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ORIGINAL ARTICLE

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Oxygen uptake-heart rate relationship in élite wheelchair racers

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Abstract The American College of Sports Medicine (ACSM) recommends that, as a general rule for health purposes, individuals should exercise at 40%–85% of their maximal oxygen uptakes. Moreover, it has been suggested that 55%–90% of the maximal heart rate may be used as an alternative estimate of these percentage maximal oxygen uptake values. The present study examined the relationship between percentage peak heart rate (% HR_{peak}) and percentage peak oxygen uptake (% $\dot{V}O_{2peak}$) during steady-state incremental intensity wheelchair propulsion of 16 élite, male wheelchair racers (WR). Oxygen uptake was determined during each submaximal exercise stage and heart rate (HR) was continuously monitored. The $\dot{V}O_{2peak}$ was subsequently determined using a separate protocol. Linear regression equations of % HR_{peak} versus % $\dot{V}O_{2peak}$ for each participant included % HR_{peak} values corresponding to 40%, 60%, 80% and 85% $\dot{V}O_{2peak}$. The linear regression equation, derived as the group mean of the slope and intercept terms determined for each individual, was: % peak HR $= 0.681 \times$ % peak $\dot{V}O_2 + 33.2$. The group mean of the individual correlation coefficients for the $\dot{V}O_2-$HR relationship was 0.99. The values of % HR_{peak} for each of the % $\dot{V}O_{2peak}$ values below 85% were significantly greater ($P < 0.01$) than those suggested by the ACSM. This suggests that the ACSM guidelines below 85% $\dot{V}O_{2peak}$, based on % HR_{peak}, may underestimate the relative exercise intensity (i.e. % $\dot{V}O_{2peak}$) in the WR population. However, in élite level WR, % HR_{peak} can be recommended as an alternative estimate of % $\dot{V}O_{2peak}$ at wheelchair propulsion intensities of 85% $\dot{V}O_{2peak}$ or more.

Keywords Wheelchair racers · American College of Sports Medicine · Wheelchair ergometry · Exercise prescription

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Introduction

Although there are well-established recommendations for general (i.e. non-specific for the exercising limbs) exercise intensities in able-bodied people (AB) (American College of Sports Medicine 1990, 1998), similar guidelines are not available for paraplegic wheelchair road racers (WR) (Hooker and Wells 1989; Davis et al. 1993; Campbell et al. 1997). Exercise training programmes designed to influence cardiorespiratory fitness and racing performance in WR have either been based on AB programmes (Hoffman 1986; Davis et al. 1993) or they have been based upon physiological assumptions that are not considered to be valid for a disabled population (Campbell et al. 1997).

A series of studies by Swain and colleagues questioned the previously suggested relationship between percentage of maximal oxygen uptake and percentage of maximal heart rate in several different groups of AB (Swain et al. 1994, 1998; Swain and Leutholtz et al. 1997). Subsequently, the American College of Sports Medicine (ACSM) suggested a shift towards the use of heart rate (HR) reserve and oxygen uptake ($\dot{V}O_2$) reserve when recommending the intensity of general exercise to the AB (Swain et al. 1998). In order to maintain or improve cardiorespiratory fitness, the ACSM recommended that AB should exercise at intensities equivalent to 40%–85% of $\dot{V}O_2$ reserve (American College of Sports Medicine 1998). Although not specifically designed for use by disabled athletes, it is not clear whether the former (1990) or the updated (1998) ACSM exercise recommendations (i.e. using HR and $\dot{V}O_2$ reserve values) are valid for élite WR.

Given the rapid increase in participation and popularity of wheelchair racing (Hooker and Wells 1992), this study sought to establish the $\dot{V}O_2$-HR relationship in a group of élite WR. Many of these athletes use HR training methods based on the ACSM recommendations, so it is essential to these athletes to establish whether the exercise recommended for use by the general ABis also applicable to WR. Therefore, the aim of the current study was to examine the $\dot{V}O_2$-HR relationship in a group of élite, male WR and to compare the percentage peak oxygen uptake (% $\dot{V}O_{2peak}$) and percentage peak heart rate (% HR_{peak}) values to those suggested by the American College of Sports Medicine (1990).

Methods

Participants

A group of 16 paraplegic, élite male WR from the Paralympic T3 and T4 racing classification system volunteered to participate in the study. All participants gave written informed consent prior to any involvement in the study. Approval for the study procedures was obtained from the University Research Ethics Committee and all procedures complied with the ACSM recommendations regarding research with human subjects (American College of Sports Medicine 1999). All the participants were considered as élite as they had competed regularly in endurance events at an international level and were part of a squad preparing for the Paralympic Games. The disability, Paralympic racing classification, and participant descriptive characteristics are presented in Table 1. The participants were part of a Sport Science Support Programme that involved regular laboratory-based physiological and biomechanical tests using a computerised wheelchair ergometer (WERG) and were, therefore, familiar with the test procedures used in this study. Body mass was measured to the nearest 0.1 kg using a seated, beam balance scale (Seca, Germany).

Instrumentation

Tests were performed using a WERG (Bromking, UK) which simulated wheelchair velocities similar to those experienced during road racing. The calibration procedure included a *deceleration test* performed when the participants were in an intermediate inclined position as suggested by Thiesen et al. (1996). The deceleration test ensured that the friction between the ergometer and the wheelchair tyres simulated the resistance level of propulsion developed by the wheelchair manufacturers (Bromking) and software manufacturers (KingCycle, UK). The WERG system allowed each athlete to be tested in his own racing wheelchair. All wheelchairs were fitted with 0.70 m (diameter) wheels with hand-rim sizes of 0.37 m or 0.38 m.

The WERG consisted of a single cylinder (length 0.78 m, circumference 0.53 m and mass 39.6 kg, including bearings). A flywheel sensor was linked to the roller and interfaced to a PC computer, which recorded the speed of the roller, and calculated the power output. The participants' speeds were determined by an electronic speedometer, which had been calibrated according to the diameter of the rear wheel. Continuous feedback from the speedometer and the power output display allowed the participants to maintain a constant speed at each successive stage of exercise.

Sub-maximal exercise protocol

Participants completed five to seven steady-state, sub-maximal exercise stages each lasting 4 min on the WERG. Push speed was increased by 0.89 $m{\cdot}s^{-1}$ at the end of each stage. The initial speed ranged from 2.68 $m{\cdot}s^{-1}$ to 4.47 $m{\cdot}s^{-1}$ based on each participant's performance in previous WERG tests performed in the same laboratory. The initial speed was slow in order to obtain a low mean (SD) relative exercise intensity at the start of 32 (7)% $\dot{V}O_{2peak}$ that could be used with the subsequent exercise stages to determine the $\dot{V}O_2$-HR relationship. Throughout the test, HR was monitored using short-range radio telemetry (PE4000 Polar Sport Tester, Kempele, Finland). Expired air was collected into Douglas bags during the final minute of each exercise stage. The concentration of oxygen and carbon dioxide in the expired air samples was determined using a paramagnetic oxygen analyser (series 1400, Servomex Ltd., Sussex, UK) and an infra-red carbon dioxide analyser (series 1400, Servomex Ltd.). Expired air volumes were measured using a dry gas meter (Harvard Apparatus, Kent, UK) and adjusted to standard temperature and pressure (dry). The $\dot{V}O_2$, carbon dioxide output, expired minute ventilation, and respiratory exchange ratio (R) were calculated for the contents of each Douglas bag. The analysers were calibrated with gases of known concentration before each test and the linearity of the gas meter was checked using a 3 l calibration syringe.

Table 1 Participant disability, Paralympic racing classification, and physiological characteristics (mean and SD). *SB* Spina bifida, *T* thoracic, *L* lumbar, *com* complete, *inc* incomplete. *PRC* Paralympic Racing Classification: *T3* complete or incomplete paraplegia below T1 down to and including *T7* or comparable disability, *T4* complete or incomplete paraplegia below *T8* down and including *S5* or comparable disability

Participant no.	Disability	PRC	Age (years)	Body mass (kg)	$\dot{V}O_{2peak}$ ($l{\cdot}min^{-1}$)	HR_{peak} ($beats{\cdot}min^{-1}$)	R_{peak}
1	Amputee	T4	19.0	56.9	2.66	200	1.12
2	Post polio	T4	19.0	49.5	2.68	209	1.36
3	SB	T4	18.3	56.5	2.53	194	1.10
4	SB	T3	32.8	47.8	1.46	178	1.10
5	SB	T4	22.7	61.0	2.53	202	1.10
6	SB	T4	26.0	40.3	1.80	198	1.28
7	SB	T4	29.3	47.4	2.83	190	1.10
8	SB	T4	18.2	66.1	1.94	191	1.14
9	T1/T2 (inc)	T3	21.8	51.0	2.33	197	1.24
10	T4 (inc)	T3	27.3	67.8	2.11	184	1.12
11	T5 (inc)	T3	28.1	75.6	2.30	179	1.22
12	T7/T8 (com)	T4	29.9	65.5	3.09	200	1.12
13	T8 (com)	T4	39.2	76.8	2.31	193	1.22
14	T11 (com)	T4	43.8	67.4	2.75	169	1.11
15	T12/L1 (com)	T4	40.8	69.0	2.55	190	1.20
16	T12/L1 (inc)	T4	33.7	71.0	3.28	197	1.13
Mean	–	–	28.1	60.6	2.45	191.9	1.17
SD	–	–	8.3	11.0	0.47	10.2	0.08

Peak oxygen uptake

A 5 min active recovery period followed the last sub-maximal exercise stage and then $\dot{V}O_{2peak}$ was determined for each participant using a continuous WERG test with 0.5 $m{\cdot}s^{-1}$ increments every minute until the subject became exhausted. The initial speed for each participant was based on the previous sub-maximal protocol, and ranged from 3.13 $m{\cdot}s^{-1}$ to 7.15 $m{\cdot}s^{-1}$. The mean (SD) time to complete this test was 8.9 (1.2) min. The HR was continuously monitored using radio telemetry and expired air samples were collected and analysed using the Douglas bag technique over the last two consecutive stages of the test. The HR_{peak} was defined as the highest value recorded during this test. The criteria for a valid $\dot{V}O_{2peak}$ were a maximal R of 1.10 or more and/or an HR_{peak} of 95% or more of the age-predicted maximum (200 $beats{\cdot}min^{-1}$ minus chronological age in years; Lockette and Keyes 1994). All of the participants satisfied these criteria.

Analyses

Standard descriptive statistics (means and SD) were obtained for all variables measured using SPSS 6.0 for Windows (SPSS, Chicago, Ill.). The $\dot{V}O_2$ and HR data at the end of the $\dot{V}O_{2peak}$ test and each sub-maximal steady-stage were expressed as percentages of their respective peak values. For each participant a linear regression analysis was conducted using the paired data of % $\dot{V}O_{2peak}$ and % HR_{peak} values. Data obtained at each completed submaximal exercise stage and peak values were included in the analyses. The % $\dot{V}O_{2peak}$ values were included in the analyses as the independent variable. The data for the whole group were not pooled together for a single linear regression equation as this would have statistically obscured the individual relationships (Swain et al. 1994). The mean (SD) values for the intercept, slope, standard error of the estimate (SEE), and Pearson's r correlation are presented in Table 2. Using the individual linear regressions, the % HR_{peak} corresponding to 40%, 60%, 80%, and 85% of $\dot{V}O_{2peak}$ were determined for each of the WR (Table 2). The mean % HR_{peak} data were then compared to those previously used by the ACSM (i.e. 55%, 70%, 85%, and 90%, respectively) using Student's t-test, with the ACSM value as the designated population norm (see Fig. 1). The a priori significance α level chosen for all statistical tests was 0.05.

Results

The mean (SD) of the 16 individual linear regression equations were used to calculate the following prediction equation: $\%HR_{peak} = [(0.681) \times \%\ \dot{V}O_{2peak}] + 33.2$. The group mean (SD) Pearson product moment correlation coefficient of 0.989 (0.008) and the SEE of 2.58 (1.0) suggests that there was a strong linear fit between % HR_{peak} and % $\dot{V}O_{2peak}$. The % HR_{peak} for the WR were significantly greater ($P < 0.01$) than those used by the ACSM at all exercise intensities except 85% $\dot{V}O_{2peak}$ ($P > 0.05$; see Fig. 1). The discrepancy between the WR values and the population norm (ACSM) decreased

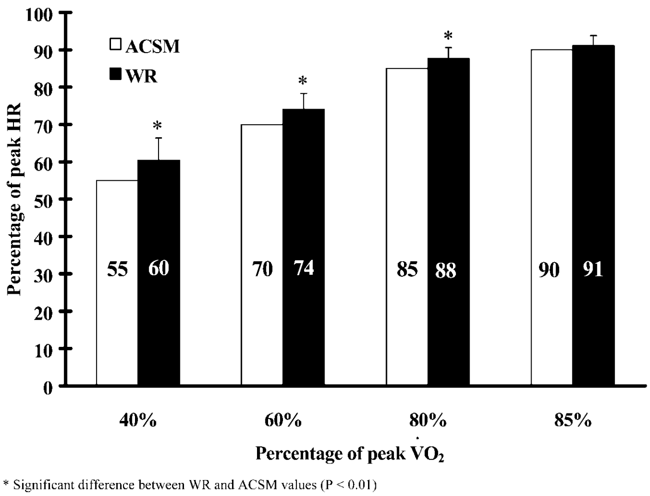

Fig. 1 Percentages of peak heart rate (*peak HR*) attained by wheelchair racers (*WR*) at indicated percentages of peak oxygen uptake (peak $\dot{V}O_2$). *ACSM* American College of Sports Medicine. *Significant difference between WR and ACSM values ($P < 0.01$)

Table 2 Individual linear regression characteristics (mean and SD). *SEE* Standard error of the estimate, r correlation coefficient HR_{peak} peak heart rate, $\dot{V}O_2$ oxygen uptake

Participant	Slope	Intercept	SEE	Pearson's r	% HR_{peak} at 40% $\dot{V}O_2$	% HR_{peak} at 60% $\dot{V}O_2$	% HR_{peak} at 80% $\dot{V}O_2$	% HR_{peak} at 85% $\dot{V}O_2$
1	0.544	46.381	2.372	0.987	68.13	79.01	89.89	92.61
2	0.727	32.360	4.249	0.981	61.43	75.97	90.50	94.13
3	0.671	35.365	2.737	0.991	62.19	75.60	89.01	92.37
4	0.548	47.251	2.917	0.987	69.17	80.13	91.10	93.84
5	0.724	26.457	1.339	0.998	55.41	69.88	84.36	87.98
6	0.673	33.503	1.851	0.995	60.44	73.91	87.38	90.75
7	0.843	19.006	4.555	0.975	52.74	69.60	86.47	90.68
8	0.630	37.639	1.082	0.998	62.83	75.42	88.01	91.16
9	0.812	21.372	2.620	0.992	53.84	70.08	86.32	90.37
10	0.712	31.903	2.525	0.992	60.37	74.60	88.83	92.39
11	0.525	45.666	2.534	0.974	66.67	77.16	87.66	90.29
12	0.635	38.346	2.240	0.992	63.73	76.43	89.12	92.29
13	0.696	31.274	1.162	0.996	59.12	73.04	86.96	90.44
14	0.627	42.213	3.534	0.978	67.29	79.83	92.37	95.51
15	0.760	19.736	3.355	0.988	50.13	65.32	80.52	84.32
16	0.778	22.130	2.213	0.993	53.26	68.83	84.39	88.29
Mean	0.681	33.163	2.580	0.989	60.42	74.05	87.68	91.09
SD	0.094	9.506	0.999	0.008	5.94	4.29	2.93	2.69

from 5% at 40% $\dot{V}O_{2peak}$ (60% vs 55%) to only 1% at 85% $\dot{V}O_{2peak}$ (91% vs 90%).

Discussion

This study suggests that the $\dot{V}O_2$-HR relationship recommended by American College of Sports Medicine (1990) for general (i.e. non-specific exercise limb) exercise may be only strictly applicable to élite level WR when they train at the higher exercise intensities. Elite WR exercising at an intensity below 85% $\dot{V}O_{2peak}$ would not be training at the intensity the ACSM general exercise guidelines suggest (see Fig. 1). This finding is in contrast to the recommendation of Hooker et al. (1993) that ACSM guidelines are appropriate across the exercise intensity continuum for arm-crank exercise. It is clear, however, that the discrepancy between the WR values reported here and the ACSM recommendation is still quite small even below 85% $\dot{V}O_{2peak}$ (ranging from a 5% HR_{peak} discrepancy at 40% $\dot{V}O_{2peak}$ to only 1% at 85% $\dot{V}O_{2peak}$).

Depending on the level of impairment of the sympathetic nervous system (Haas et al. 1986; Drory et al. 1990), it is known that a reduction in venous return results in a lower cardiac preload (Gass and Camp 1979; Coutts et al. 1983). In order to compensate for the subsequent reduction in stroke volume, the HR may be higher during upper body exercise in WR compared to AB at equivalent exercise intensities (Jehl et al. 1991). Previous studies have suggested that using HR to estimate the exercise intensity in quadriplegics may not be appropriate due to the previously described reductions in venous return and the lack of sympathetic innervation to the heart (Glaser 1989; McLean et al. 1995). Hopman et al. (1991) stated that the level of spinal cord injury (SCI) is an important determinant of the cardiovascular response during exercise. However, Hooker et al. (1993) noted no significant difference between the mean regression slopes of % HR_{peak} and % $\dot{V}O_{2peak}$ in persons with high lesion SCI (T1–T6) and low lesion SCI (T7–T12). Furthermore, a Mann–Whitney *U* analysis of the regression characteristics (slope and intercept) between participants 1–8 and 9–16 in the current study (see Table 1) did not reveal any significant differences. An examination of the relationship between % $\dot{V}O_{2peak}$ and % HR_{peak} in paraplegics during wheelchair racing propulsion should help provide information necessary to recommend the exercise intensities required for training by this population of athletes.

To the authors' knowledge, no previously published studies have directly sought to examine the $\dot{V}O_2$-HR relationship in paraplegic WR whilst exercising in their racing wheelchairs. The results of a study of sedentary participants using arm-crank exercise indicated that established exercise recommendations (American College of Sports Medicine 1990) need not be modified (Hooker et al. 1993). Moreover, these authors concluded that HR could be confidently used as an indicator of arm crank exercise intensity in this population, and that the findings would have vital implications for coaches and SCI athletes involved in wheelchair sports. It is possible that these conclusions may not be directly applicable to élite WR if, as in AB endurance athletes, the $\dot{V}O_2$-HR relationship is significantly altered as a result of their training. The participants in the Hooker et al. (1993) study were all considered to be either sedentary or minimally active, and not aerobically trained in the upper body. Furthermore, their test protocol was based on arm-crank ergometry with increases in intensity every minute and the participants completed the test on only one occasion. It is unlikely that the participants would have reached a physiological steady state in these short exercise stages and it is doubtful whether the mode of exercise would have reflected the physiological responses seen during wheelchair exercise. It is recognised that the research conducted by Hooker et al. (1993) was not designed to replicate wheelchair racing conditions nor did the authors recommend that their findings be applied to all SCI athletes. However, it is important to note that Hooker et al. (1993) used % HR_{peak}, rather than % $\dot{V}O_{2peak}$, as the independent variable in their linear regression analyses. Swain et al. (1994) have suggested that the subsequent transposition of the resultant regression equation to predict % HR_{peak} from a given % $\dot{V}O_{2peak}$ is mathematically erroneous and would lead to errors in prediction.

The results of the current study indicate that at training intensities of 85% or below of $\dot{V}O_{2peak}$, the WR would not be training as intensively as the ACSM guidelines suggest. As previously mentioned, the discrepancy is quite small (5% HR_{peak} discrepancy at 40% $\dot{V}O_{2peak}$ down to only 1% at 85% $\dot{V}O_{2peak}$). Whether differences of this magnitude are meaningful to élite WR athletes preparing for competition has to be carefully considered by the athletes and their coaches alike. On the other hand, the results indicate that at 85% $\dot{V}O_{2peak}$ and above the former ACSM guidelines for healthy AB (American College of Sports Medicine 1990) do not need to be adjusted for élite WR. This is partially explained by the fact that the American College of Sports Medicine (1990) regression equation and the average regression equation from the present study both approach the same termination point of 100% HR_{peak} at 100% $\dot{V}O_{2peak}$ (Swain et al. 1994). The similarity between the current study of paraplegic athletes and the AB participants in Swain and colleagues (1994) study is perhaps related to peak physiological responses. That is, all the WR reached a HR_{peak} of 95% or more of the age-predicted maximum 200 beats·min^{-1} minus chronological age in years; Lockette and Keyes (1994), thus satisfying the $\dot{V}O_{2peak}$ test criteria. Therefore, the group's mean (SD) HR_{peak} of 192 (10) beats·min^{-1} would suggest that HR was not impaired by abnormal autonomic cardiac regulation secondary to the nature of the disability (Kerk et al. 1995), and that the HR_{peak} were comparable to those of AB runners at exhaustion (Ramsbottom et al. 1987). Furthermore, the mean

$\dot{V}O_{2peak}$ value of 2.45 l·min^{-1} demonstrated that these athletes were well-conditioned (Kerk et al. 1995; Goosey and Campbell 1998) and that standards of performance have improved when compared to previously reported physiological responses of athletes in the UK (Lakomy et al. 1987; Campbell 1992).

Some authors have suggested that even in wheelchair athletes where there is full sympathetic innervation of the heart, a lower-stroke volume is compensated by a higher HR, leading to a similar cardiac output for a given $\dot{V}O_2$ to that in AB (Sawka et al. 1980; Hopman et al. 1991). It is possible that this explanation is pertinent for exercise intensities below 85% $\dot{V}O_{2peak}$ when studying the $\dot{V}O_2$-HR relationship in paraplegic athletes. Venous blood pooling may have been present at lower exercise intensities and may have resulted in higher submaximal $\dot{V}O_2$-HR ratios for the WR when compared to the former guidelines for AB (American College of Sports Medicine 1990).

The very recent adoption of both $\dot{V}O_2$ and HR reserve values for AB exercise recommendations by the ACSM (American College of Sports Medicine 1998) may be warranted when considering élite WR training at less than 85% $\dot{V}O_{2peak}$. Former ACSM recommendations (American College of Sports Medicine 1990) may only be applicable to exercise at high intensity. The newly proposed guidelines (American College of Sports Medicine 1998) do require studies on exercise training sessions at intensities below 85% $\dot{V}O_{2peak}$ and within wheelchair specific populations in order to see if they are suitable for recommending training to less experienced and/or younger WR.

In summary, the group of WR in the present study exhibited physiological responses representative of a well-trained population. It appears that applying the American College of Sports Medicine (1990) guidelines to exercise yielding HR below 85% of the HR_{peak} may slightly underestimate the relative exercise intensity (% $\dot{V}O_{2peak}$) in this WR population. However, at the upper end of the exercise intensity continuum (i.e. 85% $\dot{V}O_{2peak}$ or more), the continued use of % HR_{peak} as an alternative estimate of % $\dot{V}O_{2peak}$, as originally proposed by the ACSM, in élite level WR, is recommended $\%\dot{V}O_2$ $\%\dot{V}O_2$.

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