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REVIEW ARTICLE **Open Access**

Gross efficiency and cycling performance: a brief review

Simon A Jobson[1]✉, James G Hopker[2], Thomas Korff[3] and Louis Passfield[2]

Abstract

Efficiency, the ratio of work generated to the total metabolic energy cost, has been suggested to be a key determinant of endurance cycling performance. The purpose of this brief review is to evaluate the influence of gross efficiency on cycling power output and to consider whether or not gross efficiency can be modified. In a re-analysis of data from five separate studies, variation in gross efficiency explained ~30% of the variation in power output during cycling time-trials. Whilst other variables, notably VO_{2max} and lactate threshold, have been shown to explain more of the variance in cycling power output, these results confirm the important influence of gross efficiency. Case study, cross-sectional, longitudinal, and intervention research designs have all been used to demonstrate that exercise training can enhance gross efficiency. Whilst improvements have been seen with a wide range of training types (endurance, strength, altitude), it would appear that high intensity training is the most potent stimulus for changes in gross efficiency. In addition to physiological adaptations, gross efficiency might also be improved through biomechanical adaptations. However, 'intuitive' technique and equipment adjustments may not always be effective. For example, whilst 'pedalling in circles' allows pedalling to become mechanically more effective, this technique does not result in short term improvements in gross efficiency.

Keywords: cycle training, biomechanics, pedalling, pedaling

✉ **Contact email:** *simon.jobson@winchester.ac.uk* (SA. Jobson)

[1] Department of Sports Studies, University of Winchester, Hampshire, England.

[2] Centre for Sports Studies, University of Kent, Kent, England.

[3] School of Sport and Education, Brunel University, Middlesex, England.

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Introduction

Efficiency, defined as the ratio of work generated to the total metabolic energy cost, has been suggested to be a key determinant of endurance cycling performance (Joyner & Coyle 2008). The efficiency of energy consumption during cycling has been reviewed previously (Ettema & Lorås, 2009). However, whilst some consideration of the factors that influence gross efficiency (e.g. muscle fibre type) has been given (Coyle et al. 1992), several fundamental assumptions related to the importance of gross efficiency have received very little experimental verification. The purpose of this brief review is to evaluate the influence of gross efficiency on cycling power output and to consider whether or not gross efficiency can be modified. In theory, gross efficiency could be affected both by physiological and biomechanical changes. However, there is much debate over the relative importance, indeed, existence, of such changes. This brief review will consider: 1) the influence of gross efficiency on cycling power output; 2) the effects of training on gross efficiency in cycling; and 3) the relationship between pedalling mechanics and gross efficiency in cycling.

The influence of gross efficiency on cycling performance

Athletic performance has long been known to have a wide range of physiological determinants. In 1925 A.V. Hill emphasised the importance of muscle fatigue and discussed issues related to energy stores and oxygen demand (Hill 1925). Recently, more comprehensive models of athletic performance have been presented. Joyner and Coyle (2008) described a model where performance velocity or performance power is dependent upon 3 key parameters: performance VO_2, performance O_2 deficit, and gross efficiency. The determinants of performance VO_2, suggested to be primarily VO_{2max} and lactate threshold, and performance O_2 deficit, have received comprehensive research attention. In contrast, very few studies have evaluated the relative influence of gross efficiency. Indeed, despite being elevated to one of the 3 determinants of performance by Joyner and Coyle (2008), to the authors' knowledge, only two studies have described any link between efficiency and performance (Horowitz et al. 1994; Passfield & Doust 2000). Horowitz et al. divided an apparently homogeneous group of 14 endurance-trained cyclists according to gross efficiency during a 1-hour laboratory time-trial (i.e. a high- and a low-efficiency group). Both groups maintained the same VO_2 throughout the time-trial, but the high-efficiency groups were able to generate 10% more power. Whilst providing an initial insight into the importance of gross efficiency, it is difficult to generalize this result because of the homogeneous nature of the participants used and limitations in the determination of gross efficiency.

In order to clarify the link between gross efficiency and cycling performance, we here provide a re-analysis of data from three published and two unpublished investigations. Linear regression was used to determine the correlation between gross efficiency and cycling power output data from five separate studies (S1–S5). S1 (Jobson et al. 2008) measured gross efficiency at 3 $W•kg^{-1}$ and power output during a 40-km laboratory time-trial. S2 (Horowitz et al. 1994) measured gross efficiency during a 1-hour laboratory time-trial. Gross efficiency values were derived from Figure 1 in Horowitz et al. (1994). S3 (Hopker et al. unpublished observations) measured gross efficiency at 200 W and 300 W in a group of 10 untrained and 9 trained cyclists respectively. S4 (Jobson et al. unpublished observations) measured gross efficiency at 150 W in a group of 10 trained cyclists. S5 (Passfield & Doust 2000) measured gross efficiency at 208 W. Power output was measured during a 5-min laboratory time-trial in S3, S4, and S5.

Gross efficiency was correlated with 'long' (40-km and 1-hour) time-trial cycling power output (S1: r=0.74, p=0.04; S2: r=0.51, p=0.06; S1 and S2 combined: r=0.58, p=0.004) and 'short' (5-min) time-trial cycling power output (S3: r=0.53, p<0.0001; S4: r=0.59, p=0.73; S5: r=0.51, p=0.02; S3, S4 and S5 combined: r=0.48, p<0.0001).

Variation in gross efficiency explained 34% and 26% of the variation in power output during long and short cycling time-trials respectively. Whilst other variables, notably VO_{2max} and lactate threshold, have been shown to explain more of the variance in cycling power output, these results confirm the important influence of gross efficiency.

The effects of training on gross efficiency

Given that gross efficiency has been shown to correlate with cycling power output, it is important to consider whether or not efficiency can be modified. There is growing evidence in the scientific literature for the possibility of increasing gross efficiency in cycling through training (Hopker et al. 2007; Hopker et al., 2009; Santalla et al. 2009; Hopker et al. 2010). Recent results indicate that gross efficiency increases over the period of one (Hopker et al. 2009) and many cycling seasons (Santalla et al. 2009). Thus, increases in gross efficiency may be related to the volume and intensity of training undertaken by cyclists.

To investigate this hypothesis, Hopker et al. (2010) evaluated the impact of training intensity on efficiency in competitive cyclists. In this study, 29 endurance-trained competitive male cyclists completed three laboratory visits over a 12-week training period. At each visit, gross efficiency and maximal oxygen uptake were determined. Cyclists were randomly split into two groups (A and B). Over the first 6 weeks, group A was prescribed two specific high-intensity training sessions per week, whereas group B did not complete high-intensity training. For the second 6-week period, group B introduced high-intensity training, whilst group A continued unrestricted. Gross efficiency increased in group A (+1.6 ± 1.4%; p<0.01) following the high-intensity training, whereas no significant change was seen in group B (+0.1 ± 0.7%; p>0.05) (*see* Figure 1). Group B cyclists did increase their gross efficiency over weeks 6 to 12 (+1.4 ± 0.8%; p<0.01). No changes in gross efficiency were observed in group A over this period (+0.4 ± 0.4%; p>0.05).

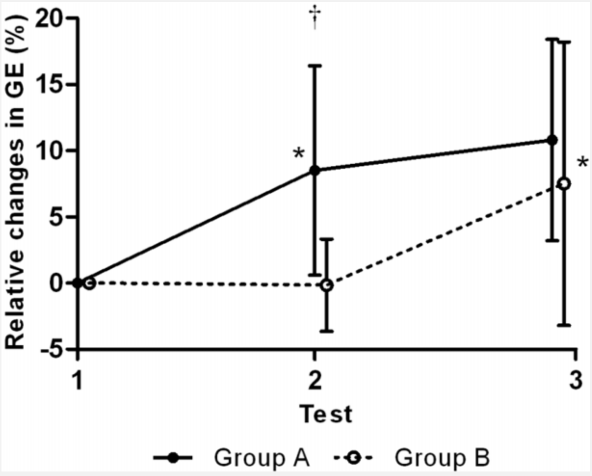

Figure 1. Relative changes in gross efficiency (GE) across the study period. Values are averaged across intensities to the highest common work rate and presented as means ± standard deviation. Group A completed: high intensity training between tests 1 and 2; unrestricted training between tests 2 and 3. Group B completed: no high intensity training between tests 1 and 2; unrestricted training between tests 2 and 3. * = significant increase above previous test (p < 0.05); † = significant difference between groups (p < 0.05). Source: Hopker et al. (2010).

To our knowledge, this was the first study to experimentally demonstrate that exercise training alone increases efficiency. These changes in efficiency appear to be influenced by the volume and intensity of training undertaken by cyclists. More specifically, it would appear that high intensity training is the most potent stimulus for changes in gross efficiency. However, our work (Hopker et al. 2009; Hopker et al. 2010) also suggests that in trained cyclists, training increases GE, but not VO_{2max}. Indeed, an inverse relation between GE and VO_{2max} appears to exist. Cyclists with a high VO_{2max} seem to be less responsive to training related changes in GE than those with a lower VO_{2max} (Hopker et al. 2012).

Improvements in cycling efficiency have also been shown following a period of acclimatization at altitude in a group of mountaineers (Green et al. 2000). Following return to sea level, the climbers demonstrated increases in cycling net efficiency. This finding was repeated by Gore et al. (2001) using a group of trained athletes living in a normobaric hypoxic environment (O_2 15.48%) for 9.5 hours per night for twenty-three consecutive nights. Using groups matched for fitness, participants followed either a live high (simulated 3000 m): train low (600 m) (LHTL), or a control (600 m) training strategy. Exercise tests for cycling net efficiency were conducted at baseline, 11 days into the training regimen, and after a 23-day acclimatization period. Results of the study demonstrated that submaximal VO_2 was reduced (4.4%, $p<0.05$) and net efficiency improved (0.8%, $p<0.05$) in the LHTL condition, fuel utilization shifting from fat to carbohydrate oxidation (as shown by a higher RER post acclimatization). Interestingly, Gore et al. also demonstrated a significant decline in VO_{2max} in the altitude-acclimatized group, resulting in an inverse relation between efficiency and VO_{2max}.

Whilst many factors no doubt influence both gross efficiency and VO_{2max}, a possible mechanism for the inverse relation between these parameters is suggested by studies that have investigated the effects of nitrate supplementation. A simple inorganic anion abundant in green leafy vegetables, nitrate appears to be readily reduced to nitric oxide and other reactive nitrogen intermediates (Lundberg et al. 2008). Short-term nitrate supplementation has been shown to reduce exercise oxygen cost (i.e. to increase efficiency) (Bailey et al. 2009, 2010; Larson et al. 2007, 2011) and to decrease VO_{2max} (Larson et al. 2010).

The results of Larson et al. (2011) suggest that nitrate supplementation has a direct impact on mitochondrial function, reducing proton leak as a result of the downregulation of adenine nucleotide translocator (and possibly uncoupling protein 3). This necessarily increases the number of molecules of ATP generated per atom of oxygen consumed (the P/O ratio) and, therefore, mitochondrial efficiency. The nitrate-induced reduction in VO_{2max} appears to be the result of a small increase in p50, the oxygen tension where half-maximal respiration occurs. Larson et al. (2011) have shown that such an increase leads to an oxygen limitation remarkably similar to observed reductions in VO_{2max}. Thus, nitrate may increase gross efficiency, by increasing the P/O ratio, and reduce VO_{2max}, by increasing p50. Given the similarity of the gross efficiency/ VO_{2max} response in these studies to those described in the training studies above, we might speculate that training leads to a natural increase in the body's nitrate levels.

Whilst this 'nitrate hypothesis' might be dismissed for its disconnect from the real exercise training-related inverse relation described above, it finds support in research on high-altitude-living Tibetans. These high altitude natives have been shown to have significantly lower VO_2 at submaximal work rates (i.e. higher gross efficiency), lower VO_{2max} values and >10-fold higher circulating nitrate levels than inhabitants of lower altitudes (Curran et al. 1998; Erzurum et al. 2007; Ge et al. 1994).

Recent research findings suggest that short-term strength training can also enhance gross efficiency (Paton & Hopkins 2005; Sunde et al. 2010; Ronnestad et al. 2011). Ronnestad et al. (2011) have shown that a 12-week period of heavy strength training can enhance gross efficiency during the last hour of a 3-hour bout of submaximal cycling. This was also accompanied by reductions in blood lactate concentration and reductions in ratings of perceived exertion. The mechanisms linking strength training and improvements in gross efficiency are unknown, though this link is no doubt dependent upon the mechanism that causes the strength gain. Whilst we cannot discount a neurological mechanism, we speculate that the improvement in gross efficiency is due to strength gains resulting from muscle hypertrophy. Heavy strength training increases maximal force. Consequently, the peak force, or muscle fibre tension, developed in each pedal thrust becomes a lower percentage of the maximal force. In turn, this might allow greater recruitment of more efficient and fatigue-resistant type I muscle fibers.

The biomechanics of efficiency in cycling

Using instrumented force pedals or cranks in combination with kinematic analyses allows us to determine the mechanical effectiveness of the pedal stroke or the magnitude of rotational forces that muscles generate about the ankle, knee and hip joints. From a basic science perspective, biomechanical analyses enable us to understand how the muscles of the lower limb work in synergy to deliver force to the crank. Such knowledge has practical implications for cycling coaches. In this section, we discuss the relationship between mechanical effectiveness of the pedal stroke and efficiency and the usefulness of mechanical variables in the context of a cyclist's selection of the preferred pedalling cadence.

Pedal force effectiveness can be defined as the proportion of the effective force (the force component that acts in the direction of the movement) relative to the resultant pedal force. The meaningfulness of this measure and its association with gross efficiency has been under debate. From a purely mechanical perspective, it seems intuitive to associate greater force effectiveness with increased cycling efficiency as a greater proportion of total force is used to propel the crank. However, this association is limited for two reasons. First, forces measured on the pedal include gravitational and motion dependent influences. Thus, only a portion of the measured pedal force can be attributed to muscular effort (Kautz & Hull 1993; Neptune & Herzog, 1999). The second reason for the limited meaningfulness of pedal force effectiveness is the unique configuration of our musculo-skeletal anatomy. Maximising the effective force relative to total force implies minimizing the radial force (the force component acting along the crank toward the centre of rotation). Due to the constrained positions of body segments with respect to the bicycle and of muscles with respect to the bones, a certain amount of radial force is needed for muscles to work efficiently. In an elegant modelling study, Höchtl et al. (2010) demonstrated that a significant amount of radial force is necessary to maximize cycling efficiency, demonstrating the limited usefulness of measures of mechanical effectiveness of pedal forces.

Several authors have investigated the relationship between force effectiveness and cycling efficiency experimentally. Both Zameziati et al. (2006) and Leirdal & Ettema (2011) showed that mechanical force effectiveness is positively correlated with gross efficiency when analysed across participants. This result is in contrast to Edwards et al. (2009) who found no association between mechanical force effectiveness and gross efficiency across participants and across a range of cycling conditions. The different results are possibly explained by differences in the measurement of efficiency. Edwards et al. (2009) measured efficiency at absolute power outputs and cadences, whilst Leirdal & Ettema (2011) measured efficiency at relative power outputs and with participant selected cadences.

A limitation to all of these studies is the cross sectional nature of the study design, as the correlational analyses do not provide incontrovertible evidence about cause and effect. Using a within subject design, which overcomes this limitation, Korff et al. (2007) showed that, when a cyclist is instructed to change his/her preferred pedalling style to increase the ratio of force effectiveness ("pedal in circles" or "pull on the pedal"), gross efficiency is significantly reduced. This suggests that short-term changes in pedalling technique can be detrimental to submaximal cycling performance. In this study, participants performed all tests on one day without the possibility of getting used to the new pedalling style. Therefore, the question arises as to whether or not changes in pedalling technique can affect cycling efficiency if participants are given the opportunity to adapt to a new pedalling style. To address this question, several authors have used the decoupled crank paradigm to investigate the issue longitudinally. Training with decoupled cranks forces the cyclist to actively pull on the pedal during the upstroke, with potential implications for pedalling technique and cycling efficiency. Luttrell & Potteiger (2003) reported that 6 weeks of training with decoupled cranks resulted in improved cycling efficiency. However, the participant selection in this study was poorly controlled, and thus, the meaningfulness of these results is limited. Williams et al. (2009) quantified the effect of training with decoupled cranks on pedalling technique and cycling efficiency in a more controlled fashion. These authors found no significant effects of training with decoupled cranks on cycling efficiency. Expanding on these results, Böhm et al. (2008) showed that training with decoupled cranks can change certain aspects of the pedalling technique without changing physiological variables. Together, the experimental evidence suggests that the acquisition of new pedalling techniques does not result in significant increases in gross efficiency in the short to medium term. However, more research is needed to thoroughly address long-term adaptations to changes in pedalling technique with respect to cycling efficiency. Specifically, the aforementioned studies by Zameziati et al. (2006) and Edwards et al. (2009) allow us to speculate that years of practicing a mechanically effective pedalling style may result in improved cycling efficiency. Within this context, and bearing in mind the aforementioned limited usefulness of measures of force effectiveness, researchers may wish to investigate more meaningful mechanical parameters (Leirdal & Ettema, 2011).

Biomechanical analyses of cycling can also help us better understand how cyclists choose their preferred pedalling cadence during submaximal cycling. When adults are asked to ride at their preferred pedalling rate at a power output typically experienced during submaximal cycling, they tend to choose a cadence between 90 and 100 revolutions per minute (rev•min^{-1}) (Hagberg et al. 1981; Marsh & Martin 1993; Marsh & Martin 1997; Marsh & Martin 2000). (It should be noted that that the preferred cadence depends on multiple factors including power output as well as a cyclist's cycling experience, fitness level and fibre type distribution. However, an exhaustive discussion of these factors is beyond the scope of this brief review.) However, we also know that the cadence at which metabolic efficiency is maximised is between 60 and 70 rev•min^{-1} (Seabury et al. 1977; Hagberg 1981; Böning et al. 1984; Coast & Welch 1985; Sidossis et al. 1992) suggesting that maximising metabolic efficiency is not an important contributor to the selection of the preferred cadence. Here, biomechanical analyses of cycling provide further insights. Several authors have quantified the magnitude of muscular torques (Redfield & Hull 1986; McLean & LaFortune 1991; Marsh & Martin 2000) or forces (Neptune & Hull 1999) across cadences. These studies consistently show that joint torques are minimal close to the preferred cadence, which suggests that the minimisation of muscular forces is a priority of the nervous system within the context of the selection of the preferred pedalling rate. Another mechanical variable, which potentially influences the selection of the preferred cadence is the production of (inefficient) negative muscular work. Neptune and Herzog (1999) quantified negative muscular work across a range of cadences and found that there is a significant amount of negative mechanical work above the preferred cadence of 90 rev•min^{-1}. The authors concluded that at higher cadences, the nervous system might not be able to activate and deactivate the muscles fast enough to produce more efficient force patterns (Neptune & Herzog 1999). Together, these findings demonstrate that the selection of preferred cadence is driven by mechanical factors (rather than the maximisation of metabolic efficiency). Specifically, they suggest that cyclists choose their preferred cadence to minimise muscular forces, muscular stress and inefficient, negative muscular work, possibly with the goal of avoiding or delaying muscular fatigue.

Summary

Variation in gross efficiency explains ~30% of the variation in power output during cycling time-trials. Whilst other variables, notably VO_{2max} and lactate threshold, explain more of the variance in cycling power output, this result confirms that gross efficiency is an important determinant of cycling performance. Furthermore, it is apparent that exercise training can enhance gross efficiency.

Improvements have been seen with a wide range of training types (endurance, strength, altitude), though high intensity training appears to provide the most potent stimulus for changes in gross efficiency. Short or medium term changes in pedalling technique have no or detrimental effects on gross efficiency. Further research is needed to test the effect of long-term changes in pedalling technique on gross efficiency.

Conflict of interest

The authors declare that they have no conflict of interest.

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