Effect of cadence, cycling experience, and aerobic power on delta efficiency during cycling

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ABSTRACT

MARSH, A. P., P. E. MARTIN, and K. O. FOLEY. Effect of cadence, cycling experience, and aerobic power on delta efficiency during cycling. *Med. Sci. Sports Exerc.*, Vol. 32, No. 9, pp. 1630–1634, 2000. **Purpose:** To examine the influence of cadence, cycling experience, and aerobic power on delta efficiency during cycling and to determine the significance of delta efficiency as a factor underlying the selection of preferred cadence. **Methods:** Delta efficiency (DE) was determined for 11 trained experienced cyclists (C), 10 trained runners (R), and 10 less-trained noncyclists (LT) at 50, 65, 80, 95, and 110 rpm. Preferred cadence (PC) was determined at 100, 150, and 200 W for C and R and at 75, 100, and 150 W for LT. Gas exchange at each power output (PO) was measured on a separate day, and the five cadences were randomly ordered on each occasion. It was hypothesized that: a) cyclists are most efficient at the higher cadences at which they are accustomed to training and racing, i.e., there will be a trend for DE to increase with increases in cadence; b) cyclists and runners will exhibit similar DE across the range of cadences tested; and c) DE of less-trained subjects will be lower than that of cyclists and runners. **Results:** PCs of C and R were similar and did not change appreciably with PO (100 W: C, 95.6 ± 10.8; R, 92.0 ± 8.5: 150 W: C, 94.4 ± 10.3; R, 92.9 ± 7.8: 200 W: C, 92.2 ± 7.2; R, 91.8 ± 7.9 rpm). The PC of LT was significantly lower and decreased with increases in power output (75 W: 80.0 ± 15.3; 100 W: 77.5 ± 15.1; 150 W: 69.1 ± 11.9 rpm). The first hypothesis was rejected because analysis of the cyclists' data alone revealed no systematic increase in DE as cadence was increased [$F(4,40) = 0.272$, $P = 0.894$]. Repeated measures ANOVA on all three groups revealed no group × cadence interaction [$F(8,112) = 0.589$, $P = 0.785$]. Again there was no systematic effect of cadence on DE [$F(4,112) = 1.058$, $P = 0.381$]. The second and third hypotheses were also rejected since there was no group main effect, i.e., DE of cyclists, runners, and less-trained subjects were not significantly different [$F(2,28) = 1.397$, $P = 0.264$]. **Conclusion:** Pedaling cadence did not have a dramatic effect on DE in any group. Muscular efficiency, as measured indirectly by delta efficiency, appears to remain relatively constant at approximately 24%, regardless of cycling experience or fitness level. **Key Words:** BICYCLING, HUMAN EFFICIENCY, CYCLING EXPERIENCE, TRAINING, FITNESS

The underlying reasons for the high cadences typically observed in experienced cyclists have been the source of considerable speculation and research (2,3,8,18,19,21–23). In general, studies that have manipulated cadence during constant power output cycling have produced consistent results, and several observations can be made. First, the preferred cadences of experienced cyclists are approximately 85–95 rpm, whereas the most economical cadences are approximately 55–60 rpm. Therefore, cyclists do not appear to minimize aerobic demand, i.e., maximize economy, at their preferred cadence during constant power output cycling (3,12,13). Based on this observation, cyclists do not maximize gross efficiency at the preferred cadence. Second, cyclists do not minimize their perceived exertion at the preferred cadence, although results have varied between studies (9,10,14). Third, cadences higher than those that are the most economical result in longer times to exhaustion (16) and appear to result in reduced neuromuscular fatigue (21–23). Recently, Boning et al. (1) and Sidossis et al. (19) reported that delta efficiency for experienced cyclists increased with increases in cadence. Delta efficiency is the ratio of the change in work accomplished to the change in energy expended. These data (1,19) provide further explanation for the selection of high preferred cadences by cyclists during training and competition, that is increased muscular efficiency at the expense of economy (i.e., steady-

0195-9131/00/3209-1630/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

Submitted for publication August 1999.
Accepted for publication November 1999.

state submaximal oxygen uptake per unit of body mass). Other sources, however, have reported conflicting trends showing that delta efficiency decreases with increases in pedaling frequency during cycling at constant power output (6,16), which does not support the use of high cadences. Therefore, one purpose of this study was to assess the significance of delta efficiency as a factor underlying selection of the preferred cadence.

Two frequently cited studies (3,8) highlight the widely held belief that experienced cyclists have adapted via their training to the higher preferred cadences, implying that experienced cyclists differ from noncyclists in biomechanical and/or physiological factors. These studies combined with the previous data on delta efficiency in experienced cyclists (1,19) suggest that cyclists are likely to be more efficient at the cadences at which they train and race, i.e., a trend for delta efficiency to be maximized close to the preferred cadence. However, experienced cyclists and well-trained noncyclists tested in our previous studies showed considerable similarity in a number of physiological and biomechanical variables, suggesting there would be little difference in muscular efficiency between these two groups. In addition, Boning et al. (1) reported only minor differences in delta efficiency of cycling between trained cyclists and untrained subjects, although cyclists did appear to exhibit slightly higher efficiencies. Recently, Nickleberry and Brooks (16) showed that there were no differences in muscular efficiency (as estimated via delta efficiency) between competitive and recreational cyclists. However, it remains unclear if differences in cycling efficiency exist between experienced cyclists and individuals with no cycling experience.

The purpose of this study was to compare delta efficiencies of trained experienced cyclists, trained noncyclists (runners), and a group of less-trained noncyclists at cadences of 50, 65, 80, 95 and 110 rpm to determine the significance of delta efficiency as a factor underlying the selection of preferred cadence. It was hypothesized that: a) cyclists are most efficient at the higher cadences at which they are accustomed to training and racing, i.e., delta efficiency will be maximized close to the preferred cadence; b) cyclists and runners will exhibit similar delta efficiencies across the range of cadences tested; and c) the delta efficiency of less-trained noncyclists will be lower than that of cyclists and trained noncyclists.

METHODS

Details on the subjects for this study have been reported previously (13). In brief, 11 experienced male cyclists (age: 24.8 ± 3.7 yr; mass: 72.4 ± 7.7 kg; height: 177.1 ± 5.4 cm; $\dot{V}O_{2max}$: 71.2 ± 3.8 mL·kg^{-1}·min^{-1}), 10 aerobically trained male runners with no cycling experience (26 ± 5.5 yr; 68.7 ± 7.5 kg; 175.8 ± 7.5 cm; 72.5 ± 2.2 mL·kg^{-1}·min^{-1}), and 10 less-trained male noncyclists (24.6 ± 4.5 yr; 83.6 ± 8.1 kg; 177.8 ± 7.6 cm; 44.2 ± 2.8 mL·kg^{-1}·min^{-1}) were selected based on their responses to a questionnaire and a bicycle maximal oxygen consumption test. Before testing, potential subjects provided written informed consent following guidelines outlined by the American College of Sports Medicine and the Institutional Review Board. Noncyclists were classified as individuals who did not use a bike as a training mode or for daily commutes longer than 15 min (13).

A bicycle maximal oxygen uptake ($\dot{V}O_{2max}$) test was administered to all subjects to ensure that the trained and less-trained subjects fell into two distinct levels of aerobic fitness. The details of this test have been reported previously (13). The three groups had dramatically different fitness and cycling experience characteristics. They did not differ in height, but the less-trained subjects were significantly heavier than the trained subjects. The cyclists and runners did not differ in maximal aerobic capacity and both trained groups were significantly higher on this variable than the less-trained group.

Preferred cadence was determined at 100, 150, and 200 W for cyclists and runners and at 75, 100, and 150 W for less-trained subjects. All subjects rode without cadence feedback for 8 min at each randomly assigned power output while cadence was recorded every 15 s. The preferred cadence was calculated as the average cadence over the final 6 min of each power output condition. Details of this test and the reliability of the preferred cadence measurement have been reported previously (13).

On three separate occasions, cadence was manipulated while subjects pedaled at constant power output and measurements were made of cycling economy. A Velodyne electromagnetic trainer (Schwinn Corp., Chicago, IL) was used to control external power output independent of cadence. A metabolic cart (Sensormedics 2900, Anaheim, CA) calibrated with gases of known concentration was used to quantify $\dot{V}O_2$ during these testing sessions. Cyclists and runners rode at 100, 150, and 200 W during the $\dot{V}O_2$-cadence manipulations, whereas less-trained subjects rode at 75, 100, and 150 W. Testing at each power output was usually 24 h apart. On each occasion subjects pedaled at 50, 65, 80, 95, and 110 rpm for 5 min. The power output conditions were randomly ordered and the cadence conditions were randomly ordered within each power output condition. Six 20-s $\dot{V}O_2$ values (2 min of data), that were within 1 mL·kg^{-1}·min^{-1} of each other and considered representative of the steady state, were averaged to determine economy at each cadence condition. To minimize effects due to fatigue, cadence conditions were separated by a minimum of 5 min of rest or until the subject's heart rate dropped below 80 bpm.

The rate of energy expenditure was calculated from the economy and RER values at each cadence combined with the table developed by Lusk (11). Energy expenditure and power output were expressed in watts. Delta efficiency at each cadence was calculated as the reciprocal of the slope of the linear relationship between power output and energy expenditure (3 data points). The mean r^2 (goodness of fit) for this linear least squares fit collapsed across cadences were 0.98 ± 0.04 (range: 0.75–0.99), 1.00 ± 0.004 (range: 0.97–1.00), and 0.99 ± 0.02 (range: 0.90–1.0) for the cyclists, runners, and less-trained subjects, respectively.

The statistical package, SPSS for Windows (SPSS, Chicago, IL), was used for all statistical procedures. A two-factor (group × cadence) ANOVA with repeated measures on cadence was used to test for main effects of group and cadence and to examine the interaction effect. A probability level of 0.05 was used in all statistical procedures.

RESULTS

Mean delta efficiency scores in this study ranged from ~23 to 26% (Fig. 1). Inspection of Figure 1 suggests that there was no clear trend for delta efficiency to increase or decrease in a systematic fashion with increases in cadence in cyclists, runners, or less-trained subjects. The preferred cadences of the cyclists and runners did not change as power output increased from 100 to 200 W (Table 1). Both groups maintained a cadence of 92–96 rpm as power output increased from 100–200 W, whereas the less-trained subjects decreased cadence from 80 to 69 rpm as power output increased from 75 to 150 W. Interestingly the preferred cadences of cyclists and runners were not different at any power output. The less-trained subjects selected significantly lower preferred cadences at all power output compared to the cyclists and runners.

The first hypothesis, that cyclists maximize delta efficiency at or near the preferred cadence, was not supported. A repeated measures ANOVA on the cyclists' data alone showed a nonsignificant cadence effect ($P = 0.894$). A trend analysis showed that the delta efficiency-cadence relationship were not described by either a linear ($P = 0.643$) or

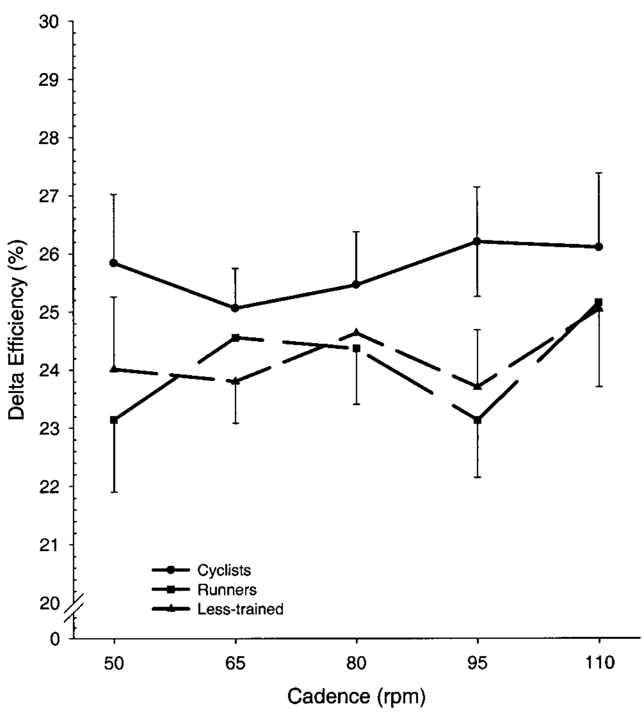

Figure 1—Delta efficiency during cycling at different cadences. Values are means ± SE for cyclists ($N = 11$), runners ($N = 10$), and less-trained subjects ($N = 10$). There was no systematic effect of cadence, and the three groups did not differ significantly from one another. Some error bars have been omitted for clarity.

TABLE 1. Preferred cadences at each power output.

Power Output (W)	Cyclists	Runners	Less Trained
75			80.0 (15.3)
100	95.6 (10.8)	92.0 (8.5)	77.5 (15.1)
150	94.4 (10.3)	92.9 (7.8)	69.1 (11.9)
200	92.2 (7.2)	91.8 (7.9)	

Preferred cadences of cyclists and runners were not different at any power output. The preferred cadences of the less-trained subjects were significantly lower than cyclists and runners at every power output and decreased as power output increased. Data are mean values with standard deviations in parentheses.

quadratic ($P = 0.665$) relationship. However, the data from 65 to 95 rpm for the cyclists were similar to those of Sidossis et al. (19), who showed delta efficiency increased from 20.6 to 23.8% as cadence increased from 60 to 100 rpm in well-trained cyclists. The data of the present study do not support the notion that delta efficiency is maximized near the preferred cadence. Although the mean data show that delta efficiency was highest at 95 rpm in cyclists (close to the mean preferred cadence for this group), the range of delta efficiencies was only approximately 1% across the cadence range (50–110 rpm).

The second hypothesis, i.e., cyclists and runners exhibit similar delta efficiencies across the range of cadences tested, was supported because there was no group main effect [F (2,25) = 1.734, $P = 0.197$]. Planned comparisons at 80, 95, and 110 rpm revealed that cyclists did not differ significantly from either runners or less-trained subjects. However, the difference between the cyclists and the other groups approached significance at 95 rpm ($P = 0.072$). The third hypothesis, i.e., the delta efficiency of less-trained subjects is lower than that of cyclists and runners, was rejected because there was no group main effect. The group × cadence interaction was also not significant [F (8,100) = 0.843, $P = 0.567$].

DISCUSSION

Several methods have been described for the calculation of efficiency (6). Delta efficiency, as opposed to gross, net, or work efficiency, has been proposed as the best estimate of the efficiency of the working muscle (6,19). Calculations of muscular efficiency obtained through expired respiratory gas analysis provide an indirect estimate of actual working musculature efficiency. However, Poole et al. (17) have shown for cycling that the slope of pulmonary $\dot{V}O_2$ was not different to that of leg $\dot{V}O_2$ between 20 and 90% $\dot{V}O_{2max}$ and also that the estimation of delta efficiency was not significantly different between the two methods. They stated "under the conditions of this investigation, changes in $\dot{V}O_2$ measured from the expired gas reflected closely those occurring within the exercising legs" (p. 805).

The range of values obtained for delta efficiency in this study is consistent with previous work. However, there are notable differences between the present study and previous literature with regard to the effect of cadence manipulations on delta efficiency. Gaesser and Brooks (6) and Nickleberry and Brooks (16) showed that delta efficiency decreased with increases in cadence, whereas Boning et al. (1) and Sidossis et al. (19) reported that delta efficiency increased with increases in cadence. Our data do not suggest a trend for delta efficiency to increase or decrease as cadence increases. Rather, delta efficiency varied between 23 and 26% in cyclists, trained noncyclists, and less trained noncyclists.

An analysis of the cyclists' data from 65 to 95 rpm was conducted so that we could directly compare our data with those of Sidossis et al. (19). Again neither the cadence main effect ($P = 0.465$) nor the linear trend ($P = 0.343$) was significant. Sidossis et al. reported a linear increase in delta efficiency (20.6–23.8%) as cadence increased from 60 to 100 rpm, which was larger than that seen in the present study. In general, the trends in our data are consistent with Sidossis et al. However, there is more variability in the delta efficiency data in our study, which might account for the nonsignificant effect of cadence.

Gaesser and Brooks (6) observed that at a constant power output, efficiency decreased as cadence increased, regardless of which definition of efficiency they used. Both earlier and subsequent studies have also shown decreased gross or net efficiency with increases in cadence during constant power output cycling (1,4,7,18). With respect to efficiency, these data suggest that higher cadences are not beneficial to the cyclist. However, Faria et al. (5) used a group of experienced cyclists who were familiar with high cadences and power outputs. They found that at a low power output (140 W), gross efficiency decreased from 18 to 14% as cadence increased from 68 to 132 rpm, but at approximately 290 W, gross efficiency remained constant at approximately 22%. Sidossis et al. (19) also found that gross efficiency was similar at cadences of 60, 80, and 100 rpm during cycling at power outputs corresponding to 80% (280 W) and 90% (300 W) of an individual's maximal aerobic power ($\dot{V}O_{2max}$). However, at 50 and 60% of $\dot{V}O_{2max}$, the efficiency of 100 rpm was significantly lower than either 60 or 80 rpm. Therefore, at high power outputs, increases in cadence did not appear to affect efficiency. Their data provide evidence that cyclists are not disadvantaged via a reduction in efficiency during cycling at a high power output and high cadence. Our data suggest a similar conclusion since it does not appear that cadence affected delta efficiency appreciably regardless of cycling experience or fitness level. From a practical standpoint, it appears that cyclists can select a cadence within a broad range without paying a substantial economy or efficiency penalty that might have a detrimental effect on performance. This may be important when pedaling over hilly terrain or during a race situation where cadence might vary substantially depending on the rider's location in a peloton.

To explain the difference between their results and previous research, both Faria et al. (5) and Sidossis et al. (19) speculated that the skill level of the subjects may have played a role. They suggested that less skilled riders might engage non-cycling–specific muscle groups especially during the higher cadences and power outputs, resulting in increased oxygen consumption without any increase in useful work. Interestingly, Boning et al. (1) reported only minor differences in gross and net efficiency of cycling between trained cyclists and untrained subjects. Stuart et al. (20) have reported no difference in delta efficiency between sprinters and distance runners, individuals likely to have differences in muscle fiber types, at either the same work rate or relative work rate at a cadence of 60 rpm. There were no significant differences in delta efficiency between the groups in our study. Given the cycling task and specificity of training it might be expected that there would be greater differences between the experienced cyclists and the trained and less-trained noncyclists. However, it appears that familiarity with the task (i.e., cycling experience) and maximal aerobic capacity had little effect on delta efficiency during cycling.

We had previously speculated that similarities in preferred cadences between cyclists and runners may be due to the similarity of the lower extremity training undertaken by these two groups, i.e., cyclical activity, high repetition, relatively low force (12). We have also shown remarkable similarity between these groups of trained cyclists and runners and less-trained subjects in an array of physiological, psychological, and biomechanical data (13–15). The data of the present study suggest that any adaptations in the mechanical or physiological properties that may occur due to training have a minor effect on delta efficiency. Despite significantly lower general aerobic capacity and no history of endurance training, the less-trained group did not exhibit markedly different delta efficiencies compared with the cyclists and runners.

Some methodological differences exist between this study and previous studies on delta efficiency during cycling. Sidossis et al. (19) and Nickleberry and Brooks (16) both used an incremental power output protocol at a fixed cadence with increases in power output after 5 and 4 min, respectively. Therefore, subjects completed different cadences on separate days. We had subjects pedal at constant power output while cadence was manipulated randomly with rest periods between cadence conditions. Therefore, subjects completed different power outputs on separate days. It is unclear whether any of these differences influenced the delta efficiency-cadence relationship leading to differences in the results of the three studies. Despite this difference, we were still able to achieve high r^2 values when calculating the slope of the power output-energy expenditure relationship. Another potential reason for the different trends seen in the delta efficiency-cadence relationship may be the method of calculation of delta efficiency. Gaesser and Brooks (6) used a definition of delta efficiency that incorporated not only a change in workload but also a change in cadence making it difficult to examine the influence of cadence alone on delta efficiency (see Footnote 2, sample calculations in ref. 6). This may help to explain differences between the present study, Sidossis et al. (19), Boning et al. (1), and the Gaesser and Brooks paper. Boning et al. (1) used data from Gaesser and Brooks to estimate the independent effect of cadence on delta efficiency. They noted that there was a trend for delta efficiency to increase from 40–80 rpm (see Fig. 2 in ref. 6).

In conclusion, cadence did not affect delta efficiency in a systematic fashion. Although cyclists exhibited slightly higher delta efficiencies across the cadence range (~1–2%), their delta efficiencies were not statistically different from trained noncyclists or less trained noncyclists. Whether a difference of 1–2% in delta efficiency has any practical significance with respect to performance is less clear. Cyclists did not appear to maximize delta efficiency near their preferred cadence. Runners and less-trained individuals who had substantially different levels of aerobic fitness did not differ in delta efficiency. Muscular efficiency, as measured indirectly by delta efficiency, appears to remain relatively constant at approximately 24–26%, regardless of cycling experience or fitness level.

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