

Energy system contribution during 200- to 1500-m running in highly trained athletes

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ABSTRACT

SPENCER, M. R., and P. B. GASTIN. Energy system contribution during 200- to 1500-m running in highly trained athletes. *Med. Sci. Sports Exerc.*, Vol. 33, No. 1, 2001, pp. 157–162. **Purpose:** The purpose of the present study was to profile the aerobic and anaerobic energy system contribution during high-speed treadmill exercise that simulated 200-, 400-, 800-, and 1500-m track running events. **Methods:** Twenty highly trained athletes (Australian National Standard) participated in the study, specializing in either the 200-m ($N = 3$), 400-m ($N = 6$), 800-m ($N = 5$), or 1500-m ($N = 6$) event (mean $\dot{V}O_2$ peak [$\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$] \pm SD = 56 ± 2 , 59 ± 1 , 67 ± 1 , and 72 ± 2 , respectively). The relative aerobic and anaerobic energy system contribution was calculated using the accumulated oxygen deficit (AOD) method. **Results:** The relative contribution of the aerobic energy system to the 200-, 400-, 800-, and 1500-m events was 29 ± 4 , 43 ± 1 , 66 ± 2 , and $84 \pm 1\% \pm$ SD, respectively. The size of the AOD increased with event duration during the 200-, 400-, and 800-m events (30.4 ± 2.3 , 41.3 ± 1.0 , and $48.1 \pm 4.5 \text{ mL}\cdot\text{kg}^{-1}$, respectively), but no further increase was seen in the 1500-m event ($47.1 \pm 3.8 \text{ mL}\cdot\text{kg}^{-1}$). The crossover to predominantly aerobic energy system supply occurred between 15 and 30 s for the 400-, 800-, and 1500-m events. **Conclusions:** These results suggest that the relative contribution of the aerobic energy system during track running events is considerable and greater than traditionally thought. **Key Words:** MAXIMAL ACCUMULATED OXYGEN DEFICIT, OXYGEN DEMAND, ANAEROBIC CAPACITY, SUBMAXIMAL, SUPRAMAXIMAL

Specificity of training is perhaps the most significant principle used in athlete preparation. Evaluation of event or sport requirements therefore precedes both training planning and implementation. Energy supply is usually critical such that the relative contribution of the aerobic and anaerobic energy systems becomes an important factor. Little data exist that specifically and accurately evaluate energy system contributions in discrete sporting events. Considerable information can be found that attempts to do so (15,16), but this has generally been based on data originating in the 1970s that inappropriately used oxygen debt to quantify anaerobic energy release.

The use of the accumulated oxygen deficit method popularised by Medbø et al. (21) has enabled a number of researchers to report relative energy system contributions for exhaustive exercise over varying durations (8,22,29). These and other studies employed either all-out exercise over a given time period or constant intensity exercise, usually at a percentage of maximal oxygen uptake, until exhaustion. Few studies have set out to simulate a specific cycling or running event. Most events are staged over set distances, with velocity usually being dependent on individual energetic rates and capacities. Although extrapolations from available data in the literature have appeared (5,6), few direct event analyses exist. Data from these stud-

ies suggest considerably greater aerobic energy system contributions than have previously been presented.

Given the paucity of data relating to energy system contributions to sporting events and the need to reevaluate traditional information presented in the literature, the present study was designed to profile the aerobic and anaerobic energy system response during high-speed treadmill exercise that simulated 200-, 400-, 800-, and 1500-m track running events.

METHODS

Subjects. Four independent subject groups were used for this study. The sample population was restricted to highly trained athletes of the selected running events of 200-m ($N = 3$), 400-m ($N = 6$), 800-m ($N = 5$) and 1500-m ($N = 6$). The athletes who participated in the study were all male and competed at a state, national, and in some cases international level (Table 1). The personal best times of the athletes suggested they were of good to high quality. Five of the 20 subjects had represented Australia at either junior or open international competition. All athletes were tested either during or immediately after completion of the competition phase of their yearly program; most cases being post Australian National Championships. Before participation, subjects were given a written explanation of the time commitments and testing procedures involved in the study. The University of Ballarat Experimentation Ethics Committee cleared all testing procedures, and subjects were given both written and verbal explanations before signing a declaration of informed consent.

0195-9131/01/3301-0157/\$3.00/0

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Received for publication January 2000.

Accepted for publication May 2000.

TABLE 1. Descriptive characteristics of the subjects.

	Age (yr)	Weight (kg)	Peak O ₂ Uptake (mL·kg ⁻¹ ·min ⁻¹)	Personal Best Time (min:s)
200 m (<i>N</i> = 3)				
Mean ± SD	19 ± 4	76 ± 4	56 ± 3	21.29 ± 0.08
Range	17–22	70–80	54–61	21.19–21.39
400 m (<i>N</i> = 6)				
Mean ± SD	23 ± 3	74 ± 9	59 ± 3	47.58 ± 1.51
Range	18–27	65–91	55–62	45.70–49.50
800 m (<i>N</i> = 5)				
Mean ± SD	21 ± 3	64 ± 5	67 ± 2	1:50 ± 0:02
Range	19–26	56–67	64–72	1:48–1:53
1500 m (<i>N</i> = 6)				
Mean ± SD	24 ± 3	66 ± 5	72 ± 4	3:46 ± 0:05
Range	21–27	57–71	64–75	3:39–3:52

Experimental overview. All subjects attended two sessions at the Human Performance Laboratory at the University of Ballarat, separated by 4–7 d. To minimize any effects of diurnal variation, the two testing sessions for each athlete were conducted within 2 h of the same time of day. Pretest preparation included the absence of strenuous exercise and the consumption of caffeine and alcohol. All subjects documented their dietary intake for the 24 h preceding the first testing session and were instructed to replicate this in the preparation for their second testing session. The subjects reported to the laboratory in a 3-h fasted state and were free to consume fluids before testing. A custom built Austradex Hercules Mark II (Melbourne, Australia) treadmill was used during the study. Due to the high treadmill velocities required to simulate 200- to 1500-m running, a harness body support system was used as a precautionary safety measure. Expired gases were analyzed during all tests using an automated on-line metabolic analysis system (Sensor Medics V_{max} 29 series, Yorba Linda, CA), in the breath by breath mode. The Sensor Medics Paramagnetic O₂ Analyzer (accuracy ± 0.02% O₂; response time < 130 ms) and NonDispersive Infrared CO₂ analyzer (accuracy ± 0.02% CO₂; response time < 130 ms) were calibrated before and after each test by using two precision reference gases of known concentrations. Pulmonary ventilation was measured using a Sensor Medics Mass Flow Sensor and was calibrated before and after each test with a standard 3-L syringe.

Submaximal oxygen uptake and $\dot{V}O_2$ peak determination. The first testing session involved a series of submaximal discontinuous treadmill runs (*N* = 5–6) that were of 6-min duration. Steady state $\dot{V}O_2$ was determined by averaging the $\dot{V}O_2$ during the last 2 min of each submaximal run. The relative intensity of the treadmill runs ranged between 48 ± 7% and 85 ± 10% $\dot{V}O_2$ peak and was separated by rest periods increasing progressively from 5 to 9 min. The linear relationship between steady state $\dot{V}O_2$ and treadmill velocity was extrapolated and used to estimate energy demand, or O₂ cost, during supramaximal treadmill exercise. Based on the findings of Jones and Doust (13), a treadmill gradient of 1% was used to reflect the energy cost of outdoor running. After approximately 20-min rest, $\dot{V}O_2$ peak was determined via a progressive incremental protocol that involved increasing treadmill velocity 1 km·h⁻¹·min⁻¹ for 6 min, followed by increasing treadmill gradient 2%·min⁻¹ until volitional exhaustion. Final treadmill veloc-

ities and gradients varied between the four groups, ranging from 16 km·h⁻¹ and 2% for the 200-m group (initially 10 km·h⁻¹ and zero gradient) to 20 km·h⁻¹ and 8% for the 1500-m group (initially 14 km·h⁻¹ and zero gradient).

Supramaximal test. The second testing session involved one specific event simulation on the treadmill (either 200, 400, 800, or 1500 m). Before the event simulation, athletes completed their typical prerace warm-up in an attempt to simulate competition conditions. Individual times for the specific event simulation were based on race times in the previous 1–3 wk. Athletes stepped on to a moving treadmill, with the required velocity being achieved within a few seconds of the commencement of the trial. Changes in running velocity (i.e., rate of acceleration and deceleration) during the race simulations were individualized, due to different race strategies preferred by the athletes. Individualization of running velocity changes, despite being relatively minor, was of greater importance during the longer distances of 800 and 1500 m. As the 800- and 1500-m events are run at an intensity that is relatively less than the 200- and 400-m events, the variation in preferred race strategies appears to be greater. For example, 800- and 1500-m athletes from an endurance training background usually prefer to run an even paced race, whereas athletes from a speed training background usually prefer to run a slower initial pace then exploit their speed during the final 400 m. Although the differences in energy system contribution during varying race strategies for the selected running events have not been specifically investigated, no differences in maximal accumulated oxygen deficit (AOD) have been reported during exhaustive constant intensity and all-out cycle exercise (8).

Calculations. The AOD was defined as the difference between the estimated O₂ cost of the supramaximal treadmill run and the actual $\dot{V}O_2$ (21). The O₂ cost of the supramaximal treadmill runs were calculated using the mean running velocity for each subject. Before the commencement of the present study, reliability data for AOD estimation were collected using the same methodological procedures on a group of physically active male subjects (*N* = 7). Five subjects completed a 400-m exhaustive run, with one subject each completing an 800- and 1500-m. The calculated technical error of measurement of the AOD was 6.1%. Relative aerobic and anaerobic energy system contribution was calculated directly from the re-

TABLE 2. Oxygen deficit, aerobic metabolism, and other calculated variables of the 200-, 400-, 800-, and 1500-m simulated running events.

	200 m	400 m	800 m	1500 m
Exercise intensity (% $\dot{V}O_2$ peak)	201 ± 3 ^{abc}	151 ± 4 ^{de}	113 ± 9 ^f	103 ± 6
Duration (min:s)	22.3 ± 0.2 ^{abc}	49.3 ± 0.2 ^{de}	1:53 ± 0:02 ^f	3:55 ± 0:03
Accumulated oxygen deficit (mL·kg ⁻¹)	30.4 ± 3.2 ^{abc}	41.3 ± 2.3 ^{de}	48.8 ± 10.1	47.1 ± 9.2
Aerobic metabolism (%)	29 ± 5 ^{abc}	43 ± 2 ^{de}	66 ± 4 ^f	84 ± 3
Aerobic energy release first 20 s (mL·kg ⁻¹)	12.9 ± 2.0 ^{ab}	9.5 ± 1.2 ^e	10.0 ± 1.6 ^f	14.6 ± 2.4
Anaerobic energy release first 20 s (mL·kg ⁻¹)	24.6 ± 3.6 ^{abc}	20.2 ± 1.6 ^{de}	15.3 ± 3.6 ^e	10.1 ± 1.7
Regression line slope* (mL·kg ⁻¹ ·min ⁻¹)	0.349 ± 0.014 ^{ab}	0.294 ± 0.013 ^e	0.303 ± 0.013 ^f	0.344 ± 0.022
% $\dot{V}O_2$ peak obtained (%)	70 ± 8 ^{abc}	89 ± 1 ^e	88 ± 2 ^f	94 ± 2

Values are mean ± SD.

Large effect size between groups (ES > 0.8); ^a 200 m vs 400 m; ^b 200 m vs 800 m; ^c 200 m vs 1500 m; ^d 400 m vs 800 m; ^e 400 m vs 1500 m; ^f 800 m vs 1500 m.

search data, although no correction was made for the contribution of stored $\dot{V}O_2$. Individual running economy was established using linear regression from the relationship between steady state $\dot{V}O_2$ and treadmill speed during five to six submaximal treadmill runs (Delta Graph 3.5, Delta Point, CA). Data obtained during supramaximal treadmill running (i.e., event simulation) were averaged over 10-s time intervals and the O_2 deficit was accumulated with time.

Statistics. Group comparisons were investigated via the effect size, which is a method of comparing treatment effects, independent of sample size. Cohen (2) suggested the most meaningful analyses for comparing data obtained from small, uneven groups may be via effect size calculations, as the use of standard ANOVA procedures may increase the chance of producing type 1 statistical errors. Cohen (2) indicated that effect size values of <0.2 represent small differences, approximately 0.5 represent moderate differences, and 0.8 and above represent large treatment differences. The effect size formula is listed below:

$$\text{Effect size} = [(m G1 - m G2)] / \sqrt{((SD^2 G1)(n - 1 G1) + (SD^2 G2)(n - 1 G2)) / (n G1 + n G2 - 2)}$$

where G1 = group one, m = group mean, SD = standard deviation, N = group subject size.

In relation to the present study, group differences were acknowledged if a large effect size was reported (effect size ≥ 0.8). Data are reported as mean ± SD.

RESULTS

The contribution of aerobic metabolism increased with event duration, as differences were evident between all events (Table 2). The total relative contribution of the aerobic energy system for the 200-, 400-, 800-, and 1500-m events were 29, 43, 66, and 84%, respectively. It is evident that the aerobic energy system responds quickly to the demands of all four events (Fig. 1), with the crossover to predominantly aerobic energy supply occurring between 15 and 30 s for the 400-, 800-, and 1500-m groups.

Figure 2 depicts the aerobic and anaerobic energy system contributions to each of the simulated sprint and middle distance running events. The 1500 m is characterized by the oxygen uptake reaching a high % $\dot{V}O_2$ peak (94%) and an early crossover to predominantly aerobic energy supply

(Fig. 1). Although the % $\dot{V}O_2$ peak reached in the 200 m (70%) is considerably less than in the other groups, the rate of aerobic energy release in the initial 20 s of exercise is similar to 1500 m and greater than both 400 and 800 m (Table 2).

The exercise intensity (% $\dot{V}O_2$ peak) was significantly different between all four running events and was inversely related to event duration (Table 2). The total O_2 cost (mL·kg⁻¹) increased with event distance. The majority of this increased O_2 cost was supplied by the aerobic energy system (Fig. 3). The size of the AOD increased with event duration except for the comparison between the 800- and 1500-m trials (Table 2; effect size = 0.29). Therefore, the

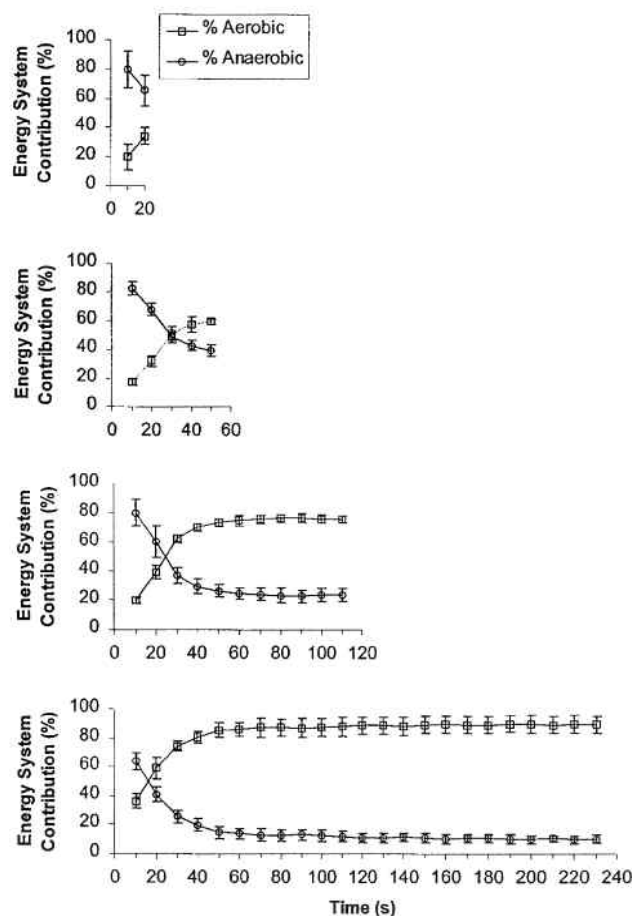


FIGURE 1—Energy system contribution in 10-s time intervals for the 200, 400, 800, and 1500 m. Data are mean values ± SD.

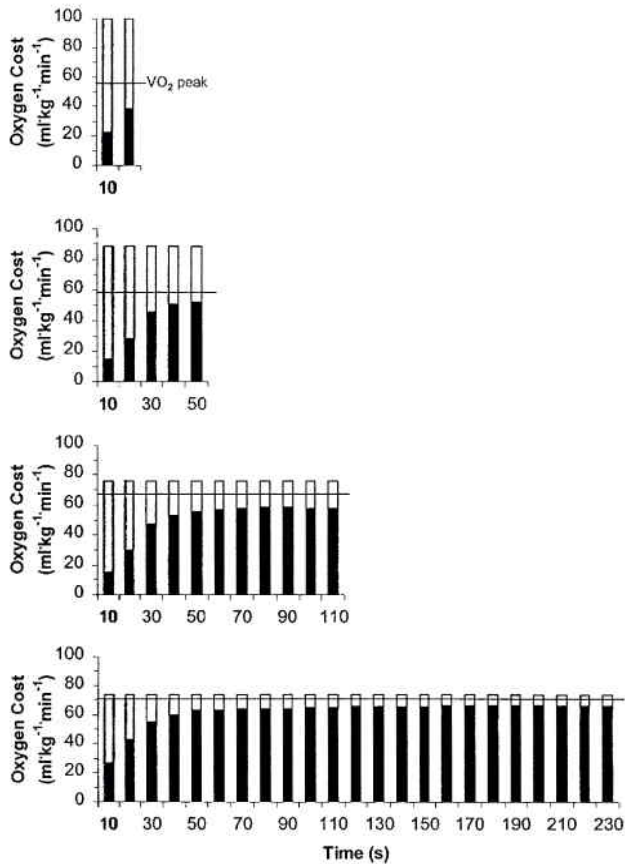


FIGURE 2—Oxygen deficit and oxygen uptake in 10-s time intervals for the 200, 400, 800, and 1500 m. Data are mean values.

difference in event duration between the 800 m (112.8 s) and 1500 m (234.5 s) had no influence on the total anaerobic energy release.

The initial measurements of O_2 uptake and calculated O_2 deficit in 10-s time intervals, for the first 20–30 s of each event, are presented in Fig. 4. The calculated O_2 deficits were different between all four events at each time interval. In contrast, the rate of O_2 uptake was not directly related to event intensity. The 400-m and 800-m events showed similar rates of O_2 uptake. Both the 200 m and 1500 m had greater rates of O_2 uptake than the 400 m and 800 m. No differences were observed in the rate of O_2 uptake between the 200-m and 1500-m events at either the 10- or 20-s time points, although moderate effect size were found (0.72 and 0.79, respectively).

DISCUSSION

The principal finding of this research was that the aerobic energy system contributes significantly to the energy supply during long sprint and middle distance running. The study was unique in that event distances were simulated on the treadmill, as opposed to a run to exhaustion at a speed approximating average velocity during a specific event. The relative aerobic and anaerobic energy system contributions of the four simulated running events compared favorably to

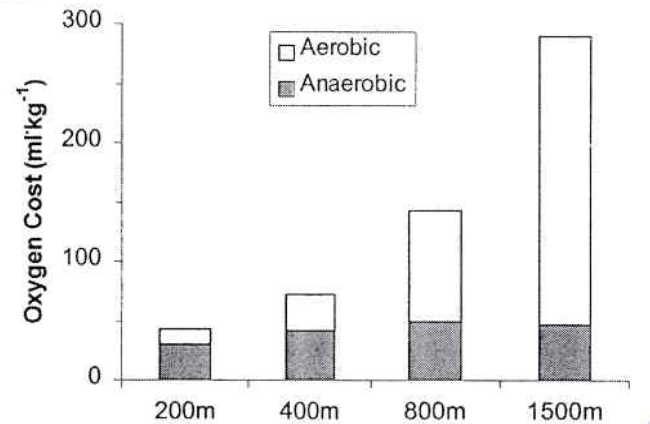


FIGURE 3—Aerobic and anaerobic contribution to the total oxygen cost of the 200-, 400-, 800-, and 1500-m runs. Data are mean values.

recent research conducted over similar time periods, during running and cycle exercise that were also exhaustive in nature. The mean aerobic contribution for the 200-m trials, which was 22 s in duration, was 29%. This is similar to the 28–40% that has been calculated during 30 s of exhaustive cycling (17,22,29). The 400-m trials, which had a mean duration of 49 s, produced an aerobic contribution of 43%. These data are comparable to the 37–44% (sprint trained) and 46–50% (endurance trained) aerobic contribution seen

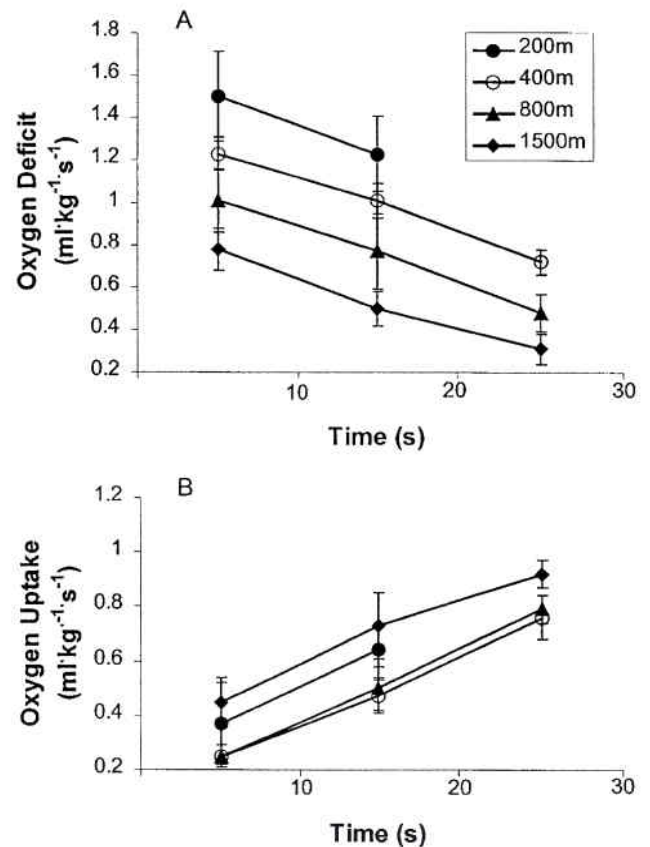


FIGURE 4— O_2 deficit (A) and O_2 uptake (B) during the initial 30 s of exercise for the 200, 400, 800, and 1500 m. Data are mean values \pm SD and are presented in 10-s time intervals.

in 49–57 s of exhaustive treadmill running (18,24) and the 40% aerobic contribution observed during 45 s of maximal cycling (29). An aerobic contribution of 66% was determined for the 800-m simulation in the present study, with a mean duration of 113 s. These data are similar to the 58–69% reported during 116–120 s of running using subelite athletes (4,11,27). The 1500-m simulation, which was 236 s in duration, realized an aerobic contribution of 84%. These data are comparable to the 75–83% aerobic contribution reported for subelite 1500-m runners (11,27).

The AODs calculated in the present study increased in relation to increasing distance and duration of the 200-, 400-, and 800-m events, but no further increase was found for the 1500-m trials. These data support previous research which suggests the AOD is not maximal (i.e., anaerobic capacity is not attained) until a constant intensity supramaximal exercise bout of approximately 120-s duration is completed (21). Therefore, the mean duration of the 1500-m and possibly the 800-m events (234 and 112 s, respectively) were sufficient to obtain a maximal AOD. The data would suggest that the 800-m and 1500-m athletes have similar anaerobic capacities, although the possibility that the 800-m athletes failed to obtain a maximal AOD cannot be excluded as exercise duration is slightly less than the 2 min often recommended for exhausting the anaerobic capacity (21). The calculated AODs of the middle distance athletes in the present study are similar to those reported elsewhere (26–28). Weyand et al. (28), using similar testing procedures, reported very similar AODs for a group of distance runners (AOD = 46.8 mL·kg⁻¹, $\dot{V}O_2$ peak = 70.9 mL·kg⁻¹·min⁻¹) that were comparable to the 1500-m group of the present study (AOD = 47.1 mL·kg⁻¹, $\dot{V}O_2$ peak = 71.6 mL·kg⁻¹·min⁻¹). Larger AODs have been reported in the literature for sprint and middle distance runners (20,25). Differences in results are most likely attributable to variations in treadmill gradient, as Olesen (25) has demonstrated significantly different AODs at gradients of 1% (59.9 mL·kg⁻¹·O₂ equivalents), 15% (78.3), and 20% (99.8) for a group of anaerobically trained subjects.

Data from the present study and those cited in the previous paragraph were all obtained using variations of the AOD methodology developed by Medbø et al. (21). Earlier investigations that employed methodology that did not calculate individual $\dot{V}O_2$ -velocity/power relationships (12,14) appear to overestimate the anaerobic energy system's contribution. Unfortunately, the findings from these studies, in which the validity of their methodologies has been questioned (7,21), have formed the basis for summary material presented in the education and coaching literature from the early 1970s (15) to the mid 1990s (16). The fact that several of the world's elite 800-m running coaches have vastly different perceptions on the relative aerobic energy system contribution in their event (35–65%) indicates the level of misconception within the sport (23).

The rate of aerobic energy release, taken as the O₂ uptake during the initial 20 s of exercise, produced a large effect size for all comparisons except for the 200 m versus 1500 m and 400 m versus 800 m (Table 2, Fig. 4). An unexpected result from the present study was the relatively high mean aerobic

energy release of the 1500-m group (0.59 mL·kg⁻¹·s⁻¹) compared with the significantly higher intensity trials of the 200-, 400-, and 800-m groups (0.51, 0.36, and 0.38 mL·kg⁻¹·s⁻¹). Gastin et al. (8) reported a significant increase in the rate of aerobic energy release in the same subjects exercising at higher intensities during the first 30 s of supramaximal cycling. Gastin (7), however, reported no differences in the rate of energy release during the first 30 s of a 90-s all-out bout of cycle exercise between untrained, endurance-trained, and sprint-trained subjects when expressed in relative terms (mL·kg⁻¹·min⁻¹). In contrast, Nummela and Rusko (24) found that endurance-trained athletes produced a significantly higher rate of aerobic energy release than sprint-trained athletes at the 30-s time point during a 49-s bout of supramaximal treadmill running. Interestingly, the highest $\dot{V}O_2$ (% $\dot{V}O_2$ peak) obtained during the 800-m and 1500-m trials were quite low, 88 and 94%, respectively. This may be due to differences in active muscle mass recruited during horizontal and inclined treadmill running (3) as a higher treadmill gradient was used during the $\dot{V}O_2$ peak test (6–8%) compared with the performance runs (1%). This finding is supported by Hermansen and Saltin (10), who reported a higher $\dot{V}O_2$ peak during exhaustive running on an inclined treadmill (5%) compared with a horizontal treadmill (0%) protocol of similar duration.

Previous investigations that have evaluated the relative aerobic and anaerobic energy system contributions during exhaustive exercise have been conducted over set time durations which are not specific to a sporting event (8,21,22,29). To accurately profile the energy system contribution during sporting events, specifically trained athletes should be used as subjects. The training status of subjects is an important issue as Nummela and Rusko (24) calculated the relative aerobic energy system contribution during 49 s of exhaustive treadmill running and reported a significantly greater contribution for endurance-trained subjects compared with sprint-trained (46% and 37%, respectively). The present study used specifically trained athletes to profile the 200-, 400-, 800-, and 1500-m track running events in an attempt to accurately assess the energetics of these events.

The energy system profiles of the selected events may be of most value for the middle distance coach. The relative exercise intensity (% $\dot{V}O_2$ peak) of the 200, 400, 800, and 1500 m were 201, 151, 113, and 103%, respectively. In terms of exercise intensity, the 800 and 1500 m appear to be the most closely related. This finding may help to explain the observation why many elite 800-m runners are highly competitive over 1500 m rather than 400 m (23). The relative aerobic energy system contribution (percent of total energy demand) clearly increases in significance during the longer duration events but is considerably greater in the shorter duration events than traditionally thought (12,14). This finding suggests that the role of the aerobic energy system during the 200 m (29%) and especially the 400 m (43%) should be acknowledged and considered when planning the training program for athletes competing in these two events. The relative interaction of the aerobic and

anaerobic energy systems for the selected running events is presented in Figure 1. It is evident that, for all four events, the aerobic energy system contributes considerably to the initial energy demand. Furthermore, the transition from predominantly anaerobic energy supply to predominantly aerobic energy supply occurs between the 15- and 30-s time period for the 400-, 800-, and 1500-m events. If the AOD calculations had been corrected for the body's O₂ stores, estimated to represent approximately 10% of the maximal AOD (21), this energy system transition may have been recorded earlier. This is supported by Medbø et al. (17), who reported the total aerobic energy system contribution (measured $\dot{V}O_2$ plus the assumed use of stored O₂) to be 31% and 38% during exhaustive cycling of 12.5 s and 31 s, respectively.

The results pertaining to anaerobic metabolism and relative energy system contribution in this study are dependent on the acceptance of the AOD as a valid method of quantifying anaerobic energy release during high intensity exercise. The AOD methodology attempts to estimate the metabolic response of the active muscles to a particular exercise

bout, via the "whole body" metabolic response of expired gases. The underlying assumptions of the method are complex and difficult to prove, but have been discussed in great detail previously (1,7,19). Despite theoretical concerns (1,9) the method is considered a valid procedure for estimating anaerobic energy release during intense whole body exercise (7,19,21).

It is concluded that the relative contribution of the aerobic energy system is considerable and greater than has been traditionally accepted during 200-, 400-, 800-, and 1500-m running. The results demonstrate that the aerobic energy system is the predominant energy system by the 30-s time period during the 400-, 800-, and 1500-m running events.

The authors would like to acknowledge the contribution of Asst. Prof. Warren Payne during this study and earlier preliminary work. Thanks also go to Andrew Russell, Bob O'Brien, Justin Grantham, and Dr. David Bishop for their assistance. This study was funded by the Australian Sports Commission.

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Running economy and distance running performance of highly trained athletes

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ABSTRACT

CONLEY, DOUGLAS L. and GARY S. KRAHENBUHL. Running Economy and distance running performance of highly trained athletes. *Med. Sci. Sports Exercise*. Vol. 12, No. 5, pp. 357-360, 1980. The purpose of the study was to determine the relationship between running economy and distance running performance in highly trained and experienced distance runners of comparable ability. Oxygen uptake ($\dot{V}O_2$) during steady-state and maximal aerobic power ($\dot{V}O_{2max}$) were measured during treadmill running using the open-circuit method. Distance running performance was determined in a nationally prominent 10 km race; all subjects (12 males) placed among the top 19 finishers. The subjects averaged 32.1 min on the 10 km run, $71.7 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ for $\dot{V}O_{2max}$, and 44.7, 50.3, and $55.9 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ for steady-state $\dot{V}O_2$ at three running paces (241, 268, and $295 \text{ m}\cdot\text{min}^{-1}$). The relationship between $\dot{V}O_{2max}$ and distance running performance was $r = -0.12$ ($p = 0.35$). The relationships between steady-state $\dot{V}O_2$ at 241, 268, and $295 \text{ m}\cdot\text{min}^{-1}$ and 10 km time were $r = 0.83$, 0.82 , and 0.79 ($p < 0.01$), respectively. Within this elite cluster of finishers, 65.4% of the variation observed in race performance time on the 10 km run could be explained by variation in running economy. It was concluded that among highly trained and experienced runners of comparable ability and similar $\dot{V}O_{2max}$, running economy accounts for a large and significant amount of the variation observed in performance on a 10 km race.

DISTANCE RUNNING, OXYGEN UPTAKE, RUNNING ECONOMY

Successful performance in competitive distance running has been attributed primarily to the athlete's ability to consume oxygen maximally (3,6,15). A variation of this view is that a high $\dot{V}O_{2max}$ may be a prerequisite for success in distance running, but that among runners possessing this essential attribute, the fractional utilization of $\dot{V}O_{2max}$, muscle fiber composition, peak muscle and blood lactate accumulation, and running economy may be important (4,10,11,12,14,16).

Running economy is considered to be the steady-state oxygen consumption ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) for a standardized running speed (10). Running economy varies considerably among trained runners (1,7,9,10,13,14). Costill (6) suggests that intraindividual variations in running economy at standardized speeds are "random" and of little value in differentiating distance running ability. Correlations between running economy and performance in running events have ranged from $r = 0.36$ (23 experienced runners

in the marathon (12) to $r = 0.60$ (18 experienced distance runners on a 9.7 km race (10)).

Previous reports on the relationship between running economy and distance running performance have been peripheral to other purposes in experiments and have been based on populations exhibiting heterogeneity on both $\dot{V}O_{2max}$ and running ability. The purpose of the present study was to determine the relationship between running economy and distance running performance in highly trained distance runners more homogeneous in ability.

METHODS

The subjects for the study were 12 highly trained and experienced male runners who placed among the top 19 in a nationally prominent 10 km race. The laboratory data were collected during the third to sixth days following the competitive run. Maximal oxygen uptake and skinfolds were measured on the first of two laboratory visits. Each subject wore the same shoes and clothing for the laboratory testing as he had worn during the 10 km run. Body weights included the weight of this clothing since it contributed to the running workload. Shoes were removed for height measurement. Skinfolds were measured at six sites (triceps, subscapular, suprailiac, umbilical, pectoral, and anterior mid-thigh) using a Harpenden caliper.

Maximal oxygen uptake was determined using the open-circuit method, treadmill running, and a continuous protocol. Treadmill speed was kept at $214 \text{ m}\cdot\text{min}^{-1}$ for all stages. Stage one was a 4-min warm-up at level grade. At the close of the fourth and each subsequent minute until the subject reached exhaustion, grade was increased $2\frac{1}{2}\%$. The criteria described by McMiken and Daniels (13) were used in determining the subject's $\dot{V}O_{2max}$.

All three submaximal tests were conducted on the subject's second visit to the laboratory. The laboratory was air-conditioned and kept at 18°C for all runs. The procedure was identical to that utilized by McMiken and Daniels (13). After a warm-up of 5 min at $214 \text{ m}\cdot\text{min}^{-1}$, the subjects completed runs, 6 min in duration, at $241 \text{ m}\cdot\text{min}^{-1}$, $268 \text{ m}\cdot\text{min}^{-1}$, and $295 \text{ m}\cdot\text{min}^{-1}$ with 3 min rest between tests. Serial, 1-min collections were made over the last 3 min of each 6-min run. The values obtained for individual

subjects indicated that they were all in steady-state for the three collections at each speed. The mean of the three collections was taken as the aerobic requirement. No respiratory exchange ratios exceeded 1.00. Treadmill belt speed was calibrated prior to each submaximal test and rechecked during the first minutes of the run for every subject. This procedure resulted in an accuracy of ± 0.5 treadmill belt revolutions per minute.

Expired gas samples from both the maximal and submaximal tests were collected in meteorological balloons through a breathing valve and collection system described by Daniels (8). Gas samples were passed through a drying tube and analyzed for CO₂ and O₂ with the Beckman LB-2 and 4-digit OM-11, respectively. The gas analyzers were calibrated at the beginning and end of each test, using standards previously analyzed with a Callenkamp-Lloyd volumetric analyzer. Drift between calibrations was, in each case, within the published instrument error in overall accuracy; therefore, no corrections in the data were indicated. Expired gas volumes were determined with a Parkinson-Cowen, CD-4 gas meter.

RESULTS AND DISCUSSION

The subjects in this study exhibited a tight cluster of excellent 10 km run times (Table 1). The ranges for $\dot{V}O_{2\max}$ and relative fat were also narrow and the mean values were what would be expected for the caliber of runner studied.

When comparing the mean physical characteristics in this study to the mean values reported in studies by

McMiken and Daniels (13), Daniels et al. (9), and Costill, Thomason, and Roberts (6) involving groups of 8, 10, and 16 highly trained male distance runners, marked similarities are found. The range in mean heights varies by 9 cm (174-183). Mean weights vary by only 3 kg (63.1-66.1). Finally, means for $\dot{V}O_{2\max}$ are separated by 7.6 ml·kg⁻¹·min⁻¹ (66.1-73.7).

The relationship between $\dot{V}O_{2\max}$ and performance in the 10 km run was $r = 0.12$, which was not significantly ($p = 0.35$) different from zero, due to the homogeneity of the group, and was much lower than the relationships reported from earlier studies (Table 2). Although the test race distances were similar to a number of previous studies (3,6,10,11), the current subject group was much more homogeneous on both performance and $\dot{V}O_{2\max}$ than were the group members from these earlier investigations.

It cannot be argued from these data that $\dot{V}O_{2\max}$ is unimportant, for all the subjects exhibited high values. The current data, however, suggest that a high $\dot{V}O_{2\max}$ helped each subject gain membership in this elite performance cluster, but it did not discriminate success on a 10 km race within this group.

The submaximal aerobic requirements depicted in Figure 1 are very similar to those reported in earlier studies (6,9). At submaximal speeds of 241 and 268 m·min⁻¹, Daniels et al. (9) recorded mean $\dot{V}O_2$'s of 44.6 and 50.5 ml·kg⁻¹·min⁻¹ for 10 highly trained male distance runners. Costill, Thomason, and Roberts (6) reported mean $\dot{V}O_2$'s of 45.6, 51.7, and 59.0 ml·kg⁻¹·min⁻¹, for the respective speeds of 241, 268, and 295 m·min⁻¹, for 16 highly trained male distance runners. The mean aerobic requirements for the 12

TABLE 1. Physical characteristics of the subjects.

Subject	Age (Years)	Years of Training	Height (cm)	Weight (kg)	Skinfold Sum ^a (mm)	$\dot{V}O_{2\max}$ (ml·kg ⁻¹ ·min ⁻¹)	10 km Run Time (min)
A	25	9	183	63.3	34.8	77.74	30.52
B	28	14	178	60.6	26.0	67.74	30.98
C	28	14	196	78.1	31.8	70.55	31.15
D	24	10	185	70.4	35.3	70.30	31.28
E	30	15	175	62.0	33.5	71.95	31.75
F	18	05	175	67.2	30.5	73.95	31.95
G	25	12	180	68.6	28.1	70.55	32.57
H	19	06	173	71.7	29.6	72.28	32.57
I	20	03	175	65.4	29.5	72.69	32.62
J	34	13	173	68.6	43.9	67.30	32.93
K	23	11	180	69.0	30.5	71.79	33.30
L	21	08	178	74.9	29.2	73.72	33.55
Mean	24.6	10.0	179.3	64.6	31.9	71.70	32.10
SD	4.8	3.9	6.4	5.9	4.65	2.80	1.00

^aTricep, subscapular, suprailiac, umbilical, pectoral, and anterior mid-thigh

TABLE 2. Relationship of $\dot{V}O_{2\max}$ to running performance in this and previous studies using similar distances.

Study	Subjects	$\dot{V}O_{2\max}$ Range	Test Race Distance	Performance Range (min)	Relationship between $\dot{V}O_{2\max}$ and Performance
Costill (3)	Collegiate Cross Country (n=17)	50 - 67	4.7 mi	24.3 - 33.3	- 0.82
Costill et al. (6)	Trained Distance Runners (n=16)	55 - 82	10.0 mi	48.3 - 68.2	- 0.91
Foster et al. (11)	Well-Trained Runners (n=26)	49 - 73	6.0 mi	29.9 - 46.6	- 0.88
Farrell et al. (10)	Experienced Runners (n=18)	46 - 74	15.0 km 9.7 km	45.9 - 73.6 28.4 - 44.3	- 0.89 - 0.86
Present Investigation	Highly-Trained and Experienced Runners (n=12)	67 - 77	10.0 km	30.5 - 33.6	- 0.12

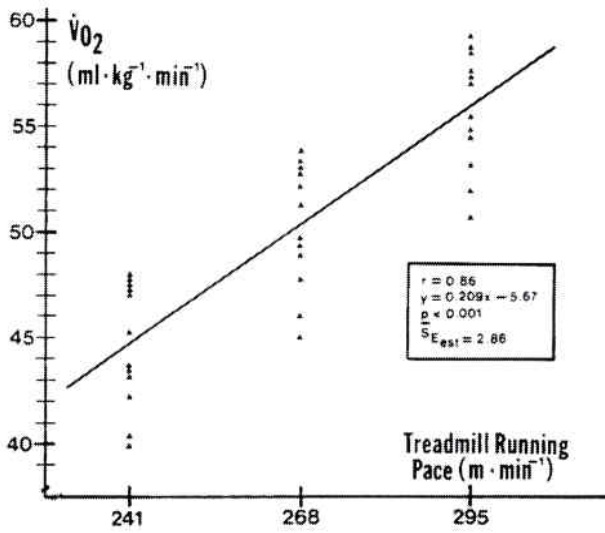


Figure 1—The relationship between steady-state oxygen uptake and treadmill running pace in 12 highly-trained and experienced male distance runners.

subjects in this study were 44.7, 50.3, and 55.9 ml·kg⁻¹·min⁻¹ for the same submaximal speeds.

The relationship between oxygen uptake and running pace is depicted in Figure 1. The slope of the group regression line (+0.209) is very similar to the ones reported by Costill and Fox (5) (+0.204), Daniels et al. (9) (+0.211), and Bransford and Howley (2) (+0.204 and +0.203). The individual data points showed close adherence to their respective linear regression lines. Subject correlation coefficients calculated from the three data points ($\dot{V}O_2$ at 241, 268, 295 m·min⁻¹) ranged from 0.995 to 0.999 with a mean of 0.998. Standard errors of the estimate ranged from 0.008 to 0.814 with a mean of 0.405 ml·kg⁻¹·min⁻¹. These data support the concept that the relationship between the aerobic requirements of running and the running pace between 241 and 295 m·min⁻¹ can be adequately described by a linear regression equation.

The importance of running economy among runners of comparable ability is suggested in Figure 2. The relationship between performance on a 10 km race and the aerobic requirements of three standardized running paces (241, 268, and 295 m·min⁻¹) is shown. The coefficients range from $r = 0.79$ to $r = 0.83$. All are statistically significant at or beyond the 99% level of confidence. By averaging r^2 for the three paces, it may be stated that within this elite cluster of finishers 65.4% of the variation observed in race performance on the 10 km race can be explained by variation in running economy.

Costill et al. (6) have shown that the fractional utilization of aerobic capacity (% $\dot{V}O_{2max}$) at submaximal speeds is highly related to running performance among runners with a wide range of abilities and $\dot{V}O_{2max}$. In the current study, the relationships between running performance and percent of $\dot{V}O_{2max}$ at submaximal speeds were nearly iden-

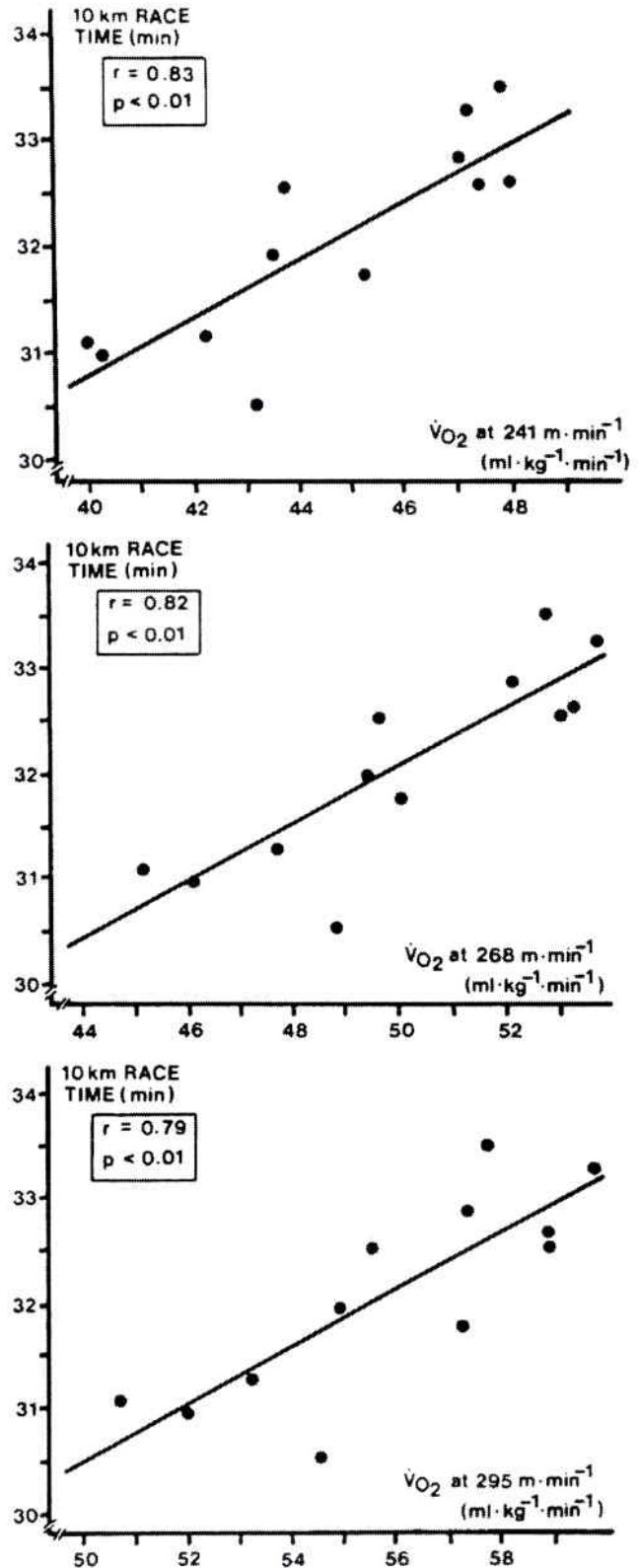


Figure 2—The relationship between 10 km race time (y-axis) and steady-state oxygen uptake at 241 m·min⁻¹ (x-axis; top), 268 m·min⁻¹ (x-axis; middle), and 295 m·min⁻¹ (x-axis; bottom) in 12 highly-trained and experienced male distance runners.

tical to the relationships between performance and $\dot{V}O_2$. Percent $\dot{V}O_{2max}$ is derived from $\dot{V}O_{2max}$ and $\dot{V}O_{2submax}$, therefore, in a group homogeneous in $\dot{V}O_{2max}$ it is not surprising that percent of $\dot{V}O_{2max}$ accounted for no more variation in performance than did $\dot{V}O_{2submax}$ alone.

Once a minimal threshold of work is passed, lactic acid accumulation is a function of percent of $\dot{V}O_{2max}$ (2,10). Farrell et al. (10) recently demonstrated that the onset of plasma lactate accumulation is closely related to the pace a runner is able to maintain for long races. It seems reasonable to assume, albeit speculation, that running economy is important to distance running because the relative intensity (percent of $\dot{V}O_{2max}$) of a given pace would be lower for an economical runner than it would be for a less economical runner with a comparable $\dot{V}O_{2max}$. The variation in performance not accounted for by the economy of the subjects may be due to interindividual differences in muscle fiber composition, anaerobic threshold, and peak muscle and blood lactate tolerance.

Two questions which are typically raised when compar-

ing treadmill with track data are: (1) does the lack of wind resistance on the treadmill nullify the implications suggested for overland running, and (2) do treadmill determinations of the aerobic requirements of running at 85% of $\dot{V}O_{2max}$ (the highest relative workload observed at 295 $m \cdot min^{-1}$) seriously underestimate the energy requirement during heavy exercise? Previous authors (2,6,13) have provided data and discussion which suggest that for the paces and relative intensities in the present study, error from these two sources may be regarded as inconsequential.

In summary, the most important finding of this study is that among highly trained and experienced runners of comparable ability and similar $\dot{V}O_{2max}$, running economy accounts for a large and significant amount of the variation observed in performance in a 10 km race. This conclusion does not argue against the importance of $\dot{V}O_{2max}$, for all subjects exhibited high values. Rather, it appears that the importance of economy may be expressed only when performers are of comparable ability with similar maximal aerobic capacities.

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