of 50 Hz using an m-image video captive board interfaced with an Acorn Archimedes 440 microcomputer.

The athlete was modeled as five rigid segments, defined by seven bony landmarks: the head, neck, shoulder, elbow, wrist, fingers, and hip (Figure 1). The digitized data were smoothed and differentiated using generalized cross-validated quintic splines.

The following temporal parameters and displacement data were obtained and recorded for each athlete: (a) cycle time, defined as the time to complete one push cycle; (b) push rate, defined as the number of pushes completed in 1 min; (c) angle of lean and range of trunk inclination with respect to the horizontal; and (d) elbow angle and the range of elbow flexion. The minimum and maximum values of the angular displacement data were recorded, and all data were expressed as means and standard deviations.

Physiological Measures

Pushing economy, defined as the energy cost (oxygen uptake; in l/min) of wheelchair propulsion at a constant fixed speed (Lakomy & Williams, 1996), was determined at three speed levels (6.0, 6.5, and 7.0 m/s). During the last minute of each 4-min speed level, a mouthpiece with a two-way valve connected to low-resistance, wide-bore tubing allowed the collection of expired air in 150 L Douglas Bags. Expired air was analyzed for oxygen and carbon dioxide concentration (Servomex, series 1400). The

![Figure 1 — Model of an athlete, defined by seven bony landmarks, lower limb and chair shown for completeness.](image-url)
analyzer had been calibrated using three calibration gases (O₂, CO₂, and nitrogen) of known concentrations. Expired ventilatory volume was determined using a Harvard dry gas meter calibrated against a Tissot spirometer.

Capillary blood samples were obtained from an ear lobe immediately after completing each exercise stage. The first drop of blood was discarded, and 25 ml of this blood was collected in a heparinized capillary tube (Hawksley, UK). An automatic analyzer (YSI 1500 Sport; yellow springs) was used to assess blood lactate concentration. The analyzer was calibrated with known lactate standards at 5 mmol/l. Linearity throughout the operating range was checked with 15 mmol/l lactate standard.

Following the submaximal economy test, VO₂ peak was determined via a separate test using a continuous incremental gradient ramp protocol. During this test, the speed of the treadmill remained constant and the treadmill gradient was increased at 3 min intervals. The treadmill speed selected for each subject was based on the submaximal economy test. The validity and reliability of these methods have been previously reported (Campbell, 1992; Campbell et al., 1995; Campbell & Williams, 1996).

Statistical Analysis

Kinematic Changes Across Speeds. The mean minimum and maximum values of the selected parameters were analyzed by a one-way analysis of variance with repeated measures, using a level of significance of .05. Significant differences were analyzed by performing a Tukey post hoc test in order to identify where the differences were located across the three speed levels.

Pushing Economy and Propulsion Technique. Several Pearson Product Moment correlations were employed to determine the association between pushing economy (l/min) and each kinematic variable at three common speeds (6.0, 6.5, and 7.0 m/s). A stepwise linear regression on VO₂ was employed to examine how much of the variance was accounted for by these kinematic variables.

Results

The mean ± SD VO₂ peak value for the group was 2.52 ± 0.49 l/min, with a range of 1.90 l/min to 3.37 l/min (Table 1). Figure 2 shows the oxygen cost of wheelchair propulsion at 6.0, 6.5, and 7.0 m/s. At each speed there was a wide range of oxygen uptake values within the group (Figure 2).

The temporal data shown in Figure 3 and Figure 4 revealed that the push rate increased (p < .01) as the propulsion speed increased. This was accompanied by a decrease in cycle time (p < .01). The initial push rate increased from 61 ± 18 push/min to 72 ± 18 push/min as the speed increased from 6.0 m/s to 7.0 m/s. The greatest change occurred between 6.0 m/s to 6.5 m/s, with a mean increase of seven pushes per minute. There was a mean increase of four pushes per minute as the speed increased from 6.0 m/s to 7.0 m/s, cycle time decreased by 0.2 s, with the greatest change occurring between 6.0 m/s to 6.5 m/s (Figure 4).

The elbow and trunk angular displacement data for the three propulsion speeds (mean ±SD) are shown in Table 2. It was found that an increase in speed resulted in greater flexion of the elbow (p < .05).
Pushing Economy and Propulsion Technique

Table 1  Physical and Physiological Data of the Athletes

<table>
<thead>
<tr>
<th>Subject/gender</th>
<th>Body mass (kg)</th>
<th>Lesion level</th>
<th>Paralympic racing class</th>
<th>Age</th>
<th>Years racing experience</th>
<th>VO₂ peak (l/min)</th>
<th>VO₂ peak (ml/kg/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 F</td>
<td>67.6</td>
<td>L4 (inc.)</td>
<td>T4</td>
<td>39</td>
<td>6.0</td>
<td>1.90</td>
<td>28.1</td>
</tr>
<tr>
<td>2 M</td>
<td>69.7</td>
<td>T12/L1</td>
<td>T4</td>
<td>38</td>
<td>3.0</td>
<td>3.08</td>
<td>44.2</td>
</tr>
<tr>
<td>3 M</td>
<td>68.9</td>
<td>T6</td>
<td>T3</td>
<td>31</td>
<td>12.0</td>
<td>2.53</td>
<td>36.7</td>
</tr>
<tr>
<td>4 M</td>
<td>78.6</td>
<td>T5 (inc.)</td>
<td>T3</td>
<td>26</td>
<td>4.5</td>
<td>2.57</td>
<td>32.7</td>
</tr>
<tr>
<td>5 M</td>
<td>52.2</td>
<td>SB</td>
<td>T4</td>
<td>18</td>
<td>4.0</td>
<td>2.21</td>
<td>42.3</td>
</tr>
<tr>
<td>6 M</td>
<td>84.7</td>
<td>T8</td>
<td>T4</td>
<td>36</td>
<td>2.0</td>
<td>2.28</td>
<td>26.9</td>
</tr>
<tr>
<td>7 M</td>
<td>52.1</td>
<td>T1/2 (inc.)</td>
<td>T4</td>
<td>20</td>
<td>4.0</td>
<td>2.25</td>
<td>43.2</td>
</tr>
<tr>
<td>8 M</td>
<td>70.0</td>
<td>T12/L1 (inc.)</td>
<td>T4</td>
<td>31</td>
<td>7.0</td>
<td>3.37</td>
<td>47.9</td>
</tr>
<tr>
<td>Mean</td>
<td>68.0</td>
<td>—</td>
<td>—</td>
<td>30</td>
<td>5.5</td>
<td>2.52</td>
<td>37.8</td>
</tr>
<tr>
<td>SD ±</td>
<td>11.3</td>
<td>—</td>
<td>—</td>
<td>08</td>
<td>3.0</td>
<td>0.49</td>
<td>7.9</td>
</tr>
<tr>
<td>Min</td>
<td>52.1</td>
<td>—</td>
<td>—</td>
<td>18</td>
<td>2.0</td>
<td>1.90</td>
<td>28.1</td>
</tr>
<tr>
<td>Max</td>
<td>78.6</td>
<td>—</td>
<td>—</td>
<td>39</td>
<td>12.0</td>
<td>3.37</td>
<td>47.9</td>
</tr>
</tbody>
</table>

Note. SB = spina bifida; inc. = incomplete lesion.

Further significant relationships may have been masked by large interindividual differences in the propulsion styles. This is shown by the large standard deviations associated with the push rate at each speed (Figure 3).

Table 3 shows the Pearson Product Moment correlation coefficients between selected kinematic variables and pushing economy at speeds of 6.0, 6.5, and 7.0 m/s for the eight subjects. At each speed, there was a high correlation between
Table 2  Elbow and Trunk Angular Displacement Data Across 6.0, 6.5, and 7.0 m/s (Mean ± SD)

<table>
<thead>
<tr>
<th>Parameter (deg.)</th>
<th>Propulsion speeds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.0 m/s</td>
</tr>
<tr>
<td>Maximum elbow angle</td>
<td>177 ± 3.0</td>
</tr>
<tr>
<td>Minimum elbow angle</td>
<td>100 ± 6</td>
</tr>
<tr>
<td>Range of elbow angle</td>
<td>77</td>
</tr>
<tr>
<td>Maximum angle of lean</td>
<td>35 ± 12</td>
</tr>
<tr>
<td>Minimum angle of lean</td>
<td>26 ± 11</td>
</tr>
<tr>
<td>Trunk range</td>
<td>9 ± 3</td>
</tr>
</tbody>
</table>

Note. Significance: (*p < .05) = Between speeds 6.0 m/s to 7.0 m/s.

pushing economy and body mass ($r < .83$, $p < .01$). A greater range of elbow movement ($r < -.63$) and minimum elbow angle ($r < .63$) was associated with lower pushing economy at each speed. There was also a tendency for a lower push rate to be associated with a greater pushing economy ($r < .63$) at each speed. The remaining variables that described pushing mechanics (e.g., maximum elbow angle, angle of lean, and range of trunk motion) did not correlate significantly with pushing economy.

The stepwise multiple linear regression analysis indicated that body mass (BM) significantly contributed to the prediction of pushing economy ($\text{VO}_2$ at a given speed). At 6.0 m/s, 79% of the variance was accounted for by BM, which was reduced to 69% at 7.0 m/s. The kinematic variables examined did not significantly contribute to this variance.
Figure 4 — Cycle time at three speeds ($n = 8$) (Mean ± SD).

Table 3 Pearson Product Moment Correlation Coefficients ($r$) Between Selected Kinematic Variables and Pushing Economy (Oxygen Uptake (l/min)) at 6.0, 6.5, and 7.0 m/s

<table>
<thead>
<tr>
<th>Parameter</th>
<th>6.0 m/s</th>
<th>6.5 m/s</th>
<th>7.0 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body mass (kg)</td>
<td>.89**</td>
<td>.86**</td>
<td>.83**</td>
</tr>
<tr>
<td>Push rate (push/min)</td>
<td>.73*</td>
<td>.81*</td>
<td>.63</td>
</tr>
<tr>
<td>Cycle time (s)</td>
<td>.54</td>
<td>-.43</td>
<td>-.34</td>
</tr>
<tr>
<td>Elbow angle (deg.) (Max)</td>
<td>.31</td>
<td>.62</td>
<td>.38</td>
</tr>
<tr>
<td>Elbow angle (deg.) (Min)</td>
<td>.73*</td>
<td>.65</td>
<td>.63</td>
</tr>
<tr>
<td>Elbow range (deg.)</td>
<td>-.85**</td>
<td>-.65</td>
<td>-.63</td>
</tr>
<tr>
<td>Angle of lean (deg.) (Max)</td>
<td>.32</td>
<td>.08</td>
<td>.30</td>
</tr>
<tr>
<td>Angle of lean (deg.) (Min)</td>
<td>.25</td>
<td>.10</td>
<td>.34</td>
</tr>
<tr>
<td>Trunk range (deg.)</td>
<td>-.05</td>
<td>-.14</td>
<td>.39</td>
</tr>
</tbody>
</table>

Note. Significance: *$p < .05$ and **$p < .01$ ($n = 8$).

Figure 5 shows VO$_2$ during the submaximal incremental test for two athletes from the same racing classification with similar body mass and VO$_2$ peak values. Subject 5 was more economical (consumed less oxygen) than Subject 7 at speeds ranging from 6.0 m/s to 7.5 m/s. Figure 6 demonstrates the greater range of elbow movement during one push cycle at 7.0 m/s for Subject 5 when compared with Subject 7.
Figure 5 — The relationship between oxygen uptake (l/min) and propulsion speed (m/s) for two male (T4 / Racing Classification) athletes with similar VO$_2$ peak values.

![Graph](image)

Figure 6 — A comparison of the elbow angle for two athletes from the T4 racing classification with equal VO$_2$ peak, but different VO$_2$ value at 7.0 m/s.

![Graph](image)

**Discussion**

*Kinematic Patterns Across Speeds.* It was clearly shown that the mechanics of wheelchair propulsion are speed dependent. The observed speed-related changes in the wheelchair propulsion mechanics across 6.0 m/s to 7.0 m/s were: (a) a reduction in cycle time, (b) an increase in push rate, and (c) a greater flexion of the elbows. It was interesting to note that there were differences in the sequential timing of these parameters from 6.0 m/s to 6.5 m/s and from 6.5 m/s to 7.0 m/s. These
findings, in general, are consistent with the findings of Veeger and coworkers (1989) using a standardized wheelchair across slower propulsion speeds. However, Veeger and coworkers (1989) found no difference in the minimum elbow angle as speed increased. This may be because only a small amount of trunk flexion was noted by Veeger et al. (1989), which may be associated with standardized testing conditions.

As the speed increased from 6.0 m/s to 6.5 m/s, it was accompanied by a decrease in cycle time and an increase in push rate. There was no significant change in the displacement data, suggesting that the athletes were performing the same movement pattern, only at a greater rate.

The increase in speed from 6.5 m/s to 7.0 m/s resulted in a significant increase in elbow flexion. This was accompanied by nonsignificant changes in both the cycle time and push rate, suggesting that the athletes were beginning to adapt to the increase in speed by a change in their technique (i.e., the movement pattern). This was also found by Wang and coworkers (1995) who noted that greater trunk and elbow flexion occurred at higher speeds. This finding is consistent also with researchers examining the range of trunk motion under various conditions, who have generally found that the trunk moves forward as the demand of the activity increases (Lees, 1991).

**Pushing Economy**

*Intraindividual Variation Across Speeds.* Large intraindividual variation occurred in pushing economy (Figure 2). When expressed as a percentage of the mean, the variation varied from 35% at 6.0 m/s to 26% at 7.0 m/s. The faster speeds of 6.5 m/s to 7.0 m/s reflect typical race/training intensities for this group of athletes. Previous studies have implied that it seems logical that the more an athlete trains at a given speed, the more finely tuned the associated mechanical movements become (Williams, 1990). In this case, there was less variability at 7.0 m/s within these wheelchair racers, possibly because they had to adjust their propulsion mechanics (e.g., stroke frequency) at the slower speeds. The variability observed in pushing economy between subjects is consistent with that reported in previous studies examining the oxygen cost of wheelchair propulsion (Campbell, 1992; Campbell & Goosey, 1996; Lakomy et al., 1987). However, the interindividual variation is considerably higher than that reported for running economy studies, which have reported variations between 2% to 11% for a given speed within groups of runners with similar performance abilities (Morgan et al., 1989).

*The Relationship Between Wheelchair Propulsion Mechanics and Economy.* One of the reasons for the study was to determine which biomechanical factors may account for the differences in pushing economy. The main findings suggested that when the relationship between selected kinematic variables and pushing economy was examined, greater pushing economy was associated with (a) lower body mass (lighter athletes), (b) greater range of elbow flexion/minimum elbow angle, and (c) tendency for a lower push rate.

*Body Mass.* Oxygen uptake was expressed in l/min and was not normalized to body mass. This method conforms with other research reporting the VO₂ peak or submaximal values in wheelchair propulsion (Campbell, 1992; Glaser, 1985; Lakomy et al., 1987) because body weight is continually supported during the activity. Furthermore, body mass is a poor estimate of the skeletal musculature employed during wheelchair propulsion. When VO₂ was expressed as l/min, the lighter athletes were found to be more economical than the heavier athletes. The differences observed
in the submaximal VO₂ values between the lighter and heavier athletes may possibly be a function of the size of the contracting muscle mass. Generally, the lighter athletes are of smaller build and therefore do not require a high rate of oxygen use. The results from this study suggest that oxygen uptake (VO₂) should be adjusted in future research to account for differences possibly in body size. However, there are insufficient data at present to know what this adjustment might be.

Range of Elbow Motion. A greater range of elbow movement was associated with lower pushing economy. An explanation for this finding is not immediately apparent, although greater elbow extension may suggest that there was greater use of the shoulder muscles. Meijs, Oers, Veeger, and Woude (1989) found that an increase in the seat height significantly affected the trajectory of the elbow (decreased extension/flexion). Therefore, a greater range of elbow motion may be a function of seating position in the racing wheelchair. It was interesting to note that angle of lean was not associated with greater pushing economy. This may be explained by the large variability found with the angle of lean, which may be the result of the different seating positions adopted by the athletes.

Push Rate. Finally, there was a tendency for a lower push rate to be associated with a greater pushing economy, which supports the findings of Jones and coworkers (1992). As the speed increased from 6.5 m/s to 7.0 m/s, the push rate appeared to be reaching a plateau, which may indicate the athletes’ optimum frequency. This plateau is similar to what has been described by Cavanagh and Williams (1982) as runners’ select a combination of stride frequencies and stride lengths that minimizes metabolic cost during level running. Likewise, during cyclic movements, researchers examining pedal frequencies of cyclists (Boning, Gonen, & Maassen, 1989) or cycle frequencies during wheelchair propulsion (Woude, Veeger, Rozendal, & Sargeant, 1989) have found that experimentally induced deviations from the individuals’ freely chosen pedal/cycle frequency tend to result in an increase in oxygen cost. In the present study, although individuals had different preferred push rates at a given speed (Figure 3), they appeared to maintain their chosen push rate across the speeds 6.5 m/s and 7.0 m/s.

In order to determine how much of these combined kinematic variables accounted for the variance in pushing economy, the variables associated with pushing economy were introduced into a stepwise multiple regression equation. It was found that 89% of the variance was accounted for by both the minimum elbow angle and body mass at 6.0 m/s. Body mass alone accounted for 70% of the variance in pushing economy at 6.5 m/s and 63% at 7.0 m/s.

Figure 5 illustrated that Subject 5 was more economical than Subject 7, although these two athletes were matched according to their racing classification, racing experience and age, and had a similar body mass and VO₂peak value. Subject 5 demonstrated a greater range of elbow movement (Figure 6), which was a factor associated with better pushing economy. However, other factors, such as the nature of the disability, may have also contributed to Subject 5 being more economical. In this respect, the disability of Subject 5 was spina bifida, which may suggest that other mechanisms related to disability are responsible.

Summary

It can be concluded that adaptations to speed changes occur, initially by a decrease in cycle time and an increase in cycle rate, and later by an increase in the flexion of the elbows.
Generally, the differences in propulsion technique do appear to influence oxygen uptake. In terms of pushing economy, the lighter athletes with a greater range of elbow movement and a lower push rate were more economical. In general, the variations in pushing economy were not accounted for by the variations in the kinematic variables examined (elbow angle and angle of lean) but were partly explained by the differences in body mass (63% to 89% of the variance). Furthermore, as the speed increased from 6.0 to 7.0 m/s, the relationship between pushing economy and the kinematic variables in the present study (push rate, minimum elbow angle, and elbow range) were reduced. This suggests that possibly as the physiological demands increase, other factors such as the nature of the disability/lesion level and the wheelchair design, or more probably a combination of these, may explain the differences in pushing economy between athletes.

The results from the present study add to our understanding of pushing economy and propulsion techniques of wheelchair racers and provide a platform for future studies. However, it must be noted that the limitations of the present study may be with (a) the limited kinematic analysis employed, (b) the use of a two-dimensional analysis (2D), (c) combining the one female with the seven males for statistical analysis, and (d) the decision to ignore the influence of body size on pushing economy. Other variables of interest for future studies are the shoulder angles and the wrist, elbow, and shoulder velocities. An increased wrist velocity at the strike and release of the handrim have been associated with better economy (Jones et al., 1992), and maximal shoulder velocity at initial contact of the drive phase has been associated with maximizing wheelchair racing speed (Wang et al., 1995).

Three-dimensional (3D) angular velocities/displacements and linear velocities may be more appropriate than the 2D analysis used in this study. However, Roeleveld, Lute, Veeger, Gwinn, and Woude (1994) stated that a two-dimensional (2D) analysis was suitable for stroke, timing, and displacement of segments in the sagittal plane. Furthermore, Sanderson and Sommer (1985) stated that because of the symmetry of motion, there would be negligible or no rotation of the trunk about its longitudinal axis. It should be noted that only recently have 3D experimental designs been employed (Vanlandewijck, Spaepen, & Lysens, 1994; Wang et al., 1995). These studies have allowed the movements of the arm in the frontal plane to be described and 3D linear and angular velocities to be obtained. This may be more noticeable and relevant for wheelchair racers at high propulsion speeds. However, limited data are available on the 3D kinematic features of wheelchair racers and pushing economy, which is an area certainly worthy of future investigation.

Studies that include spinal cord injured athletes (SCI) should recognize the limitations inherent in the experimental methods employed that might affect the relationships identified. These might include combining athletes of different racing classifications or combining male and female athletes. Athletes in this study were grouped together because of the small number of subjects available. Consequently, there is a need to establish the relationship between selected kinematic variables and pushing economy for each specific subpopulation in the future.

Generally, in the literature, running economy has been normalized to body mass (Morgan et al., 1989), which follows the ratio-standard linear relationship. However, the relationship between peak oxygen uptake/submaximal oxygen uptake and body mass has not been examined in the wheelchair population. Therefore, the definition of pushing economy measured in this study ($V_{O_2 \text{ submax}}$; in l/min) did not account for
body weight. Nevill (1994) stated that a fundamental issue is that the physiological variable is influenced by active muscle mass, with body mass usually used as a proxy in the absence of muscle mass estimates. Body mass is a poor estimate of the skeletal musculature employed during wheelchair propulsion. Furthermore, there are errors associated with estimating body composition in SCI athletes (Hooker & Hooker, 1990). Generally VO$_2$ submaximal and peak values found in wheelchair racers are expressed in absolute values (Lakomy et al., 1987; Lakomy & Williams, 1996). At this stage, it is not appropriate to express VO$_2$ values relative to body mass. However, the results from our study suggest that future studies may need to address this issue. Although a common $2/3$ exponent has been found in the able-bodied literature, we are not confident in the use of this value until it has been carefully evaluated in this specific population. For example, if we were to find that VO$_2$ corresponded to $2/3$ body mass and we had used the ratio standard methods (BM'), we would be overcorrecting and the heavier athletes would become more economical.

References


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