Pattern of Energy Expenditure during Simulated Competition

CARL FOSTER[1], JOS J. DE KONING[2], FLOOR HETTINGA[2], JOANNE LAMPEN[2], KERRY L. LA CLAIR[1], CHRISTOPHER DODGE[1], MAARTEN BOBBERT[2], and JOHN P. PORCARI[1]

[1]Department of Exercise and Sport Science, University of Wisconsin-La Crosse, WI; and [2]IFKB, Faculty of Human Movement Sciences, Vrije Universiteit-Amsterdam, THE NETHERLANDS

ABSTRACT

FOSTER, C., J. J. DE KONING, F. HETTINGA, J. LAMPEN, K. L. LA CLAIR, C. DODGE, M. BOBBERT, and J. P. PORCARI. Pattern of Energy Expenditure during Simulated Competition. *Med. Sci. Sports Exerc.*, Vol. 35, No. 5, pp. 826–831, 2003. **Purpose:** To determine how athletes spontaneously use their energetic reserves when the only instruction was to finish in minimal time, and whether experience from repeated performance changes the strategy of recreational athletes. **Methods:** Recreational road cyclists/speed skaters ($N = 9$) completed three laboratory time trials of 1500 m on a windload braked cycle. The pattern of energy use was calculated from total work and from the work attributable to aerobic metabolism, which allowed computation of anaerobic energy use. Regional level speed skaters ($N = 8$) also performed a single 1500-m time trial with the same protocol and measurements. **Results:** The serial trials were completed in (mean ± SD) 133.8 ± 6.6, 133.9 ± 5.8, 133.8 ± 5.5 s ($P > 0.05$ among trials); and in 125.7 ± 10.9 s in the skaters ($P < 0.05$ vs cyclists). The $\dot{V}O_{2peak}$ during the terminal 200 m was similar within trials (3.23 ± 0.44, 3.34 ± 0.44, 3.30 ± 0.51 ($P > 0.05$)) versus 3.91 ± 0.68 $L \cdot min^{-1}$ in the skaters ($P < 0.05$ vs cyclists). In all events, the initial power output and anaerobic energy use was high and decayed to a more or less constant value (~25% of peak) over the remainder of the event. Contrary to predictions based on an assumed “all out” starting strategy, the subjects reserved some of their ability to perform anaerobic work for a terminal acceleration. The total work accomplished was not different between trials (43.53, 43.78, and 47.48 kJ in the recreational athletes, or between the cyclists and skaters (47.79 kJ). The work attributable to anaerobic sources was not different between the rides (20.67, 20.53, and 21.12 kJ in the recreational athletes). In the skaters, the work attributable to anaerobic sources was significantly larger versus the cyclists (24.67 kJ). **Conclusion:** Energy expenditure during high-intensity cycling seems: 1) to be expended in a manner that allows the athlete to preserve an anaerobic energetic contribution throughout an event, 2) does not appear to have a large learning effect in already well trained cyclists, and 3) anaerobic energy expenditure may be the performance discriminating factor among groups of athletes. **Key Words:** ANAEROBIC EXERCISE, SPORTS PERFORMANCE, CYCLING, ANAEROBIC CAPACITY

To achieve optimal performance, it is essential for athletes to use their available energetic resources efficiently. To avoid wasting kinetic energy, all possible energy stores should have been used before 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 (e.g., the pacing strategy), there are comparatively few data regarding the pattern of energy expenditure during competition. Recent studies have provided perspective regarding the pattern of energy system contribution during high-intensity exercise (2–5,7,8,11,14,25,26,30,31). However, studies that have attempted to document proportional energy contributions 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 trials) or fixed duration trials with the pacing pattern dictated by the investigators (e.g., Wingate type tests). In competitions, athletes have a very different goal, finishing a certain distance in the shortest possible time. Studies in longer events have shown that the reliability of competitive simulations is much better than fixed duration trials (23,24). To our knowledge, there are only very limited data available regarding how athletes spontaneously expend their anaerobic resources in middle-distance (1–5 min) events (2,7,8,27).

Experimental studies of spontaneous patterns of energy expenditure are rare. In an experimental study of pacing patterns in a 2000-m time trial (~2.5 min), we (7) 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 (5,30,31). These models suggest that in events of less than ~1.5-min duration, a relatively ‘all out’ pacing strategy might be optimal, with most of the energy attributable to anaerobic sources used during the first part of the event. As the duration of events increases beyond 1.5 min, a more constant pattern of energy expenditure appears

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Address for correspondence: Carl Foster, Ph.D., Department of Exercise and Sport Science, University of Wisconsin-La Crosse, La Crosse, WI 54601; E-mail: foster.carl@uwlax.edu.

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TABLE 1. Characteristics of the subjects (mean ± SD).

	Males (N = 7)	**Females (N = 2)**
Main group		
Age (yr)	32.6 ± 9.9	26.3 ± 7.5
Height (cm)	174.9 ± 12.6	174.3 ± 5.8
Mass (kg)	72.1 ± 3.8	68.0 ± 9.9
$\dot{V}O_{2peak}$ ($L \cdot min^{-1}$)	3.77 ± 0.34	3.02 ± 0.44
$\dot{V}O_2$ @ VT ($L \cdot min^{-1}$)	2.63 ± 0.38	1.93 ± 0.22
Speed skaters	(N = 7)	(N = 1)
Age (yr)	21.1 ± 5.1	20
Height (cm)	181.4 ± 4.7	157
Mass (kg)	78.1 ± 7.7	61
$\dot{V}O_{2peak}$ ($L \cdot min^{-1}$)	4.34 ± 3.14	3.14
$\dot{V}O_2$ @ VT ($L \cdot min^{-1}$)	2.99 ± 0.46	1.88

to be optimal (5,31). However, these models still have significant limitations in that there are few data on how athletes spontaneously pace themselves, when the only goal is to finish in minimal time (32). Earlier experimental or observational studies (16,22) of pacing are limited by experimental design or have measured only velocity without direct measurement of aerobic and anaerobic power output (32). A better understanding of how athletes expend their energetic resources is critical to improving our fundamental understanding of how humans organize their available resources to optimize muscular performance. Accordingly, there were two overall purposes of this study. The first was to determine the pattern of expending energetic resources during spontaneously paced 1500-m time trials, particularly whether the anaerobic energy resources are fully expended before the end of the event. The second purpose was to determine how well-trained but nonelite athletes use their energetic resources in relation to the pattern adopted by more accomplished athletes, and whether the pattern evolves with repeated performance of a criterion time trial.

METHODS

There were two groups of volunteer subjects for this study. The subjects in the primary group were serious recreational level cyclists/speed skaters (males, $N = 7$, females, $N = 2$) (Table 1). Typically, these athletes trained ~10 h weekly and were competitive within their competitive group in local competitions but were clearly noncompetitive at the regional level. These subjects participated in a series of three 1500-m cycle time trials. The subjects in the second group were speed skaters who were members of the Milwaukee regional team of U.S. Speedskating (males, $N = 7$, females, $N = 1$). Two of these subjects subsequently represented the U.S. at the 2002 Junior World Championships, and all subjects met qualification criteria for participation in the U.S. Olympic Trials for the 2002 Olympic Winter Games. These subjects performed a single 1500-m cycle time trial. They were very familiar with the task via participation in periodic physiological testing provided by the speed skating national governing body. Subjects provided written informed consent before participation. The study was approved by the university human subjects committee. To characterize the subjects and to ensure familiarity with the gas collection system, each subject performed incremental exercise (25 W for 3 min + 25 $W \cdot min^{-1}$) to fatigue on an electrically braked cycle ergometer, with measurement of respiratory exchange by open circuit spirometry (Cosmed K4b^2, Rome, Italy), to allow definition of $\dot{V}O_{2peak}$ (30-s measurement) and ventilatory threshold by using the V-slope technique (1).

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 (6). We have previously used this device in other studies of competitive simulations (7,8). Power output and distance were measured using a dynamometer (SRM, Konigskamp, Germany) based on a strain gauge and revolution counter built into the chain ring. Power output variables were recorded every second. Metabolic data were measured breath-by-breath using open-circuit spirometry. HR was measured every 5 s using radio telemetry.

All studies were conducted in the early Fall of the year, when the subjects were quite fit. In the primary study with the recreational athletes, the subjects were studied on three different days while completing cycle time trials of 1500 m. There was a minimum of 48 h between trials, with no more than two trials per week by any subject. For all trials, the subjects were instructed to perform easy training the day before the trial, as if the trial were a competition. Each subject warmed up before the ride according to a standard protocol (Fig. 1). As a portion of the warm-up, a 5-min submaximal ride was completed at a power output just below the ventilatory threshold determined during the incremental exercise test for the purpose of defining the relationship between power output and $\dot{V}O_2$ (~200 W (men) and ~150 W (women)). During the time trials, the only instruction to the subject was to complete each trial as quickly as possible. Feedback including their performance (e.g., mean velocity) during previous rides, momentary velocity and cumulative distance completed was provided to the subject, just as they would be during competition. Throughout the trials, the subjects were apprised of their split times and provided strong verbal support.

From the $\dot{V}O_2$ and power output during the submaximal trial, the mechanical work during the submaximal trial divided by the metabolic work (calculated according to Garby and Astrup (10)) gives efficiency. Subsequently, the average power output and the average $\dot{V}O_2$ during each segment of each trial were calculated, and the work attributable to aerobic metabolism calculated from the metabolic work × efficiency. We assumed that respiratory exchange ratios in excess of 1.00 were attributable to nonmetabolic CO_2 production attributable to buffering of lactate by bicarbonate. Accordingly, during the time trials $\dot{V}CO_2/\dot{V}O_2$ ratios in excess of 1.00 were treated as if they equaled 1.00 relative to calculating metabolic work. 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 has been

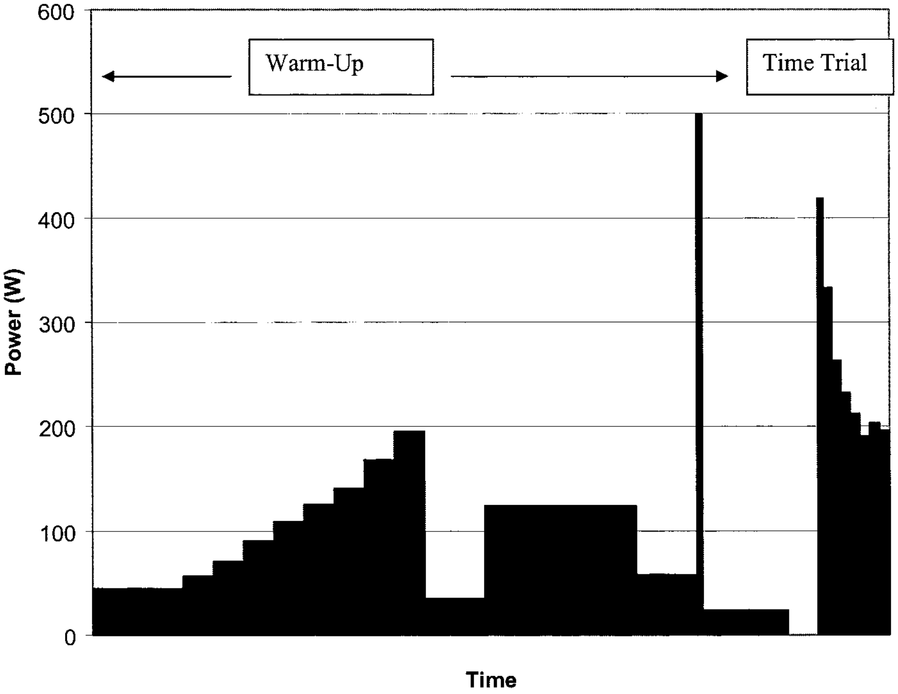

FIGURE 1—Schematic presentation of the warm-up protocol. Before the trial, each subject performed an incremental warm up to nearly maximal momentary intensity. After a brief period of low-intensity exercise, the subject then performed 5 min of steady state exercise at an intensity just below the ventilatory threshold to allow matching of the power output–$\dot{V}O_2$ relationship. The warm-up was completed with a brief sprint and then several minutes of low-intensity exercise and/or rest before the beginning of the time trial.

previously used by Serresse et al. (25,26) and is conceptually similar to the accumulated O_2 deficit technique used in other studies (11,19,20), although the computational approach is somewhat different.

In the second study, the speed skaters performed a single 1500-m time trial according to the same protocol (Fig. 1). The skaters were generally familiar with the task since this type of time trial is commonly used in evaluations provided by the national governing body, and because 1500 m is a common speed skating distance that is frequently performed by both sprint and all-around specialists. Again, the only instruction provided to the subject was to finish the trial in minimal time. As in the primary trial, feedback was provided to the athlete. To maintain the competitive environment, split times and coaching advice was provided by the Milwaukee regional coach during the trial.

Statistical analysis was accomplished using repeated measures ANOVA to compare aerobic and anaerobic energy expenditure both within each trial and between trials. Statistical significance was accepted when $P < 0.05$. On the basis of previous observations (5,31), we hypothesized that a relatively "all out" pattern of energy expenditure would be observed, with anaerobic energy expenditure being minimal (or even negative) during the terminal portion of the event. We hypothesized that the recreational level athletes in the primary trial would change the pattern of their energy expenditure to more closely match that of the skaters over successive trails. Pairwise comparisons were performed when justified by ANOVA using the Tukey test.

RESULTS

The time (mean ± SD) required for completion of the three 1500-m trials by the cyclists was 133.8 ± 6.6 s, 133.9 ± 5.8 s, and 133.8 ± 5.5 s, versus 125.7 ± 10.9 s for the skaters. The time of the skaters was significantly ($P < 0.05$) less than the fastest time by the recreational athletes. There were no significant differences among trials in the recreational athletes.

The calculated efficiency during the submaximal ride during the warm-up period was 17.1 ± 2.8, 16.6 ± 3.1, and 19.1 ± 1.9% for trials 1, 2, and 3, and 15.2 ± 1.2% for the skaters. The calculated efficiency values were not significantly different among trials in the cyclists or between the cyclists and skaters. These values are lower than observed in elite cyclists (17) but reasonable compared with other studies of humans during cycle exercise (21).

The pattern of velocity, total power output, aerobic power output, and calculated anaerobic power output during each trial is presented in Table 2 and Figure 2. Contrary to our hypothesis of an "all out" starting strategy, it appears that all subjects adopted a pattern in which there was a continuing contribution to total power output from nonaerobic energetic sources throughout the duration of each trial. In general, the pattern of power output across successive trials was remarkably similar and was highly similar to that observed in the skaters. Although we could not evaluate changes in the pattern statistically, it appeared that the subjects evolved during the second and third trials toward a higher power output during the first 100 m with a steady decline in power output until terminal values were attained during the last 400 m.

The relative proportional contribution of aerobic and anaerobic energetic sources is presented in Figure 3. As expected from the duration of the event, the relative anaerobic contribution was about 50%. There was little change in the proportional energetic contribution across trials, and the general proportional contribution was similar between the volunteer subjects and the skaters, although the absolute

TABLE 2. Results (mean ± SD) in the 1500-m trial for trial 1, trial 2, and trial 3 in the primary study of recreational athletes; the upper line is the mean value, the lower line is the SD.

Distance (m)	Velocity ($m \cdot s^{-1}$)	$\dot{V}O_2$ ($L \cdot min^{-1}$)	Total (W)	Aerobic (W)	Anaerobic (W)
100	8.50/8.49/8.37	1.25/1.31/1.37	452/451/452	72/76/92	380/375/360
	0.56/0.63/0.70	0.17/0.15/0.13	90/92/104	19/17/11	84/93/93
300	12.64/12.26/12.19	2.32/2.42/2.52	444/390/417	144/137/154	300/253/263
	0.97/0.97/0.87	0.34/0.27/0.24	112/94/93	41/17/17	93/89/79
500	12.50/12.07/12.20	3.08/3.20/3.29	380/384/401	176/179/215	204/168/186
	0.83/0.86/0.71	0.34/0.37/0.41	76/57/47	36/25/34	52/55/50
700	11.90/11.70/11.90	3.22/3.31/3.39	322/314/371	184/184/224	138/130/147
	0.62/0.62/0.55	0.38/0.42/0.45	49/40/47	41/31/26	37/39/44
900	11.34/11.35/11.50	3.28/3.36/3.37	286/292/339	189/189/222	97/103/117
	0.57/0.42/0.44	0.40/0.46/0.44	39/42/38	44/36/26	32/32/35
1100	10.97/11.11/11.17	3.25/3.34/3.37	265/278/317	186/186/222	79/92/95
	0.62/0.48/0.44	0.40/0.46/0.52	45/48/38	47/36/38	34/30/35
1300	10.80/11.06/10.96	3.31/3.29/3.31	258/280/305	194/184/219	64/96/86
	0.72/0.58/0.43	0.48/0.44/0.50	47/53/34	48/37/36	37/38/28
1500	10.79/11.06/10.90	3.23/3.34/3.30	264/283/303	189/189/217	75/94/86
	0.76/0.75/0.50	0.44/0.44/0.51	51/66/45	44/40/44	42/49/27

magnitude of the anaerobic contribution was significantly larger in the skaters (Fig. 4). The faster time by the skaters appeared to be largely attributable to the larger anaerobic capacity in these athletes. In support of this, the correlation between the 1500-m time (in trial 3 by the cyclists and in the skaters) and anaerobic work accomplished was ($r = -0.74$). On the other hand, the correlation between the 1500-m time and aerobic work accomplished was $r = -0.04$.

DISCUSSION

The primary finding of this study is that in middle-distance cycling time trials, both accomplished athletes and well-trained recreational level athletes appear to distribute their energetic resources over the duration of the event in a manner that preserves the ability to provide for anaerobic power output until the closing stages of the event. These data suggest that athletes may be engaging in a monitoring process that allows them to optimize the distribution of their energetic resources. The failure to observe large changes in the pattern of power output with repeated performance of the criterion event suggests that the postulated ability to monitor energetic resources is learned relatively early in an athletes' experience and is not a highly specialized learned response. On this basis, models of sports performance, which assume that the anaerobic energetic resources are expended rapidly (5,30,31) may have to be reconsidered. That we never observed our subjects achieving a zero anaerobic energetic output suggests that this is comparatively rare and may only occur with extreme pacing strategies. There are comparatively few data regarding anaerobic energy expenditure during competitive simulations. Unlike the modeling results of de Koning et al. (5) and van Ingen Schenau et al. (30,31), our subjects did not fully use their anaerobic capacity before the end of the event. The present data agree with

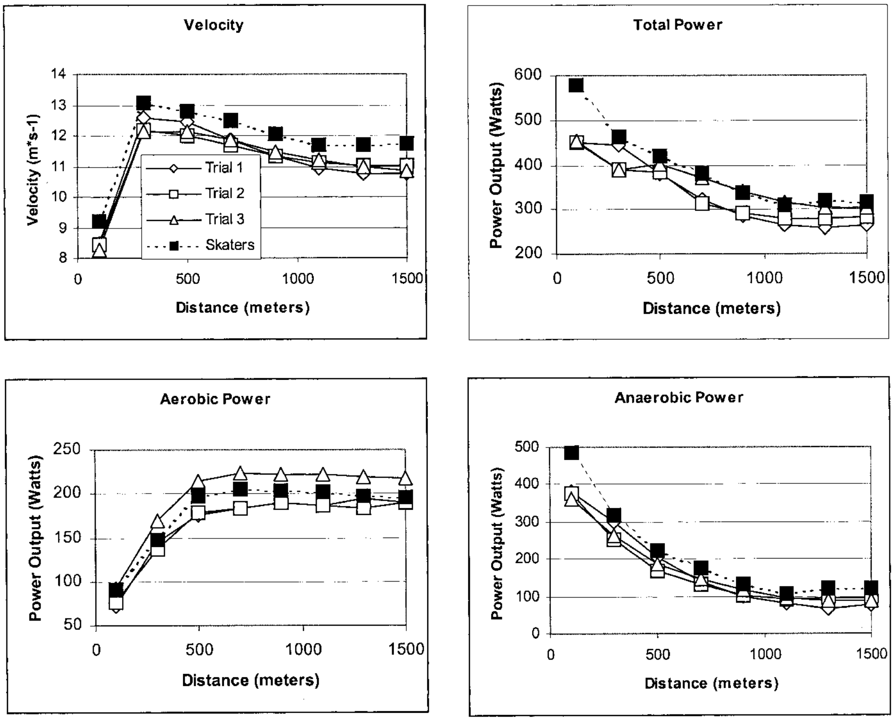

FIGURE 2—Serial pattern of velocity, total power output, aerobic power output, and anaerobic power output in the three trials of the primary study are compared with the responses in the skaters. Note the general stability of the pattern across trials and the general similarity of the pattern in the recreational cyclists and the speed skaters.

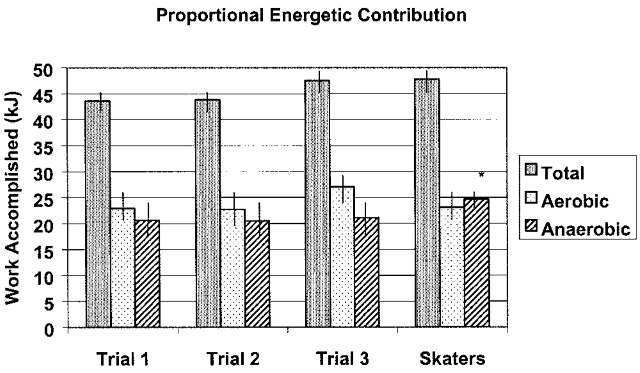

FIGURE 3—Proportional contribution to total work accomplished (kJ) by aerobic and anaerobic energy systems in the recreational athletes (trials 1, 2, and 3) and skaters. Values are the group mean ± SD; $*P < 0.05$

a previous study in which we (7) found that during a 2-km cycle time trial anaerobic power output never fell to zero.

To our knowledge, the present data are among the first to systematically evaluate aerobic and anaerobic power output during competitive simulations, particularly in high-level athletes. They are similar to the recent data from Bishop et al. (2) with the added feature of having the athlete compete over a specified distance, rather than for a specified time. They support earlier findings of the relative contribution of energy systems by Spencer and Gastin (27), using a fixed intensity experimental model and the accumulated O_2 deficit technique. 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. Although the metabolite accumulation model of muscular fatigue has been vigorously debated, our results indirectly support the implications of a metabolite accumulation (12,13,15) or phosphagen depletion model (18). Observations of highly consistent muscle lactate concentrations at exhaustion during 2- and 6-min exercise bouts (15) suggest that the athletes may be sensitive to proton accumulation in the muscle and may control their momentary power output to delay reaching critical values of metabolite accumulation until the end of the event. As such, the data are consistent with the central governor hypothesis put forth by St Clair Gibson et al. (28), 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 downregulation of muscle fiber recruitment as proposed by St Clair Gibson et al. (28) or to some direct muscular effect of metabolite accumulation. However, the present competitive simulation experimental model appears to be appropriate to test the central governor hypothesis.

The differences in performance between the skaters and the recreational cyclists were largely due to the larger amount of work attributable to anaerobic sources. It is unclear whether this difference is constitutional or the result of the different training programs by these athletes. Medbo et al. (19) have previously demonstrated that sprint type athletes, including speed skaters, have very high values for accumulated O_2 deficit (e.g., anaerobic capacity). Medbo and Burgers (20) have demonstrated only very modest increases in accumulated O_2 deficit after high-intensity training in nonathletic volunteers. This suggests that constitutional and/or selective factors may define anaerobic capacity. Whether this is related to anatomical differences such as muscle fiber type or to physiological differences such as buffer reserve remains to be determined.

In this study, we used an approach that is the same as used by Serresse et al. (25,26) and conceptually similar to the accumulated O_2 deficit approach to allow us to estimate the anaerobic energetic contribution. The use of these approaches to estimating anaerobic energy expenditure requires several assumptions. The first is that the efficiency of cycling is relatively constant during both the 5-min submaximal trial at an intensity just below the ventilatory threshold and during the supra-$\dot{V}O_{2peak}$ intensities used during the time trial. This assumption is broadly equivalent to the assumption that the power output–$\dot{V}O_2$ relationship can be extended to supramaximal intensities, which is supported by the observations of Moseley and Jeukendrup (21). We are not aware of data demonstrating changes in efficiency at very high relative power outputs, which would be very difficult to measure since steady state $\dot{V}O_2$ is difficult to demonstrate at high relative workloads. The second assumption relates to the nature of anaerobic energy expenditure. As pointed out by Medbo et al. (19) in the original report of the accumulated O_2 deficit approach, the estimation of anaerobic energy expenditure is fundamentally a process of subtraction. No inferences regarding the composition of nonaerobic energetic resources (phosphagen depletion, lactate accumulation, and blood and tissue O_2 desaturation) can be made without extensive data that are not available in the present data. We do know, however, that relative muscle O_2

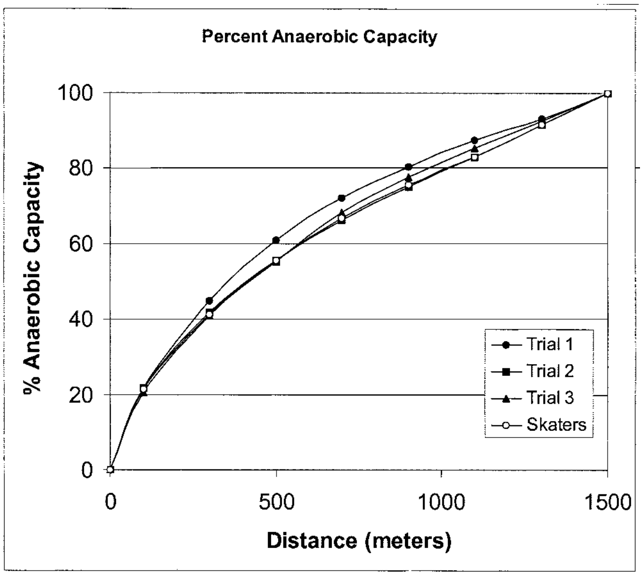

FIGURE 4—Proportional use of the normalized anaerobic capacity in relation to the distance completed in the trial. Although none of the differences are statistically significant, there is a trend for a more "all out" starting strategy in the first trial by the cyclists.

desaturation does occur during this type of exercise bout (9,29) and that it is more pronounced during higher-intensity exercise (9). By definition, this process represents aerobic metabolism, just as does arterial desaturation. Both, however, contribute to the calculation of anaerobic energetic contributions as they are not accounted for in the measurement of $\dot{V}O_2$ during the ride. As such, the anaerobic contribution to energetic resources may be overestimated in the present data. However, we are not aware of data that would allow an individually meaningful computation of this overestimation. As such, we feel that this limitation of the method can only be acknowledged.

In summary, the data appear to support the concept that athletes are managers of their energetic reserves and that they regulate their muscle power output in such a way that both aerobic and anaerobic energetic sources are contributing to the total muscular power output throughout the course of an event. The data suggest that the pattern of expending energetic resources is somewhat general and does not evolve greatly with repeated performance of a criterion task in athletes with even minimal experience with a particular task. Why and how higher level athletes develop a particular anaerobic capacity and how much it may be modified by training remain to be determined.

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