Economy of running: beyond the measurement of oxygen uptake

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Fletcher JR, Esau SP, MacIntosh BR. Economy of running: beyond the measurement of oxygen uptake. *J Appl Physiol* 107: 1918–1922, 2009. First published October 15, 2009; doi:10.1152/japplphysiol.00307.2009.—The purpose of this study was to compare running economy across three submaximal speeds expressed as both oxygen cost ($ml \cdot kg^{-1} \cdot km^{-1}$) and the energy required to cover a given distance ($kcal \cdot kg^{-1} \cdot km^{-1}$) in a group of trained male distance runners. It was hypothesized that expressing running economy in terms of caloric unit cost would be more sensitive to changes in speed than oxygen cost by accounting for differences associated with substrate utilization. Sixteen highly trained male distance runners [maximal oxygen uptake ($\dot{V}_{O_{2max}}$) 66.5 ± 5.6 $ml \cdot kg^{-1} \cdot min^{-1}$, body mass 67.9 ± 7.3 kg, height 177.6 ± 7.0 cm, age 24.6 ± 5.0 yr] ran on a motorized treadmill for 5 min with a gradient of 0% at speeds corresponding to 75%, 85%, and 95% of speed at lactate threshold with 5-min rest between stages. Oxygen uptake was measured via open-circuit calorimetry. Average oxygen cost was 221 ± 19, 217 ± 15, and 221 ± 13 $ml \cdot kg^{-1} \cdot km^{-1}$, respectively. Caloric unit cost was 1.05 ± 0.09, 1.07 ± 0.08, and 1.11 ± 0.07 $kcal \cdot kg^{-1} \cdot km^{-1}$ at the three trial speeds, respectively. There was no difference in oxygen cost with respect to speed ($P = 0.657$); however, caloric unit cost significantly increased with speed ($P < 0.001$). It was concluded that expression of running economy in terms of caloric unit cost is more sensitive to changes in speed and is a more valuable expression of running economy than oxygen uptake, even when normalized per distance traveled.

caloric cost; distance running; respiratory exchange ratio; running performance

SUCCESSFUL DISTANCE RUNNING performance, particularly in long-distance events, depends on the interaction of several physiological factors (15), including a high maximal oxygen uptake ($\dot{V}_{O_{2max}}$), the ability to sustain a high percentage of $\dot{V}_{O_{2max}}$ (fractional utilization of $\dot{V}_{O_{2max}}$), and a low energy cost to run at a particular speed (8, 14). This latter factor is one form of running economy (RE). There is a strong association between RE and distance running performance, with RE being a better predictor of performance than $\dot{V}_{O_{2max}}$ in elite runners who have a similar $\dot{V}_{O_{2max}}$ (1, 3, 4, 6, 26). Early research comparing elite distance runners ($\dot{V}_{O_{2max}} = 79$ $ml \cdot kg^{-1} \cdot min^{-1}$) with good distance runners ($\dot{V}_{O_{2max}} = 69$ $ml \cdot kg^{-1} \cdot min^{-1}$) indicated that the elite runners had a better RE than the good runners (24). Clearly, RE is an important determinant of success in distance running (21). Particular attention to RE has increased with the emergence of highly economical runners from East Africa dominating long-distance running events over the last 20 years (16, 25). Thus RE is widely understood to be an important factor for optimal distance running performance.

A standard approach to quantifying RE involves measuring oxygen uptake ($\dot{V}_{O_2}$) while running on a treadmill at constant speeds. Measurement of steady-state $\dot{V}_{O_2}$ is used in the determination of economy because $\dot{V}_{O_2}$ reflects the quantity of ATP used in the task under investigation when aerobic metabolism provides all of the energy for that task. A duration of 4–15 min is sufficient to achieve a physiological steady state (20) if the speed is less than that which results in accumulation of lactate in the blood. The highest intensity for which blood lactate does not accumulate is called the maximal lactate steady state (29). It is important to keep the intensity of running below the maximal lactate steady state, since at speeds above this intensity the slow component of $\dot{V}_{O_2}$ dictates that steady-state conditions are unlikely to be achieved. Furthermore, it is expected that above the maximal lactate steady state, nonaerobic metabolism contributes to the energy cost. Assuming the lactate threshold corresponds with the maximal lactate steady state (30), the measurement of $\dot{V}_{O_2}$ can account for all of the energy use when the running speed is slower than the speed at the lactate threshold (sLT) (29).

Many studies have used relative $\dot{V}_{O_2}$ ($ml \cdot kg^{-1} \cdot min^{-1}$) at absolute speeds as a surrogate for RE of elite and nonelite distance runners (2, 4, 7, 9, 12, 16, 25, 28). For example, Conley and Krahenbuhl (4) have shown that a $\dot{V}_{O_2}$ of 50.3 $ml \cdot kg^{-1} \cdot min^{-1}$ at a speed of 268 m/min can be considered an "average running economy" among highly trained distance runners. However, assessing RE by simply measuring $\dot{V}_{O_2}$ does not take into account that the energy equivalent of a volume of oxygen can vary, depending on the substrate metabolized (17). This additional information, often ignored, could permit more precise determination of RE.

Also, making comparisons between athletes at an absolute running speed potentially ignores any differences that might occur because of differences in relative intensity or sLT. We define sLT as the speed of locomotion just less than that associated with a substantial increase in blood lactate during an incremental exercise test (29). A handful of studies have expressed RE in terms of oxygen cost to cover a given distance ($ml \cdot kg^{-1} \cdot km^{-1}$) rather than a rate of $\dot{V}_{O_2}$ ($ml \cdot kg^{-1} \cdot min^{-1}$) to better reflect differences in speed among groups (9, 13, 16). We refer to this as O_2 unit cost. It is known that substrate use is affected by changes in relative velocity (5). A given speed may be a higher relative percentage of sLT for one runner compared with another, and this could influence substrate use and therefore energy made available per liter of oxygen.

Furthermore, it has been suggested that distance running performance, particularly distances such as the marathon, relies partly on a runner's ability to utilize fat as a fuel at high work rates and thereby "spare" carbohydrate (26). Of importance, the energy yielded per liter of oxygen is dependent on the substrate metabolized. The respiratory exchange ratio (RER) can be used as an indicator of the mix of carbohydrate and fat used and permits conversion of the $\dot{V}_{O_2}$ for a given workload into units of energy (17). Caloric unit cost ($kcal \cdot kg^{-1} \cdot km^{-1}$) would appear to be a more appropriate way to express RE, yet very few studies take advantage of RER to calculate actual energy use (18, 23).

Therefore, the purpose of this study was to compare RE across three different submaximal speeds expressed as both O_2 unit cost and caloric unit cost in a group of trained male distance runners. It was hypothesized that expressing RE in terms of caloric unit cost would be more sensitive to changes in speed than O_2 unit cost by accounting for differences in substrate utilization and the corresponding difference in energy provided per volume of $\dot{V}O_2$.

In addition, the data collected for this study were used to consider the controversy regarding the relationship between economy and $\dot{V}O_{2max}$. The notion that economy is worse as $\dot{V}O_{2max}$ increases (19, 22) is at odds with the idea that better runners have better economy (23).

METHODS

Subjects. Sixteen highly trained male middle- and long-distance runners (body mass 67.9 ± 7.3 kg, height 177.6 ± 7.0 cm, age 24.6 ± 5.0 yr; means ± SD), all having regularly participated in regional, national, or international competition in events ranging from 1,500 m to the marathon, took part in the study. The runners gave their written informed consent to participate in the experimental procedure, which was approved by the University of Calgary Conjoint Health Research Ethics Board. All subjects performed distance running training between 6 and 12 times per week. The training volume of the subjects was 118 ± 32 km/wk. None of the subjects had any neuromuscular or musculoskeletal injuries at the time of the study.

Maximal oxygen uptake and lactate threshold. On the first visit to the laboratory, $\dot{V}O_{2max}$ and lactate threshold were determined. Subjects were instructed to wear cool, loose clothing and their own lightweight running shoes and were instructed not to consume any food or drink, other than water, during the 90 min before the testing session. They were also asked to refrain from caffeine and vigorous physical activity for 24 h before the session. After a self-selected warm-up, the subjects began running on a motorized treadmill (Woodway Pro, Woodway USA, Waukesha, WI). The initial speed was ∼3 km/h below the subject's most recent 10-km race performance, and there was no gradient. Expired gases were measured by a Parvomedics TrueMax 2400 metabolic measurement cart (Salt Lake City, UT) for the determination of $\dot{V}O_2$ (ml·kg^{-1}·min^{-1}) and carbon dioxide output ($\dot{V}CO_2$, ml·kg^{-1}·min^{-1}). The treadmill belt speed was increased 0.8 km/h every 2 min. After each 2-min stage, subjects briefly straddled the treadmill belt and a fingertip blood sample was taken for blood lactate measurement (Lactate Pro). Once blood lactate concentration rose >1 mM from the previous sample, the treadmill speed was returned to the previous speed and the grade was increased 2%. This increment in grade was repeated every minute until volitional fatigue.

The metabolic cart was calibrated before and after each session by means of a two-point calibration using room air and a gas mixture of known composition (4% CO_2, 16% O_2, balance N_2). The flow sensor (Hans Rudolf 3813 heated pneumotachometer) was calibrated with a manual 3-liter syringe. The accuracy values provided by the manufacturer are 0.03% and 0.1% for O_2 and CO_2 and ±2% for volume. The technical error of measurement for this system in our lab is reported to be 0.09 l/min (1.9 ± 0.3%).

sLT was defined as the speed at the stage preceding the stage for which there was a blood lactate increase ≥1.0 mM. $\dot{V}O_{2max}$ was defined as the highest 30-s average $\dot{V}O_2$ during the test. $\dot{V}O_{2max}$ was considered to have been achieved if there was no increase (<100 ml·kg^{-1}·min^{-1}) in $\dot{V}O_2$ with an increase in treadmill slope or if two of the following occurred: *1*) RER was >1.15, *2*) blood lactate concentration was >8 mM, or *3*) subjects reached their age-predicted maximal heart rate (220 − age). All tests were terminated by volitional exhaustion, and all subjects achieved $\dot{V}O_{2max}$ by these criteria.

Running economy. On a separate day, each subject's RE was determined. The subjects were reminded of the same pretesting instructions as for the first testing session. After a warm-up period of 10 min at a running speed of 9.6 km/h, the subjects ran three different speeds for 5 min on a treadmill in the same order: 75%, 85%, and 95% sLT. For each speed, the breath-by-breath $\dot{V}O_2$ was averaged every 30 s. Steady state was defined as an increase of <100 ml O_2 over the final 2 min of each stage. In the one case for which the difference was >100 ml, the stage was continued for another 30 s, which resulted in a confirmed steady state. The $\dot{V}O_2$ over the final 2 min was taken as the steady-state $\dot{V}O_2$ for that speed. Between stages, the subjects stood stationary on the treadmill for 5 min. Fingertip blood samples were taken for lactate analysis immediately before and after each 5-min stage.

RE at each speed was expressed as both a gross oxygen cost (ml O_2·kg^{-1}·km^{-1}) as well as a gross caloric unit cost (kcal·kg^{-1}·km^{-1}). With the average RER over the same 2 min, the caloric equivalent of the $\dot{V}O_2$ (kcal/l O_2) was determined (17) and caloric unit cost was calculated as caloric unit cost (kcal·kg^{-1}·km^{-1}) = $\dot{V}O_2$·caloric equivalent·s^{-1}·BM^{-1}·K, where $\dot{V}O_2$ is measured in liters per minute, caloric equivalent is in kilocalories per liter, speed (*s*) is in meters per minute, body mass (BM) is in kilograms, and K is 1,000 m/km. Resting metabolic rate was not subtracted, because it cannot be confirmed that resting metabolic demand continues at the same rate during the running. This is a baseline subtraction issue as described by Stainsby and Barclay (27).

Statistics. Values are presented as means ± SD. One-way ANOVA with repeated measures and Tukey's post hoc test were used to test for differences between the three speeds. Pearson product-moment correlation was used to identify significant relationships. Statistical significance was set at $P ≤ 0.05$.

RESULTS

The average $\dot{V}O_{2max}$ for the 16 subjects was 66.5 ± 5.6 ml·kg^{-1}·min^{-1}. The average sLT was 263.4 ± 30.1 m/min. Individual values for $\dot{V}O_{2max}$, sLT, and caloric unit cost at each speed are presented in Table 1. Blood lactates were 1.5 ± 0.4, 2.0 ± 0.6, and 3.5 ± 1.0 mM after 5 min at 75%, 85%, and 95% of sLT, respectively. A small increase in blood lactate would be expected for each speed because of the oxygen deficit.

Table 1. *Individual values for $\dot{V}O_{2max}$, sLT, and caloric unit cost, ranked by sLT*

Subject	$\dot{V}O_{2max}$, ml·kg^{-1}·min^{-1}	sLT, m/min	% $\dot{V}O_{2max}$	Caloric Unit Cost, kcal·kg^{-1}·km^{-1}		
				75%	85%	95%
1	70.6	317.0	87.8	0.91	0.95	1.01
2	72.4	302.8	90.1	1.04	1.08	1.14
3	70.9	292.0	89.7	0.96	1.00	1.09
4	72.2	290.2	85.5	1.00	1.01	1.07
5	73.6	290.2	88.7	0.99	1.06	1.10
6	67.4	264.9	88.4	1.04	1.07	1.13
7	64.1	264.9	86.2	1.04	1.06	1.06
8	74.4	264.4	77.8	1.01	1.05	1.09
9	66.4	253.1	88.0	1.26	1.26	1.28
10	64.4	252.3	88.4	1.15	1.12	1.17
11	63.6	252.3	83.4	1.00	1.01	1.04
12	57.5	252.3	73.2	1.10	1.11	1.11
13	64.4	251.5	82.5	1.00	1.02	1.06
14	67.2	249.9	79.4	1.03	1.04	1.07
15	58.0	215.1	81.0	1.13	1.14	1.12
16	57.3	201.7	83.6	1.20	1.16	1.21
Mean	66.5	263.4	84.6	1.05	1.07	1.11
SD	5.6	30.1	4.8	0.09	0.08	0.07

$\dot{V}O_{2max}$, maximal oxygen uptake; sLT, speed at lactate threshold.

Fig. 1. Caloric unit cost ($kcal \cdot kg^{-1} \cdot km^{-1}$) and oxygen unit cost ($ml\ O_2 \cdot kg^{-1} \cdot km^{-1}$) measured at 75%, 85%, and 95% of speed at lactate threshold (sLT). Caloric cost increased significantly with speed ($P < 0.001$). Values are expressed as means ± SD.
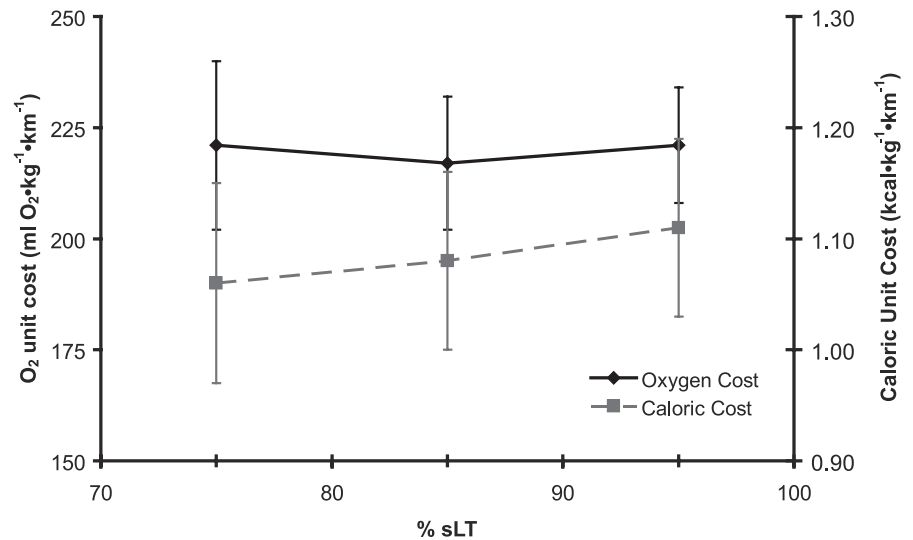
Average caloric unit cost and O_2 unit cost at these relative test speeds are presented in Fig. 1. There was no difference in O_2 unit cost across the relative test speeds ($P = 0.657$); however, caloric unit cost significantly increased with relative speed ($P < 0.001$).

RER increased significantly across the three measured speeds as shown in Fig. 2, indicating that relative intensity did affect the mix of substrates metabolized during the treadmill run trials.

Relative rate of oxygen uptake ($ml\ O_2 \cdot kg^{-1} \cdot min^{-1}$) at 85% sLT and 95% sLT was significantly related to the relative $\dot{V}O_{2max}$ ($P < 0.001$) and approached significance at 75% sLT ($P = 0.052$) (Fig. 3). However, this relationship probably exists because those with a higher $\dot{V}O_{2max}$ ran at a higher absolute speed in the treadmill tests. When caloric unit cost is plotted against absolute speed, a different relationship emerges (Fig. 4). The better runners are those with a higher sLT, and these runners had a lower energy cost of running. This relationship can be further investigated by considering the caloric unit cost across the various absolute speeds (Fig. 4).

Here it is clear that the better runners (those associated with a higher sLT) have lower caloric unit cost (a better RE) compared with the runners with lower sLTs. The relationship between caloric unit cost and sLT at each of the measured speeds was significant ($P = 0.001$, $P = 0.01$, and $P = 0.04$, respectively).

DISCUSSION

The main finding of this study was that expressing RE as a caloric unit cost was more sensitive to changes in relative speed than RE expressed as O_2 unit cost. It is proposed that expression of RE as a caloric unit cost is a more appropriate expression of the economy of running since it takes into consideration the different substrate mixtures used by subjects when running at any submaximal speed. The common practice of expressing economy as a rate of $\dot{V}O_2$ at a common running speed is even less desirable than expressing economy as a O_2 unit cost. O_2 unit cost, like caloric unit cost, is expressed per unit distance (km) as opposed to unit time (minute) to permit comparisons when absolute speed is different.
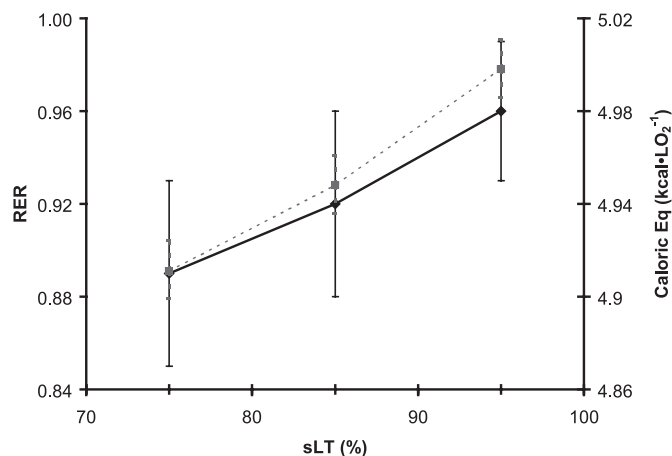

Fig. 2. Respiratory exchange ratio (RER) and the caloric equivalent of oxygen uptake ($\dot{V}O_2$) measured at 75%, 85%, and 95% sLT. RER, represented by solid line, increased significantly across the measured speeds ($P < 0.001$). Caloric equivalent, represented by dashed line, increased significantly across the measured speeds ($P < 0.001$). Values are expressed as means ± SD.
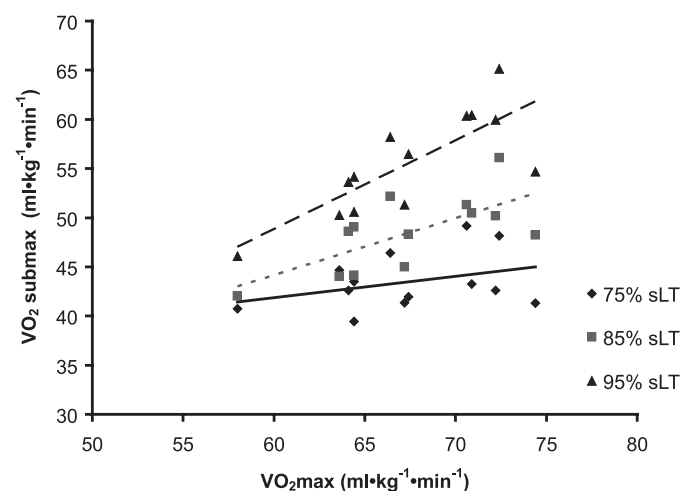

Fig. 3. Relationship between maximal $\dot{V}O_2$ ($\dot{V}O_{2max}$) and $\dot{V}O_2$ measured at 75%, 85%, and 95% sLT. The relationship was significant at 85% and 95% sLT.
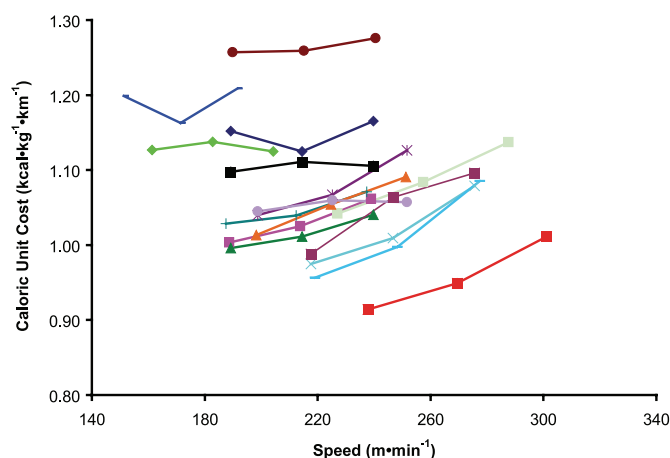
Fig. 4. Caloric unit cost for each subject measured at his absolute speeds. Each group represents 1 subject's caloric unit cost at the 3 measured speeds corresponding to 75%, 85%, and 95% sLT for that subject.

It is further argued that RE should be compared between individuals at a similar relative intensity. RE in the present study was measured at speeds expressed as a percentage of sLT in order to normalize for differences in economy associated with a higher threshold speed and to ensure steady-state oxygen consumption. Comparing different athletes at the same absolute running speeds does not acknowledge differences in speed associated with the lactate threshold or differences in substrate utilization associated with differences in intensity relative to $\dot{V}_{O_{2max}}$.

It might be argued that RER is highly variable and influenced by a number of factors including preexercise diet, training status, resting muscle glycogen content, muscle fiber composition, and various hormone concentrations (10). Many of these factors cannot be easily controlled. Does this justify not using RER? We would argue that variability in substrate use affects $\dot{V}_{O_2}$ but not the energy required to perform the task. Therefore, it is necessary, because of the variability of substrate use, to go the extra step and calculate actual energy.

The difference in energy per liter of oxygen for a change in RER from 0.87 to 0.95 is only 2%. However, using RER to calculate true energy cost allowed us to identify that the energy cost of running does increase as the runner approaches his/her sLT, an important concept in gaining an understanding of energetics of locomotion. Furthermore, small differences in energetics can contribute to the difference between a podium performance and an also-ran. This is tremendously important to the individual athlete (11).

Our data also allowed us to consider the reported relationship between $\dot{V}_{O_{2max}}$ and economy of locomotion in running (19, 22). This relationship suggests that athletes with higher relative $\dot{V}_{O_{2max}}$ consume more oxygen at submaximal running speeds than athletes with lower $\dot{V}_{O_{2max}}$. We saw a similar relationship, but this can easily be explained by the fact that those with a higher $\dot{V}_{O_{2max}}$ actually ran faster at their test speeds; therefore they needed a higher rate of $\dot{V}_{O_2}$. The true relationship becomes clear when economy is plotted against absolute speed. It can then be seen that the better runners had a lower energy cost for running (Fig. 4). Pate et al. (22) have previously acknowledged that comparing subjects running at one absolute speed corresponds to a wide range of relative

intensities: 46–91% $\dot{V}_{O_{2max}}$. As a result, a given speed may be at a higher relative percentage of sLT for one runner compared with another and the measured oxygen uptake will be different. For example, in comparing runners with high $\dot{V}_{O_{2max}}$ or sLT values with slower runners with lower $\dot{V}_{O_{2max}}$ requires all runners to run at a common speed, corresponding to a high percentage of the sLT of the slow runners and a low percentage of the sLT of the fast runners. This same absolute speed may be appreciably lower than the typical training intensity of the fast runners and they may be less economical at this slower pace because of mechanical and/or neuromuscular factors (22). This is not obvious from our data. Comparing economy between runners at a common absolute speed (i.e., 220 m/min; see Fig. 4) shows that for our subjects the better runners still had the lowest energy cost per kilometer. Expressing economy as a caloric unit cost illustrates that the runners with higher sLT are the most economical. This is consistent with the report by Pollock (24) that better runners have better economy.

There are two additional reasons why $\dot{V}_{O_2}$ at a given speed might have a negative correlation with $\dot{V}_{O_{2max}}$. One reason has to do with substrate selection and would be expected to disappear upon conversion to energy equivalent. The second reason has to do with subject selection. If a group of relatively homogeneous runners are chosen (homogeneous with respect to performance), runners in the group with a lower $\dot{V}_{O_{2max}}$ would have to compensate by having better economy or by having the ability to use a larger fraction of their $\dot{V}_{O_{2max}}$ at race pace. This latter property would relate to the lactate threshold. This required compensation would create the negative correlation. The performance level of our subjects was quite broad. For this reason, we had a substantial range of sLT. sLT would be determined by these factors: $\dot{V}_{O_{2max}}$, fractional utilization of $\dot{V}_{O_{2max}}$ at lactate threshold, and economy. It is clear that for our sample of runners improved economy is associated with better running performance.

It is also known that the percentage of energy expenditure due to fat oxidation at any given absolute running speed is inversely related to $\dot{V}_{O_{2max}}$ (5). Thus, at any given submaximal speed, runners with higher $\dot{V}_{O_{2max}}$ probably require higher $\dot{V}_{O_2}$ partly because of the greater reliance on fat utilization. Thus a runner's economy may be considered "poor" simply because of the additional oxygen required to metabolize fat as opposed to carbohydrate. The fact that O_2 unit cost ($ml \cdot kg^{-1} \cdot km^{-1}$) did not change with increasing relative velocity, yet RER increased with increasing velocity, further suggests that substrate utilization is worth considering when interpreting economy of locomotion. As a result, RE was calculated as a caloric unit cost ($kcal \cdot kg^{-1} \cdot km^{-1}$) in the present study.

Conclusions. The present study suggests that expression of RE as a caloric unit cost is a more sensitive and more appropriate measure of RE compared with economy as a function of $\dot{V}_{O_2}$ or O_2 unit cost. It is suggested that caloric unit cost is a better reflection of energy use during running than $\dot{V}_{O_2}$ or O_2 unit cost. Our data also support the notion that better runners have a better RE.

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DISCLOSURES

No conflicts of interest are declared by the author(s).

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