An Approach to Estimating Gross Efficiency During High-Intensity Exercise

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Purpose: Gross efficiency (GE) is coupling power production to propulsion and is an important performance-determining factor in endurance sports. Measuring GE normally requires measuring VO2 during submaximal exercise. In this study a method is proposed to estimating GE during high-intensity exercise.

Methods: Nineteen subjects completed a maximal incremental test and 2 GE tests (1 experimental and 1 control test). The GE test consisted of 10 min cycling at 50% peak power output (PPO), 2 min at 25 W, followed by 4 min 100% PPO, 1 min at 25 W, and another 10 min at 50% PPO. GE was determined for the 50%-PPO sections and was, for the second 50%-PPO section, back-extrapolated, using linear regression, to the end of the 100%-PPO bout.

Results: Back-extrapolation of the GE data resulted in a calculated GE of 15.8% ± 1.7% at the end of the 100%-PPO bout, in contrast to 18.3% ± 1.3% during the final 2 min of the first 10-min 50%-PPO bout. Conclusion: Back-extrapolation seems valuable in providing more insight in GE during high-intensity exercise.

Keywords: fatigue, anaerobic capacity, recovery, mechanical efficiency

Understanding human performance requires understanding power production and power losses.1 Although maximum oxygen uptake (VO2max) and ventilatory threshold (VT) are important, recent attention has focused on the coupling of power production to propulsion, that is, gross efficiency (GE).2 Measuring GE requires measuring VO2 during submaximal exercise, at intensities below VT, and assuming that submaximal GE is representative of GE and aerobic-power production (Paer) during high-intensity exercise. Increases in the cost of ventilation (VE), temperature, other homeostatic disturbances, as well as changes in muscle-fiber recruitment, make assuming a constant GE questionable. Passfield and Doust3 showed that GE was lower after moderate-intensity exercise, and there have been attempts to quantify efficiency during high-intensity exercise.4

Knowledge of GE during intense exercise makes it possible to quantify Paer. If Paer is subtracted from total power output (Ptot), anaerobic power output (Pan) can be calculated. Summated over the duration of a fatiguing task, the anaerobic capacity can be estimated.5 Conceptually similar, the maximal accumulated oxygen deficit, this approach is based on the power output (PO)–VO2 relationship during submaximal exercise.5

An alternative approach to estimating GE during high-intensity exercise is to measure GE during recovery after high-intensity exercise and back-extrapolate GE values to estimate GE at the end of high-intensity exercise. The intent of this study was to measure GE before and during recovery after a high-intensity bout and to estimate GE during high-intensity exercise.

Methods

Nineteen subjects (11 men, 8 women, recreational to national-level athletes in a variety of sports, none competitive cyclists) provided written informed consent. The protocol was approved by the local ethics committee. The average peak PO (PPO), the highest exercise-intensity steps attained during the maximal incremental test, were 298 ± 38 W and 234 ± 17 W for men and women, respectively, representing 3.9 ± 0.5 W/kg and 3.7 ± 0.3 W/kg.

All subjects completed a maximal incremental test and on separate days, randomly ordered, 2 experimental tests on a bicycle ergometer (Lode, Groningen, The Netherlands). The experimental test started with 10 minutes at 50% PPO (warm-up), followed by 2 minutes at 25 W, a 4-minute high-intensity bout at 100% PPO, 1 minute at 25 W, and 10 minutes at 50% PPO (recovery). In the control condition, exercise during the “4-minute high-intensity bout” was replaced by 4 minutes at 50% PPO. The 1 minute at 25 W immediately after the 4 minutes at 100% PPO was included to allow VO2 to drop below the level at 50% PPO. Pedal frequency was ~80 rpm. Respiratory-gas exchange was measured using open-circuit spirometry with 30-second data integration (AEI, Pittsburg, PA). GE was computed for every 30 seconds from external PO and gas-exchange data5; only measurements with RER ≤1.0 were included.
To estimate GE at the end of 4 minutes at 100% PPO, a linear regression line was fitted through the GE data of the last 8 minutes of the 10-minute recovery. The best fit line was back-extrapolated to the end of the 100%-PPO bout.

Results

VO₂ values during the experimental trials are presented (Figure 1). There were no significant differences between both warm-up periods. VO₂ during the 100%-PPO ride was significantly higher than during the control ride and remained elevated during the entire recovery period. Similar results were observed for heart rate and VE. GE was not significantly different between trials during warm-up but was significantly decreased after the 100%-PPO ride versus the control condition. GE recovered toward control values during recovery but was still lower after 10 minutes (Figure 1). Back-extrapolation of GE to the end of the 100%-PPO ride yielded a predicted GE of 15.8% ± 1.7%, versus 18.3% ± 1.3% during the final 2 minutes of the first 10-minute 50%-PPO bout. The magnitude of the decrease in GE throughout recovery was well correlated with the higher VE ($r = .91$).

Discussion

To the degree that one is willing to accept back-extrapolation of the GE recovery curve, the results suggest that GE may be meaningfully lower during heavy exercise than previously thought. This suggests that the assumption of a constant GE during heavy exercise (eg, time trials)⁶ may be questionable. An unknown part of the decrease in calculated GE during recovery is from an elevated VO₂ caused by the anaerobic work done during the 100%-PPO ride. With the described method it is not possible to discriminate between this phenomenon and the effects of fatigue on GE. However, using a 1-minute period at 25 W immediately after the 100%-PPO ride allowed the VO₂ to decrease below that during the warm-up period, which we believe allows the VO₂ measured during the recovery period to be representative of the metabolic cost of riding at 50% PPO.

Figure 1 — Mean responses during the control (solid line) and high-intensity (dotted line) rides for oxygen uptake (VO₂), heart rate, ventilation, and gross efficiency (GE). The 100%-peak-power-output (PPO) work bout and control ride were from minutes 12 to 16. GE at the end of the warm-up was 18.3%, while the back-extrapolated GE at the end of the 100%-PPO ride was 15.8%.
To illustrate the impact of a nonconstant GE during a high-intensity bout, we computed the aerobic and anaerobic contributions based on a constant GE (18.3%) and on a variable GE (based on 18.3% at the start of exercise and 15.8% at end of exercise), assuming that GE declines proportionally and reciprocally with VE during the high-intensity bout (Figure 2). Using the observed \( P_{\text{tot}} \) (271 W), observed VO2, and varying GE, we calculated \( P_{\text{aer}} \) during each minute of the ride and compared this \( P_{\text{aer}} \) to \( P_{\text{aer}} \) calculated assuming a constant GE (Figure 2). The differences in calculated \( P_{\text{aer}} \) and \( P_{\text{an}} \) are striking, particularly late in the ride when the variable GE is most different from the constant GE. The calculated anaerobic capacity (17.9 vs 23.7 kJ) is 32% larger when a variable GE is assumed.

The results of this study suggest that an alternative approach to estimating GE provides more insight into GE during high-intensity cycling exercise and may result in better understanding of aerobic and anaerobic contributions during heavy exercise.

References