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S. Tomadini[2]
F. Didonè[2]
F. Grazzina[3]
E. Rejc[3]
C. Capelli[1]

Bioenergetics of a Slalom Kayak (K1) Competition

Abstract

The aim of this study was: i) to compute an energy balance of a slalom kayak competition by measuring the percentage contributions of the aerobic and anaerobic energy sources to total metabolic power ($\dot{E}_{tot}$); and ii) to compare these data with those obtained, on the same subjects, over a flat-water course covered at maximal speed in a comparable time. Experiments were performed on eight middle- to high-class slalom kayakers (24.8 ± 8.1 years of age, 1.75 ± 0.04 m of stature, and 69.8 ± 4.7 kg of body mass) who completed the slalom race in 85.8 ± 5.3 s and covered the flat water course in 88.1 ± 7.7 s. $\dot{E}_{tot}$ was calculated from measures of oxygen consumption and of blood lactate concentration: it was about 30% larger during the flat water all-out test (1.72 ± 0.18 kW) than during the slalom race (1.35 ± 0.12 kW). However, in both cases, about 50% of $\dot{E}_{tot}$ derives from aerobic and about 50% from anaerobic energy sources. These data suggest that, besides training for skill acquisition and for improving anaerobic power, some high intensity, cardiovascular conditioning should be inserted in the training programs of the athletes specialised in this sport.

Key words
Kayaking · canoeing · metabolic power · lactate

Introduction

Slalom competitions are contested on fast running water, either with naturally or artificially engineered obstacles, with three classes of boats: kayak, canoe, and double canoe. Since 1972, slalom races are included in the Olympic programs. A slalom race is scored on the time required to complete a number of gates through a 400 – 800 m long course. The athletes should be able to plan the most appropriate route through the gates, to speed between one gate and the next and, above all, they should have the skill (and the power) to read the current and to manoeuvre the boat laterally and upstream through the gates [8]. These races are therefore a combination of a series of technical moves ("gate skills") linked by brief accelerations and full-speed paddling. Even if slalom racers spend about 50 – 70% of their training volume at skill acquisition, the importance of improving the cardio-respiratory capability as well as the ability to produce and accumulate lactate is well recognized [8]. Whereas the aerobic and anaerobic contributions to total energy expenditure during flat water canoe-kayak competitions were investigated by several authors (e.g. [10,13,15]), data for slalom racing are scarce and were mainly obtained during simulated events in the laboratory (for a review see [8]).

As shown by Zamparo and coworkers [15], an estimate of the percentage contribution of the different energy yielding processes of flat water kayak races can be obtained on the basis of simple measurements (such as the subject's maximal oxygen up-

Affiliation
[1] Dipartimento di Scienze e Tecnologie Biomediche, Facoltà di Medicina e Chirurgia, Università degli Studi di Udine, Udine, Italy
[2] Canoa Club Udine, Federazione Italiana Canoa-Kayak, Udine, Italy
[3] Corso di Laurea in Scienze Motorie, Università degli Studi di Udine, Gemona del Friuli (Udine), Italy

Correspondence
Paola Zamparo · Dipartimento di Scienze e · Tecnologie Biomediche · P. le Kolbe 4 · 33100 Udine · Italy ·
Phone: + 39 04 32 89 13 99 · Fax: + 39 04 32 49 43 01 · E-mail: PZamparo@mail.dstb.uniud.it

Accepted after revision: May 30, 2005

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Int J Sports Med © Georg Thieme Verlag KG · Stuttgart · New York ·
DOI 10.1055/s-2005-865922 · Published online 2005 ·
ISSN 0172-4622

Table **1** Principal anthropometric characteristics and $\dot{V}O_{2max}$ of the subjects

Subject	*Age (years)*	*Body mass (kg)*	*Stature (m)*	*BMI ($kg \cdot m^{-2}$)*	*% Fat*	*$\dot{V}O_{2max}$ ($l \cdot min^{-1}$)*	*$\dot{V}O_{2max}$ ($ml \cdot min^{-1} \cdot kg^{-1}$)*
S1	17	68	1.72	23.0	5.4	3.07	45.1
S2	20	70	1.70	24.2	8.2	3.50	50.1
S3	25	70	1.73	23.4	5.3	3.56	50.9
S4	30	78	1.83	23.3	8.7	3.94	50.5
S5	42	74	1.77	23.6	12.4	2.83	38.3
S6	19	62	1.73	20.7	5.8	3.06	49.4
S7	21	67	1.74	22.1	5.1	4.15	61.9
S8	24	69	1.78	21.8	10.7	2.99	43.4
Mean	24.8	69.8	1.75	22.8	7.7	3.39	48.7
± 1 SD	8.1	4.7	0.04	1.1	2.8	0.48	6.9

BMI: Body mass index. Body density was calculated according to Jackson and Pollock [7] from seven skin-fold thicknesses and percentage fat (% fat) was hence obtained, according to Siri [12]

take, the lactate accumulated at the end of the test, and the performance time) by applying a three-compartment model of human energetics proposed originally by Wilkie [14].

The aim of this study was: i) to compute an energy balance of a slalom kayak (K1) competition by measuring the percentage contributions of the aerobic and anaerobic energy sources during an on-water race; and ii) to compare these data with those obtained, on the same subjects, over a flat-water course covered at maximal speed in a comparable time.

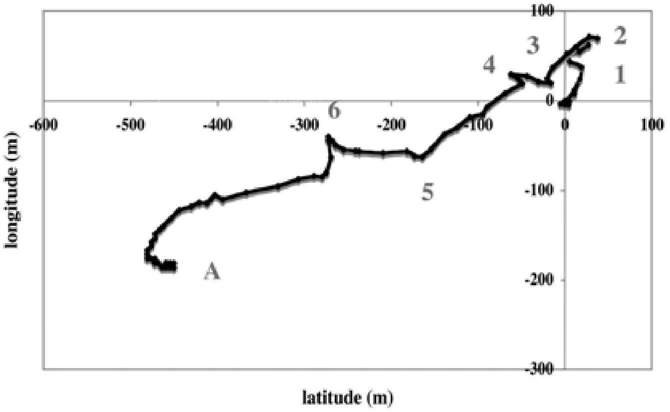

Fig. **1** Typical GPS recording during a slalom race. The starting point corresponds to the origin of the graph (0 latitude, 0 longitude), the arrival point is indicated by the letter A. The six upstream gates are indicated by progressive numbers.

Materials and Methods

Subjects

The experiments were performed on 8 middle- to high-class slalom kayakers whose anthropometric characteristics are reported in Table **1**; all but two (S5 and S8) belong to the Italian national white water team. All subjects were informed about the methods and aims of the study and gave their written consent to the experimental procedure that was approved by the local IRB. The measurements were carried out at the end of the competitive season (September – October).

Experimental protocol

The subjects participated in three experimental sessions, separated by at least 5 hours of rest and completed over a period of two weeks. During the experiments, all subjects utilized a standard K1 skull (4.0 m length, 0.60 m width, 9 kg mass).

Incremental test

The subjects were asked, after a brief warm-up, to perform an incremental test on a paddling ergometer in order to calculate their maximal oxygen uptake ($\dot{V}O_{2max}$). The test was started with a paddling frequency of 60 cycles · min^{-1} and the subjects were asked to increment the force and/or the frequency every minute, until exhaustion. The workload increased, approximately, by 2 – 3 cycles · min^{-1}. During the experiments, heart rate (HR), oxygen consumption ($\dot{V}O_2$), carbon-dioxide production ($\dot{V}CO_2$), minute ventilation ($\dot{V}_E$), and respiratory exchange ratio (RER) were assessed on a breath-by-breath basis. At the end of the incremental test a capillary blood sample was obtained at the 3rd and 5th minute of recovery to determine blood lactate concentration (La_b). Selected criteria for assessing the attainment of the maximal oxygen uptake were a RER equal or above 1.1, a La_b above 10 mM, and a HR close to the maximal heart rate computed on the basis of the subject's age.

Slalom race

The subjects were asked to complete, as fast as possible, a typical slalom course with six upstream gates traced along the Isonzo river (Solkan, Nuova Goriza, SLO). In Fig. **1** a typical GPS recording during the race is reported (the six upstream gates are indicated by progressive numbers in the figure). The starting point for this test corresponds to the origin of the graph (0 latitude, 0 longitude), the subjects rested in this position for 3 – 4 minutes before the race to allow for measuring their resting $\dot{V}O_2$. The race ended at point A (arrival) where the subject rested for 5 minutes to allow for capillary blood withdrawal. The course was covered in an average time of 85.8 ± 5.3 s. HR, $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}_E$, and RER were measured throughout the tests.

Flat water all-out test

The subjects were asked to cover a linear path at maximal speed in still water (and in the absence of wind). The distance, of about 300 m, was covered in a time comparable to that of the slalom race: 88.1 ± 7.7 s. During these experiments only the subject's HR was recorded.

After the completion of both experiments (the slalom race and the maximal test in flat water), a capillary blood sample was withdrawn for lactate analysis at the 3rd and 5th minute of recovery. The net increase of lactate (ΔLa_b) was obtained by subtracting the pre test value (assumed to be 1 mM) from the value assessed at the end of the test (average of the 3rd and 5th minute).

Methods

Breath-by-breath gas exchanges were determined by means of portable metabolimeter (K4b^2, Cosmed, Italy) whose sensors and flow transducer were calibrated before each experimental run. During the experiments carried out on the slalom track, the metabolimeter was placed in a waterproof knapsack on the subject's shoulders. Blood lactate concentration was measured by means of a portable lactate analyzer (Lactate pro LT 1710, Arkray, Japan). Track distance, direction, and speed were recorded by means of a GPS interfaced to the metabolimeter (Cosmed, Italy). During all-out tests, HR was recorded by using a short-distance telemetry cardio tachometer (Polar S610, Polar Electro, Finland).

Calculations

Flat water all-out test

During an all-out test, total metabolic energy expenditure ($\dot{E}_{tot}$, kJ) can be calculated as the sum of three terms, as originally proposed by Wilkie [14] and subsequently utilized also by others (e.g. [2,15]):

$$E_{tot} = AnS + \alpha\, \dot{V}O_{2max} \cdot t - \alpha\, \dot{V}O_{2max} \cdot t\,(1 - e^{-(t/\tau)}) \qquad (1)$$

where α is the energy equivalent of O_2 (assumed equal to 20.9 $kJ \cdot l^{-1}$ O_2), τ is the time constant (s) wherewith $\dot{V}O_{2max}$ is attained at the onset of exercise at the muscular level, *AnS* is the amount of energy derived from anaerobic energy utilization, *t* is the time of performance (s), and $\dot{V}O_{2max}$ is the net maximal oxygen uptake (above resting values). The aerobic contribution to the total energy expenditure (*Aer,* kJ) can be calculated by the sum of the second and third term of Equation 1, whereas the anaerobic contribution is represented by the term *AnS* which represents the sum of the energy derived from lactic acid production (*Anl,* kJ) plus that derived from maximal phosphocreatine (PCr) splitting in the contracting muscles (*AnAl,* kJ). The former (*Anl*) can be estimated from the net increase of lactate concentration (ΔLa_b) assessed at the end of the test by assuming an energy equivalent of lactate of 0.0627 $kJ \cdot mM^{-1} \cdot kg^{-1}$ (as proposed by di Prampero [4,6]). The maximal amount of energy derived from PCr splitting (*AnAl*) amounts to about 0.418 $kJ \cdot kg^{-1}$ of body mass [3]; during exhaustive exercise it tends asymptotically to this value with a time constant (τ_{al}) of 23.4 s [9]. Finally, oxygen uptake at the muscular level attains $\dot{V}O_{2max}$ with a time constant (τ) of 24 s, as measured by NMR spectroscopy [1].

These three terms (*Aer, Anl*, and *AnAl,* kJ) can be divided by the exercise duration (*t,* s) to yield the corresponding metabolic power ($\dot{E}_{Aer}$, $\dot{E}_{Anl}$, and $\dot{E}_{AnAl}$, kW).

Slalom race

Oxygen uptake ($\dot{V}O_2$, $l \cdot min^{-1}$) was directly measured during the slalom race on a breath-by-breath basis. B-by-b data were then integrated from time 0 (t_0) to the end (t_e) of exercise

$$\int_{t0}^{te} \dot{V}O_2 dt$$

to compute the aerobic contribution (*Aer*, kJ) to the total metabolic energy expenditure. The values of *Aer,* in litres of oxygen, were corrected subtracting the product of the oxygen consumption at rest, which was assessed before the experiments, times the duration of the exercise ($t_e - t_0$) and converted into kJ assuming an energy equivalent for oxygen (α) equal to 20.9 $kJ \cdot l^{-1}$ O_2. These values were then divided by the exercise duration (*t,* s) to yield the average corresponding metabolic power ($\dot{E}_{Aer}$, kW). The anaerobic lactic and alactic contributions ($\dot{E}_{Anl}$ and $\dot{E}_{AnAl}$, kW) were calculated as described above.

Statistics

Data are presented as means ± 1 SD. Differences between the values of energy expenditure as calculated for the two tests (the slalom race and the flat water all-out test) were evaluated by means of a non-parametric Wilcoxon matched-pairs signed-ranks test (StatWorks, PA, USA). The statistical significance level was set at $p < 0.05$.

Results

The $\dot{V}O_{2max}$ values of the subjects assessed in the incremental test are reported in Table **1** both in absolute values and normalized for kg of body mass. At the end of the incremental test (during the last 30" of exercise, at $\dot{V}O_{2max}$) the average values of $\dot{V}_E$, RER, HR, and La_b turned out to be 129 ± 20 $l \cdot min^{-1}$, 1.2 ± 0.1, 192 ± 8 bpm, and 12.9 ± 1.2 mM.

The speed traces corresponding to a maximal test in flat water and a slalom race are reported in Fig. **2 a** and **b**, respectively. Time zero corresponds to the beginning of the test in both cases (data are from S3 who did complete the two tests roughly in the same time). The all-out effort in flat water could be compared to a "square wave test" since the speed rapidly increases and is maintained almost constant throughout the test. On the contrary, the speed profile during the slalom race indicates that this exercise is more comparable to an intermittent test where periods of high speed (where the athletes go downstream from a gate to the next) are alternated with periods of reduced speed (where the athletes manoeuvre the kayak through the upstream gates).

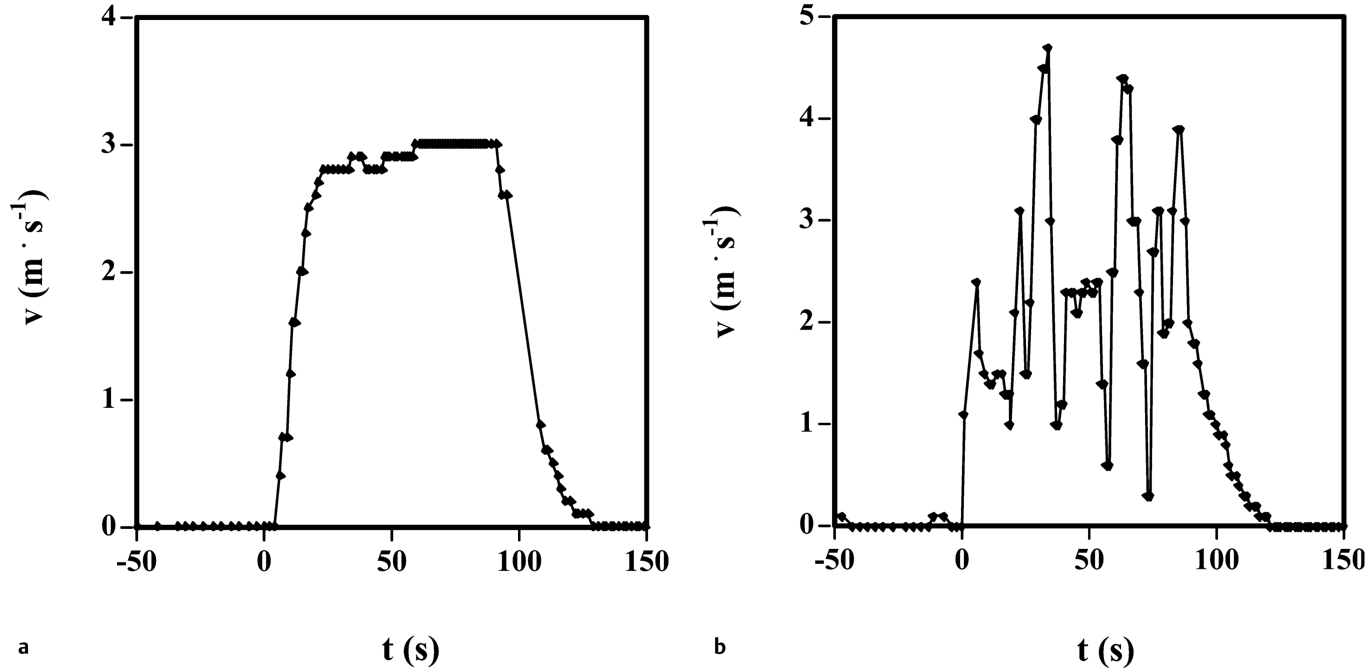

Fig. **2a** and **b** Speed traces corresponding to an all-out test in flat water (**a**) and to a slalom race (**b**). Time zero corresponds to the beginning of the test in both cases. In **b** the periods of reduced speed are those where the athletes manoeuvre the kayak through the upstream gates whereas the periods of high speed are those where the athletes go downstream from a gate to the next.

Table **2** Individual values of heart rate (HR) and blood lactate concentration (La_b) at the end of the three tests (incremental exercise, slalom race, and all-out effort in flat water). Individual HR values are the averages of the last 30 s of exercise (at $\dot{V}O_{2max}$ or at "steady state"). The individual times taken to complete the two tests "in water" are reported as well

Subject	*$\dot{V}O_{2max}$*		*Slalom race*			*Flat water all-out test*		
	HR_{max} (bpm)	*La_{bmax} (mM)*	*HR (bpm)*	*La_b (mM)*	*Time (s)*	*HR (bpm)*	*La_b (mM)*	*Time (s)*
S1	189	11.6	171	10.3	90	177	11.9	93
S2	202	14.3	186	8.9	81	193	13.7	79
S3	182	–	166	7.1	85	175	11.3	84
S4	191	12.4	173	8.3	79	185	11.4	86
S5	185	13.2	177	10.2	93	181	14.2	102
S6	206	14.6	188	7.7	84	194	11.8	81
S7	187	13.1	179	5.6	82	181	11.5	86
S8	193	11.3	177	7.1	92	185	9.4	94
Mean	192	12.9	177	8.1	85.7	184	11.9	88.1
± 1 SD	8	1.2	7	1.6	5.3	7	1.5	7.7

The individual values of HR as measured "at steady state" (average of the values measured during the last 30" of exercise) during the slalom race and the all-out test in flat water are reported in Table **2** along with the values of La_b assessed at the end of the test (average of the values collected at the 3rd and 5th minute of recovery) and with the values of the times taken to complete the tests. In the same table the individual values of HR at $\dot{V}O_{2max}$ and of La_b assessed at the end of the incremental test are also reported.

As indicated in Table **2**, HR during a slalom race reaches about 92% of HR_{max} and La_b about 63% of La_{bmax} (the HR and La_b values measured at the end of the incremental test with the paddle ergometer). At the end of the all-out test in flat water HR and La_b are 96% and 92% of HR_{max} and La_{bmax}, respectively.

In Fig. **3** tracing of breath-by-breath $\dot{V}O_2$ values obtained in a typical subject during a slalom race is reported. $\dot{V}O_2$ increases rapidly at the beginning of the test and reaches an almost steady level in about 60 s; the values of $\dot{V}O_2$ in this phase (calculated averaging the data collected in the last 30 s of the race) amount, on the average, to $2.60 \pm 0.41\ l \cdot min^{-1}$ (i.e. to about 77% of $\dot{V}O_{2max}$). The aerobic contribution during this race, calculated by comput-

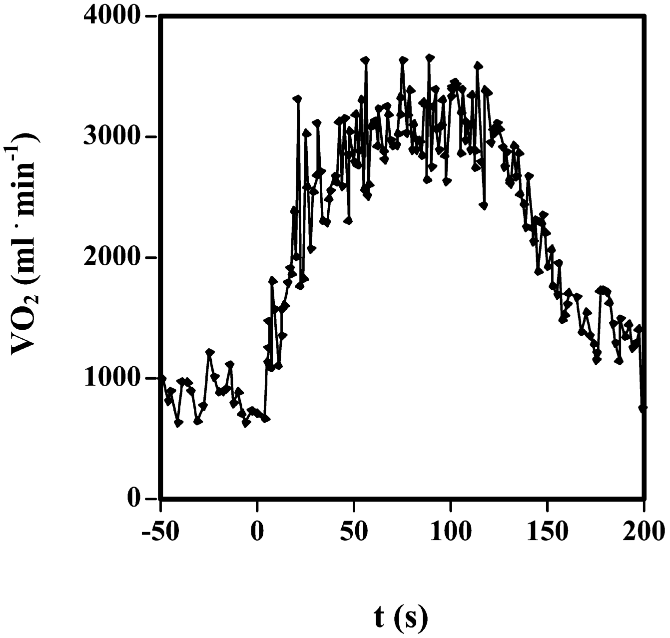

Fig. **3** Typical tracing of breath-by-breath $\dot{V}O_2$ values obtained in a typical subject during a slalom race as a function of time. $\dot{V}O_2$ increases rapidly at the beginning of the test and reaches an almost steady level in about 60 s.

ing the time integral of the curve (see methods), amounted to 3.10 ± 0.33 l.

The individual values of total net metabolic power ($\dot{E}_{tot}$, kW) are reported in Table **3a**. These data show that $\dot{E}_{tot}$ is significantly larger (about 30%, $p < 0.05$) during a flat water all-out test (1.72 ± 0.18 kW) than during a slalom race (1.35 ± 0.12 kW) of comparable duration. Accordingly, the absolute values of metabolic power derived from the aerobic ($\dot{E}_{Aer}$) and anaerobic energy sources ($\dot{E}_{Anl}$ and $\dot{E}_{AnAl}$) are proportionally (and significantly) lower in the latter case ($p < 0.05$). However, as shown by Table **3b**, the percentage contribution of the energy sources to $\dot{E}_{tot}$ is remarkably similar (and not significantly different) in the two cases as about 45% of total energy expenditure derives from aerobic energy sources ($p > 0.1$) and about 30% from the lactic ones ($p > 0.05$).

Discussion

Energy balance of a flat water all-out test

Data reported in Table **3b** are in agreement with those reported by Zamparo et al. [15] for kayaking and by Capelli et al. [2] for swimming at maximal speeds over different distances. Indeed, the percentage contribution of the aerobic and anaerobic energy sources is independent of type of exercise, style, gender, or skill and depends essentially upon the duration of the exercise. For a performance time comparable to that of our experiments (88.1 ± 7.7 s) about 50% of total energy expenditure is derived from aerobic energy sources, 30% from PCr splitting, and 20% from lactate production.

The approach applied in this study to evaluate the energy balance of the flat water test is discussed in detail by Capelli et al. [2] and should be strictly applied only to "square wave" exercises of intensity close or above maximal aerobic power where a true steady state of oxygen uptake can not be attained and where energy contributions other than the aerobic one can not be neglected. That this was indeed the case is shown by data reported in Table **2** (HR and La_b are 96% and 92% of HR_{max} and La_{bmax}), which indicate that the subjects' metabolic power output was practically overlapping their $\dot{V}O_{2max}$.

Energy balance of a slalom race

The method we applied to evaluate the energetics of kayaking over flat water could not be applied to study the energy balance of a slalom race where the energy requirement was neither maximal (HR and La_b are 92% and 63% of HR_{max} and La_{bmax}) nor constant (see Table **2** and Fig. **2b**). The aerobic energy expenditure had, therefore, to be directly determined: it amounted to 3.10 ± 0.33 l. Whereas the term $\dot{E}_{Anl}$ can be calculated from the values of lactate concentration assessed at the end of the race (as for the flat water all-out test) the amount of energy derived from PCr splitting can be estimated only for exhaustive exercises [9]. Since for the slalom race this is not the case, the alactic contribution ($\dot{E}_{AnAl}$) could have been overestimated. Therefore, if any, the percentage contributions of $\dot{E}_{Aer}$ and $\dot{E}_{Anl}$ to total energy expenditure could be slightly underestimated in our calculations. As an example, if we assume that $\dot{E}_{AnAl}$ is half the value reported in Table **3a**, the % $\dot{E}_{Aer}$ changes from 45 to 52% and the %$\dot{E}_{Anl}$ from 30 to 34%. Even taking this into account, as shown by Table **3b**, the percentage contribution of the energy sources to $\dot{E}_{tot}$ is remarkably similar in the two races (of different intensity but similar duration): about 45 – 50% of total energy expenditure is derived from aerobic energy sources and about 30 – 35% is obtained from the lactic ones. This result is of somewhat practical meaning since it indicates that in a slalom race the aerobic energy yielding pathway accounts for about the 50% of the total metabolic energy turnover. Thus, besides training for skill acquisition and for improving anaerobic power, some high-intensity, cardiovascular conditioning should be inserted in the training programs of the athletes specialised in this sport.

Even if the percentage of energy derived from the lactic sources is similar to that of a flat water all-out test, the lactate accumulated at the end of the slalom race is, in absolute values, about 30% lower (Tables **3a** and **b**). Since the slalom race is comparable to an "intermittent exercise" these differences in La_b could be due either to a lower lactate production during the high intensity phases or to a partial re-oxidation during the phases of lower intensity. This suggests that some advantage could be obtained by training the subjects with intermittent exercises in order to improve their oxidative capabilities.

The energy cost of paddling with a slalom K1 scull

The all-out test in flat water was carried out at an average speed of 2.9 $m \cdot s^{-1}$. The energy cost of paddling with a slalom kayak (C_k) can then be calculated from the ratio of total net energy expenditure ($\dot{E}_{tot}$, which amounts to 1.73 kW, see Table **3a**) to the speed of progression ($C_k = \dot{E}_{tot} \cdot v^{-1}$ [5]); C_k turned out to be 0.59 $kJ \cdot m^{-1}$. This value is about 3 times higher than that reported by Zamparo et al. [15] for paddling with a flat water sprint K1 skull at the same speed (0.22 $kJ \cdot m^{-1}$) but it is close to the value reported by Pendergast and co-workers for the same type of boat (a slalom

Table **3 a** Individual values of metabolic power derived from aerobic ($\dot{E}_{Aer}$), anaerobic alactic ($\dot{E}_{AnAl}$), and lactic ($\dot{E}_{Anl}$) energy sources during a slalom race and a flat water all-out test. In the former case the term $\dot{E}_{Aer}$ was derived from measures of oxygen uptake during the test whereas, in the latter case, it was calculated according to Wilkie [14], see text for details. $\dot{E}_{tot}$ is total net metabolic power

Subject	*Slalom race*				*Flat water all-out test*			
	$\dot{E}_{Aer}$ (kW)	*$\dot{E}_{AnAl}$ (kW)*	*$\dot{E}_{Anl}$ (kW)*	*$\dot{E}_{tot}$ (kW)*	*$\dot{E}_{Aer}$ (kW)*	*$\dot{E}_{AnAl}$ (kW)*	*$\dot{E}_{Anl}$ (kW)*	*$\dot{E}_{tot}$ (kW)*
S1	0.59	0.31	0.47	1.36	0.74	0.30	0.55	1.59
S2	0.54	0.37	0.48	1.39	0.80	0.36	0.78	1.94
S3	0.65	0.34	0.35	1.37	0.84	0.34	0.35	1.52
S4	0.71	0.38	0.46	1.55	0.90	0.37	0.65	1.92
S5	0.43	0.30	0.46	1.19	0.69	0.30	0.66	1.65
S6	0.70	0.32	0.35	1.37	0.71	0.31	0.57	1.59
S7	0.63	0.33	0.25	1.21	0.99	0.32	0.56	1.87
S8	0.41	0.31	0.31	1.03	0.72	0.30	0.43	1.45
Mean	0.61	0.34	0.40	1.35	0.81	0.33	0.59	1.72
± 1 SD	0.10	0.03	0.09	0.12	0.11	0.03	0.13	0.18

Table **3 b** Individual values of metabolic power derived from aerobic ($\dot{E}_{Aer}$), anaerobic alactic ($\dot{E}_{AnAl}$), and lactic ($\dot{E}_{Anl}$) energy sources during a slalom race and a flat water all-out test expressed as a percentage of total net metabolic power ($\dot{E}_{tot}$)

Subject	*Slalom race*			*Flat water all-out test*		
	$\dot{E}_{Aer}$ (%)	*$\dot{E}_{AnAl}$ (%)*	*$\dot{E}_{Anl}$ (%)*	*$\dot{E}_{Aer}$ (%)*	*$\dot{E}_{AnAl}$ (%)*	*$\dot{E}_{Anl}$ (%)*
S1	43.0	22.5	34.5	46.4	18.9	34.7
S2	38.6	26.7	34.7	41.5	18.5	40.1
S3	49.7	25.1	25.3	55.2	22.0	22.8
S4	46.0	24.5	29.5	46.8	19.3	33.9
S5	35.8	25.5	38.7	41.8	18.2	40.1
S6	50.9	23.3	25.8	44.6	19.5	35.9
S7	52.5	27.0	20.5	53.0	16.9	30.1
S8	40.1	29.8	30.0	49.7	20.8	29.4
Mean	45.2	24.9	29.9	47.0	19.0	33.9
± 1 SD	6.4	1.7	6.4	5.3	1.6	6.0

canoe: 0.63 $kJ \cdot m^{-1}$ at 2.9 $m \cdot s^{-1}$). As discussed by Zamparo et al. [15] and Pendergast et al. [11] the difference in energy expenditure between the two types of kayaks is attributable to differences in hydrodynamic resistance between the sculls.

Conclusions

Data reported in this study indicate that even if the total metabolic power required to complete a slalom race is 30% lower than that of a flat water all-out test of similar duration (about 87 s), the percentage contribution of the aerobic energy sources to $\dot{E}_{tot}$ is similar in the two cases (45 – 47%). These data suggest that, besides training for skill acquisition and for improving anaerobic power, these athletes could improve their performance if they also train their oxidative capability.

Acknowledgements

We would like to thank Drs. Tamara Durat, Francesca Della Bianca, Elena Tosoratti, and Paola Saccheri for their assistance during the experiments and the subjects of this study for their kind cooperation. We also would like to thank Prof. Pietro E. di Prampero for his help in revising the manuscript. This work was partially supported by the Italian Canoe-Kayak Federation.

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