Effect of Endurance Training on Different Mechanical Efficiency Indices During Submaximal Cycling in Subjects Unaccustomed to Cycling

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Abstract/Résumé
The purpose of this study was to evaluate different efficiency indices, i.e., gross (GE: no baseline correction), net (NE: resting metabolism as baseline correction), and work (WE: unloaded exercise as baseline correction), to reveal the effect of endurance training on mechanical efficiency. Nine healthy sedentary women undertook an incremental test and submaximal cycling exercise, at an intensity corresponding to 50% of the pretraining peak oxygen uptake, before and after 6 weeks of endurance training (18 sessions of 45 min). The training effects on efficiency indices were tested by comparisons based on GE, NE, and WE as well as by the differences between the percentage changes of all indices (%GE, %NE, %WE). Endurance training resulted in significantly higher GE (+11.1%; p < 0.001) and NE (+9.1%; p < 0.01). Only minor significant improvement (+2.4%; p < 0.05) was observed with the WE index because the value used for baseline subtraction was significantly reduced by the training sessions, due perhaps to improvement in pedaling skill. As a conse-

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Endurance training improves physical work capacity and the specific skills of exercise performance, depending on which training program is used (Jones and Carter, 2000). For example, Gimenez et al. (1982) showed that specific leg training with the Square-Wave Endurance Exercise Test (SWEET) significantly increased endurance capacity in healthy subjects. Both physiological and pedaling skill adaptations are usually observed after cycling training (Jones and Carter, 2000; Takaishi et al., 1998). Repeated exposures to cycling activity should improve the mechanical efficiency of the cycling motion, that is, the ratio of external work to energy expended (Whipp and Wasserman, 1969). However, very few studies have been conducted as to the effects of training on cycling efficiency. There have been cross-sectional studies as to the effects of cycling experience on efficiency, but the results of these studies are inconclusive.

Some studies have found no effect of cycling experience on mechanical cycling efficiency (Marsh et al., 2000; Nickleberry and Brooks, 1996), whereas Kaneko et al. (1983) showed that trained subjects have higher mechanical efficiency than untrained subjects. Finally, some researchers have even found contradictory results, i.e., positive effect on cycling experience or not, depending on the mechanical efficiency indices they calculated when comparing two groups with different training backgrounds (Böning et al., 1984; Stuart et al., 1981). Moreover, elite cyclists produce more effective force on the pedals and generate larger propulsive torques for similar power output than good cyclists (Coyle et al., 1991).
These studies are cross-sectional by design in that they compare groups of subjects who have various levels of training. Indeed, the training effect on efficiency cannot be precisely dissociated from other factors such as psychological and/or morphological differences between subjects. It would be more appropriate to use a longitudinal approach during which the same subjects would be evaluated before and after the training period, as suggested by Saltin et al. (1968). However, to our knowledge no study using a longitudinal protocol has measured the mechanical efficiency before and after an endurance training program. Moreover, the intensity, population characteristics, and mechanical efficiency indices used by these other studies could also explain many discrepancies. Mechanical efficiency has sometimes been compared between groups at a given absolute intensity, i.e., with similar power output for both trained and untrained subjects (Kaneko et al., 1983; Marsh et al., 2000). However, the same absolute intensity may represent a higher relative intensity for untrained vs. trained subjects due to their lower maximal tolerated power output. Since mechanical efficiency is significantly influenced by exercise intensity (Gaesser and Brooks, 1975), the differences in mechanical efficiency data published in the literature could in part be explained by the different absolute intensity imposed.

In sedentary or recreationally trained subjects, endurance training elicits marked improvement in endurance performance and in several cardiovascular and metabolic markers (e.g., Green et al., 1989). By contrast, endurance training in highly trained cyclists may not always induce an improvement in either endurance performance or physiological markers (e.g., Hawley and Stepto, 2001; Laursen and Jenkins, 2002). For this reason, if training is likely to result in increased efficiency, this is more likely to be seen in untrained individuals.

Finally, the term mechanical efficiency includes numerous indices calculated according to the baseline subtracted from total energy expenditure. Gross (GE), net (NE), work (WE), and delta (DE) efficiency indices are calculated without baseline subtraction, with resting baseline subtraction, with unloaded (zero work) baseline subtraction, and with measurable work-rate baseline subtraction, respectively (Gaesser and Brooks, 1975; Whipp and Wasserman, 1969). Since the specific cycling training or cycling experience allowed cycle propulsion technique to improve (Coyle et al., 1991), the baseline could also be influenced by the cycling experience. As a consequence, the training effect can be interpreted differently depending to the efficiency indices used. The indiscriminate use of these efficiency indices in previous studies dealing with training may have introduced a measurements bias.

In view of these numerous factors influencing the link between training and mechanical efficiency, we proposed first to analyze the last factor, i.e., the effect of the index selected. GE, NE, and WE indices were calculated during a submaximal cycling exercise before and after a specific endurance-training program, i.e., with a longitudinal protocol, on a cycle ergometer. The purpose of this study was then to evaluate the effect of an endurance-training program on submaximal cycling efficiency as reflected by different efficiency indices in a group of healthy untrained women.
Methods

SUBJECTS AND EXPERIMENTAL PROTOCOL

Nine healthy sedentary young women participated in this study. Their physical characteristics were (mean ± SD): age 21.8 ± 3.1 years, height 165.7 ± 5.4 cm, and weight 61.0 ± 3.6 kg. None of them were engaged in any regular endurance physical activity nor involved in competition sports except the training program in this study. During the training program they performed their usual daily activities. None were familiar with cycling exercise. All subjects gave written informed consent after being informed of the study protocol, which complies with the Helsinki Declaration for Human Experimentation.

The subjects completed two sets of tests before and after an endurance-training program which lasted 6 weeks. Each set of tests included an incremental cycling test and a submaximal constant-load cycling test on a mechanically braked cycle ergometer (Monark type 818E, Stockholm, Sweden).

**Incremental Cycling Test.** The subjects underwent an incremental cycling test at a pedaling rate of 60 rpm where the load was increased by 30 W every 3 minutes, starting from an initial power output of 60 W up to voluntary maximum. The highest load which could be maintained for 3 min with a constant pedaling rate of 60 rpm was taken as the maximal tolerated power output (POpeak). The associated peak oxygen uptake value was then calculated (VO2peak). A linear regression relating submaximal oxygen uptake (VO2) to power output (PO) was used to calculate (a) power output corresponding to 50% of each subject’s VO2peak and (b) oxygen uptake corresponding to unloaded pedaling (VO2unload) as the y-intercept value (Hintzy-Cloutier et al., 2003).

**Constant-Load Cycling Test.** Each subject started with a 10-min seated resting period followed by 6 min of cycling at a constant power output corresponding to 50% of her VO2peak. Pedaling rate was maintained at 60 rpm with the aid of a visual pedal rate indicator, and accuracy of load setting was checked systematically throughout the exercise. Baseline (resting) oxygen uptake (VO2rest) was obtained during the last minute of the prior 10-min seated resting period.

**Endurance Training Program.** The subjects exercised three times (SWEET session of 45 min) per week for 6 weeks on the same cycle ergometer adjusted to their individual anthropometric characteristics. A 45-min SWEET session consisted of 9 consecutive periods of 5 minutes including a 4-min exercise period (base level) followed by a 1-min exercise period (peak level) initially performed at a power output corresponding to ventilatory threshold and POpeak, respectively. Pedaling rate was fixed at 60 rpm. More details are presented in Gimenez et al. (1982).

MEASUREMENTS AND ANALYSIS

During the pre- and posttraining tests, VO2 (L·min⁻¹) and carbon dioxide output (VCO2, L·min⁻¹) were measured continuously on a breath-by-breath basis by means of a computerized analyzer-flowmeter combination (Medical Graphics CPX/D, St. Paul, MN) and then averaged every 30 sec. Prior to each exercise test, the gas
analyzers were calibrated with known gases. Volume calibration was performed with a 3-L syringe (Hans Rudolph, Kansas City, MO). The subjects breathed through a mouthpiece connected to a low-resistance pneumotachograph.

Mechanical efficiency was calculated as the ratio of external work accomplished to the energy expenditure based on VO$_2$ adjusted for respiratory exchange ratio (RER) during the last minute of the pre and post constant-load cycling tests (McArdle et al., 1981). Three efficiency indices were calculated depending on the baseline subtracted from the total energy expended: GE, without baseline correction; NE, rest VO$_2$ rest subtracted; WE, unloaded VO$_2$ unload subtracted (Gaesser and Brooks, 1975).

**Statistics**

All data are expressed as mean ± standard deviation. The effect of the training program on mechanical (POpeak, PO), physiological (VO$_2$peak, VO$_2$rest, VO$_2$unload), and efficiency (GE, NE, WE) parameters was tested with a Student $t$-test (pre vs. post values). The effect of training on GE, NE, and WE indices was evaluated by the percentage change (posttraining-pretraining/pretraining × 100). These were designated %GE, %NE, and %WE, respectively. Significant differences between %GE, %NE, and %WE were analyzed using a repeated-measures one-way ANOVA. Post hoc comparisons using the Scheffé procedure were done when significant differences were evident with the analysis of variance. Statistical significance limit was defined as $p < 0.05$.

**Results**

VO$_2$peak (2.43 ± 0.14 vs. 2.12 ± 0.13 L·min$^{-1}$) and POpeak (180.0 ± 11.3 vs. 138.7 ± 11.2 W) were significantly higher ($p < 0.001$) after the training program than before, respectively. VO$_2$rest (0.26 ± 0.02 vs. 0.31 ± 0.04 L·min$^{-1}$; $p < 0.01$) and VO$_2$unload (0.47 ± 0.02 vs. 0.60 ± 0.06 L·min$^{-1}$; $p < 0.001$) were significantly lower in post than in pre submaximal tests, respectively. PO of 64.5 ± 9.8 W (corresponding to 50% of VO$_2$peak in the premaximal test) was used in both pre and post submaximal tests. Gross VO$_2$ values were, respectively, 1.19 ± 0.13 L·min$^{-1}$ and 1.06 ± 0.11 L·min$^{-1}$ in pre and post submaximal tests, and were significantly higher ($p < 0.0001$) in pre vs. posttests. RER was significantly lower ($p < 0.05$) in post (0.83 ± 0.06) than in pre (0.88 ± 0.06) submaximal tests. All values of efficiency indices are presented in Figure 1. The training program elicited significant increase in GE ($p < 0.001$), NE ($p < 0.01$), and WE ($p < 0.05$) values. The percent changes of efficiency values between pre and post submaximal tests were 11.1 ± 4.5% for GE, 9.1 ± 7.7% for NE, and 2.4 ± 3.2% for WE. The ANOVA showed that the percent changes were significantly different ($F = 6.32; p < 0.01$) according to the efficiency indices used: %WE was significantly lower than %GE ($p < 0.01$) and %NE ($p < 0.05$), while %GE and %NE were not significantly different.

**Discussion**

The present endurance-training program allowed a significant improvement ($p < 0.001$) of VO$_2$peak and POpeak, as previously found in the literature (Gimenez et
al., 1982; Horowitz et al., 1994; Nickleberry and Brooks, 1996). The increase of \( \text{VO}_2 \text{peak} \) induced by the training program resulted in a lower relative PO after training compared to before. Indeed, the PO of 64.5 W imposed during both pre and post submaximal exercises corresponded to 50% of pretraining \( \text{VO}_2 \text{peak} \) and 36% of posttraining \( \text{VO}_2 \text{peak} \). By using a similar PO for mechanical efficiency comparisons before and after training, it was possible to analyze the energy expenditure needed to produce this PO.

In the present study all efficiency indices were significantly improved by the 6-week cycling training program. To our knowledge, this is the first time such a training effect on mechanical efficiencies has been reported for cycling. Indeed, previous studies showing the positive effect of cycling experience on mechanical efficiency have used a cross-sectional design (Kaneko et al., 1983; Stuart et al., 1981). Those studies reported that long-distance runners have a higher GE than sprinters during cycling (Kaneko et al., 1983) and running (Stuart et al., 1981) exercises. In the present study we showed clearly that, to perform the same amount of power output, our subjects expended more metabolic energy in the pretraining vs. the posttraining condition. Concerning the physiological responses, considerable information is already available relating to the metabolic, cardiovascular, respiratory, and neuromuscular adaptations that result from endurance training (for review, see Hawley and Stepto, 2001; Jones and Carter, 2000). We will not deal with these training adaptations here.

The repeated exposure of our subjects to the previously unfamiliar cycling movement pattern during the training period should also allow them to acquire optimal pedaling skills (Takaishi et al., 1998), especially since the pedaling rate was similar during the training program and submaximal tests. Note that the cycling inexperience of our subjects may have been an important factor contributing

![Figure 1](image.png)
to these observations. Indeed, no significant difference in GE or pattern of muscle use were observed between recreational and competitive cyclists, i.e., between two groups who differ in cycling experience but both being accustomed to the cycling pattern (Böning et al., 1984; Marsh and Martin, 1995; Nickleberry and Brooks, 1996).

The WE index also revealed a positive effect of the cycling endurance-training program, with WE values significantly higher in post- compared to pretraining conditions. But the improvement of %WE (+2.4%) with endurance training were significantly lower than those of %GE (+11.1%) or %NE (+9.1%). In contrast, %GE and %NE were not significantly different. These results confirmed that the manner of expressing efficiency would affect the outcome. This could be explained by the significantly lower VO₂-unload values (–20.3%) subtracted from the energy expenditure in post- compared to pretraining WE index. To our knowledge, the significant reduction of VO₂-unload due to training has never been reported in the literature. This result could also explain the large range of VO₂-unload values reported in some studies (from 0.28 L·min⁻¹ in Zoladz et al., 1998, to 0.85 L·min⁻¹ in Sidossis et al., 1992), but pedaling rate and the method of calculation used will also influence this.

The VO₂-unload values represented the energy expended to move the limbs with no resistance, i.e., the internal work (Gaesser and Brooks, 1975; Stainsby et al., 1980). Changes in unmeasured internal work are reflected by energy input, the crank force needed to accelerate and decelerate the pedals and the lower limbs. The lack of skill in cycling pattern in the pretraining condition for our unaccustomed female subjects probably elicited more wasted energy. The wasted energy could be explained by extra limb movements (e.g., movement of the knees in lateral directions relative to the crank movement), extra muscle contractions (e.g., cocontraction of agonists and antagonists across joints), and reduced coordination in force production (e.g., higher ineffective forces and lower effective forces applied to the crank). With repeated practice of the specific leg cycling pattern, it is likely that the subjects improved their intra- and intermuscle coordination by modifying their activation patterns and the intensity of activation of the lower extremity muscles (Patterson and Moreno, 1990; Takaishi et al., 1998). This improved skill would lead to improved efficiency.

The differences in pedaling skills between subjects who differ in cycling experience have also been confirmed by studies dealing with the optimal pedaling rate minimizing the energy expenditure (Chavarren and Calbet, 1999; Takaishi et al., 1998), the rate of perceived exertion (Pandolf and Noble, 1973), or neuromuscular fatigue (Takaishi et al., 1998).

In summary, the WE index was less sensitive to the training effect than GE or NE indices, since the more efficient muscular pattern engendered by the training program could not be detected with the WE index to the same extent as GE and NE. The WE index could be used to reduce the variability between subjects for mechanical cycling efficiency due to level of experience. Our data also confirmed the potential misleading nature of the baseline subtraction previously reported by Stainsby et al. (1980) and Hintzy-Cloutier et al. (2003). The very high value of WE (32–33%) cannot represent a muscular efficiency, considering that isolated muscles cannot achieve efficiency greater than 30% (Hill, 1922).
Previous studies dealing with the link between cycling training program or cycling experience and mechanical efficiency have used the delta efficiency index (DE), i.e., the change in actual work accomplished relative to the change in energy expended when work rate increases (Böning et al., 1984; Marsh et al., 2000; Nickleberry and Brooks, 1996; Stuart et al., 1981). These studies found no significant difference in DE between recreational and competitive cyclists (Böning et al., 1984; Nickleberry and Brooks, 1996) between trained endurance runners and sprinters (Stuart et al. 1981), or between trained experienced cyclists, trained noncyclists, and less trained noncyclists (Marsh et al., 2000). As concluded by Marsh et al. (2000), familiarity with the task and maximal aerobic capacity had no effect on DE index during cycling. These observations are consistent with our results with respect to WE. The WE is analogous to DE in that it represents the ratio of a change in mechanical work to the change in metabolic energy. In fact, since we estimated the energy cost of unloaded cycling from the linear relationship between power output and $V_O_2$, an estimated DE would have been very similar to our WE.

On the basis on the present results, we conclude that (a) all efficiency indices were positively influenced by a 6-week endurance-training program undertaken by untrained healthy women who were previously unaccustomed to cycling, and (b) it is likely that improved skill permitted the improved efficiency. This improvement differed depending on the baseline subtraction used, with greater influence on GE and NE indices compared to the WE index. The WE calculations mask the underlying changes that are relevant to the training program. Thus it seems more appropriate to use GE or NE indices when the purpose of the study is to evaluate the effect of a training program on mechanical efficiency. Moreover, other data at different submaximal intensities are needed to verify this first result since all efficiency indices were PO-dependent (Gaesser and Brooks, 1975).

References


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