Muscle Efficiency Improves over Time in World-Class Cyclists

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ABSTRACT

SANTALLA, A., J. NARANJO, and N. TERRADOS. Muscle Efficiency Improves over Time in World-Class Cyclists. *Med. Sci. Sports Exerc.*, Vol. 41, No. 5, pp. 1096–1101, 2009. **Purpose**: To determine the change in muscular efficiency in world-class professional cyclists during years of training/competition. **Methods**: Twelve male world-class professional road cyclists (mean ± SD: age = 22.6 ± 3.8 yr and $\dot{V}O_{2max}$ = 75.5 ± 3.3 mL·kg^{-1}·min^{-1}) performed an incremental test (starting at 100 W with workload increases of 50 W every 4-min interval until volitional exhaustion) before and after a five-season period. Delta efficiency (DE) was calculated from 100 W to that power output (PO) in which the RER was 1. **Results**: DE increased ($P < 0.01$) from 23.61 ± 2.78% to 26.97 ± 3.7% from the first to the fifth year, whereas $\dot{V}O_{2max}$ showed no significant increase. A significant inverse correlation ($r = -0.620$; $P = 0.032$) between DE and $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1}) was found in the fifth year, whereas no significant correlation between these variables was found in the first year. A significant inverse correlation ($r = -0.63$; $P = 0.029$) was found between the increase percentage in DE (ΔDE) and $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1}) in the fifth year, whereas no significant correlation was found between these variables in the first year. **Conclusion**: The results show an increase in DE in world-class professional cyclists during a five-season training/competition period, without significant variations in $\dot{V}O_{2max}$. The results also suggest that the increase in DE could be a possible way for performance compensation, especially in those subjects with lower $\dot{V}O_{2max}$. **Key Words:** PROFESSIONAL CYCLING, DELTA EFFICIENCY, CYCLE ERGOMETRY, POWER OUTPUT

Efficiency has been described as a physiological determinant of performance in cycling (4,8,16,20). Between two ways of measuring efficiency, mechanical or gross efficiency (GE) and delta efficiency (DE), it is DE, understood as the ratio of the change in accomplished work (kcal·min^{-1}) to the change in expended energy (kcal·min^{-1}) (8), which has been postulated to be the most valid indicator/predictive variable of muscular efficiency in road cycling (4,8,16). This is because in DE, the change in energy expended per minute is calculated only on the basis of the change in work accomplished per minute, whereas the influence of metabolic processes not contributing to work performance, such as the basal metabolic rate (8,12), the work of stabilizing muscles, and the work cost of respiratory muscles (39) and the movement cost of the lower limbs of the body (29,35), is eliminated. In this sense, DE may be more valid for understanding changes in muscle efficiency.

This is especially relevant because a correlation between DE and the percentage of Type I muscular fibers has been described (8), and the relationship between this percentage and the kinetic of oxygen uptake ($\dot{V}O_2$) (21) is known. Pedal cadence (3,11,24,29) and age (27) have been postulated too as factors responsible for muscle efficiency.

Accumulated training along the years is one of the variables whose relative influence on DE has recently generated controversy. An increase in $\dot{V}O_2$ kinetics above the blood lactate threshold (LT) has been described with endurance training in both constant-load (33,38) and incremental tests (21), but DE ranges only from 24% to 26% regardless of cyclists' physical fitness or cycling experience (26). It is known that training may alter physiological and biomechanical factors in humans (5), and plasticity may extend to gross mechanical efficiency because it extends to both the percentage of fibers (18) and the change in the recruitment model (34). Hence, it seems surprising that no effects of years of training on DE have been clearly described (2,7,32). In that sense, it would be possible that the studies on changes in efficiency are limited by the fact that the data are cross-sectional.

Böning et al. (2) and Nickleberry et al. (32) did not find any differences in DE when recreational and professional cyclists were compared at similar work and pedal rate. This suggests that training volume does not seem to be a decisive

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factor in DE. Similar results have also been obtained in other studies (25,36). Moseley et al. (31) do not describe any significant differences in incremental tests between world-class professional cyclists (classified as the top 200 in the International Cycling Union (ICU) ranking) and nonexperienced cyclists. On the other hand, an inverse relationship between efficiency—measured as GE—and maximal oxygen uptake ($\dot{V}O_{2max}$) during constant-load cycling has been described in professional cyclists by other authors (23).

It is surprising that the different studies published about DE seem not to have reached a consensus on the effect of training. Perhaps the cross-sectional nature of all these studies is one of the reasons why no changes in DE have been found despite the existence of changes on key factors of $\dot{V}O_2$ kinetics (20), such as motor unit recruitment (13) and the distribution percentage of Type IIx fibers (22).

A case report on efficiency changes as the cyclist matures, carried out on seven-time Tour de France champion Lance Armstrong, has been published (6). This study describes an increase in both DE and GE throughout this cyclist's professional career and suggests the possibility that such increase may be responsible, at least in part, for the cyclist's sport success. One of the causes suggested by the authors is a change in myosin type of the muscle after years of intense training and competition. This publication has evoked considerable debate within the scientific community (28).

Although longitudinal studies would give more information, all studies published to date have a cross-sectional design, comparing cyclists of all categories and not always elite cyclists. We have no evidence of longitudinal studies focused on the changes in DE during several years of training/competition in world-class professional cyclists. The aim of this work was to study the effect of accumulated years of training and competition on muscular efficiency in world-class cyclists. We hypothesize that DE may change over time in elite world-class cyclists.

METHODS

Subjects. Of a group of 42 male world-class professional cyclists, physiologically tested at the same period of the season in the same laboratory for at least five seasons (with a minimum of four tests, including the first and the fifth years), those who had annually participated in at least one of the 3-wk stage races (Giro d'Italia, Tour de France, and Vuelta a España) were selected for this study. Twelve world-class professional cyclists (mean ± SD: starting age = 22.6 ± 3.8 yr, height = 177.3 ± 5.5, body weight = 68.9 ± 5.5 kg, and $\dot{V}O_{2max}$ = 75.5 ± 3.3 mL·kg^{-1}·min^{-1}) met the selection requirements and were chosen as subjects. These specific requirements were selected to guarantee that all the different variables had the same impact conditions. Some of the subjects were considered among the best cyclists on the world (one winner of the Tour de France, one winner of the Vuelta a España and first in the annual ICU world ranking, one three-time Tour de France Podium, two Vuelta a España podia, one Junior World Time Trial Champion, and two 1-wk stages race winners). Before the physiological laboratory testing, the subjects gave their written consent for the tests. The ethics committee of the Unidad Regional de Medicina Deportiva del Principado de Asturias approved this study.

Exercise test. Subjects were tested annually, and only the data from the first and fifth seasons were used for analysis. They performed an incremental test on the same electromagnetic braked cycle ergometer at the same week and at the same period of the competitive season. This ergometer allowed the subject to choose his own pedal frequency and to adopt a position similar to that on his bicycle (Orion S.T.E., Toulouse, France). The tests were always conducted during the first phase of the cyclists' competitive season (in January and February). The distances and dimensions for saddle, handlebars, and connecting rod were monitored and remained constant during the entire test period. The test began at a power output (PO) of 100 W, after which PO was increased by 50 W every 4 min until exhaustion. This exercise protocol had already been used in previous research work (10). Ventilation and respiratory gases were measured, and the highest 30-s $\dot{V}O_2$ value was considered as $\dot{V}O_{2max}$. The participants freely chose their pedaling cadence, which generally ranged from 77 to 115 revolutions per min (rpm). HR was monitored using radiotelemetry (Sport tester PE 4000; Polar, Kempele, Finland), whereas $\dot{V}O_2$, RER, and other ventilation variables were measured breath by breath (b × b) using a gas analyzer (Vmax 29; Sensormedics, Yorba Linda, CA), which was calibrated before every exercise session. During the data collection period (five seasons), neither the cycle ergometer nor the gas analyzer was replaced, and all the equipment passed the maintenance testing recommended by the manufacturers. The ergometer was calibrated by the manufacturers annually. In addition, all the tests were performed under similar ambient temperature conditions (20–24°C and 45%–65% of relative humidity).

Efficiency calculation. Mechanical gross efficiency was calculated as the ratio of work accomplished per minute (watts converted to kilocalories per minute) and the energy cost or energy expended per minute (measured in kilocalories per minute). For estimation of the work accomplished, we used the conversion factor 69.7 W·kcal^{-1}·min^{-1}, whereas for estimation of energy cost, we used a regression equation

TABLE 1. Characteristics of the sample: physiological and anthropometric variables registered in the incremental test performed at the same week and at the same period of the season during the first and fifth years of monitoring.

	First Year	Fifth Year	Statistical Significance
Height (cm)	177.3 ± 5.5	177.3 ± 5.5	n.s.
Weight (kg)	68.9 ± 5.5	68.9 ± 6.3	n.s.
Age (yr)	22.6 ± 3.8	26.6 ± 3.8	—
$\dot{V}O_{2max}$ (mL·min^{-1})	5189.3 ± 481	5114.4 ± 329	n.s.
$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	75.5 ± 6.3	75.3 ± 10.4	n.s.
Cadence (rpm)	93.1 ± 9.4	91.7 ± 8.8	n.s.

Values are expressed as mean ± SD.

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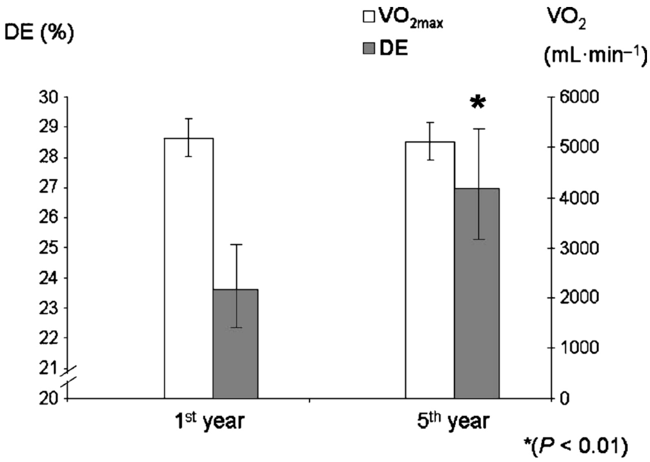

FIGURE 1—Comparison of DE and $\dot{V}O_{2max}$ between the first and fifth years of monitoring (values are expressed as mean ± SD). DE values were obtained from a 100-W load to a power output equivalent to an RER = 1. *P < 0.01, comparing first with fifth year.

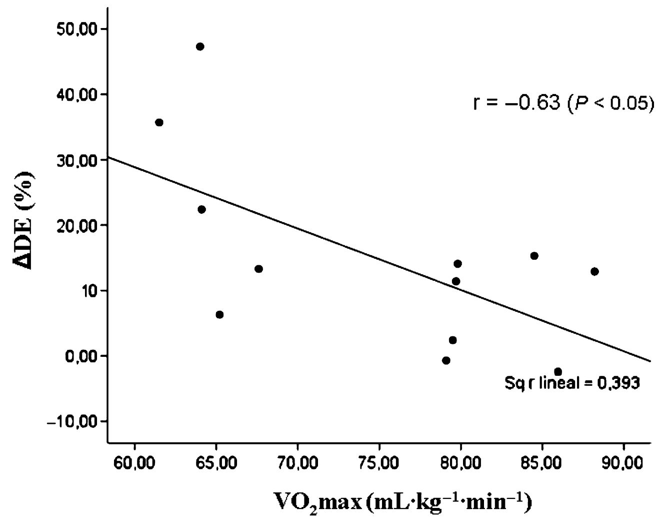

FIGURE 3—Relationship between the increase in delta efficiency (DE) during the 5-yr period and $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1}) in the fifth year.

based on the oxygen thermal equivalent for nonprotein respiratory quotient: cost (kcal·min^{-1}) = $\dot{V}O_2$ (1.2341RER + 3.8124) (29). For this calculation, we used the mean values measured during the last 30 s of each of the workload. DE was calculated as the inverse of the slope in the linear regression ($y = ax + b$), where y is the rate of expended energy (kcal·min^{-1}) and x is the rate of accomplished work (kcal·min^{-1}) (8). This calculation was made from the end of the first workload (100 W) until the power output (PO) where the RER was 1, which typically occurred between 350 and 400 W.

Statistical analysis. A Student's t-test was used for paired data to compare the DE mean values in the first and fifth years and the different anthropometric/ergospirometric parameters. Correlation coefficients were calculated to determine the possible relationships between DE values (initial and final values and variations in the latter during a five-season period) and the rest of the registered parameters. The level of statistical significance was established at $P < 0.05$. The statistical software used was SPSS version 14.0 (SPSS Inc., Chicago, IL).

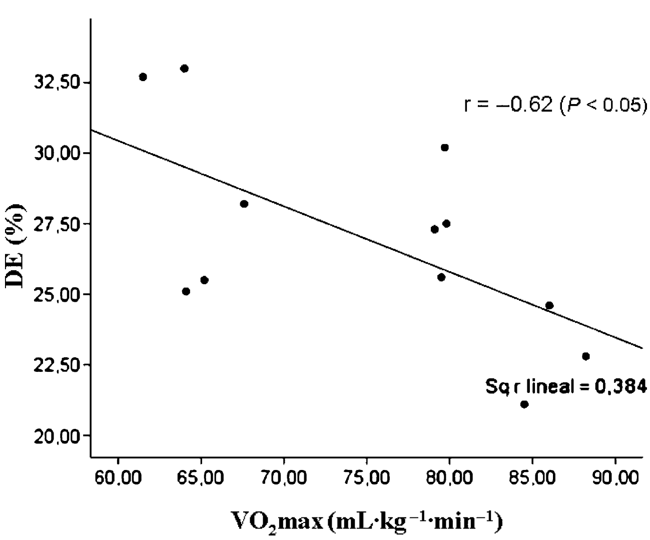

FIGURE 2—Relationship between delta efficiency (DE) and $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1}) in the fifth year.

RESULTS

Mean ± SD values of height (cm), body weight (kg), age (yr), $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1} and mL·min^{-1}), and pedal cadence (rpm) at the initial (first year) and final phases (fifth year) are described in Table 1.

Mean ± SD DE increased from 23.61 ± 2.78% to 26.97 ± 3.7% ($P < 0.01$) from the first to the fifth year, whereas $\dot{V}O_{2max}$ showed no significant increase either in absolute or in relative values (Fig. 1).

An inverse relationship ($r = -0.620$; $P = 0.032$) between DE and $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1}) was found in the second trial (fifth year; Fig. 2). No significant correlation between these variables was found in the first trial (first year).

An inverse relationship ($r = -0.63$; $P = 0.029$) was found between the increase in DE (ΔDE) (%) during the five-season period and $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1}) in the second trial (fifth year; Fig. 3). No significant correlation was found between these variables in the first trial (first year).

DISCUSSION

The most important finding of this study is that DE increased in world-class professional cyclists during a five-season training/competition period, whereas $\dot{V}O_{2max}$ did not change. Until present, the only longitudinal study describing an increase in DE during the world-class cyclists' training/competition period has been Coyle's case report (6). The rest of the studies, all of them with cross-sectional design, compared cyclists of different competitive categories or compared cyclists with subjects who had no experience in cycling. Although some of these studies have been performed on professional cyclists (2,6,19,26,32), only a few of them have been done with world-class professional cyclists, that is, regular participants in the three 3-wk premiere road bicycle stage races, with several years of experience and/or have reached an important position in the ICU world ranking (6,23,31). This limits the comparison among the studies.

In our study, DE increased from 23.61 ± 2.78% to 26.97 ± 3.7% (ΔDE = 14.83 ± 14.6%) in a five-season period. These values are higher than those described by Moseley et al. (31) (21.2 ± 0.5%) obtained through a similar but not identical incremental protocol. Our subjects did not cycle at a predetermined cadence but at their own training cadence. Nevertheless, both experiments reported very similar $\dot{V}O_{2max}$ values: 5.19 ± 0.48 L·min^{-1} (75.5 ± 0.6 mL·kg^{-1}·min^{-1}) versus 5.32 ± 0.12 L·min^{-1} (75.2 ± 1.0 mL·kg^{-1}·min^{-1}) obtained by Moseley et al. (31). Although the cadence may have influenced the results, the difference in DE may be mainly due to the different level of the subjects. Although the values of $\dot{V}O_{2max}$ were similar, the subjects could have different competitive level. It is their athletic achievements that really differentiate the competitive level of "world-class" cyclists. In our study, subjects were among the best cyclists in the world because their athletic achievements include podium placements and victories in the final general classification of both the Tour de France and the Vuelta a España, time trial world champions, and stage victories in the three foremost road stage races. Moseley et al. (31) selected only cyclists who had been classified within the top 200 in the ICU ranking but did not describe the subjects' athletic achievements. For this reason, despite of having been described as "world-class" cyclists, those subjects could not have a similar competitive level as the subjects of the present study.

On the other hand, and combined with this possible difference in the competitive level of the samples, the subjects' experience in world-class cycling may considerably affect DE and its change over time. This DE increase (with no variation in $\dot{V}O_{2max}$) has already been described during a 7-yr period in a world-class professional cyclist (6). However, it should be remarked that this study was a case report, and therefore, it is not possible to extrapolate the conclusions obtained.

Given the direct correlation between Type I fibers and DE (8), the inverse correlation described between the percentage of Type IIx fibers and the slope in $\dot{V}O_2$ kinetics in elite professional cyclists (21) and the ability of world-class professional cyclists to develop higher power output with smaller slopes in $\dot{V}O_2$ kinetics when compared with younger cyclists (19), it would seem logical to believe that this muscle plasticity could affect to the muscular efficiency. In their study, Coyle et al. (8) calculated the percentage of Types I and II muscle fibers from muscular biopsies of the vastus lateralis of 19 well-trained cyclists and calculated their DE and GE at 50% and 70% $\dot{V}O_{2max}$, respectively. The study reports a strong positive correlation (r = 0.85) between the percentage of Type I fibers and DE (ranging from 18% to 25.6%). Similarly, the study also describes a positive correlation (r = 0.75) between the percentage of Type I fibers and GE. Animal (9) and human studies (1,17,22) reveal that Type IIx fibers are less efficient than Type I for any workload. In addition, the increase in mitochondrial efficiency has also been suggested as a possible mechanism for the increase in efficiency in humans (14). Gore et al. (14) have recently described 3%–10% improvements in efficiency in athletes in nine studies on hypoxic training. The uncoupling protein 3 (UCP3), whose role in the efficiency of mitochondrial seems clear, descends with hypoxic training (14). This, coupled with the fact that a decline of UCP3 has been associated with better GE in cyclists (30), makes it possible to think that an increase in the mitochondrial efficiency could explain, at least in part, the increase in efficiency.

Perhaps the suggestions made by Hansen and Sjogaard (15) regarding fiber type's recruitment pattern (e.g., a shift toward more active ST muscle fibers and a more efficient fibers recruitment, with a better muscular efficiency) could also explain this.

The possible change in the percentage of muscle fibers and/or recruitment pattern and/or their mitochondrial efficiency produced by the accumulated years of training/racing could explain, at least in part, the increase in DE. Nevertheless, as in other studies conducted on world-class cyclists, the absence of muscle biopsies is a methodological limitation for our work. Although the age increased during the period of the study, it does not seem to affect DE. Differences found in studies comparing children and adults are due to anthropometric factors (especially the length of their lower limbs) (27). In this regard, the height values of our subjects remained unchanged.

One of the most controversial aspects of the studies on muscular efficiency in cyclists has been the methodological design used. The disparity in the period of the season in the different tests and the changes on the cycle ergometer (or its components) during the study period have become the object of discussion (28). In our study, neither the cycle ergometer (nor its components) nor the gas analyzer was replaced during the data collection period, and all the equipment passed the maintenance testing recommended by the manufacturers. Likewise, tests were made at the same periods of the season.

Our second main finding was that, after at least 5 yr of elite professional cycling, DE was inversely correlated (r = −0.620; P = 0.032) with $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1}) in world-class cyclists. Lucıa et al. (23) described the inverse correlation (r = −0.64) between GE and $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1}) in constant-load tests in this type of cyclists. Because the authors did not have values from previous tests, they hypothesized that cyclists may compensate low $\dot{V}O_{2max}$ with high GE to continue as elite professional cyclists. The results from Lucıa et al. (23) were an object of debate (31).

APPLIED SCIENCES

Calculating DE according to McDaniel et al. (29), our results describe an inverse correlation between DE and $\dot{V}O_{2max}$ in the fifth year, a relationship similar to that which is described by Lucıa et al. (23) between GE and $\dot{V}O_{2max}$. Nevertheless, values obtained at the initial test of the period show no correlation between these variables, which is similar to the one described by Moseley et al. (31). This suggests that the different values from both studies may be due, at least in part, to both the cyclists' different competitive levels and a different number of accumulated years of training/competition rather than to the different methodological approaches of the previously mentioned studies. In addition, another of our findings is in the inverse correlation between DE variation (ΔDE) and $\dot{V}O_{2max}$ ($r = -0.63$). The subjects with the lowest $\dot{V}O_{2max}$ had the largest increase in DE during the period studied. This shows how the increase in muscular efficiency could compensate for a low $\dot{V}O_{2max}$, and it allows the world-class cyclists to continue at a high competitive level or even an innate physiological response to training and competition that allows an athlete to achieve better results.

Despite the fact that we have not been able to compare the inverse correlations between GE and $\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) (23) with DE and $\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) found in the present study, both correlations reveal a possible compensation of $\dot{V}O_{2max}$ with muscular efficiency. Between the two different calculation methods (DE and GE), DE estimation isolates the influence of metabolic processes not contributing to work performance, such as basal metabolic rate (8,12,37), the work of stabilizing muscles and the work cost of respiratory muscles (39), and the movement cost of the lower limbs (29,35), permitting a more accurate estimation of the energy cost of the muscles involved in pedaling. This could explain why the influence of muscular adaptations on muscular efficiency suggested (6,23) should be more clearly detected in DE, as done in our study.

In summary, the results from our study show an increase in DE in world-class professional cyclists during a five-season training/competition period, without significant variations in $\dot{V}O_{2max}$. There was an inverse correlation between DE and $\dot{V}O_{2max}$ during the five-season period. This fact and the inverse correlation found between the percentage of ΔDE and $\dot{V}O_{2max}$ suggest that the increase in DE could be a way to compensate $\dot{V}O_{2max}$ values and thus to maintain a high competitive level, especially in subjects with lower $\dot{V}O_{2max}$.

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APPLIED SCIENCES

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