Effect of competitive distance on energy expenditure during simulated competition

Foster, C.; de Koning, J.J.; Hettinga, F.J.; Lampen, J.; Dodge, C.; Bobbert, M.F.; Porcari, J.P.

published in
International Journal of Sports Medicine
2004

DOI (link to publisher)
10.1055/s-2003-45260

document version
Publisher's PDF, also known as Version of record

citation for published version (APA)
Foster, C., de Koning, J. J., Hettinga, F. J., Lampen, J., Dodge, C., Bobbert, M. F., & Porcari, J. P. (2004). Effect of competitive distance on energy expenditure during simulated competition. *International Journal of Sports Medicine*, *25*(3), 198-204. https://doi.org/10.1055/s-2003-45260

Effect of Competitive Distance on Energy Expenditure During Simulated Competition

C. Foster[1]
J. J. deKoning[2]
F. Hettinga[2]
J. Lampen[2]
C. Dodge[1]
M. Bobbert[2]
J. P. Porcari[1]

Abstract

Concepts of how athletes should expend their aerobic and anaerobic energetic reserves are generally based on results of tests where an “all out” strategy is imposed on/required from the athlete. We sought to determine how athletes spontaneously expend their energetic reserves when the only instruction was to finish the event in minimal time, as in competition. Well trained, and task habituated, road cyclists (N = 14) completed randomly ordered laboratory time trials of 500 m, 1000 m, 1500 m and 3000 m on a windload braked cycle ergometer. The pattern of aerobic and anaerobic energy use was calculated from total work accomplished and $\dot{V}O_2$ during the trials. The events were completed in 40.3 ± 0.6 s, 87.4 ± 4.1 s, 133.8 ± 6.6 s and 296.0 ± 7.2 s. The peak $\dot{V}O_2$ during the terminal 200 m of all events was similar (2.72 ± 0.22, 3.01 ± 0.34, 3.23 ± 0.44 and 3.12 ± 0.13 $l \times min^{-1}$). In all events, the initial power output and anaerobic energy use was high, and decreased to a more or less constant value over the remainder of the event. However, the subjects seemed to reserve some ability to expend energy anaerobically for a terminal acceleration which is contrary to predictions of an “all out” starting strategy. Although the total work accomplished increased with distance (23.14 ± 4.24, 34.14 ± 6.37, 43.54 ± 6.12 and 78.22 ± 8.28 kJ), the energy attributable to anaerobic sources was not significantly different between the rides (17.29 ± 3.82 , 18.68 ± 8.51, 20.60 ± 6.99 and 23.28 ± 9.04 kJ). The results are consistent with the concept that athletes monitor their energetic resources and regulate their energetic output over time in a manner designed to optimize performance.

Key words
Cycling · pacing · anaerobic energy expenditure

Introduction

In order to achieve maximal performance it is essential for athletes to optimize the use of their available energetic resources. To avoid wasting kinetic energy, all possible energy stores should have been used/depleted prior to finishing a race, but not so far from the end of the race that a meaningful slowdown can occur. Despite the importance of how energetic resources are used over time (e.g. the pacing strategy), there are few data regarding how athletes actually use their energetic resources during competition. Recent reviews [2,14], modeling [6,9,33 – 35], and experimental [5,7,8,11 – 13,21,22,31] studies have provided perspective regarding the pattern of the relative contributions of the aerobic and anaerobic energy systems during high intensity exercise. However, most studies which have attempted to document this pattern during high intensity exercise have used either a fixed exercise intensity that the athlete is obligated to sustain for as long as possible (e.g. accumulated O_2 deficit trails [18,19,26,27] or fixed duration trials with the pacing pattern dictated by the investigators (e.g. Wingate type tests [3,18,29,30,37]). Athletes often have the goal of finishing a competition in the shortest possible time, which is quite a different task from attempting to sustain a constant high power output for as long as possible. Achieving this goal may mean variations in momentary power output as the athlete performs an internal “negotiation” regarding their estimation of the magnitude of task remaining, their momentary aerobic power output and their remaining anaerobic energetic reserves. In support of this concept are recent data suggesting either a conscious or subconscious “teleoanticipation” in which athletes optimize per-

Affiliation
[1] Department of Exercise and Sport Science, University of Wisconsin – La Crosse, USA
[2] IFKB, Faculty of Human Movement Sciences, Vrije Universiteit-Amsterdam, The Netherlands

Correspondence
C. Foster Ph. D. · Department of Exercise and Sport Science · University of Wisconsin-La Crosse ·
La Crosse · WI 54601 · USA · Phone: 608 785 8687 · Fax: 608 785 8172 · E-mail: foster.carl@uwlax.edu

Accepted after revision: July 10, 2003

Bibliography
Int J Sports Med 2004; 25: 198–204 © Georg Thieme Verlag Stuttgart · New York
ISSN 0172-4622 · DOI 10.1055/s-2003-45260

formance of a task while minimizing the likelihood of exertion related injuries [32]. Although the "teleoanticipation" hypothesis is framed in terms of preventing injuries from overexertion [32], from the perspective of an athlete attempting to achieve maximal performance, the need to slow down excessively may represent a functional equivalent to sustaining an injury.

Experimental studies of spontaneous patterns of energy expenditure are comparatively rare. In an experimental study of pacing patterns in a 2000-m time trial (~2.5 min.), we [11] observed that athletes recorded their best performances when the pacing pattern was relatively even and fairly close to the spontaneously chosen pattern. Utilizing data on the pattern of energy expenditure derived from Wingate type tests, models have been constructed which appear to predict performances in both track cycling and speed skating with reasonable success [6, 9, 33 – 35]. These models suggest that in events of less than 1.5 min duration, an "all out" pacing strategy might be optimal. As the duration of events increases beyond 2 min, a more constant pacing strategy appears to be optimal. The reason for this change in strategy is unclear, although studies demonstrating that the anaerobic capacity may require about 2 min to be fully expended [5, 18, 19, 21, 26, 27] suggest that some factor related to the ability to provide for muscular power output from anaerobic energetic sources may be critical. We [16] have recently provided evidence that the general pattern predicted by modeling studies [9], a fast start dependent on a large anaerobic energetic contribution, is correct. In these experimental data, it appeared that athletes tended to reserve some capacity for anaerobic energy expenditure for a terminal acceleration, which was not predicted by the models. It also appeared that there was not a large learning component as even road cyclists who were unaccustomed to short time trials adopted a constant "race strategy" within a single trial. These observations were limited to a 1500-m cycle time trial, intended to mimic the most representative international speed skating event [15], which is our primary research interest. The first step in helping athletes optimize their competitive strategy in events either longer or shorter than the 1500 m is to understand how athletes spontaneously expend their energetic resources in other events. Accordingly, the purpose of this study was to determine the spontaneous pattern of energy expenditure in cycling time trials of 500 m, 1000 m, 1500 m and 3000 m in well-trained cyclists.

Material and Methods

Fourteen competitive cyclists (3 females and 11 males) volunteered as subjects for this study. The cyclists were road specialists, competitive at a regional level. Descriptive data of the subjects are presented in Table **1**. Subjects provided informed consent prior to participation, and the study had been approved by the university human subjects committee. Prior to the data collection portion of the study, each subject completed a practice trial of the 500-m, 1000-m, 1500-m, and 3000-m cycle time trials in order to ensure that they were well habituated to the different distance events and to the data collection protocol. We have previously shown that cyclists adopt a common competitive strategy after only one practice trail in the 1500 m [16]. Additionally, to characterize the subjects and to ensure familiarity with the gas collection system, each subject performed incremental exercise to fatigue on an electrically braked cycle ergometer (Lode Excalibur, Groningen, NL), with measurement of respiratory exchange by open circuit spirometry (Cosmed K4, Rome, Italy), to allow definition of $\dot{V}O_2$peak (peak 30 s measurement) and ventilatory threshold [4].

Table **1** Characteristics of the Subjects (mean ± sd)

	Males (n = 11)	***Females (n = 3)***	***All (n = 14)***
Age (years)	32.6 ± 9.9	26.3 ± 7.5	29.2 ± 8.0
Height (cm)	174.9 ± 12.6	170.3 ± 5.1	173.9 ± 10.2
Mass (kg)	65.1 ± 3.8	60.0 ± 6.9	64.0 ± 4.2
$\dot{V}O_2$peak ($l \times min^{-1}$)	3.4 ± 0.2	2.8 ± 0.3	3.3 ± 0.3
$\dot{V}O_2$peak ($ml \times min^{-1} \times kg^{-1}$)	52.3 ± 3.1	46.4 ± 2.9	51.0 ± 2.8
$\dot{V}O_2$ @ VT ($l \times min^{-1}$)	2.63 ± 0.38	1.92 ± 0.22	2.48 ± 0.24
W_{max}	310 ± 24	252 ± 19	298 ± 21
$W_{max} \times kg^{-1}$	4.76 ± 0.35	4.20 ± 0.31	4.64 ± 0.32

Time trials were performed on a racing bicycle attached to a windload simulator with a heavy flywheel (Findlay Road Machine, Toronto, Canada). This device provides for velocity-$\dot{V}O_2$ requirements and for inertia very much like cycling with a conventional bicycle [10 – 14]. Power output and distance were measured using a dynamometer (SRM, Koingskamp, Germany) based on a strain guage built into the chain ring. Power output and accumulated distance were recorded every second. Metabolic data were measured breath by breath using open-circuit spirometry.

The subjects were studied while performing cycle time trials of 500 m, 1000 m, 1500 m, and 3000 m, each on a separate day, in random order. Each subject warmed up prior to the ride according to a standard protocol, that involved ~10 min of incremental exercise to ~90 % of peak power output, a 5-min recovery period, a 5-min submaximal ride, a 5-min recovery period, and then the time trial. The protocol is similar to that reported previously from our laboratory [16]. The standard 5-minute submaximal ride was completed at a power output just below the ventilatory threshold determined during the incremental exercise test (~170 W [men] and ~120 W [women]), for the purpose of defining the relationship between power output and $\dot{V}O_2$. From the $\dot{V}O_2$ during the submaximal trial, the metabolic work accomplished was calculated according to Garby et al. [17]. The mechanical work during the submaximal trial divided by this metabolic work defined efficiency [24].

During the time trials, the only instruction to the subject was to complete each trial as quickly as possible, as if this were a competition. Feedback including their performance (e.g. mean velocity) during the habituation ride, momentary velocity, cumulative distance completed and heart rate was provided to the subject, just as they would be during competition. Vigorous verbal encouragement and coaching were provided throughout each trial by the laboratory staff. Split times were recorded at successive 100 m. Subsequently, the average power output and the average $\dot{V}O_2$ during each segment of each trial were calculated, and the

Table **2** Mean (sd) results in the 500-m trial

	Velocity *($m \times s^{-1}$)*	*$\dot{V}O_2$* *($l \times min^{-1}$)*	*RER*	*Total (W)*	*Aerobic (W)*	*Anaerobic (W)*
100 m	8.86 (0.09)	1.2 (0.3)	1.37 (0.45)	569 (15)	82 (13)	487 (12)
300 m	14.00 (0.45)	2.3 (0.3)	1.23 (0.30)	651 (23)	157 (5)	494 (18)
500 m	13.61 (0.12)	2.7 (0.2)	1.31 (0.21)	505 (19)	182 (2)	323 (18)

Table **3** Mean (sd) results in the 1000-m trail

	Velocity *$m \times s^{-1}$*	*$\dot{V}O_2$* *$l \times min^{-1}$*	*RER*	*Total (W)*	*Aerobic (W)*	*Anaerobic (W)*
100 m	8.27 (0.55)	1.3 (0.2)	1.31 (0.33)	446 (73)	88 (13)	358 (68)
200 m	12.12 (0.72)	2.1 (0.1)	1.15 (0.13)	465 (41)	138 (14)	327 (49)
400 m	12.50 (0.53)	2.9 (0.4)	1.03 (0.02)	430 (63)	192 (18)	238 (60)
600 m	12.20 (0.76)	3.1 (0.5)	1.22 (0.03)	395 (75)	201 (19)	194 (61)
800-m	11.80 (0.76)	3.1 (0.4)	1.36 (0.01)	356 (58)	202 (16)	154 (51)
1000 m	11.27 (0.41)	3.0 (0.3)	1.43 (0.06)	312 (25)	196 (17)	116 (23)

Table **4** Mean (sd) results in the 1500-m trial

	Velocity *$m \times s^{-1}$*	*$\dot{V}O_2$* *$l \times min^{-1}$*	*RER*	*Total (W)*	*Aerobic (W)*	*Anaerobic (W)*
100 m	8.46 (0.52)	1.2 (0.2)	1.41 (0.21)	451 (89)	72 (19)	379 (84)
300 m	12.57 (0.86)	2.3 (0.3)	1.15 (0.12)	444 (112)	144 (41)	300 (93)
500 m	12.45 (0.78)	3.1 (0.3)	1.15 (0.12)	380 (76)	176 (36)	204 (52)
700 m	11.87 (0.62)	3.2 (0.4)	1.30 (0.10)	322 (49)	184 (41)	138 (37)
900 m	11.31 (0.57)	3.3 (0.4)	1.36 (0.07)	285 (39)	189 (44)	96 (32)
1100 m	10.93 (0.59)	3.3 (0.4)	1.39 (0.05)	265 (45)	186 (47)	79 (34)
1300 m	10.75 (0.67)	3.3 (0.5)	1.34 (0.07)	258 (47)	194 (48)	64 (37)
1500 m	10.74 (0.69)	3.2 (0.4)	1.34 (0.11)	264 (51)	189 (44)	75 (42)

Table **5** Mean (sd) results in the 3000-m trial

	Velocity *$m \times s^{-1}$*	*$\dot{V}O_2$* *$l \times min^{-1}$*	*RER*	*Total (W)*	*Aerobic (W)*	*Anaerobic (W)*
100 m	7.90 (0.47)	1.2 (0.2)	1.12 (0.17)	357 (61)	78 (13)	279 (73)
200 m	10.19 (0.29)	2.0 (0.1)	1.04 (0.09)	265 (20)	124 (11)	141 (10)
400 m	10.21 (0.22)	2.7 (0.1)	0.94 (0.02)	256 (21)	177 (11)	79 (17)
600 m	10.17 (0.33)	2.9 (0.1)	1.05 (0.04)	256 (22)	186 (7)	70 (15)
800 m	10.19 (0.34)	3.0 (0.2)	1.15 (0.08)	256 (22)	184 (23)	72 (22)
1000 m	10.16 (0.26)	3.0 (0.2)	1.20 (0.07)	254 (13)	193 (13)	61 (9)
1200 m	10.09 (0.12)	3.0 (0.2)	1.23 (0.07)	247 (2)	191 (13)	56 (14)
1400 m	10.14 (0.15)	3.0 (0.2)	1.23 (0.05)	257 (9)	194 (9)	63 (8)
1600 m	10.12 (0.21)	3.0 (0.1)	1.24 (0.06)	251 (10)	191 (5)	60 (5)
1800 m	10.09 (0.29)	3.0 (0.2)	1.25 (0.05)	249 (17)	197 (5)	52 (14)
2000 m	10.13 (0.32)	3.1 (0.2)	1.22 (0.04)	251 (16)	195 (10)	56 (10)
2200 m	10.14 (0.33)	3.1 (0.2)	1.21 (0.05)	256 (21)	194 (13)	62 (12)
2400 m	10.19 (0.31)	3.1 (0.2)	1.20 (0.02)	257 (18)	198 (9)	59 (10)
2600 m	10.22 (0.34)	3.1 (0.2)	1.20 (0.02)	259 (24)	199 (8)	60 (16)
2800 m	10.39 (0.42)	3.1 (0.2)	1.21 (0.01)	279 (29)	195 (13)	84 (16)
3000 m	10.85 (0.35)	3.1 (0.1)	1.22 (0.05)	310 (21)	199 (11)	111 (21)

work attributable to aerobic metabolism was calculated from the metabolic work times efficiency. We assumed that respiratory exchange ratios in excess of 1.00 were attributable to buffering. Accordingly, in the calculation of metabolic work during the time trials $\dot{V}O_2/\dot{V}CO_2$ ratios in excess of 1.00 were treated as if they equaled 1.00. The mechanical work attributable to anaerobic energetic sources was calculated by subtracting the work attributable to aerobic metabolism from the total work accomplished, both for each segment of the ride as well as for the total ride. This approach is conceptually similar to the accumulated O_2 deficit technique used in other studies [5,18,19,26,27,31], although the computational details are somewhat different, and is comparable to the procedure used by Seresse et al. [29,30] and in our previous work [16].

Statistical analysis was accomplished using repeated measures ANOVA to compare aerobic and anaerobic energy expenditure both within each trial and between trials. On the basis that the anaerobic capacity is capable of being expended in ~2 min or less we hypothesized that a relatively "all out" pattern of energy expenditure would be observed in the three shorter distances, with anaerobic energy expenditure being minimal (or even negative) during the terminal portions of these events. In the 3000-m event (~4 – 5 min) we hypothesized a relatively constant pattern of anaerobic energy expenditure with a terminal acceleration [9,33,34].

Results

The time required for completion of the trails was 40.3 ± 0.6 s, 87.4 ± 4.1 s, 133.8 ± 6.6 s, and 296.0 ± 7.2 s for the 500-m, 1000-m, 1500-m and 3000-m trails, respectively. The pattern of velocity during each trial is presented in Fig. **1** and Tables **2 – 5**. With the exception of the 3000 m, there was a tendency to start relatively fast and to slow significantly through the latter half of each trial. In the 3000 m, there was remarkable constancy of velocity with an acceleration during the terminal portion of the event. This tendency was mirrored by the total power output and by the pattern of aerobic and anaerobic power output (Tables **2 – 5**, Fig. **2**). Contrary to our hypothesis of an all out starting strategy, the power output attributable to anaerobic sources never fell to zero in any subject, and in the 1500-m and 3000-m events the power output attributable to anaerobic sources increased during the terminal portion of the events. There were no significant differences in the total work attributable to anaerobic energy sources across the three longest events (Table **6**).

The relative proportional contribution of aerobic and anaerobic energetic sources is presented in Fig. **3**. As expected the relative anaerobic contribution decreased with distance, with a 50 % contribution at a duration of ~100 s.

Table **6** Expenditure of energy from aerobic and anaerobic sources during the time trails

Distance (meters)	*Total kJ*	*Aerobic kJ*	*Anaerobic kJ*
500	23.14 ± 4.24	5.84 ± 1.94	17.29 ± 3.82
1000	34.14 ± 6.37	15.46 ± 3.64	18.68 ± 8.51
1500	43.54 ± 6.12	22.94 ± 3.16	20.60 ± 6.99
3000	78.22 ± 8.28	54.94 ± 6.43	23.28 ± 9.04

Discussion

The primary finding of this study is that during sprint and middle distance cycling time trials athletes appear to distribute their energetic resources over the duration of the event in a manner that preserves the ability to contribute to muscular power output from anaerobic sources even during the closing stages of the event. With the exception of the shortest event, the absolute magnitude of anaerobic energy expenditure did not vary across distances, consistent with predictions based on the concept of a unique individual maximal value for the anaerobic energetic contribution [19,26,29,30]. These data are consistent with the concept that even in sprint and middle distance events, athletes may be engaging in a monitoring process that allows them to optimize the distribution of their energetic resources. As such, the data are consistent with the "governor hypothesis" recently put forward by St Clair Gibson et al. [32].

The pattern of power output in the 1000-m and 3000-m events was qualitatively similar to that observed during 1000-m and 4000-m track competitions, although the absolute power output was lower, consistent with the sub-elite nature of the subjects in this study [6,8,22]. The results of this study support the findings of van Ingen Schenau et al. [34] and deKoning et al. [9] who found the most desirable outcome during a 1000-m trial occurred when cyclists used a large amount of anaerobic power output early in the race. They are also consistent with observational data in elite cyclists [8,22,36]. However, unlike assumptions made in modeling studies from van Ingen Schenau et al. [33,34] and deKoning et al. [9], the subjects did not fully use their anaerobic capacity before the end of the event. This pattern of controlling the anaerobic energetic output is also consistent with a

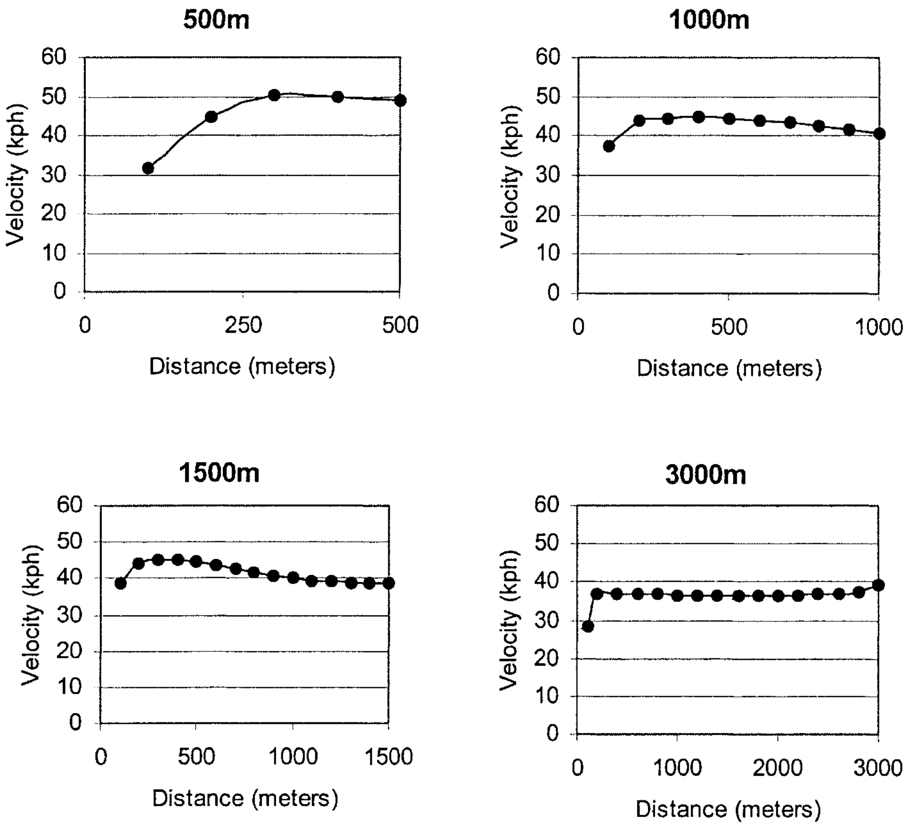

Fig. **1** Velocity profiles during each of the events. Note that with the exception of the 3000-m event, there is a general deceleration during the latter part of each event. This is typical of many air-resisted sports such as cycling and speed skating, where velocity at the end of the event represents wasted kinetic energy.

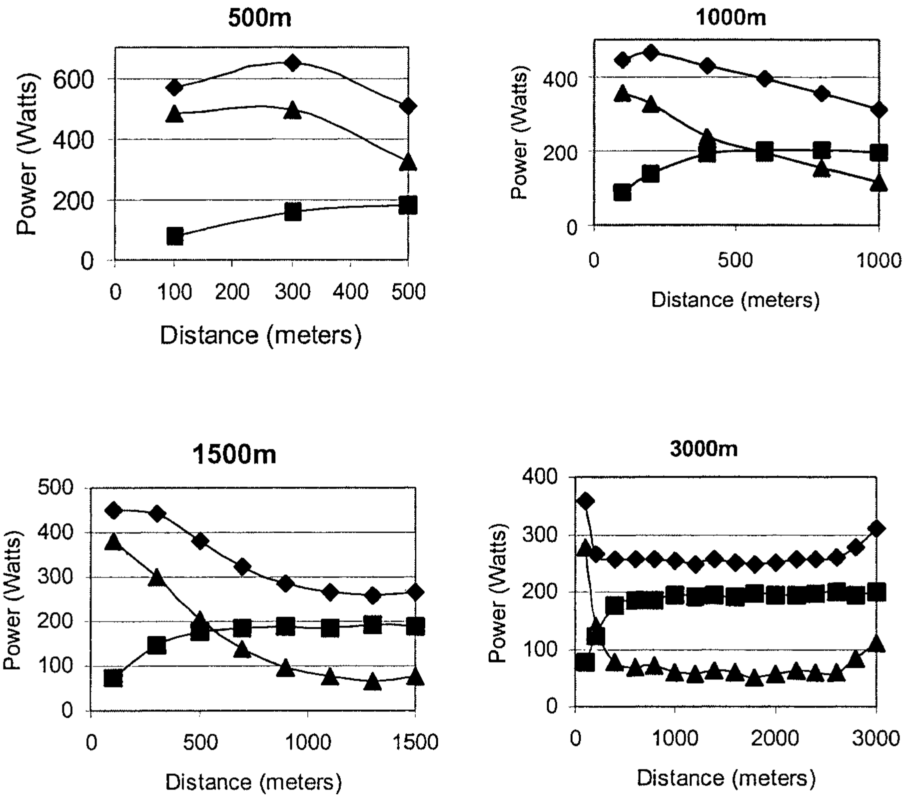

Fig. **2** Power output profiles during each of the events. Note that the high total energy expenditure (diamonds) at the beginning of the event is highly related to a high anaerobic energy expenditure (triangles), that the aerobic energy expenditure (squares) during the latter part of each event is relatively constant, that anaerobic energy expenditure never goes to zero, and that the terminal increase in power output in the 3000 m is almost solely due to an increase in anaerobic energy expenditure.

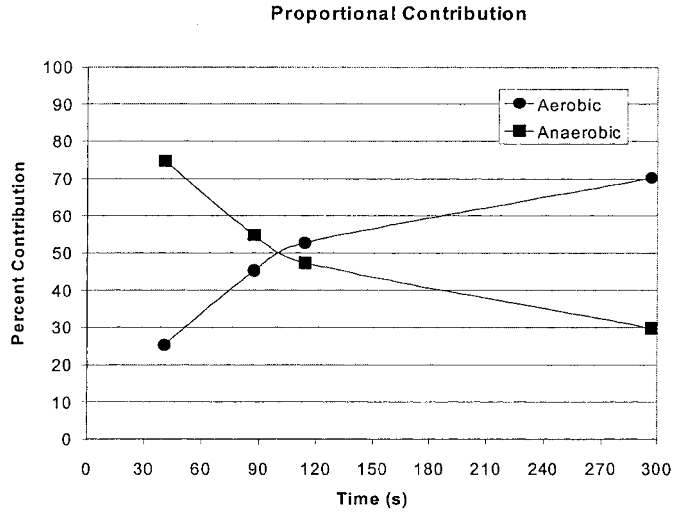

Fig. **3** Proportional contribution of aerobic and anaerobic energetic resources to power output in relation to the duration of the event. Note that an equal contribution is provided at an event duration of ~100 s.

previous study in which we found that during 2000-m trial anaerobic power output never fell to zero [11]. Throughout this study we have used the term "all out" to describe a relatively fast start with a large early anaerobic contribution. This was done on the basis of the modeling studies of deKoning [9] and ven Ingen Schenau [33,34], which were based on data collected during Wingate type tests. We suspect that it is unlikely that any athlete intentionally goes "all out" as implied by the language of these pioneering modeling studies. Nevertheless, we feel that it was appropriate to retain the use of this language.

To our knowledge, the present data are amongst the first to systematically evaluate aerobic and anaerobic power output during simulated competitions. They support earlier findings of the relative contribution of energy systems by Spencer and Gastin [31], using a fixed intensity experimental model. Our results suggest that athletes monitor some aspect of anaerobic energy expenditure during high intensity exercise, so that near zero values are not reached until the finish line is approached. As such, our results can be interpreted to support the implications of a metabolite accumulation [23] or phosphagen depletion [25] models of fatigue. A generation ago, Karlsson et al. [23] observed highly consistent muscle lactate concentrations at exhaustion during 2- and 6-min exercise bouts, and only slightly different muscle lactate concentrations at exhaustion in 14-min exercise bouts. These data suggested that the athlete may be sensitive to proton accumulation in the muscle, and that fatigue may be coincident with reaching critical values of metabolite accumulation. The present data may also be viewed as being consistent with the governor hypothesis put forth by St Clair Gibson et al. [32], suggesting that athletes organize exercise in a manner designed to prevent critical metabolic disturbances during exercise. We do not have EMG data to determine whether the loss of power output is attributable to a down-regulation of muscle fiber recruitment. However, this competitive simulation experimental model appears to be appropriate to test the governor hypothesis.

The classical view of the time dependent trade-off between aerobic and anaerobic energy expenditure is that an equal contribution is achieved in events of about 2-min duration [1]. More recent modeling data [35] suggest that the point of relatively equal energetic contributions is at approximately 100 s.

Savaglio and Carbone [28] have presented an analysis of world records in athletics and in swimming that argues that there is a fairly clear transition between aerobic and anaerobic metabolism in the range of 150 – 170 s. The present data do not support this view. The present data suggest that there is an apparently smooth transition of the relative importance of aerobic versus anaerobic energy expenditure, with more or less equivalent contributions in the range of 100 s, as suggested by Ward-Smith [35]. Further, the within trials data suggest that there is a smooth transition between aerobic and anaerobic energetic contributions within the body of the event, with no evidence of a transitional breakpoint. These data highlight an important limitation of modeling studies based on world records instead of on the balance between power production and power losses. In this sort of modeling approach, the highly unique characteristics of power production in individual athletes must be collapsed into a non-existent "record man", who has none of the characteristics of athletes actually setting world records.

The limitations of this study involve the subtraction approach to estimating anaerobic energetic requirements and the sub-elite character of the subjects. Experimental approaches to quantifying anaerobic energy expenditure depend either on direct measurements of phosphagen depletion and lactate accumulation or an indirect inference of anaerobic work performed based on subtracting work attributable to aerobic sources from the total work accomplished. The direct approach is limited by invasiveness and concerns regarding whether we are including representative samples of muscle. The indirect method has been widely used [5,11,16,18,19,26,27,29 – 31]. However, Green et al. [20] have demonstrated that the impression of the magnitude of the anaerobic energetic contribution is inconsistent between direct and indirect methods. The indirect method is limited by the necessity for assuming that the relative efficiency of exercise is the same during very high intensity exercise as during submaximal exercise. Recent data from Gastin et al. [18] demonstrating constancy of the accumulated O_2 deficit during supramaximal all-out and constant intensity exercise suggest that any changes in efficiency during supramaximal exercise do not introduce meaningful errors into the calculation of anaerobic energetic expenditure. The subjects in this study only competed at a moderate competitive level. Their intrinsic characteristics, their level of training, their level of motivation and their knowledge of managing themselves during very high intensity exercise was clearly limited compared to elite athletes. However, since the protocol included practice trials in all four distances we feel that the subjects were well habituated to the tasks to be performed. We have previously demonstrated in subjects with characteristics very similar to those in the present study, that the pattern of energy expenditure closely matches that demonstrated by regional-national level athletes [16]. Accordingly, we feel that the pattern of energy expenditure observed in this study is likely to be generalizable to more accomplished athletes, even if the magnitude of the responses is substantially less. There was no strategy imposed on the subjects. Just as in competition, they were directed to finish as quickly as possible, and were given the same type of feedback that an athlete would normally have during competition. Replicating this study with more accomplished athletes is clearly desirable, although getting high- level athletes to perform several competitively meaningless race effort trials is difficult. Similarly, additional trials with more extreme competitive strategies might prove to be most interesting. It is our impression that during competition, particularly very high-level competitions such as the Olympic Games, some athletes will start with unrealistically ambitious strategies. Expressed simply, many athletes who normally would have been expected to finish in 10th place, will go out on a pace designed to compete with the medalists, even if it will most likely result in their finishing in 30th place. This tactic succeeds just often enough to provide encouragement to other athletes to try achieving similar "breakthroughs". It would seem to be reasonable to explore the physiologic consequences of such strategies.

Acknowledgements

This study was supported by a grant from the Medical Commission of the International Olympic Committee and Pfizer, Inc. The authors express appreciation to Dr Todd Allinger for overall coordination of the IOC/Pfizer grant process. The authors acknowledge the technical assistance of Kerry LaClair, Lindsy Brucker and Joy Zeman-Haase who performed pilot studies in support of this project.

References

[1] Astrand PO, Rodahl K. Textbook of Work Physiology. 3rd ed. New York: McGraw-Hill, 1986: 325 – 325
[2] Bangsbo J. Quantification of anaerobic energy production during intense exercise. Med Sci Sports Exerc 1998; 30: 47 – 52
[3] Bar-Or O. The Wingate anaerobic test: An update on methodology, reliability and validity. Sports Med 1987; 4: 381 – 394
[4] Beaver WL, Wasserman K, Whipp BJ. A new method for detecting the anaerobic threshold by gas exchange. J Appl Physiol 1986; 60: 2020 – 2027
[5] Bishop D, Donetti D, Dawson B. The influence of pacing strategy on $\dot{V}O_2$ and supramaximal kayak performance. Med Sci Sports Exerc 2002; 34: 1041 – 1047
[6] Broker JP, Kyle CR, Burke ER. Racing cyclist power requirements in the 4000-m individual and team pursuits. Med Sci Sports Exerc 1999; 31: 1677 – 1685
[7] Craig NP, Northon KI, Conyers RA. Influence of test duration and event specifity on maximal accumulated oxygen deficit in track cyclists. Int J Sports Med 1995; 16: 534 – 540
[8] Craig NP, Norton KI. Characteristics of track cycling. Sports Med 2001; 31: 457 – 468
[9] de Koning JJ, Bobbert MF, Foster C. Determination of optimal pacing strategy in track cycling with an energy flow model. J Sci and Med Sport 1999; 3: 266 – 277
[10] Dengle DR, Graham RE, Hones MT, Norton KI, Cureton KJ. Prediction of oxygen uptake on a bicycle windload simulator. Int J Sports Med 1990; 11: 279 – 283
[11] Foster C, Snyder AC, Thompson NN, Green MA, Foley M, Schrager M. Effect of pacing strategy on cycle time trial performance. Med Sci Sports Exerc 1993; 25: 383 – 388
[12] Foster C, Thompson NN, Snyder AC. Ergometric studies with speed skaters: Evolution of laboratory methods. J Strength Cond Res 1993; 7: 193 – 200
[13] Foster C, Green MA, Snyder AC, Thompson NN. Physiological responses during simulated competition. Med Sci Sports Exerc 1993; 12: 877 – 882
[14] Foster C, Schrager M, Snyder A, Thompson N. Pacing strategy and athletic performance. Sports Med 1994; 17: 78 – 85
[15] Foster C, deKoning JJ, Rundell KW, Snyder AC. Physiology of speed skating. In: Garrett WE, Kirkendall DT (eds) Exercise and Sport Science. Philadelphia: Lippincott, Williams & Wilkins, 2000: 885 – 893

[16] Foster C, deKoning JJ, Hettinga F, Lampen J, LaClair K, Dodge C, Bobbert M, Porcari JP. Pattern of energy expenditure during simulated competition. Med Sci Sports Exerc (In Press)

[17] Garby L, Astrup A. The relationship between the respiratory quotient and the energy equivalent of oxygen during simultaneous glucose and lipid oxidation and lipogenesis. Acta Physiol Scand 1987; 129: 443 – 444

[18] Gastin PB, Costill DL, Lawson DL, Krzeminski K, McConnel GK. Accumulated oxygen deficit during supramaximal all-out and constant intensity exercise. Med Sci Sports Exerc 1995; 27: 255 – 263

[19] Gastin PB. Energy system interaction and relative contribution during maximal exercise. Sports Med 2001; 31: 725 – 741

[20] Green S, Dawson BT, Goodman C, Carey MF. Anaerobic ATP production and accumulated O_2 deficit in cyclists. Med Sci Sports Exerc 1996; 28: 315 – 321

[21] Hill DW. Energy system contribution in middle-distance running events. J Sports Sci 1999; 17: 477 – 483

[22] Jeukendrup AE, Craig NP, Hawley JA. The bioenergetics of world class cycling. J Sci Med Sports 2000; 3: 414 – 433

[23] Karlsson J, Saltin B. Lactate, ATP and CP in working muscles during exhaustive exercise. J Appl Physiol 1970; 29: 598 – 602

[24] Lucia A, Hoyos J, Perez M, Santalla A, Chicharro JL. Inverse relationship between $\dot{V}O_2$max and economy/efficiency in world-class cyclists. Med Sci Sports Exerc 2002; 34: 2079 – 2084

[25] McLester JR. Muscle contraction and fatigue: the role of adenosine 5'-diphosphate and inorganic phosphate Sports Med 1997; 23: 287 – 305

[26] Medbo JI, Mohn AC, Tabata I, Bahr R, Vaage O, Sejersted OM. Anaerobic capacity determined by maximal accumulated O_2 deficit. J Appl Phys 1988; 64: 50 – 60

[27] Medbo JI, Tabata I. Relative importance of aerobic and anaerobic energy release during short-lasting exhausting bicycle exercise. J Appl Phys 1989; 67: 1881 – 1886

[28] Savaglio S, Carbone V. Scaling in athletic world records. Nature 2000; 404: 244 –

[29] Seresse O, Lortie G, Bouchard C, Boulay M. Estimation of the contribution of the various energy systems during maximal work of short duration Int J Sports Med 1988; 9: 456 – 460

[30] Seresse O, Simoneau JA, Bouchard C, Boulay M. Aerobic and anaerobic energy contribution during maximal work in 90 s determined with various ergocycle workloads. Int J Sports Med 1991; 12: 543 – 547

[31] Spencer MR, Gastin PB. Energy system contribution during 200- to 1500-m running in highly trained athletes. Med Sci Sports Exerc 2001; 33: 157 – 162

[32] St ClairGibson A, Lambert M, Noakes TD. Neural control of force output during maximal and submaximal exercise. Sports Med 2001; 31: 637 – 650

[33] van Ingen Schonau GJ, deKoning JJ, deGroot G. A simulation of speed skating performances based on a power equation. Med Sci Sports Exerc 1990; 22: 718 – 728

[34] van Ingen Schenau GJ, deKoning JJ, deGroot G. The distribution of anaerobic energy in 1000 and 4000 meter cycling bouts. Int J Sports Med 1992; 13: 447 – 451

[35] Ward-Smith AJ. Aerobic and anaerobic energy conversion during high-intensity exercise. Med Sci Sports Exerc 1999; 31: 1855 – 1869

[36] Wilberg RB, Pratt J. A survey of the race profiles of cyclists in the pursuit and kilo events. Can J Sport Sci 1988; 13: 208 – 213

[37] Withers RT, Sherman WM, Clarket DG. Muscle metabolism during 30, 60 and 90 s of maximal cycling on an air-braked ergometer. Eur J Appl Physiol 1991; 63: 354 – 362