

In Professional Road Cyclists, Low Pedaling Cadences Are Less Efficient

ALEJANDRO LUCIA¹, ALEJANDRO F. SAN JUAN¹, MANUEL MONTILLA¹, SILVIA CAÑETE¹, ALFREDO SANTALLA², CONRAD EARNEST³, and MARGARITA PÉREZ¹

¹Exercise Physiology Laboratory, European University of Madrid, Madrid, SPAIN; ²University Alphonse X, Madrid, SPAIN; and ³Cooper Institute Center for Human Performance and Nutrition Research, Dallas, TX

ABSTRACT

LUCIA, A., A. F. SAN JUAN, M. MONTILLA, S. CAÑETE, A. SANTALLA, C. EARNEST, and M. PÉREZ. In Professional Road Cyclists, Low Pedaling Cadences Are Less Efficient. *Med. Sci. Sports Exerc.*, Vol. 36, No. 6, pp. 1048–1054, 2004. **Purpose:** To determine the effects of changes in pedaling frequency on the gross efficiency (GE) and other physiological variables (oxygen uptake ($\dot{V}O_2$), HR, lactate, pH, ventilation, motor unit recruitment estimated by EMG) of professional cyclists while generating high power outputs (PO). **Methods:** Following a counterbalanced, cross-over design, eight professional cyclists (age (mean \pm SD): 26 ± 2 yr, $\dot{V}O_{2max}$: 74.0 ± 5.7 mL \cdot kg⁻¹ \cdot min⁻¹) performed three 6-min bouts at a fixed PO (mean of 366 ± 37 W) and at a cadence of 60, 80, and 100 rpm. **Results:** Values of GE averaged 22.4 ± 1.7 , 23.6 ± 1.8 and $24.2 \pm 2.0\%$ at 60, 80, and 100 rpm, respectively. Mean GE at 100 rpm was significantly higher than at 60 rpm ($P < 0.05$). Similarly, mean values of $\dot{V}O_2$, HR, rates of perceived exertion (RPE), lactate and normalized root-mean square EMG (rms-EMG) in both *vastus lateralis* and *gluteus maximum* muscles decreased at increasing cadences. **Conclusions:** In professional road cyclists riding at high PO, GE/economy improves at increasing pedaling cadences. **Key Words:** POWER OUTPUT, GROSS EFFICIENCY, EMG, CYCLING, PERFORMANCE

Numerous studies have determined the effects of changes in pedaling cadence on the economy and/or gross efficiency of cyclists and noncyclists (e.g., 3,5,6,9,24,30). Overall, it could be generalized that, during laboratory tests at constant power outputs (PO) (usually ≤ 200 W and consistently ≤ 350 W), pedaling at low rates (~ 50 – 70 rpm) results in improved economy (i.e., lower oxygen uptake ($\dot{V}O_2$), as economy is the $\dot{V}O_2$ required to sustain a given PO) than pedaling at higher rates (>90 rpm). However, those individuals ideally interested in optimizing their cadence to make it more economical/efficient (that is, elite cyclists and especially professional ones) are able to generate much higher PO than those utilized in previous research in the field. During the most important phases of professional road cycling races, riders are often required to generate PO above 350 W (19).

Although there are recent reports on the gross efficiency of professional cyclists able to generate PO over 350 W for long time periods (20 or more min) (17,21), to the best of our knowledge, there are no data on how pedaling cadence could alter this variable in these professional athletes. Some caution is required when trying to extrapolate the findings of previous research with noncyclists or cyclists who are not professional to professional ones. The latter exhibit unique physiological adaptations, for example, considerably higher economy/efficiency at high PO compared with well-trained, amateur cyclists (21,22). On the other hand, it has been shown that the most economical of cadences tend to increase with absolute PO (3,7,15,28). For instance, Coast and Welch (7) showed that the cadences eliciting the lowest $\dot{V}O_2$ at 100 and 330 W were 50 and 80 rpm, respectively. Thus, it should be kept in mind that absolute PO is a key factor to examine when studying cadence optimization and precludes any simple answer to the question.

In this paper, we examine the effects of changes in pedaling frequency on the gross efficiency and $\dot{V}O_2$ of professional cyclists while generating high PO. Based on the results of previous research that has shown that 1) at high PO, muscle activation decreases with cadence, that is, lowest myoelectrical activity at ~ 100 rpm (23), and 2) the most economical of cadences tends to increase with absolute PO (at least up to ~ 300 W) (3,7,15,28), we hypothesized that in professional riders gross efficiency and economy are improved at high cadences (~ 100 rpm) compared with

Address for correspondence: Alejandro Lucia, M.D., Ph.D., Exercise Physiology Laboratory, European University of Madrid, E-28670 Madrid, Spain; E-mail: alejandro.lucia@mrfsc.cisa.uem.es.

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lower ones (60 rpm). In an attempt to conduct an integrative approach to explain our economy/efficiency results, we also analyzed the effects of varying cadences on the responses of different body systems: HR and pulmonary ventilation (to analyze cardio-respiratory work), lactate and pH (to determine the effects of changing cadence on the occurrence of lactic acidosis and lactate accumulation), surface electromyography (to estimate motor unit recruitment), and rates of perceived exertion (to quantify individual's subjective perception of the effort).

MATERIALS AND METHODS

Subjects. After giving their written informed consent, eight male professional road cyclists volunteered for this investigation. Four subjects had won races in the professional category, including mass-start stages in the Vuelta a España, Giro d'Italia, and Tour de France. One of the subjects finished the Tour de France in Top-10 position a few weeks after participating in this study, and another subject won a stage in the same edition of this race. Subjects' mean (\pm SD) age, height, and mass were: age: 26 ± 2 yr, 177 ± 6 cm, and 66.1 ± 6.2 kg, respectively. The institutional research ethics committee approved the study.

Study protocol. On two consecutive days during the competition phase of the season (second half of June) all the subjects performed 1) an incremental test for determination of maximal PO and 2) a testing session consisting of three bouts at fixed PO and different cadences, as explained below. The same cycle-ergometer (Monark, 818 E, Varberg, Sweden) was used during all the tests, and each subject used his own clip-on pedals. Each cyclist adopted the conventional upright cycling posture, i.e., seated position (same seat-to-pedal distance as in his road bicycle) with a trunk inclination of $\sim 75^\circ$ and hands placed on the handlebars with elbows slightly bent ($\sim 10^\circ$ of flexion). Gas exchange data were collected continuously during each test using an automated breath-by-breath system (Vmax 29C; Sensor-Medics; Yorba Linda, CA). HR ($\text{beats}\cdot\text{min}^{-1}$) were also continuously monitored during the tests (Polar S810, Polar Electro OY, Finland). A designated researcher was placed solely in charge of monitoring the subjects in order to insure that they maintained the required pedaling cadence throughout all the tests.

We separated each testing period from the other by a 24-h period during which the subjects refrained from hard physical activity. Each subject performed his tests at the same time of the day. We performed all testing sessions under similar environmental conditions ($20\text{--}24^\circ\text{C}$, $45\text{--}55\%$ relative humidity). During the day before the first test, the subjects followed a similar type of high-carbohydrate (CHO) diet (CHO intake of ~ 500 $\text{g}\cdot\text{d}^{-1}$) and performed an easy training session (i.e., $2\text{--}3$ $\text{h}\cdot\text{d}^{-1}$ of moderate bicycle training).

Incremental tests. After a warm-up period of 10-min at 100 W, the initial PO was set at 100 W. Thereafter, PO was increased by 20 $\text{W}\cdot\text{min}^{-1}$. Pedal cadence was fixed at 80 rpm throughout the tests. We considered the test complete when subjects reached exhaustion or could not main-

tain the required cadence for five or more seconds. We recorded the maximal PO that the subjects maintained for a complete 1-min period.

Tests at fixed power output and varying cadences. The constant PO test entailed three 6-min, high-PO bouts, interspersed by a 10-min recovery period. During each high-PO bout, subjects rode for 6 min at a constant PO equivalent to 75% of the maximal PO recorded during the previous maximal ramp test. (Such high, but not near-maximal, PO was chosen to ensure that RER values did not surpass 1.00, in order to adequately calculate gross efficiency, as explained below). Before beginning each test, subjects were allowed to warm-up for 10 min at 100 W. Thereafter, PO was gradually increased over a 2-min period until the subject reached the target wattage level for the 6-min bouts. Similarly, we kept PO constant at 100 W during the first 8 min of each recovery period between bouts, and PO was gradually increased during the following 2 min until reaching the target value. Pedal cadence was fixed at 80 rpm during the warm-up and recovery periods.

Following a counterbalanced, cross-over design, the cadence for each of the three bouts was set at 60, 80, or 100 rpm, respectively. These values of cadence range within the lower and higher limits commonly adopted by professional cyclists during actual races, that is, mean of ~ 70 rpm during mountain ascents (rarely below 60 rpm in this competition phase) and ~ 90 rpm during time trials and flat terrains (rarely above 100 rpm in this competition phase, except in sprints) (20).

We continually monitored gas exchange data ($\dot{V}\text{O}_2$, CO_2 output ($\dot{V}\text{CO}_2$), HR, pulmonary ventilation ($\dot{V}\text{E}$), and ventilatory equivalent of oxygen ($\dot{V}\text{E}/\dot{V}\text{O}_2$)) throughout each test and recorded the average value for the last 3 min of each 6-min bout. Capillary blood samples (75 μL) were taken from fingertips immediately after each of the three bouts for the measurement of lactate concentration and pH. Blood lactate concentration was measured with an electro-enzymatic lactate analyzer (YSI 1500; Yellow Springs, OH), whereas pH was measured with an automated blood analyzer (ABL77; Radiometer; Copenhagen, Denmark). Integrated ratings of overall perceived exertion (RPE) were obtained using the 6- to 20-point Borg scale (4) immediately upon termination of each 6-min bout.

For the last 3 min of each 6-min bout, gross mechanical efficiency (GE) was calculated as the ratio of work accomplished per minute (i.e., W converted to $\text{kcal}\cdot\text{min}^{-1}$) to energy expended per minute (i.e., average $\dot{V}\text{O}_2$ for the last 3 min of each 6-min bout, in $\text{kcal}\cdot\text{min}^{-1}$) using the corresponding energy equivalent for each $\dot{V}\text{O}_2$ value based on RER (5).

During the three constant-PO tests performed at varying cadences, EMG recordings were taken from the *vastus lateralis* muscle (at approximately one third of the perpendicular distance from the superior border of the patella to the greater trochanter) and from the *gluteus maximus* muscle (at its midpoint) of the right leg with pairs of surface electrodes (Ag-AgCl, 6-mm contact diameter, 3-cm inter-electrode distance). Reference electrodes were placed over the anterior superior spine of the iliac crest. Before electrode

placement, the skin was shaved, slightly abraded using sandpaper, and cleaned with alcohol to minimize source impedance to less than 2 k Ω . The wires connected to the electrodes were well attached with tape to minimize artifacts from leg movements. Myoelectrical activity was recorded with the aid of an I-330-C2-EMG analyzer (J&J Engineering, Poulsbo, WA). The raw EMG signals were band-pass filtered from 20 to 400 Hz, amplified, and analog-to-digital converted. The root mean square voltage (rms-EMG) was computed for every 15-s period for the three pedaling rates. The rms-EMG data obtained in each of two muscles and in the three bouts were normalized to the maximal value of rms-EMG obtained among the three bouts in the corresponding muscle. As for the gas-exchange variables and GE, normalized rms-EMG data were averaged for the last 3 min of each 6-min bout. In our study, rms-EMG was used as an estimate of the “total myoelectric activity” of the exercising muscle since it has been previously shown that this computation: 1) is an accurate measure of the EMG amplitude and 2) is highly correlated with the number of active motor units (fiber recruitment) (14,25).

Data analysis. The Kolmogorov-Smirnov test was applied to ensure a Gaussian distribution of the results. A one-factor repeated-measures ANOVA was used to compare mean values of $\dot{V}O_2$, GE, $\dot{V}E$, $\dot{V}E/\dot{V}O_2$, lactate, pH, RPE, and rms-EMG in the three bouts at 60, 80, and 100 rpm, respectively. The Newman-Keuls test was used *post hoc* to identify significant differences. Results are shown as mean \pm SD.

RESULTS

The $\dot{V}O_{2max}$ of the subjects (highest value for every 1-min period during the incremental tests) averaged 74.0 ± 5.7 mL \cdot kg $^{-1}\cdot$ min $^{-1}$. The maximal PO that the subjects maintained for a complete 1-min period during these tests averaged 490 ± 35 W.

The PO for the constant-PO tests at 60, 80, and 100 rpm averaged 366 ± 37 [range: 310–420]. Values of GE averaged 22.4 ± 1.7 [95% CI: 21.0–23.9], 23.6 ± 1.8 [95% CI: 22.1–25.2], and $24.2 \pm 2.0\%$ [95% CI: 22.5–25.9] at 60, 80, and 100 rpm, respectively. The ANOVA test showed a significant cadence effect ($P < 0.05$), and mean GE at 100 rpm was significantly higher than at 60 rpm ($P < 0.05$).

Results of $\dot{V}O_2$, HR, RPE, $\dot{V}E$, $\dot{V}E/\dot{V}O_2$, lactate, pH, and rms-EMG at 60, 80, and 100 rpm are shown in Figures 1–5. The ANOVA test showed a significant cadence effect for the following variables: $\dot{V}O_2$ ($P < 0.05$), HR ($P < 0.01$), RPE ($P < 0.05$), lactate ($P < 0.05$), and rms-EMG in both *vastus lateralis* and *gluteus maximus* muscles ($P < 0.01$). Briefly, mean values of $\dot{V}O_2$, HR, RPE, lactate, and rms-EMG in both muscles decreased at higher cadences. Significant differences were found for: $\dot{V}O_2$ at 60 rpm versus $\dot{V}O_2$ at 100 rpm ($P < 0.05$); HR at 60 rpm versus HR at both 80 ($P < 0.05$) and 100 rpm ($P < 0.01$); RPE at 100 rpm versus RPE at both 60 and 80 rpm ($P < 0.05$); lactate at 60 rpm versus lactate at both 80 and 100 rpm ($P < 0.05$); rms-EMG of the *vastus lateralis* at 100 rpm versus the same variable

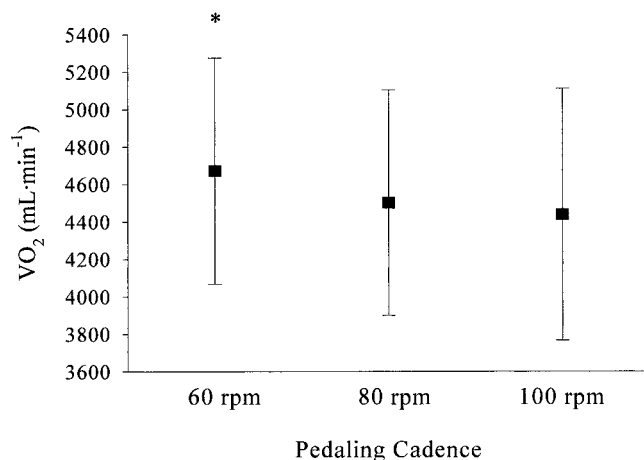


FIGURE 1—Comparison of oxygen uptake ($\dot{V}O_2$) during the 6-min bouts at fixed power output and varying cadences. * $P < 0.05$ for 60 vs 100 rpm. Data are shown as mean \pm SD.

at both 60 and 80 rpm ($P < 0.01$); and rms-EMG of the *gluteus maximus* at 100 rpm versus both 60 and 80 rpm ($P < 0.01$).

DISCUSSION

The main finding of our study is that, in professional road cyclists riding at high PO, GE/economy decreases at slow cadences (60 rpm) compared with higher pedaling rates (100 rpm). Such decreases are accompanied by significantly higher levels of both blood lactate levels and myoelectrical activity of two of the main muscles involved in pedaling (mostly in the down-stroke phase (11)), that is, the *vastus lateralis* and the *gluteus maximus*. Further, the rider’s perceptions of fatigue appear to increase at low cadences. Previous studies in the field have shown that at constant PO usually ≤ 200 W, pedaling at low rates (~ 50 – 70 rpm) frequently results in lower $\dot{V}O_2$ than pedaling at higher rates (>90 rpm) (3,5,6,9,23,30). However, it has been also shown that the most economical of cadences tends to increase with absolute PO (3,7,15,28). For instance, Coast and Welch (7) showed that the cadence eliciting the lowest $\dot{V}O_2$ at 100 and 330 W was 50 and 80 rpm, respectively. Chavarren and Calbet (5) reported that the usual pedaling-rate induced decrease in GE was attenuated at high PO in trained cyclists. Our results are supported by *in vitro* studies (10,16). For instance, the efficiency of contraction of mammalian and frog skeletal muscles increases with the speed of contraction until reaching a maximum, which corresponds to the optimal velocity of shortening (16).

The average values of GE obtained here in professional cyclists ($\sim 24\%$ at 80 and 100 rpm) while generating a mean PO of ~ 370 W are similar to those ($\sim 24\%$) recently reported in world-class professional riders pedaling at comparable PO (averaging ~ 385 W) with a mean cadence of 82 rpm (21). These values are in turn considerably higher than those (~ 18 – 22%) usually reported in competitive, but nonprofessional, riders (8) and reflect one of the main adaptations to training and cycling in the

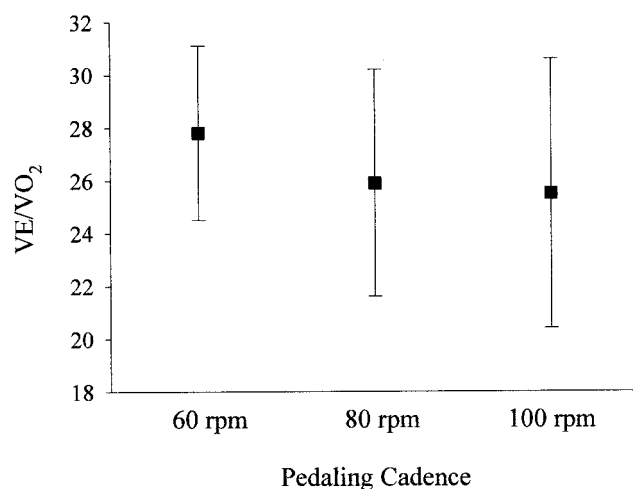
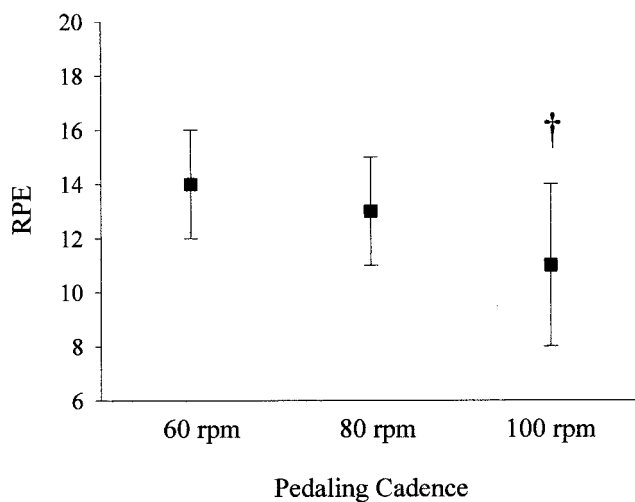
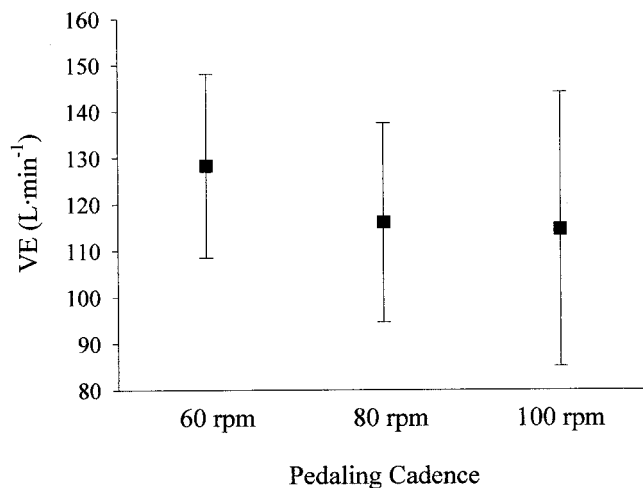
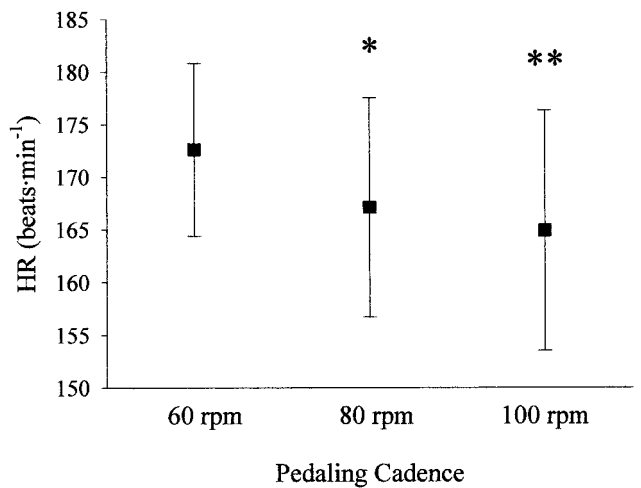


FIGURE 2—Comparison of HR (upper figure) and rate of perceived exertion (RPE, lower figure) during the 6-min bouts at fixed power output and varying cadences. * $P < 0.05$ for 60 vs 80 rpm; ** $P < 0.01$ for 60 vs 100 rpm; † $P < 0.05$ for 100 rpm vs both 60 and 80 rpm. Data are shown as mean \pm SD.

FIGURE 3—Comparison of pulmonary ventilation ($\dot{V}E$, upper figure) and ventilatory equivalent of oxygen ($\dot{V}E/\dot{V}O_2$, lower figure) during the 6-min bouts at fixed power output and varying cadences. No significant differences existed between bouts. Data are shown as mean \pm SD.

professional category, namely the ability to sustain high PO during long time intervals at the lowest possible metabolic cost (19,21). It has indeed been documented that 1) in these athletes, GE is an important performance indicator, more so than the ability to reach high values of $\dot{V}O_{2max}$ (19) and 2) some professional riders exhibit unexpectedly low $\dot{V}O_{2max}$ values ($\leq 70 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) that are compensated for by extremely high GE ($>24\%$) (21). Thus, the present findings are not without practical implications in terms of elite cycling performance. Beginning in 1999, five-time winner of the Tour de France, Lance Armstrong, introduced an unusually fast pedaling cadence, particularly in high mountain ascents, for example, $\sim 100 \text{ rpm}$ for an estimated average PO of $\sim 450 \text{ W}$ during the last, determinant ascent of Alpe d'Huez in the 2001's edition of the Tour de France (18). This cadence is clearly above the normal values previously reported in professional cycling races during this competition phase (mean of $\sim 70 \text{ rpm}$ (20)). The reason for the traditional use of lower, less efficient pedaling pat-

terns by professional cyclists during mountain ascents is not apparent. Until recently, the gear ratio used by most riders (usually harder than the combination of 39×23 frequently used by Armstrong, e.g., $39 \times 17-21$) was too hard to allow them to maintain high cadences of $\sim 100 \text{ rpm}$ during ascents of more than 20–30 min duration with a mean inclination $\geq 7\%$ (e.g., in the Tour de France). Guided by Armstrong's example, some riders currently tend to adopt a pedaling pattern faster than what they were used to in previous years (unpublished data from our research group collected in professional competitions during the last 3 yr). Finally, the extremely high speeds of modern tour races inevitably require that cyclists adopt fast pedaling patterns, at least during flat stages. Despite the rather high mean cadence ($\sim 90 \text{ rpm}$), riders still have to push hard gear ratios ($53 \times 13-14$) for 4 or 5 h during flat mass-start stages to meet the high requirements of this particular competition phase (i.e., mean speed well above $40 \text{ km}\cdot\text{h}^{-1}$). Selecting slower pedaling patterns (e.g., 70 rpm) would imply the use of extremely high

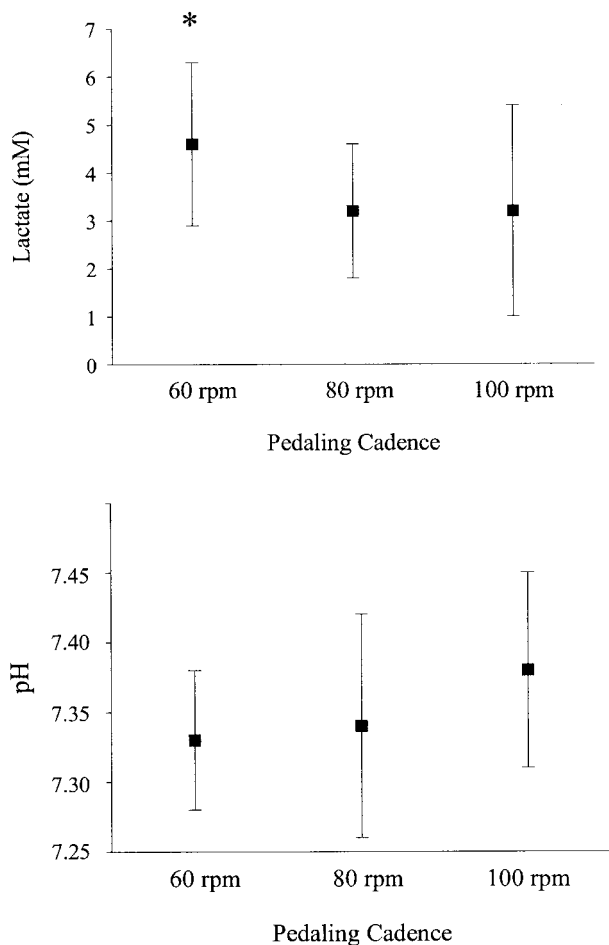


FIGURE 4—Comparison of blood lactate (upper figure) and pH (lower figure) during the 6-min bouts at fixed power output and varying cadences. * $P < 0.05$ for 60 vs both 80 and 100 rpm. Data are shown as mean \pm SD.

gears (e.g., 55 \times 11) for long periods, increasing the risk not only of acute muscle fatigue but also of muscle damage and long-term muscle soreness (20). In fact, some degree of muscle damage already occurs during tour races when pushing more “reasonable,” but still hard, gears (53 \times 13–14 on average) at around 90 rpm (19). For the same aforementioned reasons, the use of fast cadences (≥ 90 rpm) is required during flat time trials in those specialists able to sustain average speeds ≥ 50 km·h⁻¹ during long time periods.

Compared with fast pedaling patterns, the use of low cadences (60 rpm) at high PO requires forceful muscle contractions, for example, eliciting a peak pedal force ranging from 480 to 560 N for PO between 360 and 420 W, respectively (which corresponds to a flywheel impedance on the cycle-ergometer ranging from 6 to 7 kp). These contractions probably can only be sustained with an additional recruitment of motor units, particularly of fast ones, made of Type II fibers. In contrast, a higher cadence, and thus a lower level of force, may induce preferential recruitment of slow motor units, made of Type I fibers (1). Type II fibers, especially the IIX subtype, are able to generate more force than Type I fibers, although this ability is reached at the expense of a significantly higher oxygen cost, as shown in

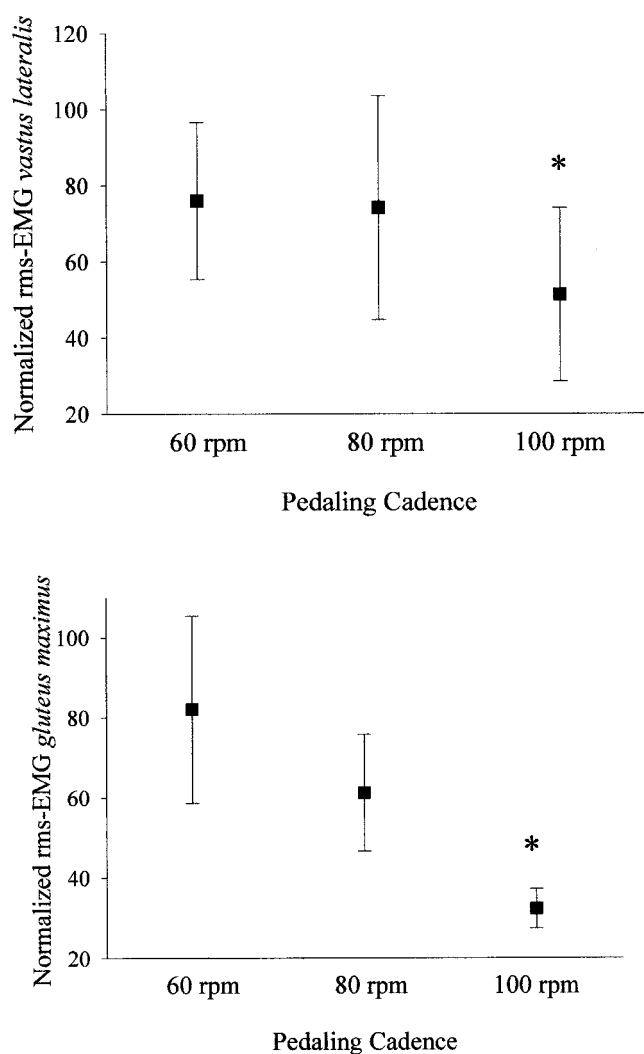


FIGURE 5—Comparison of normalized values of rms-EMG in the *vastus lateralis* (upper figure) and *gluteus maximus* muscle (lower figure) during the 6-min bouts at fixed power output and varying cadences. * $P < 0.01$ for 100 rpm vs both 60 and 80 rpm. Data are shown as mean \pm SD.

both animal (10) and human studies (8). In our experiment, the hypothesis of an increased muscle fiber recruitment at low cadences included that of Type II fibers, which consume more oxygen and produce more lactate than the Type I subtype, is supported, at least partly, by the significantly higher lactate levels obtained at 60 rpm compared with both 80 and 100 rpm. On the other hand, the higher rms-EMG values recorded with slower cadences in two of the main muscles involved in pedaling also support our hypothesis. Increases in rms-EMG are positively correlated with the number of active motor units (25). Increases in myoelectric activity during exercise are also due to the higher spike amplitudes of Type II fibers, and mostly Type IIX ones (12). These fibers tend to be more superficially located, that is, closer to the surface electrode. As the tissues between superficially located muscle fibers and surface electrode act as a low-pass filter, the amplitude of action potential from Type II fibers is further increased (2). Finally, our EMG data are in agreement with previous research. In a study with

subjects of different athletic backgrounds, MacIntosh et al. (23) elegantly showed that, at high PO (400 W), the cadence that elicited lowest rms-EMG values (and thus the lowest activation of motor units made up of Type II fibers) was ~ 100 rpm. Together with MacIntosh et al.'s findings (23), our data support the hypothesis that high cadences (100 rpm) are those eliciting the least muscle activation for sustaining high PO (>350 W).

Whereas numerous studies have analyzed the effects of varying pedaling cadence on oxygen cost, less data are available on the possible changes in cardiac responses (i.e., HR and stroke volume) and blood flow to working muscles induced by different pedaling cadences. At PO lower than those reported here, HR usually shows the same pattern as $\dot{V}O_2$, for example, if $\dot{V}O_2$ increases with pedaling cadence so does HR (7,28). Increments in the frequency of limb movement (e.g., pedaling cadence) might activate mechanoreceptors in working limbs that in turn can stimulate cardio-respiratory work (26). Increased HR and pulmonary ventilation can explain the feeling of breathlessness and central (cardiorespiratory) fatigue that some trained cyclists experience at high cadences, particularly during mountain ascents. Such perception is probably accentuated by the fact that the summit of the most important mountain passes is located at moderate altitude (~ 2000 m). Elite endurance athletes as professional road cyclists might experience severe gas exchange impairments during acute exposure to hypoxia, due to oxygen diffusion limitation (18,19). In our study, however, $\dot{V}E$ and $\dot{V}E/\dot{V}O_2$ (an estimate of ventilatory efficiency) were unchanged at higher cadences. These results might be due to the fact that the theoretically smaller ventilatory cost of lower cadences was compensated for by an increased ventilatory drive to buffer increased lactic acidosis. (No significant differences were found in pH values between the three cadence bouts despite the fact that the tests at 60 rpm elicited higher lactate levels). On the other hand, the significantly higher HR values associated with lower cadences might be explained by the deleterious effects that this pedaling pattern can have on blood flow to working muscles, especially at high PO. Few research efforts have been conducted to explore the effects of different cadences on cardiac output in adult humans. Gotshall et al (13) addressed this question and found that, for a fixed PO of 200 W, the cardiac output of cyclists and the blood flow to their quadriceps muscles increased with cadence, i.e., from 70 to 110 rpm, due to an improved effectiveness of the "skeletal-muscle" pump in facilitating venous return to the heart. Thus, despite the stimulating effect that fast limb movements can have on the cardio-respiratory center, at high PO, fast cadences might also elicit a more efficient function of the cardiac pump due to the Frank-Starling mechanism (i.e., lower HR for a given PO in the present experiments). On the other hand, muscle blood

flow is an important concern during pedaling exercise, especially at high PO, because knee extensor muscles (as the *vastus lateralis* studied here) undergo marked occlusion in their micro-vessels during the down-stroke phase of the crank cycle (29). In addition, blood flow in the iliac arteries (which irrigate all leg muscles) can be reduced during hip flexions when elite cyclists adopt the typical aerodynamic position (particularly in time trials) (27). This additional limitation for oxygenated blood delivery to working muscles is to be considered in further studies dealing with cadence optimization in trained cyclists and might speak in favor of using fast pedaling patterns to improve cardiac function and muscle blood flow.

Our study is not without practical applicability, at least for elite cyclists able to generate high PO (>300 W) during relatively long periods (e.g., 20–30 min). Since the start of the 1990s, the majority of competitive cyclists use HR telemeters to quantify exercise loads during both training and competitions (18). Despite the possibility of easily monitoring pedal cadence as well (e.g., some HR telemeters and speed-meters can also measure cadence), most cyclists are not yet aware of the importance of quantifying this variable during training sessions and competitions. Unpublished data from our group collected in some professional riders (gathered from 1999 to 2003's editions of Tour de France, Giro d'Italia, or Vuelta a España) show a tendency toward and increase in pedal frequency, especially during mountain ascents (from ~70 to 80–90 rpm). In the last years, these riders have been instructed to monitor their cadence during training and competitions and usually report a decreased perception of fatigue with these faster pedaling patterns. Based on these observations and the results of the present investigation, we recommend that competitive cyclists monitor cadence and consider this variable as an additional performance determinant. Although some individual variability is to be expected, training and racing at high cadences (~100 rpm) might prove useful at high PO (>300 W), for example, during mountain ascents. Furthermore, a relatively new trend for competitive cyclists is to train through the use of PO and several portable devices (e.g., the SRM system) are commercially available to measure PO during actual cycling. Thus, in the near future, competitive cyclists will have the opportunity to personally experience how varying pedaling cadences at a given wattage affects their perception of fatigue and its corresponding effects on performance.

In conclusion, in professional road cyclists riding at high PO, GE/economy improves at increasing pedaling cadences (from 60 to 80–100 rpm). Although further research is needed, our findings suggest that such improvement is attributable to a lower motor unit recruitment (particularly of those motor units made of Type II fibers) as cadence increases from 60 to 100 rpm. At lower cadences (60 rpm), both lactate levels and the individual's perception of fatigue are increased.

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