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Journal of Applied Physiology 99:1628-1629, 2005. doi:10.1152/jappphysiol.00507.2005

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The following is the abstract of the article discussed in the subsequent letter:

Coyle EF. Improved muscular efficiency displayed as Tour de France champion matures. *J Appl Physiol* 98: 2191–2196, 2005. First published March 17, 2005; doi:10.1152/jappphysiol.00507.2005.— This case describes the physiological maturation from ages 21 to 28 yr of the bicyclist who has now become the six-time consecutive Grand Champion of the Tour de France, at ages 27–32 yr. Maximal oxygen uptake ($\dot{V}O_{2\max}$) in the trained state remained at ~ 6 l/min, lean body weight remained at ~ 70 kg, and maximal heart rate declined from 207 to 200 beats/min. Blood lactate threshold was typical of competitive cyclists in that it occurred at 76–85% $\dot{V}O_{2\max}$, yet maximal blood lactate concentration was remarkably low in the trained state. It appears that an 8% improvement in muscular efficiency and thus power production when cycling at a given oxygen uptake ($\dot{V}O_2$) is the characteristic that improved most as this athlete matured from ages 21 to 28 yr. It is noteworthy that at age 25 yr, this champion developed advanced cancer, requiring surgeries and chemotherapy. During the months leading up to each of his Tour de France victories, he reduced body weight and body fat by 4–7 kg (i.e., $\sim 7\%$). Therefore, over the 7-yr period, an improvement in muscular efficiency and reduced body fat contributed equally to a remarkable 18% improvement in his steady-state power per kilogram body weight when cycling at a given $\dot{V}O_2$ (e.g., 5 l/min). It is hypothesized that the improved muscular efficiency probably reflects changes in muscle myosin type stimulated from years of training intensely for 3–6 h on most days.

Has Armstrong’s cycle efficiency improved?

To the Editor: The concept that extensive endurance training improves cycling efficiency is intuitively appealing but not well supported by the literature. Recently, Coyle (1) has published efficiency data from Tour de France Champion, Lance Armstrong. In this case study Coyle concluded that “the physiological factor most relevant to performance improvement as he matured over the 7-yr period from ages 21 to 28 yr was an 8% improvement in muscular efficiency when cycling” (1). Case studies documenting adaptations in truly elite endurance athletes are important (3); however, we believe Coyle’s case study is insufficient to support his conclusions because of limitations in study design and methodology.

Timing of testing sessions. Armstrong was tested five times over a period of 7 yr. Only the first and last test occurred during the same month (November), making it difficult to distinguish seasonal effects from maturation effects. Unfortunately, Armstrong’s fitness data within 3 mo of racing a Tour de France tour is not reported. The majority of the improvement in gross cycling efficiency (GE) occurred after January 1993 (21.6%) and before August 1997 (22.7%), 8 mo after cancer treatment. Consequently, if there were real changes in GE it becomes difficult to distinguish whether the improvements in GE are due to cancer treatment or important aspects of training (e.g., training load, altitude training, high-cadence training, time-trial training, or resistance training).

Accuracy and reliability of efficiency. Coyle does not present data documenting the accuracy and reliability of the techniques used to calculate cycling efficiency (oxygen uptake, carbon dioxide production, and power output). Friction-braked bicycle ergometers have been shown to be inaccurate when dynamically calibrated (4). Previous research has reported that Monark ergometers tend to underestimate power output by ~ 2 –8% (4). If Coyle’s Monark ergometer was inaccurate, then

Armstrong’s actual GE before winning his first Tour de France may have been ~ 19 –21%, values similar to those reported for recreational cyclists (5). Also of concern is the observation that the accuracy of Monark ergometers can change with age (4). Without routine assessment of accuracy with a dynamic calibration rig, it is difficult to know whether accuracy of the Monark used in Coyle’s study changed over the 7-yr period of data collection.

Were all tests performed on same ergometer? The terminology used by Coyle to describe the “same Monark ergometer (model 819) used for all cycle testing” is confusing. In the METHODS section, Coyle states that “the calibrated ergometer was set in the constant power mode” and in the DISCUSSION section that there was “a progressive loss of pedal cadence at constant power during the 30–60 s before exhaustion.” Although we are unaware of a constant power mode for Monark (model 819) ergometers, this mode of operation is commonly used with a Lode electromagnetic ergometer. A Lode ergometer has been used in Coyle’s laboratory (2). It is possible that either inappropriate terminology was used in the METHODS section or Armstrong was tested on two different types of ergometers.

Is efficiency responsible for success? Without the appropriate data, Coyle is left to speculate that, during the Tour de France tours (1999–2004), Lance possessed a maximal oxygen uptake ($\dot{V}O_{2\max}$) of ~ 6.1 l/min (based on the September 1993 testing session) and a body mass of ~ 72 kg (based on “his reported body weight”) and therefore a relative $\dot{V}O_{2\max}$ of 85 ml·kg⁻¹·min⁻¹. These estimations suggest that efficiency improved (21.2–23.1%; $\sim 9\%$), while $\dot{V}O_{2\max}$ rose (70–85 ml·kg⁻¹·min⁻¹; $\sim 21\%$ increase) and body mass fell (from 78.9 to 72.0 kg; $\sim 9\%$ decrease). In contrast to Coyle’s conclusions, it appears that conventional physiological adaptations to modifications in diet (loss in body mass) and training (gains in aerobic power) may be equally, if not more, important to Armstrong’s performance than the 9% improvements in cycling efficiency.

In summary, although great insight into human physiology can be gained from carefully controlled examinations of elite athletes, poor experimental design and methodology can lead to inappropriate conclusions, which in the case of a sporting hero can quickly become more hype than fact. Coyle’s data supporting the assumption that training can improve cycling efficiency in an elite cyclist are not compelling. It appears that other more conventional explanations describing why Armstrong is such a successful cyclist may be equally tenable.

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REPLY

To the Editor: I appreciate this opportunity to answer the four points and address the terminology that Martin et al. find “confusing” (point 3).

1) *Point 1: Timing of testing sessions.* I agree that it is not possible to distinguish what aspects of Armstrong’s training over the 7-yr period were related to his improved gross efficiency. Thus it was not discussed (4). Again, it can only be pointed out that he continued to train and his efficiency improved. Because the first measure in 1992 and the last measure in 1997 were both made in November when Armstrong’s training was similar, the most appropriate design was indeed used to control for the possibility of seasonal variations in efficiency. The idea that cancer or chemotherapy might have improved Armstrong’s efficiency cannot be determined from these data.

2) *Point 2: Accuracy and reliability of efficiency.* Oxygen uptake ($\dot{V}O_2$) and carbon dioxide production displayed a coefficient of variation of 0.87 and 0.92%, respectively, when measured on eight separate weekly occasions in a group of competitive cyclists in 1994 (6). Furthermore, the range (high minus low) of $\dot{V}O_2$ during these eight separate bouts averaged ± 0.08 l/min (6). The point that bicycle ergometers can be inaccurate is well taken and appreciated. The Monark ergometer was chosen because it can be and was statically calibrated for each test. Martin et al. raise the possibility that the calculation of efficiency changed because of Monark ergometer aging instead of Armstrong aging (i.e., maturation). First of all, the mechanical components of Monark ergometer were kept in good condition with the regular cleaning and maintenance of the friction belt, flywheel, drive chain, and bearings, and thus, according to Maxwell et al. (8), it should not have “aged” significantly. Second, an “aging ergometer” according to Maxwell et al. will raise the oxygen cost and thus lower efficiency, which is the exact opposite of what was observed in Armstrong, who increased efficiency with age. The best dynamic calibration of the Monark 819 ergometer in my experience is derived when a pedal dynamometer is compared with simultaneous integration of forces and velocity of the flywheel. This dynamic calibration was performed on this exact “same” Monark ergometer using elite cyclists as subjects (3, 7). It was observed that ergometer power outputs between 20 and 400 W agreed with the right pedal dynamometer with a range of $\pm 3\%$.

It should be noted that our references to “a specially designed ergometer” (3, 7) include continuous and integrated measurement of the Monark pendulum displacement force using a potentiometer with a reliable measurement accuracy of ± 0.4 N. Furthermore, cycling cadence was measured (± 0.18 rpm) continuously throughout each pedal revolution (3, 7).

3) *Point 3: Were all test performed on the same ergometer?* All the data presented on Armstrong in this manuscript (4) were indeed collected from the “same” ergometer (i.e., only one unit used). Monark did indeed manufacture an ergometer (819) in the 1980s that possessed electronics that integrated cadence and force in order to hold power constant. I hope this addresses the suspicions. For what it is worth, the electronic circuitry of our 819 ergometer became nonrepairable as did our system for measuring indirect calorimetry. However, Armstrong is still going strong, albeit with a few repairs.

4) *Point 4: Is efficiency responsible for success?* Improved mechanical efficiency and power (watts) accounted for approximately one-half of Armstrong’s improvement (i.e., 8–9%), and an 8–9% reduction of body weight (kilograms) accounted for the other one-half (4). Thus watts per kilogram increased by 18%. Speculation about maximal $\dot{V}O_2$ ($\dot{V}O_{2\max}$) during the Tour de France is not needed to calculate watts per kilogram. The notion that endurance performance is related only to $\dot{V}O_{2\max}$ was conventional long ago (5), and Martin et al. might find enlightenment by considering models that also integrate submaximal muscle stress (e.g., lactate threshold) and performance power or velocity (1, 2).

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