ABSTRACT

BRUCKER, L. A. Effect of competitive distance on utilization of anaerobic capacity. MS in Adult Fitness/Cardiac Rehabilitation, December 2001, 45pp. (C. Foster)

In view of published models that assume that anaerobic capacity is expended much earlier in a high intensity event, this study evaluated patterns of aerobic and anaerobic energy expenditures during simulated cycling time trials. Five competitive cyclists performed 500m, 1000m, 1500m, and 3000m cycling time trials on different days on a racing bicycle. Power output was recorded using a dynamometer connected to a windload simulator that was attached to the racing bicycle equipped with a heavy flywheel. VO_2 was measured by open circuit spirometry. Outcome variables were analyzed with repeated measures ANOVA. There was no significant difference in VO_{2peak} among the four distances. A significant difference in total joules and aerobic joules with all comparisons was found. No significant difference was found among any comparisons for anaerobic joules. The results deviate from the prediction model in previous studies, and suggest that anaerobic capacity is not used up before the end of an event. Our results are consistent with a pacing strategy for expending anaerobic capacity, showing that the rate of anaerobic energy expenditure decreased rapidly after the first seconds of exercise. Technical limitations, subject's athletic background, and training experience may have been limiting factors in the present study. Exploring the results of additional distances may bring about better understanding of the limits of anaerobic capacity in athletes.

EFFECT OF COMPETITIVE DISTANCE ON UTILIZATION OF ANAEROBIC CAPACITY

A MANUSCRIPT STYLE THESIS PRESENTED

TO

THE GRADUATE FACULTY

UNIVERSITY OF WISCONSIN-LA CROSSE

IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE

MASTER OF SCIENCE DEGREE

BY

LINDSY BRUCKER

DECEMBER 2001

ACKNOWLEDGEMENTS

It is with great appreciation that I may thank the following individuals for their help in completion of my masters thesis:

Dr. Carl Foster, my thesis chair, for his help in getting the study started and also for his guidance and time throughout the process of completing this thesis.

Drs. John Porcari and Peg Maher, my committee members, for their time and professional assistance.

My thesis volunteers for all of their time and cooperation in completing the testing procedures.

To Joy Zeman for helping me with my testing and helping me stay relaxed and have fun throughout the year.

Mr. Chris Dodge for helping with glitches that occurred during testing and putting in extra time to keep the equipment stay functional.

Most of all to my fiancé, family, and friends for their love and support while I have been in school.

TABLE OF CONTENTS

LIST OF TABLES

TABLE PAGE

LIST OF FIGURES

FIGURE PAGE

LIST OF APPENDICES

APPENDIX PAGE

INTRODUCTION

The release of anaerobic energy during bursts of high intensity exercise is significant in terms of sports performance but has been difficult to measure [17]. While the contribution of aerobic work has been well quantified for some time, there has not yet been one defining laboratory measurement of anaerobic contribution that is universally used. Anaerobic capacity has been characterized as the maximal amount of ATP formed by the anaerobic processes during a single bout of maximal exercise [10]. Given the comparative constancy of aerobic power among elite athletes, the magnitude and the pattern of anaerobic energy expenditure may contribute in a definitive way to competitively meaningful differences in performance. Athletes such as cyclists or swimmers that compete in events lasting only a few minutes are separated by very small differences in final performance times (e.g. milliseconds). It makes sense that athletes and coaches alike would find it beneficial to determine the best way to expend anaerobic sources in competition [3]. The gathering of this type of physiological information remains complex and risks hindering competition performance. Therefore, data on energetic sources during athletic competition is generally very limited. Research that encompasses "free range exercise" presents an experimental model that may be useful in better understanding the limits of the physiological responses to exercise [6,7,19,20], and allow the testing of mathematical models of performance [4,24].

Information on the interaction between aerobic and anaerobic energy yield is limited and new data on this topic is needed. According to Astrand [1], during exercise periods lasting up to 2 minutes, anaerobic power is more important than aerobic contribution; at about 2 minutes there is a 50:50 ratio, and with prolonged exercise the aerobic contribution becomes gradually more important. Astrand [1] has estimated that at a 4 minute bout of maximum effort, aerobic processes contribute 70 percent while anaerobic processes account for 30 percent. Others have found that 60%, 50%, and 30-35% of the total energy release is anaerobic during exhausting exercise bouts of 30 s, 1 min, and 2 min, respectively [16,17,18]. From these varying data, one realizes that a large anaerobic capacity is of great importance for success in physical activities that incorporate short bursts of intense exercise [18]. Therefore determining the relative contribution from anaerobic processes during a series of short-lasting cycle time trials might be of benefit relative to competition strategies for athletes.

Most sporting events involve some type of strategy. During cycling, athletes try to cover a certain distance in the shortest time possible. The strategy for achieving this goal involves decisions about how to expend the anaerobic energetic resources. Pacing has been defined as the controlling of speed throughout the race by varying the rate of energy expenditure [6]. This topic remains complicated due to very little data on pacing strategies [5,7]. There has been much attention in recent decades to improving performance in time trial cycling by enhancing the technology of the bicycle and rider relationship [22,26], and training and competition adaptations [21]. More research is needed on the important effects of pacing. The limited data that has been published on pacing strategies [7] appears to agree with model predictions [5,24]. Further data on how athletes expend their anaerobic energetic resources might provide insight into how athletes solve the problem of minimizing the time requirement for completing events of varying distances.

Strategies for measuring anaerobic capacity in the laboratory have been widely reviewed by Bouchard et al. [4]. Two of these tests are worth describing due to their popular use.

The Wingate anaerobic test [3] involves a subject pedaling a mechanically braked cycle ergometer at the maximal rate possible against a heavy resistance of about 1 N/kg body weight for 30 seconds. Ayalon et al. [2] designed this test in 1974 to determine anaerobic performance during an all-out effort, with the mean power produced during the test being accepted as a measure of anaerobic power [10]. It was originally assumed that the mean power was a reflection of anaerobic processes [3]. Since that time, it has been recognized that the mean power measured does not come entirely from anaerobic energetic sources, but is dependent on energy release form both anaerobic and aerobic processes [3]. The duration of this test is too short to completely fatigue the anaerobic energy system and long enough for the contribution from aerobic metabolism to be significant [23].

Similar to the Wingate Test is the Quebec 90-s test. In this test the subject begins pedaling at 80 rpm while the workload is adjusted (to about .5N/kg body weight). The subject then pedals as fast as possible for 90-s. The data give moment-by-moment power output, some information on the pattern of fatigue, and quantitate the total work done in 90-s, which Foster et al. [8] concludes may approach the anaerobic capacity. Yet the validity of these performance-based tests can be disputed due to the contribution of aerobic metabolism that may account for a sizeable amount of the energy requirement in tests less than a minute in duration.

Medbo et al. [16,17,18], have suggested an indication of anaerobic capacity may be derived from the accumulated oxygen deficit during exhausting exercise. Gastin [10] defines oxygen deficit as the difference between the actual oxygen uptake consumed during exercise and the total that would have been consumed had a steady state been reached immediately. Karlsson and Saltin [12,13,14] used this technique to measure the anaerobic ATP formation during intense bouts of bicycle exercise in the 1970s. Gastin [10] summarizes the detailed work of Medbo et al. [11,15,16,17] during treadmill and bicycle exercise which has sparked new interest in this concept. Foster et al. [8] argues that if accumulated O_2 deficit (AOD) is to be a reliable measure of anaerobic capacity, it should level off with exercise duration, and the amount of work performed anaerobically should increase with exercise duration until the anaerobic capacity is achieved.

Along with the concept of O_2 deficit, new approaches to ergometry merit discussion in determining the best way to simulate physiological responses during competitive situations. Conventional ergometry involves completing the performance-based tests cited above, with an incremental cycle ergometer test widely used for measuring aerobic power. With these tests, Schabort [20] has found that protocols that have employed the time to "exhaustion" at some fixed workload to measure exercise performance have mediocre reproducibility. Also, these tests do not relate to real life competitive situations where athletes compete over a set distance, trying to minimize the time to get there. Foster [6,7], Schabort [20], and Palmer [19] have experimented with the technique of simulating competition in the laboratory by having subjects complete time trials of varying distances using a racing bicycle attached to a windload simulator. This technique has been shown to be subjectively similar to the feelings experienced during competition [6]. Foster et al. [6], demonstrated that the time trial technique produced significantly higher peak VO_2 compared to an incremental cycle ergometer test. Further these results suggest that larger physiological responses may be achieved when subjects are free to adjust their power output on a moment-by-moment basis compared to a work pattern that is directed by a certain protocol. These data highlight the idea of providing near "real world" approaches within the constraints of a laboratory by modifying equipment and having athletes attempt to minimize the time to complete a task [6]. Further studies integrating the O_2 deficit along with new approaches to ergometry give possibilities for evaluating patterns of energy expenditure in competitive simulations. Our intent was to evaluate patterns of aerobic and anaerobic energy expenditures during high intensity simulated cycling time trials. We hypothesized that athletes expend their energetic sources in a way that anaerobic energy does not go to zero in these events.

METHODS

Subjects

Five healthy competitive cyclists (4 male, 1 female) volunteered to participate. The subjects were cyclists who had competed in regional and national road cycling competitions for the past several years. Descriptive data of the subjects are presented in

Table 1. Characteristics of Subjects (± SD)

	Male	Female
Age (yr)	34.8 ± 10.4	35.00
Height (cm)	179 ± 8	165.00
Weight (kg)	74.3 ± 4.3	60.00
VO_{2max} ($L \cdot min^{-1}$)	3.86 ± 0.23	2.91
VO_{2max} ($ml \cdot min^{-1} \cdot kg^{-1}$)	52.1 ± 4.3	48.50
% Predicted VO_{2max}	142 ± 15	154.00

Table 1. All subjects were informed of the testing procedures and requirements and provided informed consent prior to testing (Appendix A). The protocol was approved by the University of Wisconsin-La Crosse Institutional Review Board for the Protection of Human Subjects before any data collection.

Protocol

Each subject's height and weight was measured prior to their first test. Each subject performed 500, 1000, 1500, and 3000m practice time trials on different days to habituate to the racing bicycle and the various distances. Power output was recorded using a dynamometer (SRM, Konigskamp, Germany) connected to a windload simulator with a heavy flywheel and attached to the racing bicycle. VO_2 was not measured for the practice time trials. Respiratory metabolism (VO_2) was measured using open circuit spirometry (Quinton QMC, Seattle, WA). Heart rate was monitored using radiotelemetry

(Polar Vantage XL, Polar Instruments, Port Washington, NY). Each subject then performed the same distances, again on different days. The order of time trial distances was randomized, with each subject instructed to complete each distance as rapidly as possible, as in competition.

Each subject warmed up prior to the ride according to his or her own precompetitive preferences. However, the warm up included a 5 minute period of constant power output exercise with simultaneous measurement of power output and VO_2. From this measurement the aerobic cost per joule of exercise was calculated according to Willems et al. [25] and Garby et al. [9]. The utilization of anaerobic capacity was then measured by determining the average power output of each 200m segment of each distance, then subtracting the measured O_2 uptake from the predicted O_2 uptake. The total anaerobic contribution was computed by subtracting the aerobic work done from the total work done during each segment and summating.

Statistical treatment

Group means and standard deviations were calculated for all physical characteristics (age, height, and body weight). Outcome variables were analyzed with repeated measures analysis of variance to test the hypothesis that the anaerobic contribution is not used up before the end of these events.

RESULTS

Time. During the 500m time trial, the average split time increased progressively throughout the ride. Mean (± SD) times for the 100, 300, and 500m splits are presented in Table 2 and illustrated in Figure 2. It was found that the 300 and 500m split times

Table 2. 500m Results (± SD) for Time, Power Output, VO_2, and Energy Expenditure

Split	Time (s)	Power Output (W)	VO_2 (L/min)	Energy Expenditure Total (J)	Aerobic (J)	Anaerobic (J)
100m	10.02 (0.88)	713 (144)	1.85 (0.68)	7085 (1217)	920 (337)	5913 (1152)
300m	13.36 (1.04)	609 (109)	2.34 (1.34)	8056 (967)	1793 (1162)	6072 (1739)
500m	14.10 (0.51)	446 (63)	3.40 (0.49)	10579 (2533)	3188 (464)	3082 (444)
Total	37.48 (2.43)	1768 (316)	7.59 (2.51)	25720 (4717)	5901 (1963)	15067 (3335)

were not significantly different ($p > .05$). During the 1000m time trial, split time varied between each 200m and between individuals. Mean (± SD) times for the 200, 400, 600, 800, and 1000m splits are presented in Table 3 and illustrated in Figure 2. There was no significant difference among 200m splits during the 1000m event ($p > .05$). During the 1500m time trial, the average split time remained fairly constant throughout the entire race. Mean (± SD) times for the 100, 300, 500, 700, 900, 1100, 1300, and 1500m splits are presented in Table 4 and illustrated in Figure 2. A significant difference was found between the means ($p < .05$), with the 500m split being significantly faster compared to the 1100m split. All other splits were not significantly different from each other ($p > .05$). Lastly, a significant difference was found among split times in the 3000m race, with the split time of the initial 200m split being significantly slower than the 400 split

Table 3. 1000m Results (± SD) for Time, Power Output, VO_2, and Energy Expenditure

Split	Time (s)	Power Output (W)	VO_2 (L/min)	Energy Expenditure Total (J)	Aerobic (J)	Anaerobic (J)
200m	17.80 (1.69)	592 (123)	2.19 (0.42)	10579 (2533)	2489 (563)	8091 (2127)
400m	15.20 (2.44)	440 (113)	3.22 (0.53)	6496 (919)	3075 (589)	3420 (1181)
600m	15.90 (0.69)	358 (67)	3.50 (0.60)	5763 (1065)	3716 (866)	1987 (1180)
800m	15.80 (1.30)	312 (61)	3.54 (0.65)	4877 (761)	3799 (1007)	1078 (1316)
1000m	17.10 (0.80)	289 (60)	3.58 (0.64)	4900 (808)	4189 (1040)	711 (1164)
Total	81.80 (6.92)	1991 (424)	16.03 (2.84)	32615 (6086)	17268 (4065)	15287 (6968)

($p < .05$). Each split after that was not significantly different from others ($p > .05$). Mean (± SD) times for the 200, 400, 600, 800, 100, 1200, 1400, 1600, 1800, 2000, 2200, 2400, 2600, 2800, and 3000m splits are presented in Table 5 and illustrated in Figure 2.

Power Output (Watts). During the 500m time trial, average power output progressively decreased throughout the race, with average power being the greatest in the first 100m. Mean (± SD) power output for the 100, 300, and 500m splits are presented in Table 2 and illustrated in Figure 4. During the 1000m time trial, power output decreased following each split with the largest decrease in power occurring between the 200 and

Table 4. 1500m Results (± SD) for Time, Power Output, VO_2, and Energy Expenditure

				Energy Expenditure		
Split	Time (s)	Power Output (W)	VO_2 (L/min)	Total (J)	Aerobic (J)	Anaerobic (J)
100m	11.62 (1.03)	460 (90)	1.84 (0.50)	5291 (776)	1368 (245)	3923 (787)
300m	16.10 (2.19)	393 (133)	2.79 (0.42)	6104 (1247)	2593 (261)	3511 (1315)
500m	15.80 (1.48)	342 (79)	3.33 (0.50)	5307 (783)	3123 (350)	2184 (653)
700m	16.82 (1.24)	307 (70)	3.48 (0.54)	5122 (972)	3578 (426)	1544 (707)
900m	17.24 (1.55)	290 (51)	3.55 (0.58)	4937 (451)	3794 (512)	1142 (414)
1100m	17.70 (0.94)	268 (38)	3.51 (0.55)	4709 (454)	3890 (523)	819 (499)
1300m	17.46 (1.12)	275 (42)	3.45 (0.64)	4771 (495)	3763 (683)	1008 (441)
1500m	17.48 (0.97)	289 (48)	3.41 (0.58)	5016 (621)	3759 (553)	1256 (411)
Total	130.22 (10.52)	2624 (551)	25.36 (4.31)	41257 (5799)	25868 (3553)	15387 (5227)

400m split. Mean (± SD) power output for the 200, 400, 600, 800, and 1000m splits are presented in Table 3 and illustrated in Figure 4. During the 1500m time trial, average power output decreased continually throughout the ride. The mean (+ SD) power output

Table 5. 3000m Results (± SD) for Time, Power Output, VO_2, and Energy Expenditure

				Energy Expenditure		
Split	Time (s)	Power Output (W)	VO_2 (L/min)	Total (J)	Aerobic (J)	Anaerobic (J)
200m	20.00	373	1.95	7399	2394	5004
	(1.43)	(61)	(0.19)	(839)	(165)	(951)
400m	17.46	276	2.89	4789	3013	1775
	(0.91)	(48)	(0.28)	(632)	(294)	(437)
600m	17.78	259	3.18	4565	3441	1123
	(1.44)	(42)	(0.38)	(471)	(460)	(296)
800m	18.40	250	3.32	4576	3797	780
	(1.17)	(38)	(0.41)	(495)	(484)	(314)
1000m	18.00	236	3.35	4219	3784	435
	(1.14)	(31)	(0.41)	(364)	(399)	(325)
1200m	18.78	236	3.39	4404	4027	337
	(0.81)	(34)	(0.44)	(482)	(556)	(156)
1400m	18.86	230	3.41	4315	4059	256
	(1.32)	(30)	(0.50)	(435)	(614)	(312)
1600m	18.50	233	3.49	4276	4060	216
	(1.43)	(33)	(0.49)	(367)	(608)	(453)
1800m	18.76	233	3.49	4352	4100	252
	(0.86)	(34)	(0.56)	(455)	(679)	(393)
2000m	18.56	236	3.51	4338	4091	247
	(1.36)	(36)	(0.50)	(457)	(604)	(306)
2200m	18.74	238	3.55	4418	4165	254
	(1.23)	(38)	(0.52)	(491)	(558)	(406)
2400m	18.30	239	3.57	4339	4132	267
	(1.15)	(42)	(0.51)	(598)	(615)	(386)

2600m	18.78	245	3.57	4544	4155	389
	(1.43)	(51)	(0.48)	(623)	(403)	(441)
2800m	18.12	250	3.60	4458	4085	373
	(1.59)	(58)	(0.53)	(655)	(566)	(531)
3000m	18.00	310	3.63	5475	4082	1393
	(2.00)	(76)	(0.44)	(969)	(309)	(890)
Total	277.04	3844	49.90	70467	57385	13142
	(19.27)	*(652)*	*(6.64)*	*(7462)*	*(6721)*	*(5103)*

for the 100, 300, 500, 700, 900, 1100, 1300, and 1500m splits are presented in Table 4 and illustrated in Figure 4. During the 3000m time trial, average power decreased the most during the first 400m, then remained fairly constant throughout the majority of the race. Interestingly, all subjects demonstrated a fairly large increase in power during the last split of the race. Mean (± SD) power output for the 200, 400, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000, 2200, 2400, 2600, 2800, and 3000m are presented in Table 5 and illustrated in Figure 4.

VO_2. During the 500m time trial, cycling VO_2 increased throughout the race, plateauing in the final 200m. Mean (± SD) values for the 100, 300, and 500m splits are presented in Table 2 and illustrated in Figure 6. During the 1000m time trial, VO_2 increased the most between 200 and 400m, then remained fairly constant, with the highest average value being recorded during the final 200m of the race. Mean (± SD) values for the 200, 400, 600, 800, and 1000m splits are presented in Table 3 and illustrated in Figure 6. During the 1500m time trial, the point at which peak values were obtained varied among individuals, yet all subjects experienced their peak VO_2 between

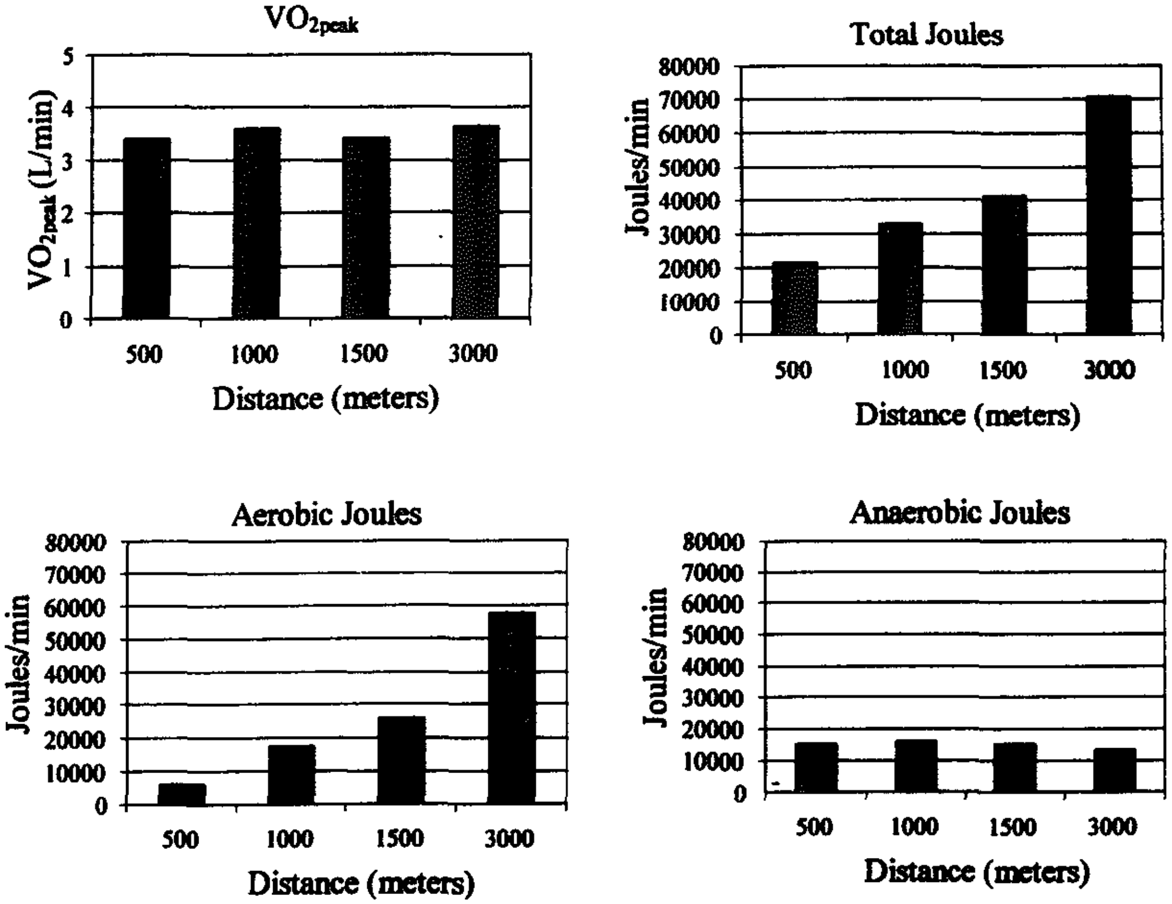

Figure 1. Average response of VO_{2peak}, total joules, aerobic joules, and anaerobic joules for the 500, 1000, 1500, and 3000m time trials.

the 500 and 1300m splits. Mean (± SD) values for the 100, 300, 500, 700, 900, 1100, 1300, and 1500m splits are presented in Table 4 and illustrated in Figure 6. During the 3000m time trial, VO_2 values increased the most between 200 and 400m for all subjects, and remained fairly constant during the second half of the race. The mean (± SD) values for the 200, 400, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000, 2200, 2400, 2600, 2800, and 3000m splits are presented in Table 5 and illustrated in Figure 6. Interestingly, average VO_2 *during the last 200m of each race* was virtually equivalent, with no significant differences found ($p > .05$).

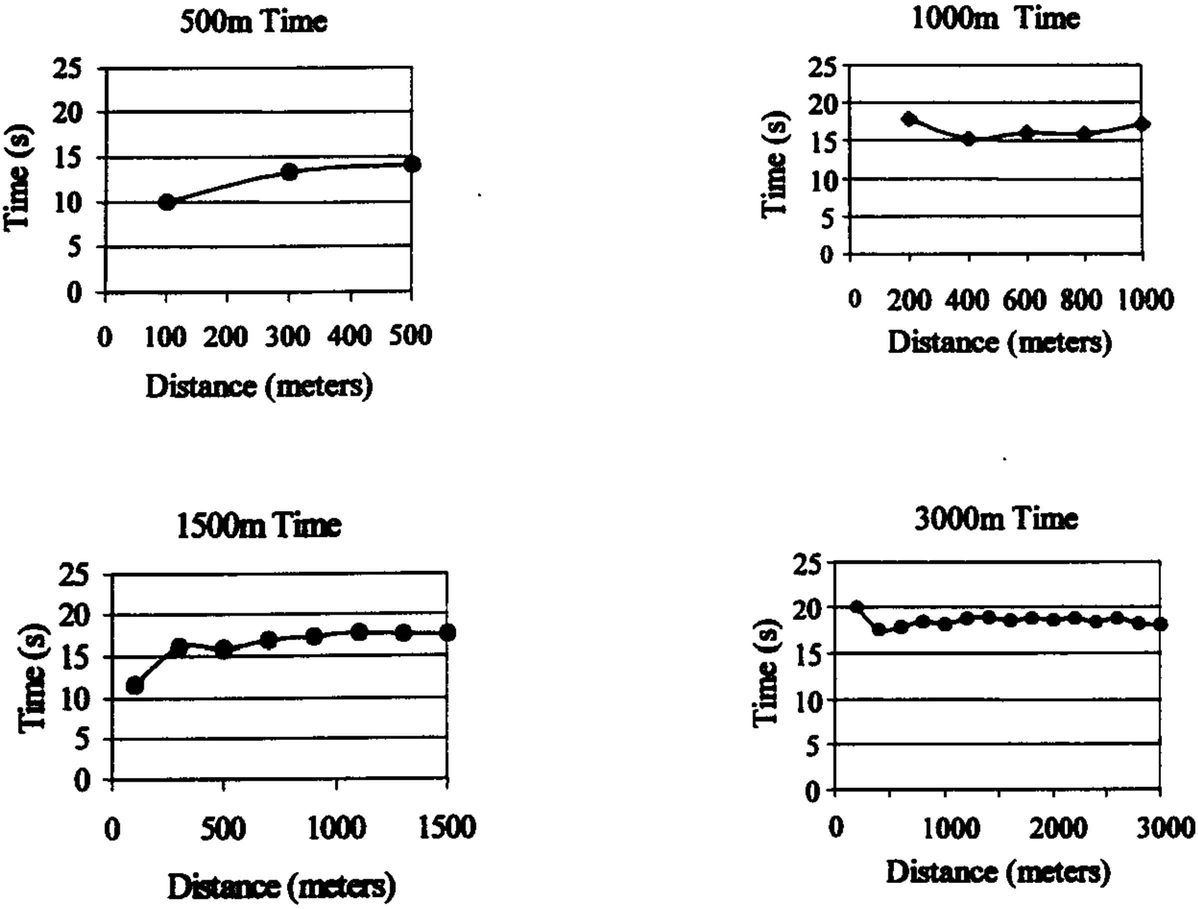

Figure 2. Average response of time for the 500, 1000, 1500, and 3000m time trials, measured every 200m (except opening 100m in 500m and 1500m).

Total Energy Expenditure. Mean (± SD) for total energy expenditure (joules) for the 500, 1000, 1500, and 3000m time trials are presented in Tables 2, 3, 4, and 5, respectively, and illustrated in Figure 8. It was found there was a significant difference among all four distances ($p < .05$).

Aerobic Energy Expenditure. During the 500m time trial, aerobic expenditure rapidly increased for each split of the race for each subject, increasing two to threefold by the end of the race. Mean (± SD) values (joules) for the 100, 300, and 500m splits are presented in Table 2 and illustrated in Figure 8. During the 1000m time trial, aerobic

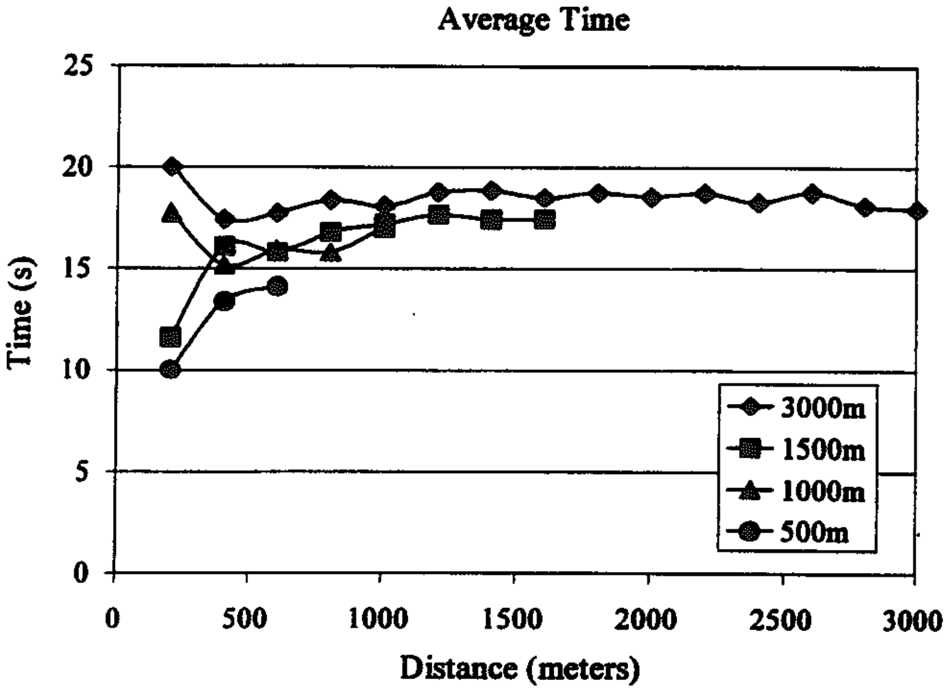

Figure 3. Combined average responses of time for the 500, 1000, 1500, and 3000m time trials, measured every 200m (except opening 100m in 500m and 1500m).

energy expenditure progressively increased throughout the race for all subjects, but not as rapidly as in the 500m trial. Mean (±SD) values are presented in Table 3 and illustrated in Figure 8. During the 1500m time trial, individuals aerobic expenditure rapidly increased in the first 600m, with a slower progression in the second half of the race. Mean (± SD) values are presented in Table 4 and illustrated in Figure 8. During the 3000m time trial, all subjects experienced a successive increase aerobic energy expenditure during the first 1000m, while the rest of the race remained at a fairly constant level. Mean (± SD) values are presented in Table 5 and illustrated in Figure 8. It was found there was a significant difference among all four distances ($p < .05$).

Anaerobic Energy Expenditure. During the 500m time trial, average peak anaerobic energy expenditure was the highest in the first 100m of the race. All subjects'

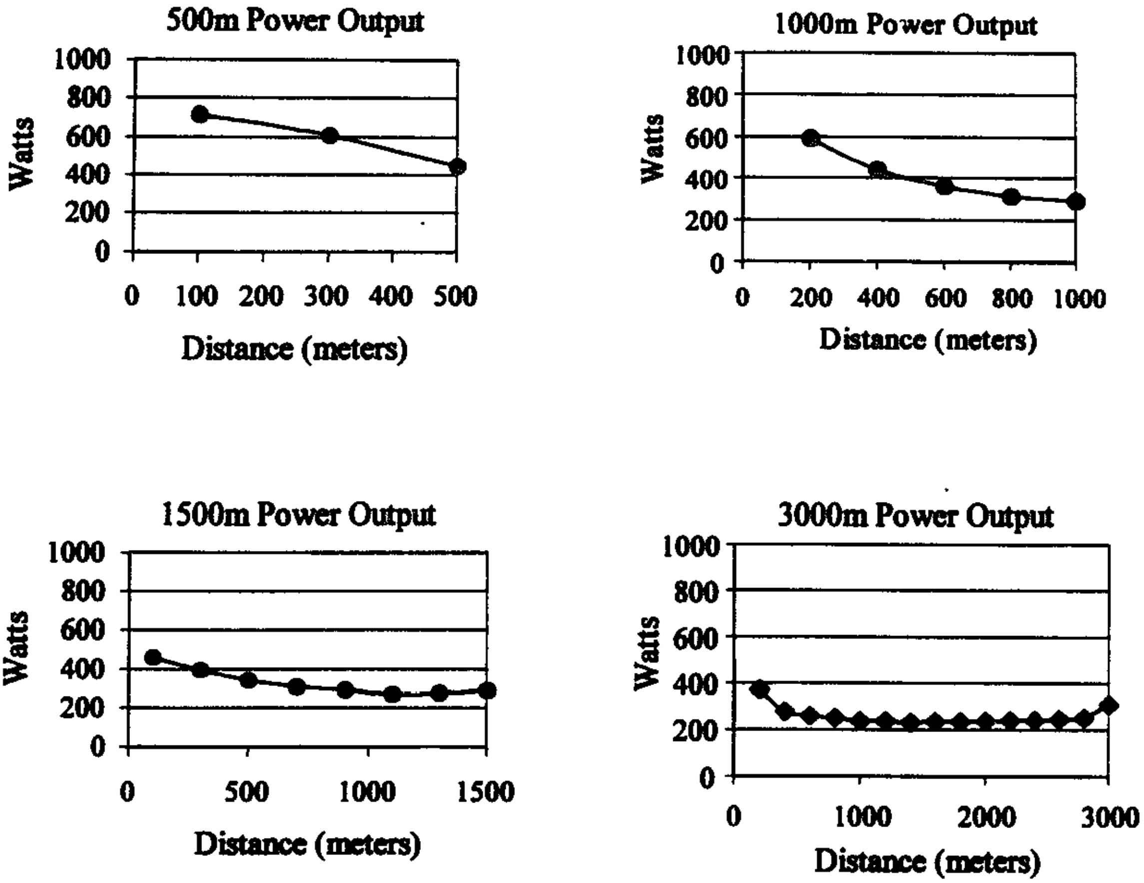

Figure 4. Average response of power output for the 500, 1000, 1500, and 3000m time trials, measured every 200m (except opening 100m in 500m and 1500m).

anaerobic energy expenditure rapidly decreased below their peak values in the last split of the race. Yet the majority of energy (59%) was produced anaerobically for the entire race. Mean (± SD) values are presented in Table 2 and illustrated in Figure 8. During the 1000m time trial, all subjects started the race with large anaerobic expenditure levels, while the second half's anaerobic contribution decreased substantially, although not reaching zero. Mean (± SD) are presented in Table 3 and illustrated in Figure 8. Overall, 47% of the energy expenditure in the 1000m was from anaerobic sources. During the 1500m time trial, average anaerobic expenditure

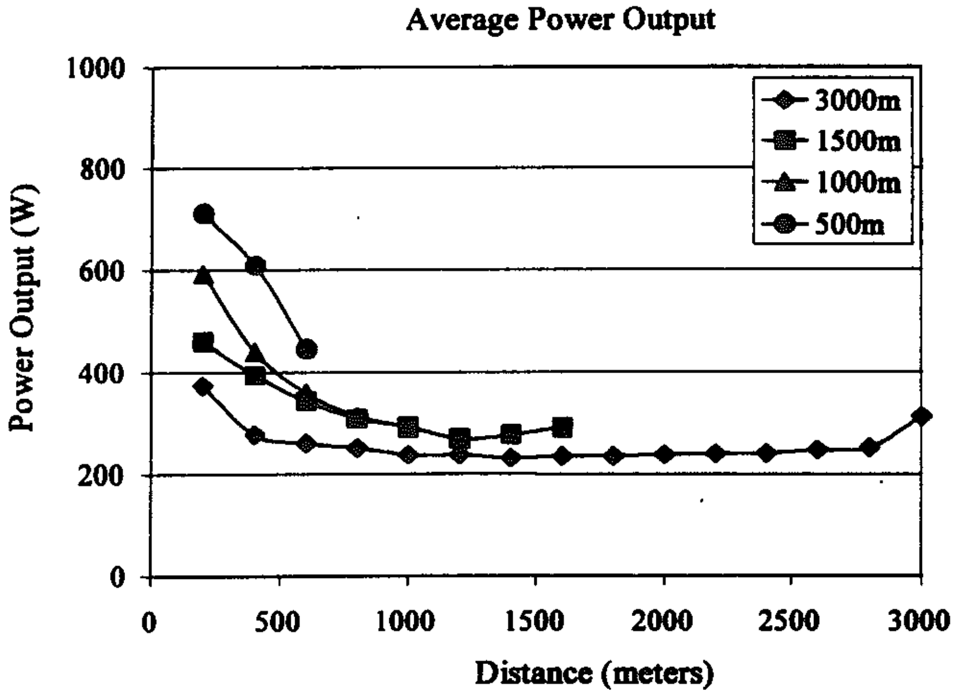

Figure 5. Combined average responses of power output for the 500, 1000, 1500, and 3000m time trials, measured every 200m (except opening 100m in 500m and 1500m).

reached a minimum at the 1100m split, with an increase in anaerobic expenditure during the final split of the race was recorded. Mean (± SD) values are presented in Table 4 and illustrated in Figure 8. Overall, 37% of the energy expenditure during the 1500m was from anaerobic sources. During the 3000m time trial, all subjects obtained peak anaerobic energy expenditure values during the first 400 meters. A sharp reduction in anaerobic energy expenditure was seen after that for all subjects, remaining constant until the last 200m, where all subjects experienced a large increase in anaerobic energy expenditure. Mean (± SD) values are presented in Table 5 and illustrated in Figure 8. Overall, 19% of the energy expenditure during the 3000m was from anaerobic sources. No significant differences in anaerobic energy expenditure were found among the four

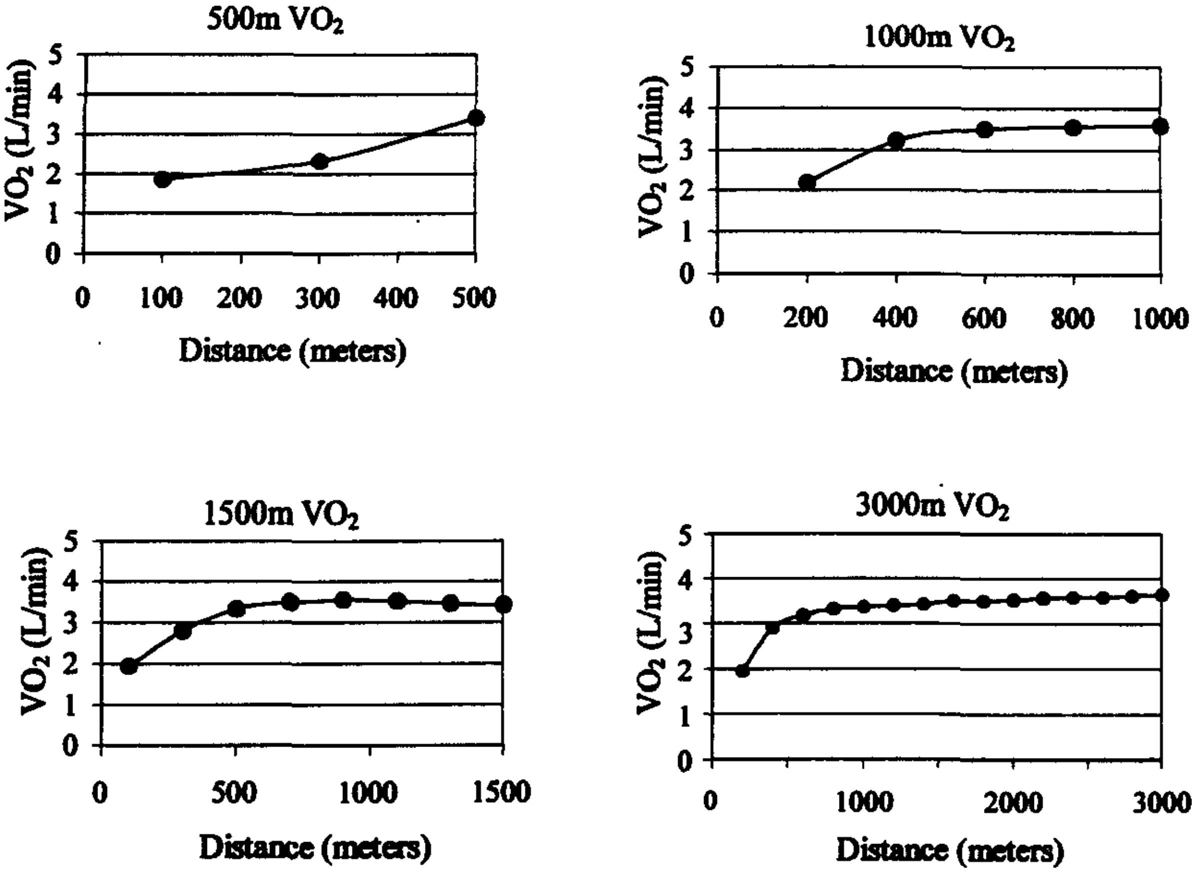

Figure 6. Average response of VO_2 for the 500, 1000, 1500, and 3000m time trials measured every 200m (except opening 100m in 500m and 1500m.

distances ($p > .05$).

DISCUSSION

The present finding supports our hypothesis that anaerobic energy expenditure is not completely used up prior to the end of a high intensity competitive event. The data demonstrates that for distances of 500, 1000, 1500, and 3000m, athletes utilize their aerobic and anaerobic sources in a way that does not exhaust anaerobic capacity before the end of the event. Even though subjects were given only one instruction, to complete each distance as rapidly as possible, all individuals accomplished the task with some anaerobic

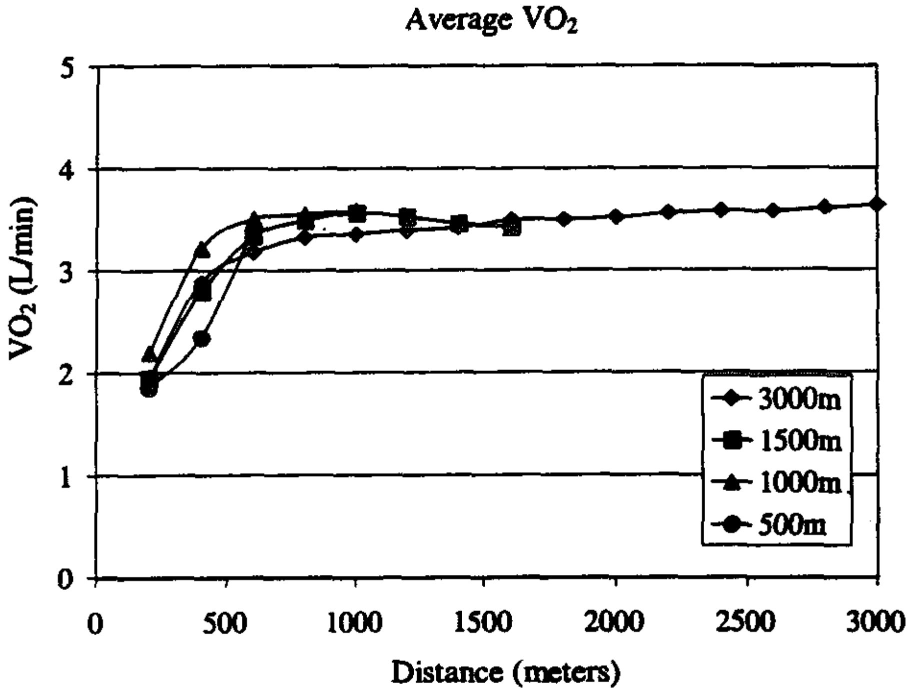

Figure 7. Combined average responses of VO_2 for the 500, 1000, 1500, and 3000m time trials, measured every 200m (except opening 100m in 500m and 1500m).

energy expenditure during the last 200m. It is remarkable that the total anaerobic energy expenditure was very similar over all four distances. These results are consistent with the suggestions of Foster [7] and Medbo [17], suggesting a fixed upper limit of anaerobic energy expenditure. However, unlike the observation of Medbo, our subjects did not require more than two minutes to fully expend their anaerobic capacity. Interestingly, in the 1500m and 3000m time trials, some subjects employed a pacing strategy that resulted in an increase in anaerobic expenditure in the final 200m of the race. Considering an athlete's internal behavior and attempting to simulate these types of competitive events in the laboratory allows us to explore the optimal way in which to expend energy sources is of great benefit to athletes and coaches. Alternatively, approaches such as that used in the present study allow testing of theoretically derived models of performance.

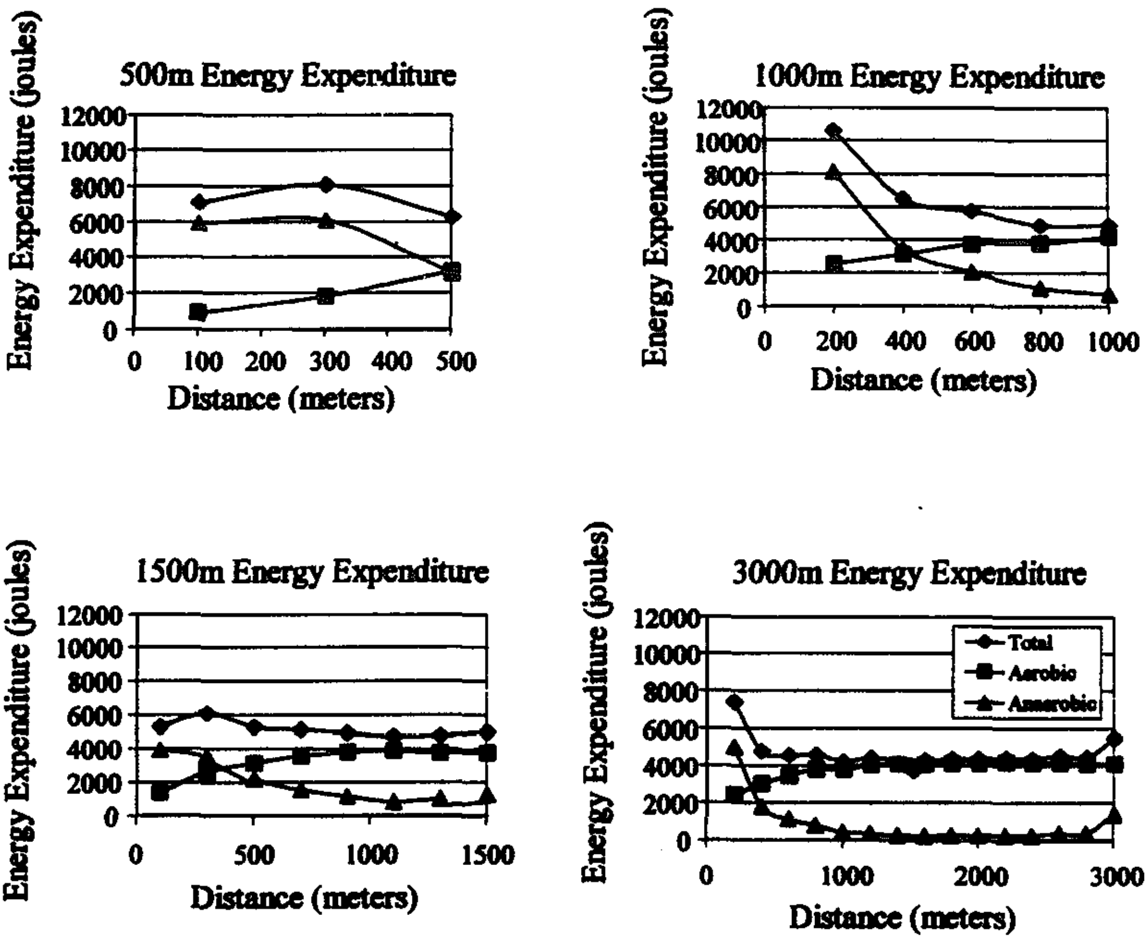

Figure 8. Average response of energy expenditure (total, aerobic, and anaerobic) for the 500, 1000, 1500, and 3000m time trials, measured every 200m (except opening 100m of 500m and 1500m).

Our results are not in agreement with previous findings. A quantitative model incorporating the observed power output capabilities of athletes and established resistance factors was developed by van Ingen Schenau [24]. The model assumes that anaerobic capacity is expended much earlier in a high intensity event (the all-out strategy), and the velocity at the end of the event is essentially wasted energy. This model has successfully been used to simulate the pacing strategies employed by high level competitive athletes. As stated above, our result deviates from this prediction, showing that anaerobic capacity is not used up before the end of an event. However, our results are consistent with a

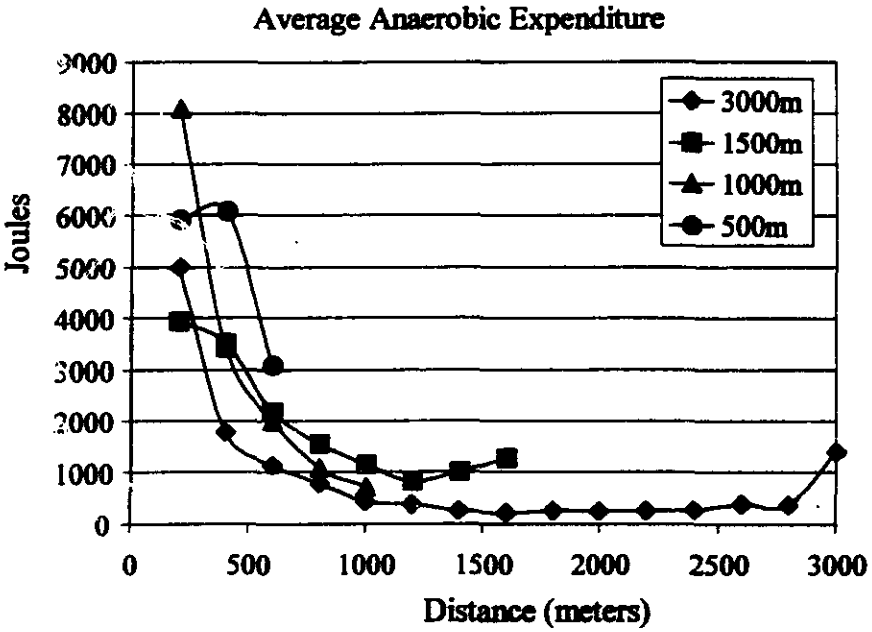

Figure 9. Average response of anaerobic energy expenditure for the 500, 1000, 1500, and 3000m time trials measured every 200m (except opening 100m of 500m and 1500m).

pacing strategy for expending the anaerobic capacity as suggested in the modeling study of de Koning et al. [5]. This pattern is clearly evident in the early stages of all four events where the rate of anaerobic energy expenditure decreased rapidly after the first seconds of exercise. However, unlike the assumptions in the de Koning model [5], our subjects did not completely expend their anaerobic energetic reserves before the conclusion of the 1000 and 1500m events.

It can be argued that technical limitations may be a factor in the current study's results. One factor is the subject's athletic background. Even though the subjects were trained cyclists and were habituated to the events pre-study, their competitive experience involved long distance endurance events. The short high intensity bouts simulated in the study were patterned after track cyclists' type of competition. Another limitation involves habituation to the methods. All subjects had practiced each distance once before to familiarize themselves with the racing bicycle. Therefore subjects may have picked up an optimal strategy that altered their final results, due to a learning phenomenon. However, it may just as easily be argued that several trials may be required to find an optimal strategy for these types of events. Lastly, the subjects' current training regimen may have been a complicating factor. Since subjects competed mainly in endurance type events, since they were tested during the late winter during primarily distance training, and since their training program did not involve a significant amount of high intensity exercise, they were potentially less accustomed to the testing protocol.

Data focusing on anaerobic energy expenditure and pacing strategies are still relatively new [5,6,7,25]. One idea that may lead to more conclusive results is to expand the number of distances evaluated. Exploring the results of additional distances may bring about better understanding of the limits of anaerobic capacity in athletes. In particular, experimental tests of the pacing model for the international standard 4 km pursuit event, as proposed by van Ingen Schenau et al. [24], need to be performed. As a final point, recruiting subjects more specifically trained and experienced in sprint/pursuit events might result in identifying even better ways to improve an athlete's performance in the laboratory and in competition.

REFERENCES

[1] Astrand PO, Rodahl K (eds). Textbook of Work Physiology. New York: McGraw-Hill: 1986

[2] Ayalon A, Inbar O, Bar-Or O. Relationships among measurements of explosive strength and anaerobic power. Int Ser Sport Sci 1974; 1: 572-577

[3] Bar-Or O. The Wingate anaerobic test; an update on methodology, reliability and validity. Sports Med 1987; 4: 381-394

[4] Bouchard C, Taylor AW, Simoneau JA, Dulac S. Testing anaerobic power and capacity. In: MacDougal JD, Wenger HA, Green HJ (eds). Physiological Testing of the High Performance Athlete. Champaign, IL: Human Kinetics, 1991: 175- 221

[5] de Koning JJ, Bobbert MF, Foster C. Determination of optimal pacing strategy in track cycling with an energy flow model. J Sci Med Sport 1999; 2(3): 266-277

[6] Foster C, Green MA, Snyder AC, Thompson NN. Physiological responses during simulated competition. Med Sci Sports Exerc 1993; 25: 877-882

[7] Foster C, Schrager M, Snyder AC, Thompson NN. Pacing strategy and athletic performance. Sports Med 1994; 17(2): 77-85

[8] Foster C, Hector LL, McDonald KS, Snyder AC. Measurement of anaerobic power and capacity. In: Maud PJ, Foster C (eds). Physiological Assessment of Human Fitness. Champaign, IL: Human Kinetics, 1995: 73-85

[9] 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

[10] Gastin PB. Quantification of anaerobic capacity. Scand J Med Sci Sports 1994; 4: 91-112

[11] Hermansen L, Medbo JI. The relative significance of aerobic and anaerobic processes during maximal exercise of short duration. Med Sport Sci 1984; 17: 56-67

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

[13] Karlsson J, Saltin B. Oxygen deficit and muscle metabolites in intermittent exercise. Acta Physiol Scand 1971; 82: 115-122

[14] Linnarsson DJ, Karlsson L, Fagraeus B, Saltin B. Muscle metabolites and oxygen deficit with exercise in hypoxia and hyperoxia. J Appl Physiol 1974; 36: 399-402

[15] Medbo JI, Sejersted OM. Acid-base and electrolyte balance after exhausting exercise in endurance-trained and sprint-trained subjects. Acta Physiol Scand 1985; 125: 97-109

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

[17] Medbo JI, Tabata I. Relative importance of aerobic and anaerobic energy release during shortlasting, exhaustive bicycle exercise. J Appl Physiol 1989; 67: 1881-1886

[18] Medbo JI, Burger S. Effect of training on the anaerobic capacity. Med Sci Sports Exerc 1990; 22: 501-507

[19] Palmer GS, Dennis SC, Noakes TD, Hawley JS. Effects of steady-state and stochastic exercise on subsequent cycling performance. Med Sci Sports 1997; 25: 684-687

[20] Schabort EG, Hawley JA, Hopkins WG, Mujika I, Noakes TD. A new reliable laboratory test of endurance performance for road cyclists. Med Sci Sports Exerc 1998; 30: 1744-1750

[21] Tanaka HD, Bassett R, Swenson TC, Sampedro RM. Aerobic and anaerobic power characteristics of competitive cyclists in the United States Cycling Federation. Int J Sports Med 1993; 14: 334-338

[22] Thompson L. Engineering the world's fastest bicycle. In: Haake S (ed). The Engineering of Sport. Blackwell Science: Oxford, 1998

[23] Vanderwalle H, Kapitaniak B, Grun S, Raveneau S, Monod H. Comparison between a 30-s all-out test and a time-work test on a cycle ergometer. Eur J Appl Physiol 1989; 58: 375-381

[24] van Ingen Schenau GJ, de Koning JJ, de Groot G. The distribution of anaerobic energy in 1000 and 4000 metre cycling bouts. Int J Sports Med 1992: 13: 447-451

[25] Willems JM, van der Worp, de Koning JJ. The effects of variation in test protocol on the anaerobic kinetics and performance during short supramaximal exercise on a cycle ergometer. Unpublished undergraduate research report. Free University of Amsterdam, 1995

[26] Zdravkovich MM, Ashcroft MW, Chisholm SJ, Hicks N. Effect of cyclist's posture and vicinity of another cyclist on aerodynamic drag. In: Haake S (ed). The Engineering of Sport. Balkema: Rotterdam: 1996

APPENDIX A

INFORMED CONSENT

EFFECT OF COMPETITIVE DISTANCE ON UTILIZATION OF ANAEROBIC CAPACITY

Informed Consent

EFFECT OF COMPETITIVE DISTANCE ON UTILIZATION OF ANAEROBIC CAPACITY

I, ________________________________, give my informed consent to participate in this study designed to measure anaerobic capacity during cycling time trials of different durations in relation to pacing strategies identified by a mathematical model of human energy expenditure. I have been informed that the project is under the direction of Lindsy Brucker, a graduate student in Adult Fitness/Cardiac Rehabilitation at the University of Wisconsin-La Crosse. I consent to the presentation, publication, and other release of the summary data from the study that is not identifiable with myself.

I have been informed that my participation in this study will involve my completing eight visits to the Human Performance Laboratory (MH 225) at UW-La Crosse. During each of first four visits, I will complete a 500m, 1000m, 1500m, and a 3000m practice time trial on separate days on a cycle ergometer. The next four visits will consist of completing the same distances in random order. During the time trials, I will ride according to directions provided by the investigators, completing the trials as rapidly as possible. During the last four trials, I will breathe through a scuba type mouthpiece so that my metabolic rate can be measured.

I have been informed that the known or expected discomforts to be expected are fatigue from the exercise tests. I have been informed that the risk of complications during clinical exercise testing is known to be about 6/10,000 tests for minor complications and 1/10,000 tests for serious complications (e.g. cardiac arrest). For prospectively healthy, athletic individuals the risk is thought to be much less (approximately zero), but is less well documented simply because complications are so rare.

I have been informed that the primary benefit that I might expect from participating in this study is a better understanding of my performance characteristics and guidelines to help me individualize my training.

I have been informed that there are no "disguised" procedures in the study. All procedures are taken at face value.

I have been informed that the investigator will answer questions regarding the procedures throughout the course of the study.

I have been informed that I am free to withdraw from the study at any time without penalty.

Concerns about any aspects of the study my be referred to Lindsy Brucker at (608) 781-3795. The thesis chairperson will be Carl Foster, PhD (608) 785-8687. Questions regarding the protection of human subjects may be addressed to Dr. Dan Duquette, Chair, University of Wisconsin-La Crosse Institutional Review Board for the Protection of Human Subjects, (608) 785-8124.

______________________________ Participant	____________________ Date
______________________________ Investigator	____________________ Date

APPENDIX B

REVIEW OF RELATED LITERATURE

REVIEW OF RELATED LITERATURE

Predictors of Performance in Athletes

The process of testing athletes in a laboratory setting to interpret functional capacity and sport specific potential is not a new concept in the field of exercise science. Depending on the type of sport, athletes and their coaches have access to a variety of types of physiological testing that can aid in future performance. The most historically important predictor, maximal oxygen uptake (VO_{2max}) is discussed below. Also highlighted are the concepts of lactate threshold, ventilatory threshold, and anaerobic power and capacity. Understanding VO_{2max} and lactate and ventilatory threshold is necessary for sporting events that rely on aerobic energy production, as in long distance running, cycling, and swimming. Athletes competing in events that are more dependent on anaerobic energy production, such as sprint running, cycling, and speed skating can benefit from understanding anaerobic power and anaerobic capacity. Understanding the concept of pacing and how various pacing strategies can be of benefit in competitive situations is also critical.

Concept of VO_{2max}

In the 1920s, Hill and Lupton [28] were the first to investigate the concept of maximal oxygen uptake (VO_{2max}). They found there is a linear relationship between oxygen intake and workload until VO_{2max} is attained. Hill and Lupton concluded that a plateau in oxygen consumption occurred at maximal effort, thus the cardiovascular and respiratory systems are the limiting factors of further exertion. This plateau theory is the most widely accepted standard for the achievement of VO_{2max} during a graded exercise test (24).

Determining VO_{2max} of runners and swimmers also dates back to the 1920s when studies were first established [27,38]. These studies found that increases in running and swimming speed correlated to increases in oxygen uptake. These, as well as the work of subsequent researchers (Astrand, 1952; Robinson, 1937), were the first to identify the important role of VO_{2max} for successful performance in endurance events [1,49]. Another factor that comes into play when determining VO_{2max} includes the size of the muscle group involved. Taylor et al. [59] found that the larger the muscle group that was active (e.g., arms and legs), the larger the VO_{2max}.

Controversy still exists in terms of the exact mechanism that limits VO_{2max}. Noakes has argued that the limiting factor is not the standard plateau theory, proposed by Hill and Lupton, but an alternate skeletal muscle contraction theory that states: "skeletal muscle contractile function is regulated by a hierarchy of controls specifically to prevent damage to any of a number of different organs" [44]. This topic has been hotly debated [5,45]. Hill and Lupton's theory remains the standard used today but further research is needed to fully understand the limiting factors of VO_{2max}. Whereas predicting endurance performance through VO_{2max} testing is widely used and accepted, lactate and ventilatory threshold are also related to the ability to perform prolonged exercise [19,24].

Anaerobic Threshold

The realization that blood lactate concentration increases disproportionately during graded exercise dates back to the 1930s [3]. Around this time it was also found that at about the same workload that blood lactate began to accumulate, there was an abrupt increase in ventilation at the same workload [18]. The concept of anaerobic metabolism during exercise began with Hill [28], hypothesizing that increases in blood lactate were due to a lack of oxygen delivery to the working muscles.

Bang [3] pointed out that there was a metabolic phase when the exercising person would begin to accumulate lactate in the muscle and blood as the exercise proceeded. The work rate at this "breaking point" is named anaerobic threshold [62] or onset of blood lactate accumulation (OBLA) [35]. Skinner and McLellan [54] and Kinderman [35] noted that in several laboratories incremental exercise testing has been standardized with the aim of finding the exercise or oxygen uptake rate at which the blood lactate concentration reaches a value between 2.5 and 4 mM. Further investigation concerning this concept is continually being carried out since it is difficult to define a single point for the anaerobic threshold [24]. Wasserman and McIlroy [62] and Hollmann [30] each described the concept of anaerobic threshold and the notion of noninvasive measurement using respiratory metabolism. The gas exchange anaerobic threshold (AT) was defined as the intensity of exercise associated with the first nonlinear increase in minute ventilation (VE) and volume of expired CO_2 (VCO_2) relative to oxygen uptake (VO_2) [12,41]. A high correlation has been observed between these variations in gas exchange and an initial increase in plasma lactate above resting values [10,63,65]. The concept of the anaerobic threshold has been a point of argument since at least the early 1980s [7, 13]. The point at which a nonlinear increase in ventilation occurs and an increase in lactate accumulation takes place may not necessarily be at the same work rate [8,17].

Consideration must also be placed on the fact that individuals vary in the maximum lactate level that can be tolerated during prolonged exercise [56]. Alternative ideas state that the amount of lactate accumulation can be attributed to inconsistencies in the rate of lactate production and removal, regardless of whether or not lactate production is related to anaerobic conditions in the muscle [17]. Terms such as aerobic threshold [36], ventilation threshold [54], and lactate threshold [33] have become apparent in the literature. Regardless of the debate over the causes of lactate accumulation and exertional hyperpnea, a general concept remains clear that the buffering of lactate by bicarbonate leads to an increased need to ventilate to maintain $PaCO_2$ within normal limits [24].

While the term anaerobic threshold is controversial, there are still practical reasons for its measurement. Increases in VO_{2max} in athletes that undergo extensive training are minor [9,20]. Yet the percent of VO_{2max} that can be sustained for extended periods of exercise, the conceptual equivalent to anaerobic threshold, increases with training far beyond the point where VO_{2max} fails to increase [11,14,25,29,31,32,34,39,47, 48,51,53,57,58]. Also, anaerobic threshold provides important information about the athlete's aerobic potential, and about the effect of training [13]. In both absolute terms and expressed as a percentage of VO_{2max}, the anaerobic threshold is high in the endurance trained athlete [13]. For example, in sedentary individuals, the AT occurs at ~50-60% of VO_{2max} [58,24], while AT occurs at ~70-80% of VO_{2max} in the endurance-trained [59].

Anaerobic Power and Capacity

While VO_{2max} has been well defined by the classic plateau of oxygen uptake [28], the measurement of anaerobic work using a single test has been less well defined. Many athletic events involve short bursts of intense muscular activity. There is a lag in the onset of the oxygen transport system during the beginning of exercise, and the result of this lag during the first few minutes of exercise is a large amount of muscular work that is completed anaerobically. Accordingly, improving one's anaerobic energy expenditure is necessary for improving performance. Unfortunately, in most events, one cannot estimate the total energy demand with sufficient precision in maximal or near maximal situations. Therefore anaerobic power and capacity are difficult to determine.

Measurement of Anaerobic Power and Capacity

In situations where aerobic energy expenditure is understood to contribute very little, measuring the rate and quantity of work has been ideal in determining anaerobic power and capacity [24]. Margaria, Aghemo, and Rovelli's development of the stair-climbing test [40] marked the beginning of evaluation of peak power production. It has been shown that peak power output can range from a mere 700 Watts (W) in untrained females to as much as 1500 W in some well trained male athletes [24]. The most widely used anaerobic power test continues to be the Wingate cycle ergometer test [4], which is usually executed on a mechanically braked cycle ergometer (Monarch) with a 30 s sprint bout. Astrand [2] describes the Wingate as consisting of exhaustive cycling exercise against a resistance related to the subject's body weight. The subject performs as many revolutions as possible in 30-s. The number of flywheel revolutions is recorded at 5-s intervals. The peak mechanical power and the decline in this power from the peak down to the last 5-s period are also calculated. Normative data are available in Bouchard et al. [6]. Former studies have shown that a 30-s test does not exhaust the anaerobic capacity [60], and does not consider the significant aerobic contribution, making the Wingate test an inappropriate anaerobic capacity test. Other research has found that an anaerobic capacity test should last 2-3 min and be exhausting [6]. Foster et al. [24] argues that performance-based tests involve large reductions in power output due to high rates of muscular power generation and, outside a laboratory setting, individuals are unlikely to ever work at their absolute highest energy expenditure rate for more than about 5-s. Further argued are real-world situations involve some aspect of pacing intended to minimize the time necessary to complete a task [24]. Thus even though performance-based tests of anaerobic power and capacity may be useful in determining peak rates and quantities of muscular work achieved during short periods of time, they may not verify the degree of anaerobic metabolism alone [24].

Accumulated O_2 Deficit

Krogh and Lindhard [37] first introduced the concept of oxygen deficit, defining it as the difference between the actual oxygen uptake consumed during exercise and the total that would have been consumed had a steady state of aerobic energy expenditure been reached instantaneously. Gastin [26] further explains the energy provided during the deficit phase of exercise represents predominantly non-aerobic energy and is a result of the immediate phosphagen stores plus anaerobic energy from glycolysis. The methods used to quantify oxygen deficit during exhaustive bicycling derived from Karlsson and

Saltin [34] in the 1970s have been re-evaluated and procedures have been formulated to measure anaerobic capacity from accumulated O_2 deficit during exhaustive treadmill exercise. Medbo and his colleagues' work in this area have attracted new awareness in this focus of exercise science. Medbo et al. [42] explains that the amount of the accumulated O_2 deficit is largest during exhaustive bouts of exercise of 2 to 5 minutes duration. They also found that the accumulated O_2 deficit is larger in sprint-trained athletes versus endurance-trained or untrained individuals, is larger in males versus females, and increases with training. Medbo et al. concluded that the accumulated O_2 deficit might be a precise indirect measure of the anaerobic energy released during running and bicycling. The measurement of anaerobic power and capacity continues to be a complex area and further investigation is important.

Pacing Strategy

In many athletic competitions that are completed in a few minutes or less, such as speed skating, sprint cycling, and some track events, the difference between a medal winner and last place can be slight. In the field of exercise science, factors that affect an athlete's performance such as training effects, nutrition, and equipment adaptations have been continually highlighted in the literature. Yet very little consideration has been directed towards an athlete's pacing strategy throughout an event. Yet in the types of intense activities mentioned above, it makes sense that determining the most effective way to utilize energy sources would be of great value.

Robinson et al. [50] collected the first data on the effects of pacing variations on performance in 1958. They concluded that higher VO_2 requirements, higher blood lactate levels, and greater perceived exertion were observed with a strategy that had a fast start versus a slower start or an even paced race. Robinson suggested that a middle distance event was best performed by delaying the greatest effort until the latest possible time. Staab et al. [55] investigated trained runners during a 30-min self-paced treadmill run. The treadmill grade included segments of inclines and declines either early or late in the run. Results in this particular study revealed that an uneven distribution of effort results in a reduced peak performance capacity, correlating with greater physiological demand. In sprinting events of short duration, performance depends not only on the mean external power output and the frictional losses but also on the distribution of anaerobic energy over the race [55].

The purpose of the most current studies relate to how athletes should distribute their energy over races of short duration in order to minimize the time necessary to cover the distances [16,21,22,23]. Foster [21], Schabort [52], and Palmer [46] have researched the technique of simulating competition by having subjects perform time trials on a racing bicycle in the laboratory. They have found athletes felt their behaviors were similar to those encountered during competition [21,23]. These types of simulations have made it practical to assess the effect of distribution of power on athletic performance.

De Konig et al. [15] have formulated a quantitative model involving the observed power output potential of athletes and the recognized resistance factors. The model relies on assumptions about how the anaerobic capacity is expended and upon the idea that velocity at the end of an event is largely wasted kinetic energy. It has been shown that in predicting performances in cycling at distances between 1000 and 4000m, the model has been reasonably successful [16]. Yet the risk of decelerating quickly as a result of both power output and loss of technique secondary to fatigue holds the possibility for losing essential time and competitive ranking.

An "all out" version of the model mentioned above is characterized by the anaerobic capacity being quickly expended while a considerable deceleration occurs towards the end of the event. This type of strategy requires the athlete to exert maximal effort during the full duration of the test. This "all out" strategy has predicted faster 500 and 1000m skating and 1000m cycling times, agreeing with observations during competition [22]. An explosive start is significant in that minimization of the time necessary to cover a distance heavily relies on the reduction of the acceleration phase during the start [61]. For example, a study by van Ingen Schenau et al. [61] found that due to the stronger initial increase of the faster sprinter, less time is lost to cover the first 500 meters of a distance. Considering the increased rate of anaerobic energy release during a short distance event, the faster starter is able to generate a higher amount of anaerobic energy than a competitor with a slower start. Secondly, there is a smaller amount of kinetic energy at the end of the race that is essentially "wasted" versus an evenly paced strategy. Using an all out strategy versus even pacing has been shown to be beneficial in races up to 90-s [15]. Yet Wilberg et al. [64] suggests athletes optimal pacing strategy is many times individually determined for races lasting 60-90-s.

Conversely, an even pacing strategy involves distributing accessible energy in a certain way such that a constant velocity can be maintained throughout the race. Van Ingen Schenau et al. [61] believes that even pacing strategies should only be implemented in events lasting longer than 80 to 100 seconds. It is known that a generally even pace after the acceleration phase leads to the fastest time in events lasting more that roughly around 2 minutes [61]. This concept of even pacing during longer races being the most beneficial was first hypothesized in the early 1970s by Morehouse and Miller [43].

Summary

For many decades, extensive information has been available to athletes on laboratory exercise tests that can aid in predicting aerobic function and performance. The measurement of maximal oxygen consumption (VO_{2max}) and lactate and ventilitory threshold are standard methods that are widely used in both athletic and clinical settings. Yet deciphering the optimal way of measuring the anaerobic portion of an individual's energy expenditure is a topic that still remains unclear. Countless investigators have varied opinions on what is the superior test in predicting performance, but there has not yet been a final consensus. In athletic events that are very short in duration, generating great amounts of anaerobic power become essential. The difference between going to the finals in an event and finishing the season early can be mere milliseconds, especially when a competitor is racing against the clock. The exercise and sports science field has spent considerable amounts of effort focusing on the external factors that come into play when trying to enhance performance. Factors such as dietary influences, exercise testing, and training modifications are all important to both athletes and their coaches. Yet considerations of athlete's internal behavior, and attempts to simulate competitive events in the laboratory have had considerably less attention. Athletes such as sprint cyclists and speed skaters are known to utilize different pacing strategies. And researching these pacing techniques can ultimately guide the athlete in determining how to finish an event in the least amount of time.

REFERENCES

[1] Astrand PO. Experimental studies of physical work capacity in relation to sex and age. Munksgaard: Copenhagen, 1952

[2] Astrand PO, Rodahl K (eds). Textbook of Work Physiology. New York: McGraw-Hill, 1986

[3] Bang O. The lactate content of the blood during and after muscular exercise in man. Scand Arch Physiol 1936; 10: 51-82

[4] Bar-Or. The Wingate anaerobic test: an update on methodology, reliability, and validity. Sports Med 1987; 4: 381-394

[5] Bassett DR, Howley, ET. Maximal O_2 uptake: “classical” versus “contemporary” viewpoints. Med Sci Sports Exer 1997; 29: 591-603

[6] Bouchard C, Taylor, AW, Simoneau JA, Dulac S. Testing anaerobic power and capacity. In: MacDougal JD, Wenger HA, Green HJ (eds). Physiological testing of the high performance athlete. Champaign, Il: Human Kinetics, 1991: 175-221

[7] Brooks GA. Anaerobic threshold: Review of the concept and directions for future research. Med Sci SPorts Exer 1985; 17: 22-31

[8] Chirtel SJ, Barbee RW, Stainsby WN. Net O_2, CO_2, lactate, and acid exchange by muscle during progressive working concentrations. J Appl Physiol 1984; 56: 161-165

[9] Daniels JT, Yarbough RA, Foster C. Changes in VO_2 max and running performance with training. Eur Appl Physiol 1978; 39: 249-254

[10] Davis JA, Vodak P, Wilmore, JH, Vodak J, Kutz P. Anaerobic threshold and maximal aerobic power for three modes of exercise. J Appl Physiol 1976; 41: 544-550

[11] Davis JA, Frank MH, Whipp BJ, Wasserman K. Anaerobic threshold alterations caused by endurance training in middle aged men. J Appl Physiol 1979; 46: 1039-1046

[12] Davis JA, Whipp BJ, Wasserman K. The relation of ventilation to metabolic rate during moderate exercise in man. Eur J Appl Physiol 1980; 44: 97-108

[13] Davis JA, Anaerobic threshold: review of the concept and directions for future research. Med Sci Sports Exer 1985; 17: 22-31

[14] Denis C, Fouquet R, Poty P, Geyssant A, Lacour JR. Effect of 40 weeks of endurance training on the anaerobic threshold. Int J Sports Med 1982; 3: 208-214

[15] de Koning JJ. Biomechanical Aspects of Speed Skating. Amsterdam: Free University of Amsterdam, 1991: 43-58

[16] de Koning JJ, Bobbert, MF, Foster C. Determination of optimal pacing strategy in track cycling with an energy model flow. J Sci Med Sport 1999; 2(3): 266-277

[17] Donovan CM, Brooks GA. Endurance training affects lactate clearance, not lactate production. Am J Physiol 1983; 244: E83-E92

[18] Douglas CG. Coordination of the respiration and circulation with variation in bodily activity. Lancet 1927; 213: 213-218

[19] Farrell PA, Wilmore JH, Coyle EF, Billings JE, Costill DL. Plasma lactate accumulation and distance running performance. Med Sci Sport 1979; 11: 338-344

[20] Foster C, Pollock ML, Farrell PA, Maksud MG, Anholm JD, Hare J. Training responses of speed skaters during a competitive season. Res Q Exer Sport 1982; 53: 243-246

[21] Foster C, Green MA, Snyder AC, Thompson NN. Physiological responses during simulated competition. Med Sci Sports Exer 1993; 25: 877-882

[22] Foster C, Snyder AC, Thompson NN, Green MA, Foley M. Effect of pacing strategy on cycle time trial performance. Med Sci Sports Exer 1993; 25: 383-388

[23] Foster C, Schrager M, Snyder AC, Thompson NN. Pacing strategy and athletic performance. Sports Med 1994; 17(2): 77-85

[24] Foster C, Hector LL, McDonald KS, Snyder AC. Measurement of anaerobic power and capacity. In: Maud PJ, Foster C (eds). Physiological Assessment of Human Fitness. Champaign, Il: Human Kinetics, 1995: 73-85

[25] Gaesser, GA, Poole DC, Gardner BP. Disassociation between VO_2max and ventilatory threshold responses to endurance training. Eur J Appl Physiol 1984; 53: 242-247

[26] Gastin PB. Quantification of anaerobic capacity. Scand J Med Sci Sports 1994; 4: 91-112

[27] Herbst R. Der gastoffweschel als mab der kopperlichen leistungs fahigkeit. Deut Arch Klun Med 1928; 162: 33-50

[28] Hill AV, Lupton H. Muscular exercise, lactic acid and the supply and utilization of oxygen. Q J Med 1923; 16: 135-171

[29] Hollman W, Rost R, Liesen H, Dufaux B, Heck H, Mader A. Assessment of different forms of physical activity with respect to preventative and rehabilitative cardiology. Int J Sports Med 1981; 2: 67-80

[30] Hollman W. Historical remarks on the development of the aerobic-anaerobic threshold up to 1966. Int J Sports Med 1985; 6: 109-116

[31] Hurley BF, Hagberg JM, Allen WK, Seals DR, Young JC, Cuddihee RW, Holloszy JO. Effect of training on blood lactate levels during submaximal exercise. J Appl Physiol 1984; 56: 1260-1264

[32] Jacobs I. Lactate, muscle glycogen and exercise performance in man. Acta Physiol Scand 1981; Suppl 495: 1-35

[33] Jones NL, Ehrsam RE. The anaerobic threshold. Exer Sport Sci Rev 1982; 10: 49-83

[34] Karlsson J, Nordesjo LO, Jorfeldt L, Saltin B. Muscle lactate, ATP and CP levels during exercise after physical training in man. J Appl Physiol 1972; 33: 199-203

[35] Kindermann W, Simon G, Keul J. The significance of the aerobic-anaerobic transition for the the determination of work load intensities during endurance training. Eur J Appl Physiol 1979; 42: 25-34

[36] Karlsson J, Jacobs I. Onset of blood lactate accumulation during muscular exercise as a theoretical concept: theoretical considerations. Int J Sports Med 1982; 3: 190-201

[37] Krogh A, Lindhard J. The regulation of respiration and circulation during the initial stages of muscular work. J Physiol 1913; 47: 112-136

[38] Liljestrand G, Stensrom N. Studien uber die physiologie des schwimmens. Skan Arch Physiol 1920; 39: 1-63

[39] MacRae HSH, Dennis SC, Bosch AN, Noakes TD. Effects of training on lactate production and removal during progressive exercise in humans. J Appl Physiol 1992; 72: 1649-1656

[40] Margaria R, Aghemo P, Rovelli E. Measurement of muscular power (anaerobic) in man. J Appl Physiol 1966; 21: 1662-1664

[41] McLellan TM. Ventilatory and plasma lactate response with different exercise protocols: a comparison of methods. Int J Sports Med 1AC985; 6: 30-35

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

[43] Morehouse LE, Miller AT. Physiology of Exercise. In: Morehouse LE, Miller AT (eds). St. Louis: CV Mosby Co, 1971

[44] Noakes TD. Challenging beliefs: ex Africa semper aliquid novi. Med Sci Sports Exer 1997; 29: 571-590

[45] Noakes TD. Maximal O_2 uptake: "classical" versus "contemporary" viewpoints: a rebuttal. Med Sci Sports Exer 1998; 30: 1381-1398

[46] Palmer GS, Burger S. Effect of training on the anaerobic capacity. Med Sci Sports Exer 1997; 25: 684-687

[47] Poole DC, Gaesser GA. Response of ventilatory and lactate thresholds to continuous and interval training. J Appl Physiol 1985; 58: 1115-1121

[48] Poole DC, Ward SA, Whipp BJ. The effects of training on the metabolic and respiratory profile of high-intensity cycle ergometer exercise. Eur J Appl Physiol 1990; 59: 421-429

[49] Robinson S, Edwards HT, Dill DB. New records in human power. Science 1937; 85: 409-410

[50] Robinson S, Robinson DL, Mountjoy RJ, Bullard RW. Influence of fatigue on the efficiency of men during exhausting runs. J Appl Physiol 1958; 12: 197-201

[51] Saltin B, Hartley LH, Kilbom A, Astrand I. Physical training in sedentary middle aged and older men II: Oxygen uptake, heart rate and blood lactate concentration at submaximal and maximal exercise. Scand J Clin Lab Invest 1969; 24: 323-334

[52] Schabort EJ, Hawley JA, Hopkins WG, Mujika I, Noakes TD. A new reliable laboratory test of endurance performance for road cyclists. Med Sci Sports Exer 1998; 25: 684-687

[53] Sjodin B, Jacobs I, Svedenhag J. Changes in onset of blood lactate accumulation (OBLA) and muscle enzymes after training at OBLA. Eur J Appl Physiol 1982; 49: 45-57

[54] Skinner JS, McLellan TM. The transition from aerobic to anaerobic metabolism. Res Q Exer Sport 1980; 51: 234-248

[55] Staab JS, Agnew JW, Siconolfi SF. Metabolic and performance response to uphill and downhill running in distance runners. Med Sci Sports Exer 1992; 24: 124-127

[56] Stegmann H, Kindermann W. Comparison of prolonged exercise tests at the individual anaerobic threshold and the fixed anaerobic threshold of 4 mmol/L lactate. Int J Sports Med 1982; 3: 105-110

[57] Svedenhag J, Sjodin B. Physiological characteristics of elite male runners in and off season. Can J Sports Med 1985; 10: 127-133

[58] Tanaka K, Watanabe H, Konishi Y, Mitsuzono R, Sumida S, Tanaka S, Fukuda T, Makadomo F. Longitudinal associations between anaerobic threshold and distance running performance. Eur J Appl Physiol 1986; 55: 248 252

[59] Taylor HL, Buskirk LE, Henshel A. Maximal O_2 intake as an objective measure of cardio-respiratory performance. J Appl Physiol 1955; 8: 73-80

[60] Vanderwalle HB, Kapitaniak S, Grun S, Raveneau S, Monod H. Comparison between a 30-s all-out test and a time-work test on a cycle ergometer. Eur J Appl Physiol 1989; 58: 375-381

[61] van Ingen Schenau GJ, de Koning JJ, de Groot G. The distribution of anaerobic energy in 1000 and 4000 metre cycling bouts. Int J Sports Med 1992; 13: 447-451

[62] Wasserman K, McIlroy MB. Detecting the threshold of anaerobic metabolism. Am J Cardiol 1964; 14: 844-852

[63] Wasserman K, Whipp BJ, Koyal SN, Beaver WL. Anaerobic threshold and respiratory gas exchange during exercise. J Appl Physiol 1973; 35: 236-243

[64] Wilberg RB, Pratt J. A survey of the race profiles of cyclists in the pursuit and kilo track events. Can J Sports Sci 1998; 13(4): 208-213

[65] Yoshida T, Nagata A, Muro M, Takeuchi N, Suda Y. The validity of anaerobic threshold determination by a Douglas Bag method compared with arterial blood lactate concentration. Eur J Appl Physiol 1981; 46: 423-430