The reliability of cycling efficiency

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ABSTRACT

MOSELEY, L., and A. E. JEUKENDRUP. The reliability of cycling efficiency. *Med. Sci. Sports Exerc.*, Vol 33, No. 4, 2001, pp. 621–627. **Purpose:** The aim of this experiment was to establish the reproducibility of gross efficiency (GE), delta efficiency (DE), and economy (EC) during a graded cycle ergometer test in seventeen male subjects. **Methods:** All subjects performed three identical exercise tests at a constant pedal cadence of 80 rpm on an electrically braked cycle ergometer. Energy expenditure was estimated from measures of oxygen uptake ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) by using stoichiometric equations. **Results:** The subjects characteristics were age 24 ± 6 yr, body mass 74.6 ± 6.9 kg, body fat 13.9 ± 2.2%, and $\dot{V}O_{2max}$ 61.9 ± 2.4 $mL \cdot kg^{-1} \cdot min^{-1}$ (all means ± SD). Average GE, DE, and EC for the three tests were 19.8 ± 0.6%, 25.8 ± 1.5%, and 5.0 ± 0.1 $kJ \cdot L^{-1}$, respectively. The coefficients of variation (confidence limits) were GE 4.2 (3.2-6.4)%, DE 6.7 (5.0-10.0)%, and EC 3.3 (2.4-4.9)%. GE was significantly lower at 95 W and 130 W when compared with 165 W, 200 W, 235 W, 270 W, and 305 W. GE at 165 W was significantly lower ($P < 0.05$) that GE at 235 W. A weak correlation ($r = 0.491$; $P < 0.05$) was found between peak oxygen uptake ($\dot{V}O_2$peak) and GE, whereas no correlations were found between $\dot{V}O_{2max}$ and DE or EC. **Conclusion:** We conclude that a graded exercise test with 3-min stages and 35-W increments is a method by which reproducible measurements of both GE and EC can be obtained, whereas measurements of DE seemed slightly more variable. **Key Words:** GROSS EFFICIENCY, DELTA EFFICIENCY, ECONOMY, $\dot{V}O_{2max}$, ENERGY EXPENDITURE

Efficiency is a measure of effective work and is most commonly expressed as the percentage of total energy expended that produces external work. During cycling, the efficiency of the human body is in the range of 10–25% (10), implying that 75–90% of all the energy obtained from ATP hydrolysis is used to maintain homeostasis or, more importantly, is wasted as heat.

Before efficiency can be examined the exact definition of efficiency needs to be established. There has been much debate in the literature on this point. The basic definition of gross efficiency (GE; (29)), as indicated above, is the ratio of work done during the specific activity to the total energy expended and expressed as a percentage. Gaesser and Brooks (10) suggested that GE distorts the essentially linear relationship between work rate and energy expenditure to make it appear that efficiency increases with work rate. This distortion occurs due to the proportion of energy expenditure that is used to maintain homeostasis becoming smaller as total energy expenditure increases. Therefore, an alternative solution is to select a baseline energy expenditure from which changes can be calculated. Two methods of this type exist, the first is net efficiency (NE), where the baseline is the energy expended at rest, the second is work efficiency (WE), where the baseline is the energy cost of unloaded (0 W) cycling (typically about 5 $kJ \cdot min^{-1}$). Both of these methods have the same flaw in their methodology (10,30), because it is unlikely that either measure of baseline energy expenditure remains constant during changes in oxygen uptake ($\dot{V}O_2$), pedal cadence, or environmental conditions. For example, NE uses the energy expenditure at rest and assumes that during exercise this is equal to the energy required to maintain homeostasis. Increasing exercise intensity, however, will cause changes in gastrointestinal (GI) blood flow (12), splanchnic processes (27), cardiac output, and ventilation rates (11,24). These changes result in an increase in the energy needed to maintain homeostasis during exercise and therefore alter the assumed "baseline" value.

A further definition of efficiency is delta efficiency (DE). DE has been calculated in two ways, either as the change in work performed, divided by the change in energy expended (10), or as the reciprocal of the slope of the linear relationship between energy expenditure and work rate (6). Coyle et al. (6) used both GE and DE when evaluating their data but suggested that DE provides the most valid estimate of muscular efficiency. DE expresses the change in energy expended relative to the change in actual work accomplished and therefore removes the influence of the maintenance of homeostasis on the energy expenditure. In addition to these definitions of efficiency, the term economy (EC) is often used as a measure of oxygen consumption per unit of power output.

Efficiency has been suggested to be an important factor in relation to obesity (9,28), weight loss (19,25), and exercise performance (14,15,23), and hence it is important to know the reproducibility of its measurement. For example, cyclists with very similar physiology and using similar equipment may display large differences in exercise performance as a result of small difference in efficiency (15). Theoretical modelling has predicted a 3% improvement in 26-km time-

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trial time with a 1-SD improvement in GE (23), whereas modelling software (15) predicts that, for a trained rider (riding an average of 300 W over 40 km), a 1% improvement in efficiency will give an 63-s improvement in 40-km time- rial time, whereas the time gain would even be greater in less skilled riders. In addition, experimental studies by Horowitz et al. (14) have suggested that gross cycling efficiency could have a large effect on cycling performance in trained athletes.

At present, there is very little conclusive information about the factors that determine or influence efficiency. Before this area can be addressed to attempt to determine the factors that influence efficiency, it is important to first establish what percentage change in efficiency can be reliably detected. Various studies have reported a range of differences in efficiency between two groups (20,21,31). For example, Nickleberry and Brooks (21) reported a decrease in DE (27% to 21%) as a function of cadence, whereas Sidossis et al. (29) reported an increase in delta efficiency (20.6% to 23.8%) with increasing cadence at a constant work rate. In addition, physiologically relevant but statistically nonsignificant differences in GE were observed between endurance trained and untrained subjects (20,21,31). However, without knowing the reliability of the measure of efficiency, it is difficult to interpret these results. These conflicting results could be due to differences in measurement, subject characteristics, or simply poor reliability of the measure. More studies are needed to elucidate the relationship between aerobic fitness and efficiency. To our knowledge, there are no studies in the literature that have quantified the reliability of a measure of efficiency. Therefore, the purpose of this study was to assess the reproducibility of GE, DE, and EC using a graded cycle ergometer test to exhaustion. In addition, we wanted to study the reliability of peak heart rate (HRpeak), peak power output (Wpeak), and peak oxygen uptake ($\dot{V}O_2$peak) as achieved by this experimental protocol. A third aim of the study was study a possible relationship between estimated of aerobic fitness ($\dot{V}O_2$peak) and measures of efficiency.

METHODS

Subjects. The subjects were 17 men, 7 of whom were club level or greater cyclists. All subjects participated in a range of sports at various levels and performed regular cycling exercise. The study was approved by the local ethics committee, and all subjects signed a consent form after reading the information and the procedure having been explained to them. Subject's individual data and the group means are shown in Table 1. Their absolute $\dot{V}O_2$peak ranged from 3.72 to 5.39 L·min^{-1} (mean 4.5 ± 0.2 L·min^{-1}).

General design. On three occasions separated by 5–7 d, subjects performed an identical graded exercise test to exhaustion on a cycle ergometer to determine $\dot{V}O_2$peak. Measures of $\dot{V}O_2$, $\dot{V}CO_2$ and power output were made throughout the exercise test. Energy expenditure was calculated using stoichiometric equations (8), and, in conjunction with workload (power output), estimations of GE and DE were made.

Experimental design. After an overnight fast, subjects arrived at the lab where their weight and height were measured. Body fat was estimated using calipers (John Bull, British Indicators Ltd., Nottingham) from the sum of four skin-fold sites (biceps, triceps, subscapular, and suprailiac) and using the formula from Durnin and Womersley (7). The subjects' bike set-up (the saddle height and reach) was recorded and reproduced for each subsequent test. Seat angle has been shown to affect efficiency (26) and therefore was also kept constant across the tests. Subjects could use their own clipless pedals or toe clips and straps were fitted. The graded exercise tests were performed on an electrically braked cycle ergometer (Lode Excalibur Sport, Lode, Groningen, The Netherlands) starting at 60 W and the workload increasing by 35 W every 3 min. Subjects were asked to maintain their pedal cadence at 80 rpm and were given visual feedback from the Lode control box in order to do this. Once the RER rose consistently above 1.00 for an entire workload, the measures of energy expenditure were no longer valid (due to the contribution of unmeasured anaerobic work), and maintenance of cadence was no longer necessary. Exercise was continued to exhaustion in order for measurements of $\dot{V}O_2$peak, peak heart rate (HRpeak) and peak power output (Wpeak) to be made. Cadence was recorded at the end of every stage. The ergometer was calibrated before the start of the study and found within 1% between 50 and 500 W. Subjects were asked to refrain from strenuous exercise the day preceding each test and subjects were asked to maintain a similar diet. No warm up was prescribed, as the initial workloads were very low.

Subjects breathed through a mouthpiece with a built-in turbine, which was worn continuously throughout the tests. The mouthpiece was connected, both electronically and via a twintube, to a breath-by-breath gas analyzer (Oxycon Alpha, Mijnhardt, Bunnik, The Netherlands). Recordings were made of the mean of eight breaths and averaged over 30 s. The Oxycon was calibrated before testing with both room air (20.93%O_2 and 0.03%CO_2) and a gas mixture (15.53% O_2 and 5.25%CO_2). The Oxycon was connected to a PC that calculated $\dot{V}O_2$ and $\dot{V}CO_2$ by using conventional equations (16). A telemetric heart rate monitor (Polar Vantage NV, Polar Electro Oy, Kempele, Finland) was used to record heart rate every 5 s and to identify HRpeak. Wpeak was defined as the sum of the final completed workload, plus the fraction of the partly completed workload performed before exhaustion.

TABLE 1. Subject characteristics.

Age (yrs)	Body mass (kg)	Height (cm)	Body fat (%)	Sum of 4 Skinfolds (mm)	$\dot{V}O_2$peak (L·min^{-1})	Wpeak (W)
24 ± 6	74.6 ± 6.9	179 ± 4	13.9 ± 2.2	31.5 ± 4.6	4.5 ± 0.2	350 ± 14

Group mean ages, weights, heights, body fat, and VO_2max measurements are all shown ± SD.

GE, DE, and GE were calculated from measures of energy expended, $\dot{V}O_2$ and work rate. DE was calculated as the reciprocal of the linear trend line joining the points on an energy expended versus work rate plot (6). Energy expended (EE) was calculated from the measures of $\dot{V}CO_2$ and $\dot{V}O_2$ obtained from the Oxycon and analyzed using the formula of Brouwer (2):

$$Energy\ Expenditure\ (J \cdot s^{-1}) =$$

$$[(3.869 \times \dot{V}O_2) + (1.195 \times \dot{V}CO_2)] \times (4.186/60) \times 1000$$

GE was calculated as the mean of all data collected in the last 2 min of every work rate over and including 95 W and until the respiratory exchange ratio exceeded 1.00.

$$GE(\%) = (Work\ Rate(W))/Energy\ Expended(J \cdot s^{-1}) \times 100\%$$

EC was calculated as the power output divided by the rate of oxygen consumption and expressed as $kJ \cdot L^{-1}$.

Statistics. GE, DE, GE, HRpeak, $\dot{V}O_2$peak, and Wpeak data from each individual test were averaged, and an overall mean for each of the three tests was obtained. The coefficients of variation (CVs) for each individual were calculated as the standard deviation expressed as a percentage of the mean (13). The 95% confidence interval was calculated as the upper confidence limit minus the lower (13).

Individual CV were calculated for each subject/variable combination. To obtain an overall CV, the mean of the CVs squared was calculated and the square root was taken of this value (13). The precision of the coefficients of variation is shown using 95% confidence limits to define the likely range of the true value in the population from which the sample was drawn.

All data is presented as mean ± SD. A repeated measures ANOVA was used to compare efficiency at different work rates and a Scheffe's *post hoc* test was used to locate the differences. A one-tailed Pearson product moment was used to calculate the correlation between GE, DE, EC, and $\dot{V}O_2$peak. A one-way ANOVA was used to examine the presence of an order effect.

RESULTS

All subjects completed all three tests. At the 60-W stage, efficiency was significantly lower ($F(12,5) = 113.8$, $P < 0.05$) compared with the other stages. The 60-W stage was regarded as warm-up and not further included in the analyses.

Table 2 illustrates the individual GE results of the 17 subjects. The mean GE was 19.8 ± 0.6%. The mean DE (Table 3) was 25.8 ± 1.5%, and the mean economy (Table 4) was 5.0 ± 0.1 $kJ \cdot L^{-1}$. The within-subject CV for GE, DE, and EC were 4.2%, 6.7%, and 3.3% with 95% confidence intervals of 3.2–6.4%, 5.0–10.0%, and 2.4–4.9%, respectively.

Although there was considerable intra-individual variation in GE, DE, and EC within the three tests, no order effect was observed (GE $F(2,48) = 1.60$; P = NS, DE $F(2,48) = 0.90$; P = NS, EC $F(2,48) = 0.14$; P = NS).

TABLE 2. Gross efficiency results of the three trials by subject.

Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Mean
Mean GE1 (%)	18.6	20.5	21.3	18.0	19.7	19.6	21.4	18.5	20.7	19.3	18.1	19.0	19.4	19.1	19.0	19.1	20.0	
Mean GE2 (%)	22.2	20.6	21.5	19.6	20.5	19.8	21.3	19.7	21.3	20.1	18.3	19.6	19.7	19.1	19.0	19.6	20.3	
Mean GE3 (%)	17.8	22.0	19.0	18.5	19.8	19.3	21.2	18.2	21.6	19.0	17.3	20.8	19.7	19.6	19.5	20.0	20.5	
Mean GE (%)	19.5	21.1	20.6	18.7	20.0	19.5	21.3	18.8	21.2	19.4	17.9	19.8	19.6	19.3	19.2	19.6	20.3	19.8
SD (%)	2.4	0.8	1.4	0.8	0.5	0.3	0.1	0.8	0.4	0.5	0.5	0.9	0.1	0.3	0.3	0.5	0.2	0.6
CV (%)	12.2	3.9	6.9	4.1	2.3	1.5	0.6	4.2	2.1	2.8	2.9	4.4	0.7	1.3	1.4	2.3	1.1	4.2
95% confidence intervals of CV (%)	9.1–48.5	2.9–5.9	5.2–10.5	3.1–6.3	1.7–3.5	1.1–2.2	0.4–0.9	3.1–6.4	1.6–3.2	2.1–4.3	2.2–4.5	3.3–6.7	0.6–1.1	1.0–2.0	1.1–2.2	1.7–3.5	0.8–1.6	3.2–6.4

No significant differences between trials 1, 2, and 3 were observed. The results of each subject can be seen in columns; mean data for each trial and variable are shown in rows.

TABLE 3. Delta efficiency results of the three trials by subject.

Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Mean
DE1 (%)	27.4	28.8	26.8	27.1	25.8	24.3	25.5	26.9	25.8	23.2	25.1	26 7	30.1	26.9	31.0	26.6	20.8	
DE2 (%)	23.1	21.7	26.5	21.9	23.7	24.3	25.4	26.0	27.3	24.2	27 1	25.6	26.1	28.4	28.9	29.3	22 8	
DE3 (%)	25.3	25.6	24.4	26.4	22.4	25.4	25.7	24.9	27.8	23.1	27.1	24.4	25.1	26.6	28.3	29.6	23.7	
Mean DE (%)	25.3	25.4	25.9	25.1	24.0	24.7	25.5	25.9	27.0	23.5	26.4	25.6	27.1	27.3	29.4	28.5	22.4	25.8
SD (%)	2.2	3.6	1.3	2.8	1.7	0.6	0.2	1.0	1.0	0.6	1.2	1.2	2.6	1.0	1.4	1.7	1.5	1.5
CV (%)	8.5	14.0	5.0	11.2	7.2	2.6	0.6	3.9	3.9	2.6	4.4	4.5	9.8	3 5	4.8	5.8	6.6	6.7
95% confidence intervals of CV (%)	6.3–13.0	10.4–21.3	3.8–7.7	8.4–17.1	5.3–10.9	1.9–3.9	0 4–0.9	2.9–5.9	2.9–5.9	1.9–3.9	3.3–6.6	3.4–6.8	7.3–14.9	2.6–5.4	3.6–7.3	4.3–8.8	4.9–10.1	5.0–10.0

No significant differences between trials 1, 2, and 3 were observed. The data are presented identically to table 2.

TABLE 4. Economy results of the three trials by subject.

Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Mean
EC1 (kJ·L^{-1})	4.4	4.7	5.4	4.8	4.9	5 2	5.3	4.8	5.1	5.2	4.8	5 1	5 0	4.9	5.3	5.1	4 2	
EC2 (kJ·L^{-1})	4.0	4.4	5.3	5.4	5.0	5 2	5.4	5.0	5.4	5.0	4.8	5.3	4 9	4.9	5.1	5.2	4 3	
EC3 (kJ·L^{-1})	4.7	4.7	5.0	5.2	5.1	5.0	5.4	4.8	5.5	4.9	4.6	5.3	4.9	5.0	5 2	5.4	4.4	
Mean EC (kJ·L^{-1})	4.4	4.6	5.2	5 1	5.0	5.1	5.4	4.9	5.3	5.0	4.7	5.2	4.9	5.0	5.2	5.2	4.3	5.0
SD (kJ·L^{-1})	0 3	0.2	0 2	0 3	0 1	0.1	0.1	0.1	0 2	0.1	0.1	0.1	0.0	0.1	0 1	0.2	0.1	0.1
CV %	7.6	3.3	3.9	5.3	2.1	2.2	1.0	2.3	3.4	2.6	2.3	2.2	0.9	1.3	1.9	3.6	2.2	3.3
95% confidence intervals of CV %	5.7–11.6	3.1–6.3	2.9–6.0	3.9–8.0	1.6–3.2	1.6–3.3	0.9–1 6	1 7–3.5	2.5–5.2	1.9–3.9	1.7–3.5	1.6–3.4	0.6–1 3	0.9–1.9	1.4–2.8	2.7–5.4	1.7–3.4	2 4–4.9

No significant differences between trials 1, 2, and 3 were observed The data are presented identically to table 2.

TABLE 5. Summary table of 770_2max shown both absolute and relative to body mass, maximal heart rate, and peak power output.

	Mean 1	Mean 2	Mean 3	Mean	SD	CV%	95% Confidence Intervals of CV
VO_2peak (ml·kg^{-1}·min^{-1})	61.4	62.4	61.8	61.9	2.4	5.7	4.3–8.6
VO_2peak (L·min^{-1})	4.50	4.60	4.45	4.5	0.2	4.4	3.3–6.6
HRpeak (bpm)	188	189	186	188	4	2.5	1.9–3.8
Wpeak (W)	342	358	356	350	14	5.6	4.2–8.4

Means and standard deviations are calculated from the individual tests and not of the overall test means.

As already mentioned, DE was calculated as the reciprocal of the gradient of the line passing through the points on an energy expended versus work rate plot. The validity of this estimation of DE can be found be examining the accuracy of the trend line. The mean R^2 value for the linear trend lines linking the points on the graphs was 0.993.

A significant but weak correlation was found between $\dot{V}O_2$peak and GE ($r = 0.491$; $P < 0.05$). No significant correlation was found between DE or economy and $\dot{V}O_2$peak ($r = 0.48$; $P > 0.05$ and $r = 0.067$; $P > 0.05$, respectively).

The variation in GE with work rate is illustrated in Figure 1. At 235 W, the GE was significantly greater ($\alpha < 0.05$) than the GE at 95 W, 130 W, and 165 W. In addition, the GE at 95 W and 165 W was found to be significantly different ($P < 0.05$) from that at 235 W. A polynomial trend line was calculated by the least squares method with the formula describing the relationship between workload and GE being $y = 0.0002x^2 + 0.0077x + 10.529$ ($R^2 = 0.991$). Of a possible 51 (17 subjects × 3 tests) completions of any one workload there were 51 at 95 W and 130 W, 47 at 200 W, 36 at 355 W, 27 at 270 W, and 10 at 305 W.

In Table 5, the means and within subject CV of $\dot{V}O_2$peak, HRpeak, and Wpeak are displayed, as well as the 95% confidence intervals. The CV for $\dot{V}O_2$peak (mL·kg^{-1} ·min^{-1}) was 5.7% similar to the CV for Wpeak (5.6%).

DISCUSSION

There is a growing interest in measures of work efficiency. For example, efficiency is believed to be an important factor in the development of obesity (28). It has also been suggested that the effect of weight loss programs is counteracted by an increase in efficiency, reducing the effectiveness of the program (19). Efficiency has also been linked to exercise performance (14,15). At present, there is very little conclusive information about the metabolic and physiological factors that will determine or influence efficiency, and surprisingly there is no information available about the magnitude of change in efficiency that can be detected using established procedures. Therefore, the main purpose of this study was to assess the reproducibility of GE, DE, and EC using a graded cycle ergometer test.

The results of this investigation show that a graded exercise test using 35-W increments and 3-min workload stages is a reproducible measure of both GE and economy. There was no significant learning effect across the tests, which can be inferred from the lack of an order effect in the mean result from each test. Although familiarization with the test protocol is generally advantageous, it seems as though that it was not necessary in this case. This may be due to many of the subjects being familiar with the ergometer and testing procedure before testing began. Values for GE and DE in the present study (Tables 2 and 3) were comparable to those in the literature in comparable subject populations (6,10,14,21,29,32). The coefficients of variation of GE (3.2–6.4%) and EC (2.4–4.9%) were smaller than that of DE (5.0–10.0%). These observations may have practical implications. For example, the smallest change in GE that can be detected would normally be the mean CV (3.2%) implying for example an improvement in GE from 20.0% to 20.6%. With DE it would be more difficult to detect small differences in efficiency. It is interesting that although it has been suggested that DE is the most valid estimate of muscular efficiency (6), it is not the most reliable measure. Possible reasons for this are addressed below. As described in the methods section, 95% confidence intervals define the likely range of the true value in the population from which the sample was drawn and are used here to describe the accuracy of the CV.

To date, the research into efficiency has mostly concentrated on identifying the variables that affect efficiency, with recent research using both GE and DE. However, it was observed that the variation of GE is approximately half that of DE, suggesting that smaller changes in efficiency can be detected in GE compared with DE. The reason for this difference in variation can only be speculated upon. It may arise from inaccuracies in the estimation of DE from the energy expenditure/work rate plot. However, this estimation relies on the accuracy of the linear regression line from which DE is calculated. Here, it was found that the mean R^2 of the linear regression lines used to calculate DE was 0.993, suggesting that the lines were an accurate representation of the relationship. It is also possible that errors arise from interpreting the relationship as linear when it is in fact curvilinear. This possibility is discussed in more detail below.

The low CV of EC indicates that this is also a reproducible measure. EC is defined as the rate of oxygen consumption per unit of power output, or in other words the amount of oxygen in L per unit of energy transferred to the cycle ergometer. Although EC is not often used in cycling, it may be very important in relation to exercise performance. This importance has been recognized for many years in runners (22). In running, EC is expressed as the rate of oxygen consumption at a constant submaximal running speed.

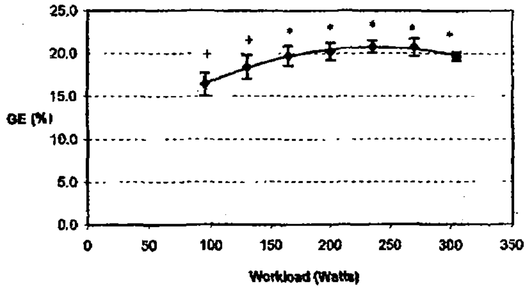

FIGURE 1—The change in gross efficiency with increasing workload. ◇ = mean total GE ± SD. The formula of the polynomial trend line is $y = 0.0002x^2 + 0.0077x + 10.529$ and the R^2 value is 0.991. * Significantly different from the efficiencies at 95 W and 130 W ($P < 0.05$). + Significantly different to the efficiency at 235 W ($P < 0.05$).

Research (5) has demonstrated that variations in EC can explain 65.4% of the variations in performance among a group of elite runners similar in $\dot{V}O_{2max}$. As already mentioned, the importance of EC in cycling has not been established but seems likely that the rate of oxygen consumption at a certain work rate is related to performance.

Figure 1 indicates that efficiency seems to be related to the exercise intensity and specifically improved at the higher work rates. The efficiency at 60 W was significantly lower than other stages and was therefore excluded from the calculations. It is likely that this is an artifact arising from the increased energy expenditure of the noncycling specific muscles needed to stabilize the body while pedalling against such a low resistance. It is also possible that a warm up period before the test began would have prepared the muscles before the exercise and increased the efficiency. Gaesser and Brooks (10), however, suggested that GE distorts the essentially linear relationship between work rate and energy expenditure to make it appear that efficiency increases with work rate. This distortion occurs due to the proportion of energy expenditure that is used to maintain homeostasis becoming smaller as total energy expenditure increases. For GE to increase at high work rates, energy expenditure must increase nonlinearly; this implies that the points on a work rate versus energy expended plot cannot be a straight line. However, the calculation of DE assumes this relationship. Therefore, no definition of efficiency is completely satisfactory as both GE and DE have flaws that are apparent during calculation. It is generally agreed that GE is a poor measure of the efficiency of muscular work (6,10,31). However, it has been suggested that GE is a better measure of whole body efficiency (3) and may also be more relevant from a practical point of view. It is therefore useful to use *both* GE and DE to assess an athlete's efficiency.

We found no correlation between DE, EC. and $\dot{V}O_{2max}$. However, we did find a weak correlation between $\dot{V}O_{2max}$ and GE, suggesting that a high aerobic capacity is linked with high efficiency, which seems to be in contrast to other research in this area (21,31). The results do concur with those reported by Kunstlinger et al. (18), who, although not looking directly at efficiency, suggested a link between cycling experience and GE. The control group in that study, however, was comprised of noncyclists and differences in technique could well have led to the effect. It is possible that this explanation may well apply in this case. Carefully planned and executed studies, using an independent measures design and specifically looking at the effect of a training regimen on cycling efficiency, still need to be conducted before a measurable link between training and efficiency can be discounted. In addition, there are indications that diet (25), genetics (4), overtraining (1), and fiber type (6) can also have an effect on efficiency. Because subjects were asked to refrain from strenuous exercise the day preceding each test and to maintain their normal diet, it is unlikely that these factors have influenced the results.

The CV determined for $\dot{V}O_2$peak ($L \cdot min^{-1}$; 3.7–7.6%) is smaller that that (4.20–11.35%) found by Kuipers et al. (17). They (17) obtained measurements over 9–12 months, and it is possible that the greater variation is due to the longer time period and the resulting greater exposure to extraneous variables. We found similar variation, however, in Wpeak (CV = 3–6%) to that found by Kuipers et al. (17) (2.95–6.83%), which would tend to discount that explanation. It is likely that the differences arise due to the confounding variables. The variation in HRpeak was smaller (1–3%) than that of Wpeak and comparable to previous reports (17).

In conclusion, a graded exercise test using 35-W increments and 3-min steps is a reproducible measure of both GE and economy. The day-to-day variability of DE with this test was somewhat greater.

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