Effect of Pedaling Technique on Mechanical Effectiveness and Efficiency in Cyclists

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ABSTRACT

KORFF, T., L. M. ROMER, I. MAYHEW, and J. C. MARTIN. Effect of Pedaling Technique on Mechanical Effectiveness and Efficiency in Cyclists. *Med. Sci. Sports Exerc.*, Vol. 39, No. 6, pp. 991–995, 2007. **Purpose:** To optimize endurance cycling performance, it is important to maximize efficiency. Power-measuring cranks and force-sensing pedals can be used to determine the mechanical effectiveness of cycling. From both a coaching and basic science perspective, it is of interest if a mechanically effective pedaling technique leads to greater efficiency. Thus, the purpose of this study was to determine the effect of different pedaling techniques on mechanical effectiveness and gross efficiency during steady-state cycling. **Methods:** Eight male cyclists exercised on a cycle ergometer at 90 rpm and 200 W using four different pedaling techniques: preferred pedaling; pedaling in circles; emphasizing the pull during the upstroke; and emphasizing the push during the downstroke. Each exercise bout lasted 6 min and was interspersed with 6 min of passive rest. We obtained mechanical effectiveness and gross efficiency using pedal-reaction forces and respiratory measures, respectively. **Results:** When the participants were instructed to pull on the pedal during the upstroke, mechanical effectiveness was greater (index of force effectiveness = 62.4 ± 9.8%) and gross efficiency was lower (gross efficiency = 19.0 ± 0.7%) compared with the other pedaling conditions (index of force effectiveness = 48.2 ± 5.1% and gross efficiency = 20.2 ± 0.6%; means and standard deviations collapsed across preferred, circling, and pushing conditions). Mechanical effectiveness and gross efficiency during the circling and pushing conditions did not differ significantly from the preferred pedaling condition. **Conclusions:** Mechanical effectiveness is not indicative of gross efficiency across pedaling techniques. These results thereby provide coaches and athletes with useful information for interpreting measures of mechanical effectiveness. **Key Words:** COACHING, BIOMECHANICS, CYCLING, ECONOMY

To optimize endurance performance it is important to maximize efficiency, which is defined as the ratio of work done to energy expended (9). In cycling, efficiency is often inferred indirectly by the ratio of work rate to total caloric expenditure (i.e., gross efficiency) (9,12). One factor that may contribute to gross efficiency is the pedaling technique (i.e., the way that the forces produced by the cyclist's muscles are transferred to the crank) (6,15,18). Forces, torques, or power delivered by the cyclist to the pedals can be measured using force pedals or instrumented cranks. Knowing the relationship between mechanical variables measured at the crank and gross efficiency would make these force, torque, or power measurements more useful to coaches and athletes.

Using force-related measurements, we can describe the mechanical effectiveness of the system. In particular, two concepts have been used to describe mechanical effectiveness. The first concept is that of maximizing the force acting perpendicularly to, and thus propelling, the crank (effective force) relative to the resultant force. The ratio between the effective force and the resultant force (index of force effectiveness) has been used to understand the interactions between workload, cadence, and mechanical effectiveness (7,15,17). It has been suggested that a mechanically more effective pedaling technique may be more efficient (11). This link is not intuitive, for two reasons. First, the mechanical effectiveness does not take nonmuscular (gravitational and motion-dependent) influences into account. Neptune and Herzog (13), for example, have shown that it

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is mainly the nonmuscular contribution that reduces the mechanical effectiveness during steady-state cycling at 90 rpm. When eliminating the nonmuscular influences from the total pedal force, the mechanically ineffective component of the force profile was also eliminated. The second reason why the assessment of mechanical effectiveness may not reflect gross efficiency during the constrained task of pedaling is that energy delivery to the crank is a result of complex mechanical mechanisms. Given that mechanical energy is produced by multiple muscles with different properties and that energy is transferred indirectly via the body segments to the crank (8,10,14), the relationship between mechanical effectiveness measured at the crank and gross efficiency is not intuitive. Information exists about this relationship across participants (6,18) and the effect of pedaling technique on muscular coordination (16). However, the question remains whether the maximization of force effectiveness across pedaling techniques improves gross efficiency.

A second concept that has been used to interpret the mechanics of the pedaling technique is that of an even distribution of crank torque throughout the crank cycle. Modern training devices and the appendant software provide information about how evenly the torque is distributed about the crank axis throughout the crank cycle. In coaching practice, an even distribution of torque throughout the crank cycle is promoted as an "efficient" technique (1,2,4,5). However, we are unaware of any scientific evidence to support this supposition.

From these considerations, it is clear that our knowledge of the interaction between mechanical effectiveness and efficiency during steady-state cycling is incomplete. Therefore, the usefulness of power and torque profiles is limited for coaches and athletes who seek to promote an optimal pedaling technique. Thus, the purpose of the present study was to determine the interaction between mechanical effectiveness and gross efficiency across different pedaling techniques in competitive cyclists. We hypothesized that across different pedaling techniques, the index of force effectiveness and the evenness of the torque distribution throughout the crank cycle would not reflect gross efficiency.

METHODS

Participants. Eight male cyclists volunteered for the study (age 35.3 ± 6.3 yr, body mass 74.4 ± 8.1 kg, maximal O_2 uptake ($\dot{V}O_{2max}$) 58.2 ± 3.1 mL·kg^{-1}·min^{-1}, peak power output (W_{peak}) 365 ± 30 W). All of the participants had at least 2 yr (6.8 ± 4.4 yr) of racing experience. The local ethics committee of Brunel University approved the methods, and participants provided written informed consent.

Procedure. Participants performed a warm-up by pedaling at 70, 90, and 110 rpm at a power output of 100 W for 2 min at each cadence. Participants were then asked to perform four trials of pedaling at 90 rpm and 200 W on an electromagnetically braked cycle ergometer (Lode Excalibur, Groningen, The Netherlands), which was calibrated before the start of the study using a dynamic calibrator (Model 17801, Vacumed, CA). For each trial, participants were instructed to employ a different pedaling technique. In one condition, participants were asked to use their preferred pedaling technique (*preferred*). In a second condition, participants were asked to pedal in circles and to concentrate on the transition phases through top dead center and bottom dead center of the crank cycle (*circling*). In a third condition, participants were instructed to emphasize an active pull during the upstroke of the crank cycle (*pulling*). Finally, they were instructed to emphasize the pushing action during the downstroke of the crank cycle (*pushing*). These instructions were reiterated throughout each exercise bout. The order of the conditions was randomized and counterbalanced. Each bout lasted 6 min, and 6 min of passive rest separated consecutive trials. Approximately 30 min after the final trial, the participants performed a maximal incremental exercise test (starting at 150–200 W and increasing 10–20 W·min^{-1}) for the determination of $\dot{V}O_{2max}$ (defined as the highest $\dot{V}O_2$ averaged for 1 min of exercise) and W_{peak} (defined as the sum of the final completed workload plus the fraction of the partly completed workload performed before exhaustion). The participants refrained from caffeine for 12 h and stressful exercise for 48 h before exercise.

Instrumentation and derivation of dependent measures. Pedal-reaction forces were measured at 960 Hz using a custom-made force pedal with two triaxial piezoelectric force sensors (Kistler, model 9251AQ01). Pedal angle and crank angle were measured at 120 Hz using a motion-analysis system (Motion Analysis, Santa Rosa, CA). Force and kinematic data were low-pass filtered (second-order Butterworth) using cutoff frequencies of 20 and 10 Hz, respectively. Pedal angle and crank angle were calculated from the kinematic data. The force data (forces normal and tangential to the pedal) were downsampled to match the kinematic data. Using the kinematic and force data, we calculated the force components perpendicular and radial to the crank. The total force (F_{tot}) was calculated as the vector sum of the normal and tangential components. The torque about the crank axis of rotation was calculated as the product of the effective force and the crank length (0.17 m).

The index of force effectiveness (IFE) was calculated according to equation 1 (6):

$$\mathrm{IFE} = 100 \times \frac{\int_0^{2\pi} F_e(\Theta)}{\int_0^{2\pi} F_{tot}(\Theta)} \qquad (1)$$

where Θ is the crank angle, F_e is the effective force, and F_{tot} is the resultant force.

The evenness of the torque distribution was computed by dividing the mean torque about the crank cycle, as measured on the right pedal, across the whole 360° pedal revolution by maximum torque multiplied by 100. For each participant, the index of force effectiveness and the evenness of torque distribution were averaged across 10 revolutions during the fifth minute of each testing bout.

Measures of $\dot{V}O_2$ and carbon dioxide production ($\dot{V}CO_2$) were made breath-by-breath using an online system (Oxycon Pro, Jaeger, Germany). Gross efficiency was calculated as the mean of all data collected in the last 3 min of every exercise bout (respiratory exchange ratio ≤ 1), using the following equation: power output (W)/energy expended ($J \cdot s^{-1}$) × 100%, where energy expended was calculated from the measures of $\dot{V}O_2$ and $\dot{V}CO_2$ using stoichiometric equations (3).

Statistical analysis. To determine whether pedaling technique affected the index of force effectiveness, the evenness of the torque distribution, and the gross efficiency, a one-way ANOVA with repeated measures was performed for each dependent variable. If the ANOVA indicated a significant main effect, *post hoc* pairwise comparisons were made using the Bonferroni adjustment. The alpha level was set at 0.05.

RESULTS

To ensure that the participants followed the instructions regarding the pedaling technique, we calculated the crank torque that was produced during the downstroke (0–180° of the crank cycle) as a percentage of total crank torque throughout the whole crank cycle. Between 0 and 180° of the crank cycle, participants produced the greatest proportion of torque while pushing and the smallest amount of torque while pulling. In this region of the crank cycle, participants also produced a greater proportion of torque during the preferred pedaling condition when compared with the circling condition (Fig. 1). The effect sizes for all pairwise comparisons were large (0.77–1.63).

Pedaling technique significantly affected the evenness of torque distribution ($F_{3,21}$ = 16.3, P < 0.001) and the index of force effectiveness ($F_{3,21}$ = 18.7, P < 0.001). Figure 1 shows the torque profiles (averaged across all participants) for the four pedaling conditions. *Post hoc* analyses revealed that evenness of torque distribution was greater during the pulling condition than during the pushing or the preferred pedaling condition (P < 0.05) (Fig. 2A). In addition, evenness of torque distribution was greater during the circling condition when compared with the pushing condition (P < 0.05). *Post hoc* analyses also revealed that during the pulling condition, the index of force effectiveness was significantly greater than during the other conditions (P < 0.05) (Fig. 2B).

The pedaling technique significantly affected gross efficiency ($F_{3,21}$ = 20.4, P < 0.001). *Post hoc* analyses revealed that during the pulling condition, gross efficiency was significantly less than during all other pedaling conditions (Fig. 3). Although not presented here, the same effect was found regardless of whether efficiency was

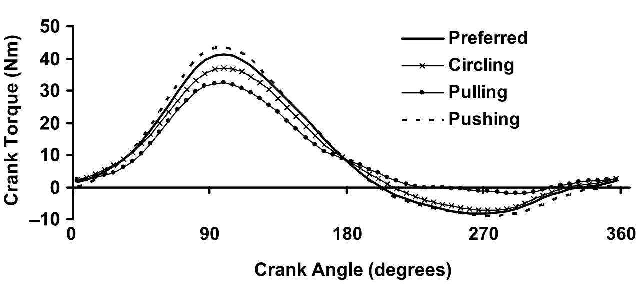

FIGURE 1—Torque profiles for different pedaling conditions. The profiles shown are the averages across all participants for each pedaling condition.

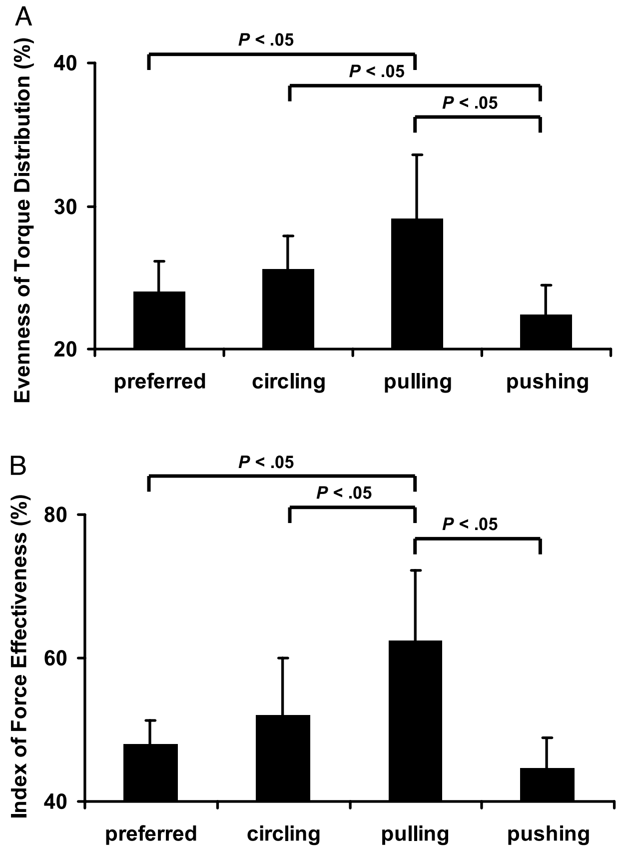

FIGURE 2—Effect of pedaling technique on the evenness of torque distribution (ET) (*A*) and the index of force effectiveness (IFE) (*B*). Group means and standard deviations are shown.

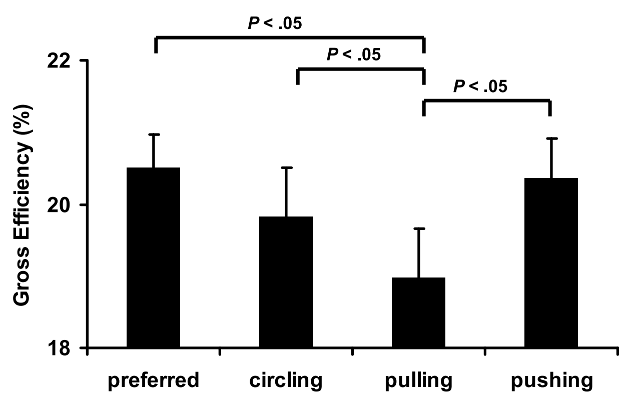

FIGURE 3—Effect of pedaling technique on gross efficiency (GE). Group means and standard deviations are shown.

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baseline corrected for resting energy expenditure (net efficiency) or the predicted energy expenditure for unloaded cycling (work efficiency).

DISCUSSION

The purpose of this study was to determine the interaction between mechanical effectiveness and gross efficiency across different pedaling techniques in competitive cyclists. In support of our hypothesis, the index of force effectiveness and the evenness of the torque distribution throughout the crank cycle were not reflective of gross efficiency across different pedaling techniques. Although participants were mechanically most effective during the pulling condition (greatest index of force effectiveness and evenness of torque distribution), they were metabolically least efficient.

Our results show that during preferred pedaling, circling, and pushing, a considerable amount of negative torque (thus, negative mechanical work) was produced during the upstroke. During the pulling condition, considerably less negative work was produced during the upstroke (Fig. 1). The greater mechanical effectiveness during the pulling condition was revealed in a greater index of force effectiveness and a greater evenness of torque distribution. Bearing in mind that gross efficiency was lowest during the pulling condition, these results demonstrate that a mechanically more effective pedaling technique is not associated with increased gross efficiency. Assuming that the increase in mechanical work during the upstroke was achieved by an increased force production of the flexor muscles of the lower limb, our results suggest that, within the context of steady-state cycling, the extensor muscles may be more efficient power producers than the flexor muscles.

Several authors have reported the relationship between mechanical effectiveness and gross efficiency during cycling between subjects (6,18). Our results add to the literature by employing a within-subject design, which allows us to draw conclusions about the importance of the instructions given to the riders regarding pedaling technique. Interestingly, the preferred pedaling condition did not differ significantly from the pushing or circling conditions in terms of mechanical effectiveness or gross efficiency. It is, perhaps, unsurprising that the preferred pedaling technique was metabolically the most efficient (although not significantly different from the circling and pushing conditions), because the participants are likely to have adopted an efficient pedaling style as a result of training and physiological adaptations. More importantly, however, the type of instruction did not influence gross efficiency unless participants were instructed to actively pull up on the pedal. We can speculate that during steady-state cycling, the pedaling technique may not be a major determinant of cycling performance, because a wide range of pedaling techniques resulted in similar levels of gross efficiency.

Our results shed doubt on the notion that evenly distributing crank torque across the crank cycle will improve efficiency. By encouraging riders to maximize the evenness of the crank torque distribution, one encourages an active pull during the upstroke, which decreased gross efficiency in our subjects. Similarly, our data do not support the notion that pedaling in circles would improve efficiency, as gross efficiency did not differ between the preferred pedaling and the circling conditions.

Before concluding that the instructions regarding the pedaling technique are counterproductive or irrelevant, two factors should be considered. First, multiple physiological systems are likely to adapt in response to training with a specific pedaling technique. Our data support this speculation by demonstrating that in all participants, the preferred pedaling style was accompanied by the greatest gross efficiency (although not significantly different from circling or pushing). A limitation of our study, however, is that it does not rule out the possibility that there may be a more efficient pedaling style if participants are given enough time to adapt to it. Longitudinal studies are needed to explore this possibility. Second, we examined the effect of pedaling technique on mechanical effectiveness and gross efficiency during steady-state cycling. Although our results suggest that actively pulling on the pedal reduces gross efficiency during steady-state cycling, there may be situations during which an active pull is beneficial in terms of adding power to the crank (e.g., during maximal power sprinting).

In conclusion, mechanical effectiveness did not reflect gross efficiency across different pedaling techniques during steady-state cycling. In addition, instructing the rider to employ a certain pedaling technique did not result in significant changes in mechanical effectiveness and gross efficiency when compared with the preferred pedaling style, unless the rider was instructed to pull up actively on the pedal. These findings suggest that during cycling, the extensor muscles are more efficient power producers than the flexor muscles. Our results have practical implications and should be considered when creating coaching plans or training interventions.

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The results of the present study do not constitute endorsement of the product by the authors or ACSM.

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