The Physiology of Cycling with Reference to Power Output and Muscularity

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The maximal average power output ($\bar{W}_{\max}$) and capacity (W_{cap}) of the short-term (anaerobic) energy processes are examined in cyclists and young adults with respect to body size and muscularity. The results show that when $\bar{W}_{\max}$ and W_{cap} are standardized for muscle size the power and capacity of the anaerobic mechanisms are similar between trained sprint and pursuit cyclists and untrained young healthy adults. Thus the efficiency of anaerobiosis appears to be a function of muscularity in man over the range of subjects studied. From the data it is estimated that the probable efficiency of supra maximal cycling is of the same order (0.22) as found for steady state submaximal (aerobic) exercise.

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Despite the increased interest in short-term power output in man little attention has been given to examining the relationship between the generation of maximal mechanical work output and performance duration. To the author's knowledge no or little attempt has been made to measure and define the total energy available (as opposed to its rate of expenditure) during supramaximal effort particularly with regard to body size and muscularity. These relationships are particularly important in sprint sports such as cycling and running where the interplay between energy availability and rate of utilization must ultimately be the major physiological determinant of performance.

The present paper which is based on recently published work (Davies and Sandstrom, 1989) from my laboratory examines these relationships in British amateur cyclists.

Measurement of Short Term Power and Capacity

Maximal mechanical power output was measured

on a modification of an isokinetic force ergometer developed in my laboratory by Sargeant et al. (1978 and 1981). Essentially the ergometer consisted of a stationary cycle driven by a high speed motor. The cranks of the cycle were instrumented with strain gauges the output of which gave a continuous record of the forces exerted during maximal effort. The precise details of the involved procedures have been given elsewhere (Davies et al., 1984). Subjects were required to exert their maximal forces on the pedals at 8-10 pre-set speeds during several different visits to the laboratory. From the continuous measurements of force at set velocities the maximal average power output ($\bar{W}_{\max}$) at a given optimal pedal frequency ($\dot{V}_{\text{opt}}$) could be determined for each subject (see Davies et al., 1984). Once $\bar{W}_{\max}$ and $\dot{V}_{\text{opt}}$ were ascertained the subjects were required to perform exercise at this level and speed for 80s. Force output from the cranks was sampled every 0.025s using an on-line micro-computer, average power output ($\bar{W}$) was determined by integration

with respect to pedal velocity. To determine the maximal capacity (W_{cap}) of the short term energy stores $\bar{W}$ was analysed with respect to time using a modification of a method first suggested by Wilkie (1977). The analysis assumes that during maximal work energy is derived from two sources; the hydrolysis of high energy phosphates and aerobic metabolism. Exponential curves were fitted to the $\bar{W}$ /Time data and empirical correction was made for the contribution of aerobic energy assuming a time constant of 6s and a baseline duration of 45s. Measurement of $\bar{W}_{max}$ and W_{cap} were made on 10 healthy male students; mean age; 23.9 yr, height; 176.4 cm and weight; 74.8 kg, 12 sprint cyclists; mean age; 18.7 yr, height; 172.3 cm and weight; 72.5 kg and 22 pursuit cyclists; mean age; 18.5 yr, height; 175.5 cm and weight; 68.0 kg. Estimates of leg muscle (plus bone) volume (LV) and cross sectional area (CSA) of calf muscle (plus bone) were obtained from simple anthropometric measurements as previously described (Davies et al., 1984).

Results and Discussion

The reproducibility of the short term maximal test measured on 8 of the 10 healthy male students is given in Table 1. The exponential decline of power output ($\bar{W}$) with time (t) is described by the equation $\bar{W} e^{-at}$ where a is a constant. The table shows the form of the equation in duplicate measurements made on separate occasions together with estimates of W_{cap} and its half time ($t_{1/2}$) and the duration (D). The intra-subject coefficient of variation of duplicate measurements of W_{cap} was $\pm 9\%$.

The inter-subject variability of $\bar{W}$, a, W_{cap} , $t_{1/2}$ and D is given in Table 2. The maximal measured average power output ($\bar{W}_{max}$) and that predicted ($\bar{W}_{pred}$) from the force velocity relationship together with the theoretical predicted maximal velocity ($\dot{V}_o$) and $\dot{V}_{opt}$ in revolution per min are given in Table 3.

The measured $\bar{W}_{max}$ was closely associated with body weight and estimates of leg muscle (plus bone)

volume (LV) and calf muscle (plus bone) cross-sectional area (CSA). However in terms of body weight the sprint cyclists had a higher $\bar{W}_{max}/kg$ weight ($p < 0.01$) than the students and pursuit cyclists and the data could not be combined:

Table 1 Reproducibility of the 80 s test. Comparison of duplicate measurements performed on separate occasions. Data for students ($n = 8$). The exponential decline of power output ($\bar{W}$) with time (t) is described by the equation $\bar{W}e^{-at}$ where a is a constant.

The estimated oxidative (W_{O_2}) and anaerobic (W_{cap}) components (see text) of the total maximal mechanical work produced during 45 s of the 80 s test together with the duration (D) and half time ($t_{1/2}$) of the W_{cap} are given.

	$\bar{W}$ (W)	a	W_{O_2} (kJ)	W_{cap} (kJ)	D (s)	$t_{1/2}$ (s)
Test 1	1039 ± 231	-0.0359 ± 0.006	8.2 ± 2.1	14.7 ± 2.8	44.4 ± 1.8	10.9 ± 0.4
Test 2	1019 ± 209	-0.0355 ± 0.007	8.3 ± 2.6	14.5 ± 2.7	44.4 ± 1.8	10.9 ± 0.4

Singnificance: N. S.

Table 2 Power output ($\bar{W}$) and the estimated oxidative (W_{O_2}) and anaerobic (W_{cap}) components of the total maximal mechanical work (W_{tot}) produced during 45 s of an 80 s test.

Symbols as for Table 1.

	$\bar{W}$ (W)	a	W_{tot} (kJ)	W_{O_2} (kJ)	W_{cap} (kJ)	D (s)	$t_{1/2}$ (s)
Sprint (n = 6)	1157 $+332$	-0.0286 $+0.006$	28.8 ± 5.2	12.1 ± 1.2	16.7 ± 4.9	45.1 ± 0.08	10.8 ± 0.6
Pursuit (n = 10)	965 $+193$	-0.0226 $+0.005$	27.8 ± 3.5	13.8 ± 2.0	14.0 ± 2.9	45.3 ± 0.7	10.1 ± 0.9
Students (n = 8)	1039 $+231$	-0.0359 $+0.008$	22.9 ⁺ ± 3.9	8.2 ⁺⁺ ± 2.1	14.7 ± 2.8	44.4 ± 1.8	10.9 ± 0.4

Singnificance: Sprinters v pursuit * $p < 0.05$

Sprinters v students * $p < 0.05$

** $p < 0.001$

Table 3 The maximal average power output ($\dot{W}_{\max}$) achieved and predicted ($\dot{W}_{\max}^1$) power output from the force/velocity relationship which could be described by a linear relationship (see Davies et al. 1984) of the form, Force = $P_0 + bV$ (ms^{-1}); P_0 = the maximal force at zero velocity, b is a constant and V = velocity of pedalling. The theoretical maximal velocity (V_p) at zero force and the "optimal" frequency of pedalling ($\dot{V}_{\text{opt}}$) for the attainment of $\dot{W}_{\max}$ expressed in revolution/min (rpm) are also given.

Group	P_0 (N)	b	$\dot{W}_{\max}^1$ (kJ)	$\dot{W}_{\max}$ (kJ)	$\dot{V}_0$ (kJ)	$\dot{V}_{\text{opt}}$ (rpm)
Sprint ($n = 12$)	989 ± 217	-201.9 ± 45.2	1212 ± 264	1241 ± 266	262 ± 8	132 ± 3
Pursuit ($n = 22$)	828*** ± 155	-180.9 ± 31.2	929*** ± 187	962*** ± 206	242*** ± 12	122*** ± 6
Students ($n = 10$)	868 ± 157	-198.8 ± 41.1	952** ± 173	1019** ± 183	235*** ± 17	118*** ± 8

Singnificance: Sprinters v pursuit *** $p < 0.001$

Sprinters v students ** $p < 0.01$

*** $p < 0.001$

Sprint cyclists:

$\dot{W}_{\max} (W) = -596.4 + 25.33 \text{ weight (kg)}$, $r = 0.93$,
 $n = 12$

Students and pursuit cyclists:

$\dot{W}_{\max} (W) = -149.8 + 16.13 \text{ weight (kg)}$, $r = 0.83$,
 $n = 32$

In terms of $\dot{W}/\text{kg}$ the $\dot{W}_{\max}$ of the students (13.6 W/kg) and pursuit cyclists (14.1 W/kg) is similar to that found previously (Davies et al., 1984) on young adults (15.9 W/kg) from my laboratory. Thus it would seem that pursuit cyclists whose event demands much in terms of aerobic endurance, are only capable of developing short term power which is statistically equal or similar to untrained young adults.

The higher relative power output of the sprint cyclists (17.1 W/kg, $p < 0.01$) is associated with a higher $\dot{V}_{\text{opt}}$ (132 ± 3 rpm) and $\dot{V}_0$ (262 ± 8 rpm) than the students ($\dot{V}_{\text{opt}} = 118 \pm 8$ rpm and $\dot{V}_0 = 242 \pm 17$

rpm) and pursuit cyclists ($\dot{V}_{\text{opt}} = 122 \pm 6$ rpm and $\dot{V}_0 = 242 \pm 12$ rpm). Thus there is an upward displacement of the absolute force/velocity relationship. However if standardisation is made for P_0 the major differences in the force/velocity relationship disappears and if $\dot{W}_{\max}$ is considered in terms of either LV or CSA the power to 'muscle' ratio is similar in the three groups studied and the $\dot{W}_{\max}$ data can be combined:

$\dot{W}_{\max} (W) = -161.34 + 80.16 \text{ LV (l)}; r = 0.72, n = 43$

$\dot{W}_{\max} (W) = -240.56 + 6.76 \text{ CSA (cm}^2\text{)}; r = 0.79, n = 43$

Thus it would appear that $\dot{W}_{\max}$ is a function of size and muscularity of the groups of subject studied. It is only in absolute terms that $\dot{W}_{\max}$ reflects the degree of specialisation of the cyclists. Sprint cyclists require a large body size and (leg) muscle mass in order to develop mechanical power output. The dilemma faced by sprint cyclists in the work performed is mainly to overcome air resistance, the magnitude of which will increase as a square of velocity and with the total projected area of the body (and bicycle - see Davies, 1980). The sprint cyclists in this study were all extremely muscular but relatively short in stature. This may be the essential compromise between power generation, wind resistance and optimal performance (in terms of velocity) in sprint cycling. Certainly the close interplay between power, muscularity and size suggests the need for careful initial selection as well as training in sprint cycling. Unlike long term (aerobic) power it seems that short-term (anaerobic) power cannot be trained independently of muscle mass.

The decline of $\dot{W}_{\max}$ during the 80 s 'all-out' test, when empirical correction is made for oxidative processes is not significantly different ($p > 0.1$) between the three groups of subjects studied. The respective half times ($t_{1/2}$) for $\dot{W}_{\max}$ were 10.9 ± 0.45 s, 10.8 ± 0.65 s and 10.1 ± 0.95 s in the students, sprint and pursuit cyclists respectively. The total work performed during the period of analysis (45 s) is

similar in the sprint (28.8 ± 5.2 KJ) and pursuit cyclists (27.8 ± 3.5 KJ) but less in students (22.9 ± 3.9 KJ, $p < 0.05$). However this difference appears to be due to the reduced amount of aerobic work performed by the students during the test. When empirically corrected for the aerobic component the area below the $\bar{W}_{\max}$ /time curve which may be taken as representative of the capacity of the short-term anaerobic mechanisms (W_{cap}), is similar in the 3 groups studied and is associated with $\bar{W}_{\max}$, LV and CSA:

$$W_{\text{cap}} \text{ (kJ)} = -2.85 + 1.196 \text{ LV(1)}; \quad r=0.64, n=23$$

$$W_{\text{cap}} \text{ (kJ)} = -3.16 + 0.098 \text{ CSA(cm}^2\text{)}; \quad r=0.74, n=23$$

The range of W_{cap} values standardized for body weight (kJ/kg) was 0.20-0.23 with a mean value of 0.22 kJ/kg for the three groups. If we assume that a 70 kg man has 25 kg of muscle, 1 mol of phosphagen is equivalent to 46 kJ and the phosphagen content of muscle is 27m mol/kg (see Wilkie, 1968) then his maximal energy yield from phosphagen stores will be 31.1 kJ or 0.44 kJ/kg. In well motivated subjects it has been shown (Hermansen, 1981) the maximal lactate yield in muscle is 23m mol/kg. Using the same set of assumptions as above and given that 1 mol of lactate is equivalent to 1.5 ATP molecules then the maximal energy yield from glycolytic processes is 39.8 kJ or 0.57 kJ/kg body weight. Thus, combining these figures the apparent mechanical efficiency of the anaerobic conversion of chemical energy into mechanical work is 0.22 ($0.22/0.44 + 0.57$), the same figure which has been found for aerobic processes. If this is true (although clearly it requires verification by direct experimentation), it has important practical consequences in the field of sports science. It suggests, in a agreement with the earlier work of Margaria (1976), that the efficiencies of whole body aerobic and anaerobic processes are

similar and that they may be combined when assessing metabolic performance at maximal and supra-maximal levels of exercise.

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