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INFLUENCE OF PEDALING TECHNIQUE ON METABOLIC EFFICIENCY IN ELITE CYCLISTS

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AUTHORS: Cámara J.[1], Maldonado-Martín S.[1], Artetxe-Gezuraga X.[1], Vanicek N.[2]

[1] Department of Physical Activity and Sport Sciences, University of the Basque Country (EHU/UPV), Vitoria-Gasteiz, Spain
[2] Department of Sport, Health & Exercise Science, University of Hull, HU6 7RX, United Kingdom

Reprint request to:
Jesús Cámara
Portal de Lasarte 71
01007 Vitoria-Gasteiz, Spain
E-mail: jesus.camara@ehu.es

ABSTRACT: Our objective was to investigate the influence of pedaling technique on gross efficiency (GE) at various exercise intensities in twelve elite cyclists ($\dot{V}O_2max=75.7 \pm 6.2$ mL·kg^{-1}·min^{-1}). Each cyclist completed a $\dot{V}O_2$max assessment, skinfold measurements, and an incremental test to determine their lactate threshold (LT) and onset of blood lactate accumulation (OBLA) values. The GE was determined during a three-phase incremental exercise test (below LT, at LT, and at OBLA). We did not find a significant relationship between pedaling technique and GE just below the LT. However, at the LT, there was a significant correlation between GE and mean torque and evenness of torque distribution ($r=0.65$ and $r=0.66$, respectively; $p < 0.05$). At OBLA, as the cadence frequency increased, the GE declined ($r=-0.81$, $p < 0.05$). These results suggest that exercise intensity plays an important role in the relationship between pedaling technique and GE.

KEY WORDS: biomechanics, blood lactate concentration, exercise

INTRODUCTION

In endurance cycling, metabolic efficiency is often expressed as gross efficiency (GE) [29], and it is considered to be a key factor in improving performance [9,14,17,25]. GE is determined by the ratio of how much mechanical work is produced compared to the overall metabolic energy expended [29,33]; hence, improvements in a cyclist's GE imply an increase in the mechanical power produced for a specific metabolic cost [23]. Previous research found that several factors may affect GE. Among these factors, type I muscle fibers have been shown to generate a higher muscular power output than type II fibers at the same steady-state oxygen uptake level. As a result, cyclists with a greater percentage of type I muscle fibers are more resistant to fatigue and exhibit a higher GE during endurance cycling [15]. Previous research also suggests that both training intensity and volume can enhance GE. According to Hopker et al., GE improved following 6 weeks of high-intensity sport-specific training. Other studies observed similar improvements in GE after long-term high-volume training, which resulted in enhanced muscle fiber oxidative capacities [4,6].

Another factor that may be associated with improvements in a cyclist's GE is pedaling technique. Pedaling technique is often characterized biomechanically by determining the evenness of torque distribution (EV), mean torque (T_{mean}), maximum torque ($T_{maximum}$), minimum torque ($T_{minimum}$), and cadence [5,8,17,22,33]. Various studies have investigated the relationship between the parameters that characterize pedaling technique and metabolic efficiency [5,8,13,17,18,22,23,33]. Since metabolic efficiency has been shown to change with rising exercise intensity [2,3,10,19,22,33], the relationship between pedaling technique and metabolic efficiency may change with increasing power requirements.

Blood lactate concentrations are used to compare power output values while taking inter-individual physiological differences into consideration [24]. Furthermore, previous research has shown that power output at a given lactate threshold (LT) and onset of blood lactate accumulation (OBLA) strongly predicts a cyclist's performance in both time trials and mass-start stage races [24]. Therefore, investigations of the relationship between pedaling technique and GE during incremental laboratory tests at exercise intensities determined by the LT and OBLA should consider inter-individual physiological differences. The purpose of this study was to investigate the relationship between pedaling technique markers (EV, T_{mean}, $T_{maximum}$, $T_{minimum}$, and cadence) and GE at submaximal intensities considering inter-individual physiological differences.

MATERIALS AND METHODS

Twelve elite cyclists volunteered for this study. The mean ± standard deviation of selected characteristics of the cyclists were as follows: age=19.9 ± 1.2 yr; height=176.7 ± 4.8 cm; mass=67.51 ± 5.62 kg; sum of six skinfolds=42.4 ± 3.9 mm (subscapular, triceps brachii, supraspinale, abdominal, anterior thigh, and medial calf); maximal heart rate (HR_{max})=187 ± 6 beats·min^{-1}; maximal lactate concentration ($[La]_{max}$)=8.94 ± 1.50 mmol·L^{-1}; and maximal oxygen uptake ($\dot{V}O_{2max}$)=75.7 ± 6.2 mL·kg^{-1}·min^{-1}. Prior to their involvement in the research, all of the subjects provided informed consent, as outlined by the Declaration of Helsinki. The study meets the ethical standards described by Harriss and Atkinson [12].

Experimental design

The cyclists were familiar with the laboratory testing and were instructed to refrain from strenuous exercise for 24 h immediately prior to the test. All of the subjects completed an incremental laboratory test on a cycle ergometer (Lode Excalibur Sport, The Netherlands). The test started with an initial power output of 100 W with further increments of 35 W every 5 min.

Blood samples were obtained immediately after each power output to determine the blood lactate concentration (Lactate Pro, Japan). The LT was defined as the point at which the lactate increased 1 mmol·L^{-1} above baseline [5]. The exercise intensity corresponding to the OBLA was identified on the blood lactate concentration–power output curve as the exercise intensity eliciting a blood lactate concentration of 4 mmol·L^{-1} [31].

The incremental laboratory test was divided into three different intensities according to the power outputs at which the LT and the OBLA were produced: the power output immediately below the intensity at which the LT was produced (I_1), the power output at which the LT was produced (I_2), and the power output at which the OBLA was produced (I_3) (Figure 1).

Maximal oxygen uptake was measured using a breath-by-breath automated gas analysis system (Jaeger Oxycon Delta System, Germany) calibrated before each testing session in line with the manufacturer's guidelines. $\dot{V}O_{2max}$ was defined as the average of the single highest four consecutive 30-s $\dot{V}O_2$ values attained toward the end of the test. Achievement of $\dot{V}O_{2max}$ was assumed on attainment of at least two of the following three criteria: a plateau in $\dot{V}O_2$ with increasing speeds, a respiratory exchange ratio above 1.10, and a heart rate within ±10 beats·min^{-1} of the age-predicted maximum heart rate (220 − age) [7]. The cycle ergometer was calibrated before each test. The GE was calculated as described by Gaesser and Brooks [10]:

Equation 1: $$GE=\frac{\text{power output}}{\text{energy expended}}\times 100$$

The GE was averaged during the last 60 s of I_1, I_2, and I_3 to ensure that the $\dot{V}O_2$ had reached a steady state. At these intensities, the respiratory exchange ratio (RER) was smaller than 1. Energy expended was calculated from the $\dot{V}O_2$ and RER using the tables of Lusk [20].

The ergometer was instrumented with force measurement pedals and adapted with clip pedals (Look Keo Carbon, USA). The crank arm was the same for all of the participants (170 mm). The position on the ergometer was adjusted to match the cyclists' riding position. The cadence was maintained at the cyclists' preferred rate. The torque (T) acting perpendicular to the crank was recorded at every 2°. The T_{mean} (mean of the propulsive and resistive T), $T_{maximum}$ (mean of the highest propulsive T during the downstroke phase), and $T_{minimum}$ (mean of the highest resistive T during the upstroke phase, mainly caused by the weight of the limb moving upwards) were

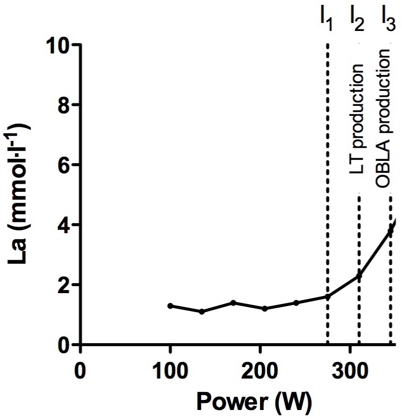

FIG. 1. EXERCISE INTENSITIES ACCORDING TO THE POWER OUTPUTS AT WHICH THE LT AND OBLA WERE PRODUCED
Legend: [La], blood lactate concentration; LT, lactate threshold; OBLA, onset of blood lactate accumulation; I1, power output below the intensity at which the LT was produced; I2, power output at which the LT was produced; I3, power output at which the OBLA was produced.

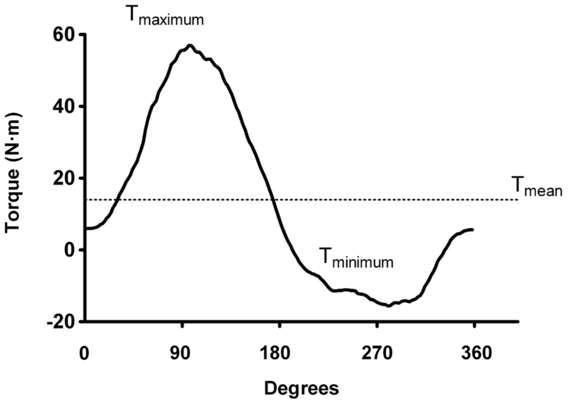

FIG. 2. TORQUE DATA FROM A SINGLE PARTICIPANT AND A SINGLE CRANK CYCLE
Legend: Tmean, mean of the propulsive and resistive torque; Tmaximum, mean of the highest propulsive torque; Tminimum, mean of the highest resistive torque.

averaged from both feet (Figure 2). The cadence was also registered. These parameters were measured during ten revolutions within the penultimate minute of each power output [17]. The EV was computed by means of the following equation [17]:

Equation 2: $$EV = \frac{T_{mean}}{T_{maximum}} \times 100$$

Statistical analysis

For descriptive purposes, the parameters are reported as means ± SD. The Shapiro–Wilk test was used to test the null hypothesis that the sample came from a normally distributed population. The inferential statistics Levene's test was conducted to assess the equality of variances. Repeated measures analysis of variance (ANOVA) was performed to examine the differences in the changes among the T_{mean}, $T_{maximum}$, $T_{minimum}$, EV, and cadence at each intensity. When significant differences were obtained, Bonferroni post-hoc tests were conducted. Mauchly's sphericity test was performed to test the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables was proportional to an identity matrix. Pearson's correlation test was used to find out whether the GE correlated with the parameters that described the pedaling technique. $p<0.05$ was considered to be statistically significant. The statistical analyses were conducted using SPSS 15.0 (SPSS Inc., USA).

RESULTS

All parameters showed equality of variances ($p > 0.07$) and all data were normally distributed: the lowest p value was obtained in cadence at I_1 (W=0.920, p=0.06). The condition of sphericity was also met for all parameters ($p > 0.06$). The GE (21.46 ± 1.24%) at I_1 (234 ± 21 W) did not show a significant correlation with any of the parameters describing the pedaling technique (T_{mean}: r=0.34, p=0.27; $T_{maximum}$: r=−0.03, p=0.99; $T_{minimum}$: r=0.12, p=0.69; EV: r=0.39, p=0.20; and cadence: r=−0.18, p=0.57). At I_2 (269 ± 22 W), the GE (21.51 ± 1.44%) showed a positive correlation with the T_{mean} (Figure 3) and with the EV (Figure 4), but not with the $T_{maximum}$ (r=0.02, p=0.95), the $T_{minimum}$ (r=0.33, p=0.29), or the cadence (r=−0.34, p=0.26). At I_3 (305 ± 23 W), the GE (21.56 ± 1.61%) was positively correlated with the T_{mean} (Figure 5) and negatively correlated with the cadence (Figure 6). No correlation was found between the GE and the rest of the parameters describing the pedaling technique at I_3 ($T_{maximum}$: r=0.35, p=0.25; $T_{minimum}$: r=−0.03, p=0.91; and EV: r=0.28, p=0.36).

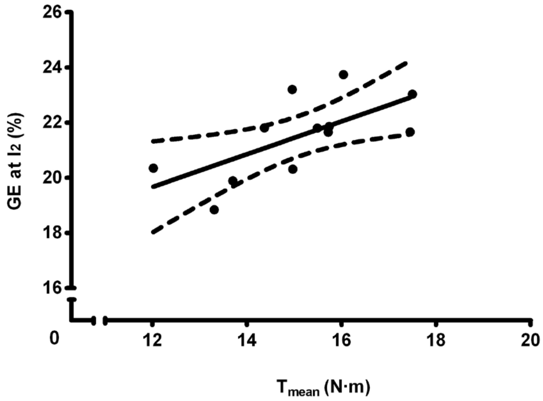

FIG. 3. DATA ILLUSTRATING THE RELATIONSHIP BETWEEN THE TMEAN AND THE GE AT THE INTENSITY AT WHICH THE LT WAS PRODUCED (I2)
Legend: Linear regression is represented by a solid black line, ± 95% confidence interval is represented by dashed lines. There is a positive correlation between the two variables (r = 0.65, p < 0.05). The formula describing the relationship is y = 0.594x + 12.532; R2 = 0.434. LT, lactate threshold; Tmean, mean of the propulsive and resistive torque; GE, gross efficiency; I2, power output at which the LT was produced.

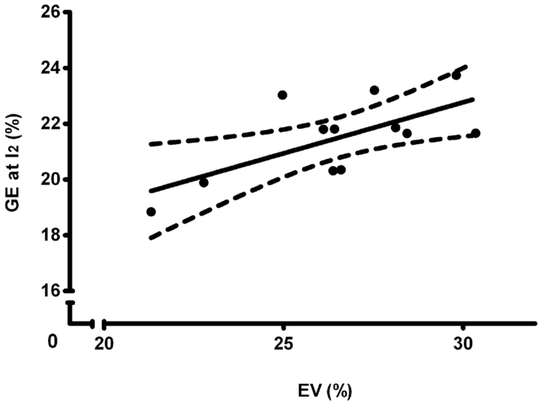

FIG. 4. DATA ILLUSTRATING THE RELATIONSHIP BETWEEN THE EV AND THE GE AT THE EXERCISE INTENSITY AT WHICH THE LT WAS PRODUCED (I2)
Legend: Linear regression is represented by a solid black line, ± 95% confidence interval is represented by dashed lines. There is a positive correlation between the two variables (r = 0.66, p < 0.05). The formula describing the relationship is y = 0.366x + 12.788; R2 = 0.445. EV, evenness of torque distribution; GE, gross efficiency; LT, lactate threshold; I2, power output at which the LT was produced.

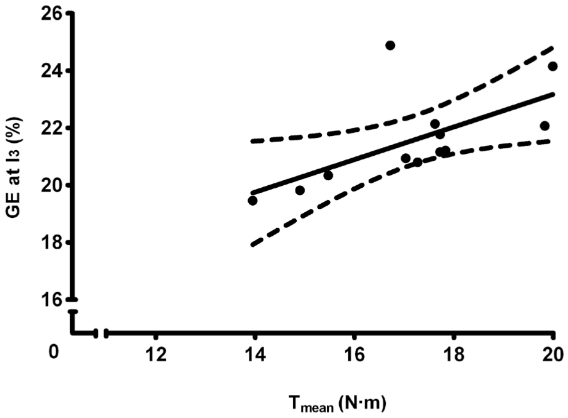

FIG. 5. DATA ILLUSTRATING THE RELATIONSHIP BETWEEN THE TMEAN AND THE GE AT THE EXERCISE INTENSITY AT WHICH THE OBLA WAS PRODUCED (I3)
Legend: Linear regression is represented by a solid black line, ± 95% confidence interval is represented by dashed lines. There is a positive correlation between the two variables (r = 0.63, p < 0.05). The formula describing the relationship is y = 0.569x + 11.781; R2 = 0.396. Tmean, mean of the propulsive and resistive torque; GE, gross efficiency; OBLA, onset of blood lactate accumulation; I3, power output at which the OBLA was produced.

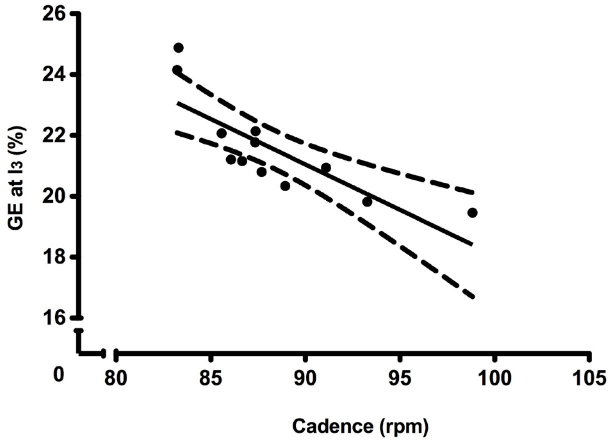

FIG. 6. DATA ILLUSTRATING THE RELATIONSHIP BETWEEN THE CADENCE AND THE GE AT THE EXERCISE INTENSITY AT WHICH THE OBLA WAS PRODUCED (I3)
Legend: Linear regression is represented by a solid black line, ± 95% confidence interval is represented by dashed lines. There is a positive correlation between the two variables ($r = -0.81$, $p < 0.05$). The formula describing the relationship is $y = -0.298x + 47.932$; R2 = 0.661. GE, gross efficiency; OBLA, onset of blood lactate accumulation; I3, power output at which the OBLA was produced.

DISCUSSION

In the present study, we did not observe a correlation at I_1 between any of the parameters characterizing the pedaling technique and the GE. Nevertheless, at I_2 the T_{mean} and the EV correlated with the GE (Figures 3 and 4, respectively), and at I_3 the T_{mean} also correlated with the GE (Figure 5). Moreover, at I_3 the cadence was negatively correlated with the GE (Figure 6).

The lack of interaction between the parameters characterizing the pedaling technique and metabolic efficiency at the power output below the intensity at which the LT was produced suggests that at this intensity, the cyclists do not adapt their pedaling technique to achieve higher metabolic efficiencies. The low physiological demands [26] might contribute to the lack of a technical pedaling adaptation. These results are in accordance with those from a previous study, which argued that the human body does not appear to care about minimizing energy expenditure [27].

Nevertheless, increased physiological demands do seem to play a role in the pedaling technique; incremental increases in the power output have been shown to lead to changes in the pedaling technique [1,28]. In our study, the increases in the exercise intensity and consequently in the physiological demands were related to changes in the relationship between the pedaling technique and metabolic efficiency. No significant relationships were observed at I_1 (46% of $\dot{V}O_{2max}$), but at I_2 (53% of $\dot{V}O_{2max}$) the cyclists producing a higher T_{mean} and EV were metabolically more efficient. Furthermore, at I_3 (60% of $\dot{V}O_{2max}$), the relationship between the pedaling technique and metabolic efficiency indicated that a higher T_{mean} and a lower cadence were related to a higher GE. The positive relationship between the T_{mean} and the GE at I_2 and I_3 and the lack of a significant relationship between the T_{max} and the GE suggest that at the power outputs at which the LT and OBLA were produced, increases in GE are associated to increments in torque applied throughout the whole pedal revolution and not to increases in the maximum torque during the downward phase of the crank cycle. This pedaling technique may redistribute the work to a greater number of muscles, thus increasing the metabolic efficiency. These results are in accordance with those of a previous study in which lower cadences were related to higher metabolic efficiencies during a simulated time trial [33]. Previous studies also found that for a given exercise intensity, lower cadences were related to higher metabolic efficiencies [2,11,21,30].

The results of the present study imply that during incremental laboratory tests, after taking inter-individual physiological differences into consideration, the relationship between pedaling technique and metabolic efficiency depends upon the exercise intensity. Knowledge of the relationship between pedaling technique and metabolic efficiency at different exercise intensities provides coaches and athletes with practical information that may be useful for training that pertains to pedaling technique. Even though it has been previously observed that the breathing and the movement pattern might have an influence on the cyclists' performance [16], these two parameters were not controlled. Further research is warranted to analyse the influence of these two parameters on the pedaling technique.

CONCLUSIONS

The results of this study show that the relationship between the parameters characterizing pedaling technique and the metabolic efficiency during an incremental laboratory cycling test in which inter-individual physiological differences were considered was dependent upon the exercise intensity: (1) no relationship was observed at the intensity below the power output at which the LT was produced; (2) at the exercise intensity at which the LT was produced, a higher mean torque and a higher evenness of torque distribution were metabolically more efficient; (3) at the intensity at which the OBLA was produced, a higher mean torque and a lower cadence were metabolically more efficient.

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