

## Maximal mechanical power output and capacity of cyclists and young adults

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**Summary.** The maximal average power output ( $\bar{W}_{\max}$ ) has been examined in 10 male students, 22 pursuit and 12 sprint cyclists. In 24 of these subjects (8 students, 10 pursuit and 6 sprint cyclists), estimates of the maximal capacity ( $\bar{W}_{\text{cap}}$ ) of the short-term anaerobic energy yielding processes were made. The results show that the sprinters had a higher absolute  $\bar{W}_{\max}$  ( $1241 \pm 266$  W) and  $\bar{W}_{\text{cap}}$  ( $16.7 \pm 4.9$  kJ) than either the students ( $1019 \pm 183$  W,  $14.7 \pm 2.8$  kJ) or the pursuit cyclists ( $962 \pm 206$  W,  $14.0 \pm 2.9$  kJ). However, the differences were removed when the values were standardised for muscle size. In the sprinters the  $\bar{W}_{\max}$  was attained at an optimal pedal frequency  $\dot{V}_{\text{opt}}$  of  $132 \pm 3$  min<sup>-1</sup> and the estimated maximal velocity of pedalling ( $\dot{V}_0$ ) was  $262 \pm 8$  min<sup>-1</sup>. The comparable figures in the students and pursuit cyclists were  $118 \pm 8$  min<sup>-1</sup>,  $235 \pm 17$  min<sup>-1</sup> and  $122 \pm 6$  min<sup>-1</sup>,  $242 \pm 12$  min<sup>-1</sup> respectively. The coefficient of variation of duplicate measurements of  $\bar{W}_{\text{cap}}$  was found to be  $\pm 9\%$ . Using data of Wilkie (1968) for muscle phosphagen and glycolytic stores ( $27$  mmol·kg<sup>-1</sup>), it was estimated that the probable efficiency of the anaerobic processes during maximal cycling was 0.22. It was concluded that  $\bar{W}_{\max}$  and  $\bar{W}_{\text{cap}}$  are largely determined by body size and muscularity. The efficiency of anaerobiosis appears to be of the same order of magnitude as found for oxidative work.

**Key words:** Exercise — Isokinetic contractions — Maximal anaerobic power and capacity — Muscle

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### Introduction

The physiological importance and contribution of the high energy producing phosphagen mechanisms to maximal exercise performance have been studied extensively in recent years (see Margaria 1976 for general review), particularly with the development of the muscle biopsy sampling technique in man (Karlsson 1971). Several authors have investigated short-term maximal power output (see for example, Sargeant et al. 1981; and McCartney et al. 1983) but apart from the original theoretical analysis of Wilkie (1960) and the study of Tornvall (1963), little attention has been given to the relationship between maximal mechanical power output and duration of effort. This relationship enables one to define not only the maximal theoretical rate of work production but also the total capacity of the (anaerobic) energy producing system. This paper examines the relationship between maximal power and capacity, with reference to body size in young male students and amateur sprint and pursuit cyclists.

### Material and methods

The physical characteristics of the students and cyclists are shown in Table 1. The estimates of leg muscle (plus bone) volume (LV) and cross-sectional area (CSA) of the calf muscle (plus bone) were obtained from anthropometric measurements of the legs of the subjects as previously described (Davies et al. 1984). All the subjects were volunteers and gave their informed consent to participate in the experiments.

During the initial visits to the laboratory the power output of each subject was measured at 8–10 speeds on a specially designed isokinetic force cycle (see Sargeant et al. 1981). From these measurements the maximal average power output ( $\bar{W}_{\max}$ ) and required frequency of pedalling ( $\dot{V}_{\text{opt}}$ ) were determined for each of the 44 subjects. The procedures and methods used to measure these variables have been described in detail else-

**Table 1.** Physical characteristics of the male students, sprint and pursuit cyclists. Age, height (Ht), weight (wt), leg muscle (plus bone) volume (LV), and an estimate of calf muscle (plus bone) cross-sectional area (CSA)

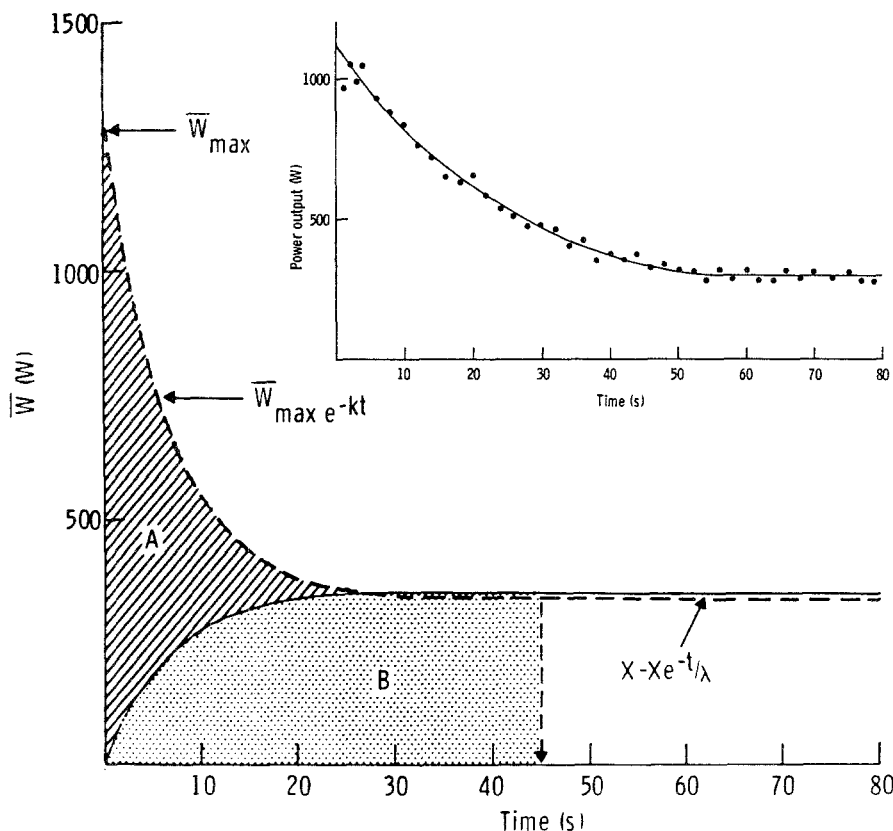
Group	Age (years)	Ht (cm)	wt (kg)	LV (l)	CSA (cm <sup>2</sup> )
Sprint (n = 12)	18.7 ± 2.7	172.3 ± 6.6	72.5 ± 9.8	15.4 ± 2.3	97.9 ± 12.3
Pursuit (n = 22)	18.5 ± 2.5	175.5 ± 9.4	68.0 ± 9.9	15.1 ± 2.2	91.3 ± 11.4
Students (n = 10)	23.9*** ± 4.7	176.4 ± 5.6	74.8 ± 10.1	14.9 ± 2.4	92.6 ± 7.6

Significance: Sprinters/pursuit NS  
Sprinters/students \*\*\*  $p < 0.001$

where (Davies et al. 1984). Once  $\bar{W}_{max}$  and  $\dot{V}_{opt}$  had been ascertained, 24 of the subjects (6 sprint and 10 pursuit cyclists and 8 students) were required to perform maximal exercise on the bicycle continuously for 80 s at  $\dot{V}_{opt}$ . During the experiment, pedal frequency was held constant by the high-powered motor of the force bicycle, and the subjects exerted their maximal isokinetic force against the cranks. Oxygen intake ( $\dot{V}_{O_2}$ ) was measured, using a low resistance open circuit technique, every 20 s during the test in 8 of the pursuit cyclists and 8 of the students. The  $\dot{V}_{O_2}$  measurements were converted to mechanical work output assuming an efficiency of 0.21 (see Fig. 4). The force output from the cranks was sampled at a frequency of 40 Hz using an on-line micro-computer (Digital (MINC II)). From the force/time data, the computer was pro-

grammed to perform the following set of calculations for each revolution of the cranks. Velocity of pedalling, which was pre-set by the motor speed, was obtained using the formula:  $\frac{2\pi r}{t}$ ,

where  $r$  = the radius of the cranks (175 mm) and  $t$  the time for one revolution of the pedals. Average power output ( $\bar{W}$ ) was determined by integration of the force output for both cranks with respect to pedal velocity. The  $\bar{W}$  from the maximal 80 s tests was analysed against time using a modification of the method suggested by Wilkie (1977). The analysis (Fig. 1) assumes that during short-term maximal work, muscular energy is derived from (i) the hydrolysis of high energy phosphagens (adenosine triphosphate and creatine phosphate) and glycogen to lactic acid, the total energy available (the capacity of the hydrolytic reactions,  $\bar{W}_{cap}$ ) being limited by the stores of these chemicals within the muscle, and (ii) oxidative metabolism. Exponential curves were fitted to the  $\bar{W}$ /time data and empirical correction was made for the contribution of the oxidative mechanism, by assuming an exponential rise of oxygen consumption with a time constant of 6 s. In the pursuit cyclists, the criteria for the two component model were adequately met. Initially there was rapid exponential fall of  $\bar{W}$ , which levelled off after 30–45 s. From this point, a constant baseline of mechanical power was maintained which approximated closely to the measured rate of aerobic metabolism. However, although showing a similar initial rapid fall in  $\bar{W}$ , the students were unable to maintain a steady baseline. In some students, the  $\bar{W}$  fell below the measured aerobic work, and gradually  $\bar{W}$  declined with time. Thus the student group presented a problem of analysis, particularly with regard to the correct baseline to apply for the computation of the oxidative component of the work performed. Clearly to use a baseline of  $\bar{W}$  values recorded at the end of the test would seriously over-estimate the



**Fig. 1.** The relationship between average mechanical power production ( $\bar{W}$ ) and duration of effort ( $t$ ) showing the method of analysis and derivation of the theoretical oxidative ( $\bar{W}_{O_2}$  — Area B) and anaerobic ( $\bar{W}_{cap}$  — Area A) of the total maximal mechanical work ( $\bar{W}_{tot}$  — Areas A+B) produced during an 80 s all-out test on an isokinetic bicycle ergometer. The exponential decline of mechanical work with time is represented by the equation  $\bar{W}_{max} e^{-kt}$ , where  $\bar{W}_{max}$  is the mechanical work at zero time,  $t$  equals time (s) and  $k$  is a constant. The theoretical rise in mechanical work production which can be attributed to the muscle oxidation is represented by the equation  $X - X e^{-t/\lambda}$ , where  $X$  is equal to average mechanical work performed during the last 20 s of exercise,  $t$  is time and  $\lambda$  (the theoretical half time of the oxidative processes) is taken to be 6 s. The analysis was performed to a constant duration of 45 s. Inset shows original data taken from a pursuit cyclist

**Table 2.** The maximal average power output ( $\bar{W}_{\max}$ ) achieved and predicted ( $\bar{W}_{\max}^1$ ) power output from the force/velocity relationship which could be described by a linear relationship (see Davies et al. 1984) of the form, Force =  $P_0 + bV$  ( $\text{ms}^{-1}$ );  $P_0$  = the maximal force at zero velocity,  $b$  is a constant and  $V$  = velocity of pedalling. The theoretical maximal velocity ( $V_0$ ) at zero force and the "optimal" frequency of pedalling ( $V_{\text{opt}}$ ) for the attainment of  $\bar{W}_{\max}^1$  expressed in revolutions/min (rpm) are also given

Group	$P_0$ (N)	$b$	$\bar{W}_{\max}^1$ (W)	$\bar{W}_{\max}$ (W)	$V_0$ (rev $\text{min}^{-1}$ )	$V_{\text{opt}}$ (rev $\text{min}^{-1}$ )
Sprint ( $n=12$ )	989 $\pm 217$	-201.9 $\pm 45.2$	1212 $\pm 264$	1241 $\pm 266$	262 $\pm 8$	132 $\pm 3$
Pursuit ( $n=22$ )	828*** $\pm 155$	-180.9 $\pm 31.2$	929*** $\pm 187$	962*** $\pm 206$	242*** $\pm 12$	122*** $\pm 6$
Students ( $n=10$ )	868 $\pm 157$	-198.8 $\pm 41.1$	952** $\pm 173$	1019** $\pm 183$	235*** $\pm 17$	118*** $\pm 8$

Significance: Sprinters v pursuit \*\*\*  $p < 0.001$   
Sprinters v students \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$

anaerobic and under-estimate the aerobic contributions to the maximal work performed. To overcome this difficulty, the total work performed ( $\bar{W}_{\text{tot}}$ ), together with the respective oxidation ( $\bar{W}_{\text{O}_2}$ ) and anaerobic ( $\bar{W}_{\text{cap}}$ ) components, were calculated to a constant duration of 45 s (see Fig. 1). Beyond this time, our results would suggest that, whether  $\bar{W}$  equalled, or was below, the measured oxygen intake, at least it was certain that the mechanical work performed could be accounted for in terms of oxidative metabolism. To assess the reproducibility of the measurements of  $\bar{W}_{\text{tot}}$ ,  $\bar{W}_{\text{O}_2}$  and  $\bar{W}_{\text{cap}}$ , duplicate 80 s maximal tests were performed on the students (Table 4).

## Results

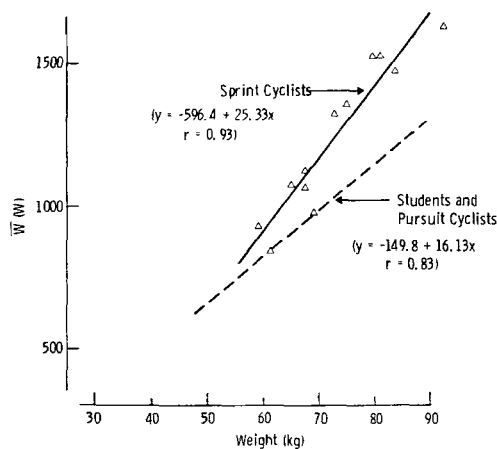
The maximal average power outputs ( $\bar{W}_{\max}$ ) of the students, sprint and pursuit cyclists are summarised in Table 2. The inter-subject variability of  $\bar{W}_{\max}$  was partly a function of body size and muscularity, since  $\bar{W}_{\max}$  was closely associated with body weight (Fig. 2). However, though the  $\bar{W}_{\max}$  of the students and the pursuit cyclists for given body weight was identical, the sprint cyclist had a higher  $\bar{W}_{\max}$   $\text{kg}^{-1}$  body weight than either of the former groups ( $p < 0.001$ ). The differences between the three groups could only be removed if either estimates of leg muscle (plus bone) volume (LV) or upper leg (thigh) cross-sectional area (CSA) were considered:

$$\bar{W}_{\max}(\text{W}) = -161.34 + 80.16 \text{ LV (L)}; \quad (i)$$

$$r = 0.72, n = 43$$

$$\bar{W}_{\max}(\text{W}) = -240.56 + 6.76 \text{ CSA (cm}^2\text{)}; \quad (ii)$$

$$r = 0.79, n = 43$$



**Fig. 2.** The relationship of maximal average mechanical power production ( $\bar{W}_{\max}$ ) to body weight in students, sprint pursuit

Standardisation of  $\bar{W}_{\max}$  for either LV or CSA removed the inter-subject differences ( $p < 0.05$ ) in maximal power output. Further if the relationship between force and velocity was standardised for variations in the force executed at zero velocity ( $P_0$ , which effectively accounts for variations in CSA), the resulting linear regression relations were similar in the three groups of subjects studied (Fig. 3). The optimal frequency of pedalling ( $V_{\text{opt}}$ ) for the attainment of  $\bar{W}_{\max}$  and the theoretical maximal velocity of pedalling at zero force ( $V_0$ ) were nevertheless higher in the sprint cyclists. The respective figures of  $V_0$  and  $V_{\text{opt}}$  in the sprint cyclists were  $262 \pm 8 \text{ min}^{-1}$  and  $132 \pm 3 \text{ min}^{-1}$ , compared with  $235 \pm 17 \text{ min}^{-1}$  ( $p < 0.001$ ) and  $118 \pm 8 \text{ min}^{-1}$  ( $p < 0.001$ ) in the students. The cor-

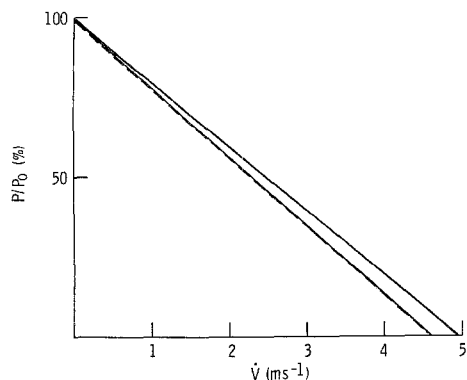


Fig. 3. The force (standardised for  $P_0$ )-velocity relationship in the students (· · ·), pursuit (---) and sprint (—) cyclists

responding comparative values for the pursuit cyclists were  $242 \pm 12 \text{ min}^{-1}$  ( $p < 0.001$ ) and  $122 \pm 6 \text{ min}^{-1}$  ( $p < 0.001$ ).

The relationship between the calculated oxidative base line ( $\bar{W}_{45}^1$ ) and the maximal mechanical power output ( $\bar{W}_{45}$ ) at the 45th s of exercise is given in Fig. 4. Assuming an efficiency of 0.21 for the conversion of energy into mechanical work, the mean values for the oxidative baseline and observed mechanical power output at 45 s were  $270 \pm 65 \text{ W}$  and  $278 \pm 87 \text{ W}$  respectively for the students and the cyclists (Fig. 4).

The reproducibility of the short-term test is given in Table 4. The coefficient of variation of duplicate measurements of  $\bar{W}_{\text{cap}}$  was  $\pm 9\%$ .

The estimated oxidative ( $\bar{W}_{O_2}$ ) and anaerobic ( $\bar{W}_{\text{cap}}$ ) components of the total mechanical work ( $\bar{W}_{\text{tot}}$ ) during 45 s of an 80 s 'all-out' test together with the total duration ( $D$ ) and half time ( $t_{1/2}$ ) of the decline of  $\bar{W}_{\text{max}}$  are given in Table 4.

The half time ( $t_{1/2}$ ) of the decline of  $\bar{W}_{\text{max}}$  (corrected for oxidative processes) was not signif-

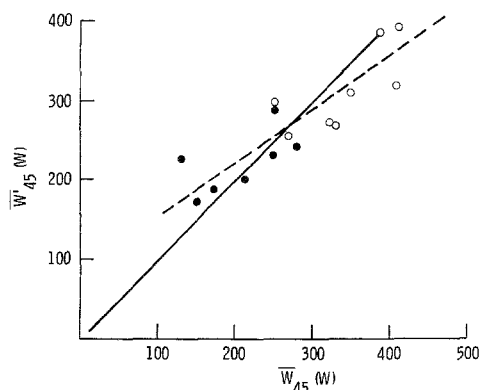


Fig. 4. The relationship of the 45 s baseline values of measured mechanical power output ( $\bar{W}_{45}$ ) and that derived from observations of oxygen intake ( $\bar{W}_{45}^1$ ) on 8 pursuit cyclists (O) and 8 students (●). The measurements of  $\dot{V}_{O_2}$  were converted to mechanical work assuming an efficiency of 0.21. The line of identity (—) and regression relationship (---) between the two variables are shown

Table 3. Reproducibility of the 80 s test. Comparison of duplicate measurements performed on separate occasions. Data for students ( $n=8$ ). Symbols as for Table 3

	$W_0$ (W)	$a$	$W_{45}$ (kJ)	$W_{\text{tot}}$ (kJ)	$W_{O_2}$ (kJ)	$W_{\text{cap}}$ (kJ)	$D$ (s)	$t$ (s)
Test 1	1039 $\pm 231$	-0.0359 $\pm 0.006$	215 $\pm 55$	22.9 $\pm 3.9$	8.2 $\pm 2.1$	14.7 $\pm 2.8$	44.4 $\pm 1.8$	10.9 $\pm 0.4$
Test 2	1019 $\pm 204$	-0.0355 $\pm 0.007$	215 $\pm 65$	22.8 $\pm 4.3$	8.3 $\pm 2.6$	14.5 $\pm 2.7$	44.4 $\pm 1.8$	10.9 $\pm 0.4$

Significance: NS

icantly ( $p > 0.1$ ) different between the three groups. The respective figures for the students, sprint and pursuit cyclists were  $10.9 \pm 0.4 \text{ s}$ ,  $10.8 \pm 0.6 \text{ s}$  and  $10.1 \pm 0.9 \text{ s}$ . The total work performed during the 45 s period was similar in the

Table 4. The estimated oxidative ( $W_{O_2}$ ) and anaerobic ( $\bar{W}_{\text{cap}}$ ) components (see Fig. 1) of the total maximal mechanical work ( $\bar{W}_{\text{tot}}$ ) produced during 45 s of an 80 s test. The exponential decline of power output ( $W$ ) with time ( $t$ ) was described by the equation  $W e^{-at}$ , where  $a$  is a constant. The total duration ( $D$ ) and half time ( $t_{1/2}$ ) of  $\bar{W}_{\text{cap}}$  are also given

Group	$W_0$ (W)	$a$	$W_{45}$ (W)	$W_{\text{tot}}$ (kJ)	$W_{O_2}$ (kJ)	$\bar{W}_{\text{cap}}$ (kJ)	$D$ (s)	$t_{1/2}$ (s)
Sprint ( $n=6$ )	1157 $\pm 322$	-0.0286 $\pm 0.006$	310 $\pm 29$	28.8 $\pm 5.2$	12.1 $\pm 1.2$	16.7 $\pm 4.9$	45.1 $\pm 0.08$	10.8 $\pm 0.6$
Pursuit ( $n=10$ )	965 $\pm 193$	-0.0226 $\pm 0.005$	346 $\pm 57$	27.8 $\pm 3.5$	13.8 $\pm 2.0$	14.0 $\pm 2.9$	45.3 $\pm 0.7$	10.1 $\pm 0.9$
Students ( $n=8$ )	1039 $\pm 231$	-0.0359 $\pm 0.008$	215 <sup>+++</sup> $\pm 55$	22.9 <sup>+</sup> $\pm 3.9$	8.2 <sup>++</sup> $\pm 2.1$	14.7 $\pm 2.8$	44.4 $\pm 1.8$	10.9 $\pm 0.4$

Significance: Sprinters v pursuit \*  $p < 0.05$   
Sprinters v students +  $p < 0.05$ ; +++  $p < 0.001$

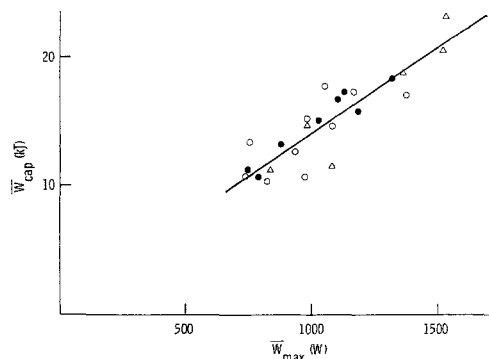


Fig. 5. The relationship of maximal anaerobic capacity ( $\bar{W}_{\text{cap}}$ ) to maximal average power output ( $\bar{W}_{\text{max}}$ ). (●) students, (○) pursuit and (△) sprint cyclists

sprint ( $28.8 \pm 5.2$  kJ and pursuit ( $27.8 \pm 3.5$  kJ cyclists, but reduced in the students ( $22.9 \pm 3.9$  kJ,  $p < 0.05$ ). The lower value in students was a reflection of the reduced "aerobic" ( $\bar{W}_{45}^1$ ) baseline, and thus in the total (theoretical) aerobic work performed (Table 4). The area below the corrected  $\bar{W}_{\text{max}}$ /time curve ( $\bar{W}_{\text{cap}}$ ) which may be taken to represent the capacity of short-term anaerobiosis ranged from  $16.7 \pm 4.9$  kJ in the sprinters to  $14.0 \pm 2.9$  kJ in the pursuit cyclists, and  $14.7 \pm 2.8$  kJ in the students, and was not significantly ( $p > 0.1$ ) different between the groups. However,  $\bar{W}_{\text{cap}}$  was related to body weight and to estimates of body muscularity, namely muscle (plus bone) volume (LV) and thigh cross-sectional area (CSA).

$$\bar{W}_{\text{cap}}(\text{kJ}) = -2.85 + 1.196 \text{ LV (L)}; \\ r = 0.64, n = 24 \quad (\text{iii})$$

$$\bar{W}_{\text{cap}}(\text{kJ}) = -3.16 + 0.098 \text{ CSA (thigh} \cdot \text{cm}^2\text{)}; \\ r = 0.74, n = 24 \quad (\text{iv})$$

and thus as one might expect from Fig. 1 and equation (i) and (ii) to  $\bar{W}_{\text{max}}$  (Fig. 5).

## Discussion

The mean maximal power output ( $\bar{W}_{\text{max}}$ ) data for the students and pursuit cyclists agrees closely with previous results (Davies et al. 1984) from this laboratory for young adults, provided account is taken of body size. In our earlier study (op. cit.), the mean  $\bar{W}_{\text{max}}$  was  $1200 \pm 208$  W or  $15.9$  W  $\text{kg}^{-1}$  body weight; the present figures for the students and pursuit cyclists are  $1019 \pm 183$  W ( $13.6$  W  $\text{kg}^{-1}$ ) and  $962 \pm 206$  W ( $14.1$  W  $\text{kg}^{-1}$ ). Thus, it would seem that pursuit cyclists, whose event demands much in terms of aerobic power but little

in terms of short-term anaerobic energy requirements, have statistically similar ( $p > 0.1$ )  $\bar{W}_{\text{max}}$  values to students and young adults.

In contrast, the sprint cyclists do have a significantly ( $p < 0.01$ ) greater absolute ( $1241 \pm 266$  W) and per kg body weight ( $17.1$  W  $\text{kg}^{-1}$ , see Fig. 2)  $\bar{W}_{\text{max}}$ , and a higher  $V_{\text{opt}}$  ( $132 \pm 3$   $\text{min}^{-1}$ ,  $p < 0.001$ ) and  $V_0$  ( $262 \pm 8$   $\text{min}^{-1}$ ,  $p < 0.001$ ) than the students or pursuit cyclists (Table 2). There is an upwards displacement of the force/velocity relationship in sprinters. However, if standardisation is made for  $P_0$  (Fig. 3) the major part of the difference in the force/velocity linear regression lines can be removed, and if  $\bar{W}_{\text{max}}$  is considered in terms of either leg muscle (plus bone) volume or calf cross-sectional area, it is similar in the three groups of subjects studied. Thus,  $\bar{W}_{\text{max}}$  would appear to be a function of size and degree of muscularity and is independent of age over the range studied (15–25 years). It is only in absolute terms that  $\bar{W}_{\text{max}}$  reflects the degree of specialisation in the cyclists. Sprint cyclists require a large body size and (leg) muscle mass commensurate with the need to develop absolute mechanical power output. Clearly, the dilemma they face is that the mechanical work performed to generate velocity is mainly dissipated in overcoming air resistance, which will increase with body size due to its effect on projected area (Ap) (see Davies 1980). It is noticeable that though the sprint cyclists were extremely muscular, they were also relatively short in stature (Table 1). This may be the essential compromise between power generation, Ap, and optimal performance in sprint cycling. If so, it indicates the need for careful selection and high resistance training (see McDonagh and Davies 1984) in this event. The close associations of  $\bar{W}_{\text{max}}$  and  $\bar{W}_{\text{cap}}$  with body size and indices of muscularity suggest that maximal anaerobic (unlike aerobic) power output (see Davies and Sargeant 1975) cannot be trained independently of muscle mass.

The equations for the relationship of power output to duration of effort are different from those of Tornvall (1963), who was essentially concerned with submaximal effort. In the present experiments, the power and capacity of the anaerobic mechanical work performed were determined from the maximal work sustained by each cyclist for 80 s. In calculating the capacity of mechanical work performed, the contribution of oxidative energy sources was removed empirically by assuming an exponential rise in  $\dot{V}_{\text{O}_2}$  with half time ( $t_{1/2}$ ) of 6 s. This choice of a rapid time constant was arbitrary though deliberate. The only available data for aerobic kinetics in man are

based on whole body intake (Davies et al. 1972), where a  $t_{1/2}$  of 17 s was found, but the measurements took no account of the oxygen stored within the body, which is readily available to the muscles at the immediate onset of work. As pointed out by Wilkie (1977), the first stages of the glycolytic Krebs cycle are extremely rapid, and it therefore seems reasonable to postulate a more rapid and effective oxidative onset at the level of the muscle cell. Using the same  $t_{1/2}$  of 6 s as proposed by Wilkie (op. cit.), the capacity of the anaerobic mechanical work processes in the students, sprint and pursuit cyclists are  $14.7 \pm 2.8$  kJ ( $0.20$  kJ  $\text{kg}^{-1}$ ),  $16.7 \pm 4.9$  kJ ( $0.23$  kJ  $\text{kg}^{-1}$ ) and  $14.0 \pm 2.9$  kJ ( $0.21$  kJ  $\text{kg}^{-1}$ ) respectively. From the data of Wilkie (1968) the phosphagen content of skeletal muscle can be shown to be approximately  $27$  mmol  $\text{kg}^{-1}$ . If we assume that a  $70$  kg man has  $25$  kg of muscle, and  $1$  mol of phosphagen is equivalent to  $46$  kJ, then the energy yield is  $31.1$  kJ or  $0.44$  kJ  $\text{kg}^{-1}$  body weight. In well motivated subjects the maximal increase of lactic acid in muscle is of the order of  $23$  mmol  $\text{kg}^{-1}$  (Hermansen 1981). Using the same set of assumptions, and knowing that  $1$  mol of lactate is equivalent to  $1.5$  ATP molecules, then the energy yield from glycolytic processes is  $39.8$  kJ or  $0.57$  kJ  $\text{kg}^{-1}$  body weight. Thus, combining these theoretical figures for energy stored within the muscle with the present mean  $\bar{W}_{\text{cap}}$  data for the three groups ( $0.22$  kJ  $\text{kg}^{-1}$ ), the efficiency for the conversion of chemical energy to mechanical work is  $\frac{0.22}{0.44 + 0.57} = 0.22$

i.e. the same value which has been repeatedly found for the corresponding aerobic processes in whole body exercise. This observation supports the view of Margaria (1976) that the efficiency of the oxidative and anaerobic processes during whole body exercise are similar, and thus from a practical viewpoint, when examining the relationship between metabolic cost and performance at maximal levels of exercise, may be considered together. This is an important but tentative finding, clearly further research involving both chemical and mechanical measurements during supramaximal exercise in the same individual is necessary before more definitive conclusions can be drawn.

Finally it can be seen (Table 3) that the  $t_{1/2}$  of the anaerobic component of the work is approximately  $10.5$  s and independent of the physical status of the subjects. Although one might regard an all-out maximal test being performed mainly anaerobically, in fact of the total mechanical work

produced ( $27.8 \pm 3.5$  kJ) by the pursuit cyclists,  $13.8 \pm 2.0$  kJ (44.6%) is accounted for in terms of aerobic metabolism. The comparable figures for the students and sprint cyclists were  $8.2 \pm 2.1$  kJ (35.8%) and  $12.1 \pm 1.2$  kJ (41.9%). Thus, an 80 s all-out test to exhaustion demands a theoretical 36–45% contribution from the aerobic pathways during the first 45 s. The level of mechanical work which can be sustained from 45 s to end of the test period is indicative of the endurance status of the subjects and closely reflects the specialist performance skills of the cyclists, compared with the students. The pursuit cyclists were able to sustain  $346 \pm 57$  W after 45 s of work compared with  $215 \pm 55$  W in the students (Table 3). In some students subjects, the mechanical power output fell below the work equivalent of the measured oxygen intake, which would indicate a gross loss of mechanical efficiency (cf. Coast and Welsh 1985). It is well known that during brief maximal exercise the rapid utilization of phosphagen and increased production of lactic acid can give rise to muscle weakness, particularly in sedentary subjects. It has been suggested (Hermansen 1981) that the fall in muscle pH and increased hydrogen ion concentration directly affects the muscle force generation processes by reducing both the rates of ATP resynthesis and utilization. If this is so, then present results would suggest that the endurance trained pursuit cyclists are able either to maintain their intracellular pH or to offset its effects by their highly developed capacity for oxygen utilization.

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