Physiological responses during wheelchair racing in quadriplegics and paraplegics

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The purposes of this study were: (1) to compare the physiological responses during simulated wheelchair racing (SR) between male quadriplegics and paraplegics, (2) to test the validity of the SR against a track race (TR) and (3) to examine the relationship between the peak oxygen uptake (peak $\dot{V}O_2$) and wheeling velocity (WV) during the SR and TR. Seven quadriplegics (C5–8 lesions) and six paraplegics (T5–L4 lesions) completed (1) an incremental wheelchair velocity test, (2) a SR (1.6 km for quadriplegics and 3.2 km for paraplegics), and (3) an indoor TR of the same distance. The subjects performed the incremental velocity test and SR in their personal wheelchairs mounted on a roller system interfaced with customized software programmed to provide velocity and distance feedback. Physiological responses were monitored using an automated metabolic cart and electrocardiogram. Blood lactate concentration [La] was determined from finger prick samples. Peak $\dot{V}O_2$ and peak heart rate (peak HR) were significantly higher in the paraplegics compared to quadriplegics: 1.90 ± 0.54 vs 1.07 ± 0.35 l/min, and 188 ± 11 beats/min vs 117 ± 12 beats/min respectively. The paraplegics exercised at significantly ($p < 0.05$) higher percentages of peak $\dot{V}O_2$ and peak HR during the SR compared to quadriplegics (95% vs 76% and 95% vs 86%, respectively). No significant relationships ($p > 0.05$) were observed between the peak $\dot{V}O_2$ and WV during the SR and TR in either group. Significant relationships ($p < 0.05$) were observed between the SR and TR for the race time, WV, HR, and [La] in both groups of subjects. These results suggest: (1) that factors other than peak $\dot{V}O_2$ influence wheelchair racing performance in quadriplegics and paraplegics, and (2) that wheelchair roller racing evaluated in the laboratory is a valid measure of track racing performance in spinal cord injured subjects.

Keywords: cardiorespiratory responses; wheelchair racing; spinal cord injury; paraplegia; quadriplegia.

Introduction

In recent years there has been a considerable surge in the participation of recreational and competitive physical activities by individuals with spinal cord injury (SCI).^{1,2} As a result, wheelchair races of various distances are included in many local, national, and international track competitions organized for this population. To enable individuals with SCI to compete on an equivalent basis from a functional standpoint, the International Stoke Mandeville

Games Federation has adopted seven competitive classes based on the level of impaired functional musculature of the individual.³ Quadriplegics assigned to classes 1A, 1B, and 1C have spinal lesions at levels C6 or above, C7, and C8 respectively. Paraplegics assigned to classes 2, 3, 4, and 5 have spinal lesions at T1–T5, T6–T10, T11–L3, and L4–S2 respectively.

Numerous studies^{4–7} have examined the peak physiological responses during

exercise in the SCI population, and the differences between quadriplegics and paraplegics have been well established (see reference 8 for a review of this literature). However, only limited information is available on the physiological responses during wheelchair racing in the SCI population, and factors associated with such performance. Asayama *et al*⁹ and Crews¹⁰ reported that the oxygen uptake ($\dot{V}O_2$) and heart rate (HR) during actual wheelchair distance racing in well trained paraplegics were approximately 90–95% of their respective peak values observed during incremental exercise. Lakomy *et al*¹¹ reported that the $\dot{V}O_2$ during simulated wheelchair distance racing on a treadmill in a mixed group of paraplegic wheelchair athletes was approximately 76% of the peak $\dot{V}O_2$ while that observed in quadriplegics was higher. In the two quadriplegics that they examined, the mean $\dot{V}O_2$ during the wheelchair race was approximately 90% of the peak $\dot{V}O_2$. In both groups of subjects, the HR during the race ranged between 80% and 90% of the respective peak values.

Studies that have examined the relationship between the peak $\dot{V}O_2$ and distance racing performance in SCI subjects are equivocal. Cooper¹² and Hooker & Wells¹³ reported no significant relationship between the peak $\dot{V}O_2$ and actual wheelchair velocity (WV) during a 10 km road race in well trained paraplegics. In contrast, Lakomy *et al*¹¹ indicated that these two variables were significantly related ($r = 0.61$) to each other during a simulated 5 km wheelchair race in a mixed group of 10 paraplegics and two quadriplegics. These investigators also reported that in a subgroup of five international calibre paraplegic athletes, the relationship between the peak $\dot{V}O_2$ and WV was 0.77.

The purposes of this study therefore were: (1) to compare the acute physiological responses during a simulated wheelchair race (SR) in quadriplegics and paraplegics, (2) to determine the validity of the SR by correlating selected physiological responses with those observed during a track race (TR) and (3) to examine the relationship between the peak $\dot{V}O_2$ and WV during the SR and TR in quadriplegics and paraplegics.

Methods

Subjects

Written, informed consent was obtained from seven male quadriplegics (lesion levels C5–8; two class 1A, two class 1B, and three class 1C) and six male paraplegics (lesion levels T5–L4; three classes 2, one each from class 3, 4, and 5). Selection criteria for participation were: (1) age range between 18 and 40 years, (2) use of a wheelchair for at least 2 years prior to participation, and (3) absence of any health problems that would contraindicate maximal exercise testing. The testing procedures utilized were approved by an ethics committee for human experimentation. All the subjects were physically active, and participated in a variety of wheelchair recreational activities. The mean and standard deviation (SD) for the age, height, and weight of the quadriplegics were: 30.6 ± 5.2 yr, 180 ± 10.7 cm, and 74.3 ± 12.8 kg respectively. The corresponding values for the paraplegics were: 29.0 ± 4.6 yr, 175 ± 9.7 cm, and 70.7 ± 14.8 kg, respectively.

Instrumentation for wheelchair exercise

Each subject exercised in his personal wheelchair which was mounted on a specially constructed, low-friction steel roller system which had a circumference of 53 cm. Reflective tape was fastened on the rim of the roller, so that a signal could be picked up by an optical sensor which was secured on the roller frame. The sensor was interfaced with an analog/digital board placed in a microcomputer, so that the number of revolutions per minute (rpm) of the roller could be recorded each time the reflective tape crossed the path of the sensor. A customized computer program calculated WV (in kilometers per hour, km/h) and distance travelled from the rpm data and the circumference of the roller. This information was updated every 5 s and displayed as a speedometer on the computer monitor to provide visual feedback to the subjects. Upon termination of the test, the results averaged over each minute of the test duration were printed out.

Protocol for evaluating the peak physiological responses during wheelchair exercise

In the first testing session, a continuous incremental velocity protocol was used to evaluate the peak physiological responses of the subjects during wheelchair exercise. The test was initiated at a WV of 5 km/h for 2 min, following which, the WV was increased by 2 km/h every 2 min until exhaustion. No attempt was made to regulate the stroke rate of the subjects during the test. Results from a previous study¹⁴ on a similar subject pool using the same exercise mode yielded test–retest reliability coefficients of 0.97 and 0.98 for the peak $\dot{V}O_2$ and peak HR respectively.

Metabolic and respiratory gas exchange measurements were continuously monitored during the exercise test using an automated metabolic measurement cart (Sensormedics MMC Horizon, Yorba Linda, California). This instrument was calibrated with commercially available precision gases prior to and following each test. The electrocardiogram (ECG, Hewlett Packard Model 1500B, Washington, DC) was monitored with the leads in the CM₅ position. An analog input board was placed in the metabolic cart to interface with the ECG. The signal transmitted was sampled by the central processing unit of the metabolic cart to calculate the HR from the R-waves of the ECG. All the results were averaged over a 30 s period, and printed while the test was in progress.

Lactate concentration [La] of whole blood was determined from arterialized blood samples that were withdrawn from a finger tip prior to and 3 min after the cessation of each exercise test. The blood samples were analyzed using a lactate analyzer (Lactate analyzer 640, Kontron Medical, Switzerland) that was calibrated according to specifications outlined by the manufacturer.

Protocols for the simulated race and track race

In the next two sessions, the subjects completed the SR or the TR in random order. The length of the race was 1.6 km (1 mile)

for the quadriplegics and 3.2 km (2 miles) for the paraplegics. This was done so as to keep the race time for the two groups approximately the same (based on pilot data). The SR was conducted on the roller system described earlier, and the physiological responses were monitored using the same instrumentation. The subject was instructed to perform his best effort and was given verbal encouragement throughout the test. The TR was administered on an oval, indoor 200 m synthetic track surface. The subjects completed this race in groups of three or four in order to create a competitive atmosphere. During the race, HR was continuously monitored using a wireless sport tester (Polar Key, Model PE3000, Kempele, Finland), and the information was subsequently retrieved from its memory using a computer link. Arterialized blood samples were withdrawn from a finger tip prior to and 3 min following the SR and TR for quantification of [La].

Statistical analysis

The mean values of the peak physiological responses of the quadriplegics and paraplegics were compared using a *t* test for independent samples. The physiological responses of these two groups at various stages of the SR, namely 25%, 50%, 75% and 100% of the completion distance, were analysed using a two way analysis of variance (group by stage) with repeated measures on the stage factor. Significant *F* ratios were analysed on a post hoc basis using the Scheffe procedure. Pearson product–moment correlations were used separately for each group: (1) to establish validity coefficients of the selected variables between the SR and TR and (2) to examine relationships between the peak $\dot{V}O_2$ and WV during the SR and TR. All the results were considered to be significant at the 0.05 level of confidence.¹⁵

Results

Peak physiological responses in quadriplegics and paraplegics

The means ($\pm$ SD) of the peak physiological responses for the quadriplegics and

paraplegics are summarized in Table I. The $\dot{V}O_2$ (l/min and ml/kg/min), HR, ventilation volume ($\dot{V}_E$), tidal volume, and [La] were significantly higher in the paraplegics by 78%, 72%, 61%, 63%, 86%, and 47% respectively. However, no significant differences were observed between the two groups for the respiratory exchange ratio (RER), oxygen pulse (O_2 pulse), $\dot{V}_E/\dot{V}O_2$ ratio, and breathing frequency.

Physiological responses during the simulated race

The time taken by the quadriplegics and paraplegics to complete 25%, 50%, 75%, and 100% of the race distance (1.6 km for quadriplegics and 3.2 km for paraplegics), as well as the $\dot{V}O_2$ and HR at these stages of the race are summarized in Table II. No significant difference was observed between the two groups for time at the four race stages. The $\dot{V}O_2$ and HR increased during the early stages of the race, and reached a steady state when 25% of the distance was completed in both quadriplegics and paraplegics. No significant differences over time were observed among the values recorded at 25%, 50%, and 75% of the race stage for either of these variables in the two groups. However, the $\dot{V}O_2$ and HR at the completion of the race (100%) were significantly higher than those obtained at the 25% stage, most likely because the subjects were accelerating towards the end of the race.

When comparing the responses of the two

groups during the SR, it is evident that at each race stage $\dot{V}O_2$ and HR were significantly higher in the paraplegics than the quadriplegics. This difference persisted even when these values were expressed as a percentage of the peak value (i.e. relative value) observed during the incremental velocity test. During the SR, quadriplegics maintained an intensity ranging from 72–82% of peak $\dot{V}O_2$ or 82–92% of peak HR. In the paraplegics, these values were significantly higher, with values for the $\dot{V}O_2$ and HR ranging from 90–98% and 91–100% respectively.

Validity of the simulated race

To determine the validity of the SR in the quadriplegics and paraplegics, the mean values and the relationships between the SR and TR were examined for the following variables: (1) racing time, (2) average WV, (3) average HR during the middle stages of the race (i.e. between 25% and 75% of the race) and (4) 3 min post race [La]. The results are summarized in Table III. In both groups of subjects, no significant differences were observed between the means of the SR and TR for each of the variables examined. As well, the values of the two races were significantly correlated to each other in both groups.

Factors related to racing performance

No significant relationships were observed between the peak $\dot{V}O_2$ and the WV during

Table I Peak physiological responses during wheelchair exercise in quadriplegics ($n = 7$) and paraplegics ($n = 6$) (means and SDs)

Variable	Quadriplegics	Paraplegics
Oxygen uptake, l/min	1.07 (0.35)	1.90 (0.54) ^a
Oxygen uptake, ml/kg/min	15.5 (2.6)	26.6 (4.0) ^a
Heart rate, beats/min	117 (13)	188 (11) ^a
Ventilation, volume l/min	60.0 (21.1)	97.7 (26.6) ^a
Tidal volume, l/breath	0.93 (0.20)	1.73 (0.57) ^a
Breathing frequency, breaths/min	65.1 (19.8)	58.0 (6.8)
Respiratory exchange ratio	1.25 (0.13)	1.28 (0.08)
Oxygen pulse, ml/beat	9.4 (2.3)	10.1 (3.7)
$\dot{V}_E/\dot{V}O_2$ ratio	56.3 (12.0)	51.6 (4.1)
Lactate, mmol/l	7.4 (2.4)	10.9 (3.1) ^a

^aindicates significant difference between the paraplegics and quadriplegics for that variable.

Table II Oxygen uptake and heart rate at various stages of the simulated roller race in quadriplegics (Q, $n = 7$) and paraplegics (P, $n = 6$) (means and SDs)

Variable	Group	25%	50%	75%	100%
Time ^a	Q	3:18 (1:06)	6:35 (2:11)	9:53 (3:17)	12:54 (4:11)
min:s	P	3:32 (0:42)	7:05 (1:24)	10:38 (3:17)	13:58 (2:35)
Oxygen uptake	Q ^b	0.73 (0.12)	0.75 (1.11)	0.74 (0.07)	0.84 (0.18) ^c
l/min	P	1.64 (0.35)	1.67 (0.33)	1.70 (0.33)	1.81 (0.42) ^c
Oxygen uptake	Q ^b	72.5 (15.5)	74.6 (11.4)	74.0 (12.3)	82.0 (11.6) ^c
% $\dot{V}O_2$ max	P	90.3 (9.0)	90.4 (11.3)	93.5 (10.9)	97.8 (9.1) ^c
Heart rate	Q ^b	96 (13)	98 (12)	99 (12)	106 (12) ^c
beats/min	P	171 (12)	173 (12)	179 (10)	187 (6) ^c
Heart rate	Q ^b	82.4 (9.7)	84.8 (11.4)	85.4 (12.7)	91.9 (8.9) ^c
%HRmax	P	90.9 (7.2)	92.2 (7.5)	94.8 (5.2)	99.5 (6.1) ^c

^aindicates time at various stages of the 1.6 km race in quadriplegics and 3.2 km race in paraplegics.

^bindicates significant differences between quadriplegics and paraplegics at each stage of the race.

^cindicates significant difference between the values at 25% and 100% of the race stage.

Table III Comparison of performance during the simulated race and track race in quadriplegics (Q, $n = 7$) and paraplegics (P, $n = 6$) (means and SDs)

Variable	Group ^a	Simulated	Track ^b	r ^c
Time	Q	12:54 (4:11)	12:16 (4:00)	0.79
min:s	P	13:58 (2:35)	15:19 (2:56)	0.82
Velocity	Q	124.7 (39.9)	132.5 (43.6)	0.81
m/min	P	230.4 (21.6)	210.1 (37.5)	0.88
Heart rate	Q	90 (12)	101 (17)	0.89
beats/min	P	175 (5)	179 (8)	0.88
Lactate	Q	5.98 (1.67)	5.97 (1.63)	0.77
mmol/l	P	10.86 (3.13)	9.97 (2.26)	0.81

^aMean values are significantly different between the paraplegics and quadriplegics for each variable.

^bNo significant difference between the simulated and track race for the means of each variable in either group of subjects.

^cCorrelation coefficients between the simulated and track races are significant for each variable.

the SR or TR in both groups of subjects. In the quadriplegics, correlations between WV during the SR and peak $\dot{V}O_2$ (l/min and ml/kg/min) were 0.23 and 0.32 respectively. For the TR, these values were 0.19 and 0.61 respectively. In the paraplegics, the corresponding correlations for the SR and TR were 0.52, 0.50, 0.65, and 0.51 respectively. The relationships between WV during the SR and the $\dot{V}O_2$ at the four different stages of the race were not significant.

Discussion

Comparison of peak physiological responses between quadriplegics and paraplegics

The results of this study indicated that the peak values of the $\dot{V}O_2$, HR, and $\dot{V}_E$ attained during incremental velocity wheel-chair exercises were significantly higher in paraplegics when compared to quadriplegics. These observations concur with the

findings of Coutts *et al*⁴ and Eriksson *et al*⁵ who compared these responses between quadriplegics and paraplegics using the same exercise mode.

In the current study, no significant difference was observed between the quadriplegics and paraplegics for the O_2 pulse, i.e. oxygen utilization per heart beat, which is in agreement with the observations of Van Loan *et al*.⁷ Coutts *et al*⁴ also reported no significant difference between quadriplegics (classes 1A, 1B and 1C) and high level paraplegics (classes 2 and 3) for O_2 pulse. However, they observed significantly greater values in the low-level paraplegics (classes 4 and 5) compared to the high-level paraplegics and quadriplegics. The discrepancy between their findings and the current ones could be due to the fact that four of the seven subjects classified as paraplegics in this study were in the high-level category, while the remainder were in the low-level category. Coutts *et al*⁴ suggested that the lower O_2 pulse in the high level paraplegics and quadriplegics was due primarily to a reduction in stroke volume (SV), and not due to changes in arteriovenous oxygen difference $\{(a-\bar{v})\text{O}_2 \text{ diff}\}$, because Hjelt-nes¹⁶ suggested that this variable was not significantly different between high- and low-level paraplegics. The reduction in SV in the subjects with high-level lesions was ascribed to their lack of peripheral vascular control, as well as their inability to maintain mean central and/or peripheral circulatory pressure.

The $\dot{V}_E:\dot{V}\text{O}_2$ ratio is considered to be an overall index of the economy of ventilation during exercise.¹⁷ In the current study, there was no significant difference between the quadriplegics and paraplegics for this variable, suggesting that the ventilatory requirements for a unit of oxygen consumption was not dependent on the lesion level. This concurs with the findings of Coutts *et al*⁴ and Van Loan *et al*,⁷ but disagrees with the results of Eriksson *et al*,⁵ who reported that the mean $\dot{V}_E:\dot{V}\text{O}_2$ ratio during maximal wheelchair exercise was significantly higher in quadriplegics than in paraplegics. While this aspect of ventilation seems to be controversial in the SCI population, it should be noted that the paraplegics seemed to be

ventilating more efficiently than the quadriplegics, because they attained their significantly higher $\dot{V}_E$ as a result of a larger tidal volume while the breathing frequency was the same between the two groups (Table I). A similar pattern in the ventilatory responses during maximal arm cranking exercise in quadriplegics and paraplegics has also been reported by Van Loan *et al*.⁷

Comparison of physiological responses between quadriplegics and paraplegics during wheelchair racing

The current findings demonstrated that quadriplegics and paraplegics were able to sustain high exercise intensities during a wheelchair race lasting approximately 14 min. The paraplegics raced at a HR which was between 91% and 100% of their peak HR recorded during the incremental velocity test, and maintained a $\dot{V}\text{O}_2$ which was between 90% and 98% of their peak $\dot{V}\text{O}_2$ (Table II). These observations concur with the findings of Asayama *et al*⁹ and Crews¹⁰ who reported that the $\dot{V}\text{O}_2$ and HR during wheelchair distance racing in paraplegics approached their peak values for most of the race duration. The $\dot{V}\text{O}_2$ responses during the SR also compare favourably with the treadmill running performance data of Farrell *et al*¹⁸ who reported that experienced male distance runners maintained an intensity corresponding to 94% of their $\dot{V}\text{O}_2$ max during a 3.2 km treadmill run lasting approximately 11 min.

The results of this study indicated that the quadriplegics sustained a significantly lower relative HR and $\dot{V}\text{O}_2$ during the SR compared to the paraplegics (Table II). Lakomy *et al*¹¹ reported that the relative $\dot{V}\text{O}_2$ during a simulated 5 km wheelchair race on the treadmill was approximately 90% in two quadriplegic wheelchair athletes. This was substantially higher than the average value of 76% that they observed in 10 paraplegic wheelchair athletes. The reasons for this discrepancy between the two studies are at present unclear, and further research on a larger group of subjects is needed to confirm this observation. Van Loan *et al*⁷ reported that the peak cardiac output during arm cranking exercise was significantly lower in

quadriplegics when compared to paraplegics and able bodied subjects. However, no significant differences were observed among these groups for the $(a-\bar{v})\text{O}_2$ diff during peak exercise. Whether the significantly lower relative $\dot{V}\text{O}_2$ during the SR observed in the quadriplegics in the current study was due to reduced blood perfusion to the exercising muscle as a result of their lower cardiac output also needs to be investigated.

Physiological factors related to wheelchair performance

In the present study, no significant relationships were observed between the racing WV during the SR or TR and the peak $\dot{V}\text{O}_2$ in the quadriplegics and paraplegics. Previous studies that have examined the relationship between the physiological responses and wheelchair performance in spinal cord injured subjects are equivocal. The studies by Asayama *et al.*,⁹ Cooper,¹² and Hooker & Wells¹³ reported that the peak $\dot{V}\text{O}_2$ during incremental exercise was not significantly related to WV during a marathon⁹ or 10 km^{12,13} race in well trained paraplegic road racers. In contrast, Lakomy *et al.*¹¹ observed a significant correlation of 0.61 between these two variables during a simulated 5 km road race in male quadriplegic and paraplegic athletes. It should be noted, however, that these investigators were able to explain only 37% of the common variance (r^2) between these two variables in their sample. They speculated that the balance could be attributed to factors such as variations in wheelchair design and racing speed, both of which have been reported to influence wheelchair performance in subjects with SCI.^{19–21} In the current study, considerable variation was observed in the $\dot{V}\text{O}_2$ among the SCI subjects during the SR. While some of it could be attributed to the differences in the design of the subjects' wheelchairs, it is postulated that factors influencing propulsion technique, such as stroke rate and stroke intensity, as well as upper-body involvement and body posture during wheeling also contributed to this variation. It is recommended that studies be undertaken to examine the effects of these variables on the wheeling economy of sub-

jects with SCI, so that factors which optimize racing performance can be established for this population.

Validity of the simulated racing test

The results of this study suggest that the SR was a valid measure of racing performance in both quadriplegics and paraplegics, because significant correlations were observed between the SR and TR for the race time, WV, HR, and [La] measurements in each group (Table III). In the quadriplegics, the common variances (r^2) between the SR and TR for these four variables (race time, WV, HR, and [La]) were 62%, 66%, 79%, and 60% respectively, while in the paraplegics these values were 67%, 77%, 77%, and 66% respectively. Comparison of the mean values for these variables between the two races revealed minor differences, which most likely were due to differences in racing surface; i.e. rollers vs track. In the current study measurements of $\dot{V}\text{O}_2$ were not obtained during the TR due to methodological problems, and therefore it was not possible to establish the validity of the SR on the basis of $\dot{V}\text{O}_2$ measurements. However, since the HR response was very similar during the TR and SR, it is likely that the $\dot{V}\text{O}_2$ also would have been similar under the two conditions had this variable been measured.

In summary, the results of the current study indicated that paraplegics were able to sustain a significantly higher percentage of their peak $\dot{V}\text{O}_2$ and peak HR during a SR lasting approximately 14 min when compared to quadriplegics. The WV during the SR and TR were not significantly related to the peak $\dot{V}\text{O}_2$ in either group of subjects. Significant relationships were observed between the SR and TR for the race time, WV, HR, and [La] responses in quadriplegics and paraplegics, suggesting that the SR was a valid measure of racing performance in SCI subjects.

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