The reliability of measuring gross efficiency during high intensity cycling exercise

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Keywords:	anaerobic capacity, excess post-exercise oxygen consumption, pacing strategy, exercise performance, maximal exercise

Abstract

Purpose: To evaluate the reliability of calculating gross efficiency (GE) conventionally and using a back extrapolation (BE) method during high intensity exercise (HIE).

Methods: 12 trained participants completed two HIE bouts (P1 = 4-min 80% Maximal Aerobic Power (MAP); P2 = 4-min at 100%$_{MAP}$). GE was calculated conventionally in the last 3 min of submaximal (50%$_{MAP}$) cycling bouts performed before and after HIE (Pre50%$_{MAP}$ and Post 50%$_{MAP}$). To calculate GE using BE (B~~E~~GE), a linear regression of ~~VO_2~~ GE submaximal values post-HIE were back extrapolated to the end of the HIE bout.

Results: B~~E~~GE was significantly correlated with Post50%$_{MAP}$ GE in P1 ($r = 0.64$; $P = 0.01$), and in P2 ($r = 0.85$; $P = 0.002$). Reliability data for P1 and P2 B~~E~~GE demonstrate a mean CV of 7.8% and 9.8% with limits of agreement of 4.3% and 4.5% in relative GE units respectively. P2 B~~E~~GE was significantly lower than P2 Post50%$_{MAP}$ GE (18.1 ± 1.6% vs 20.3 ± 1.7%; P= ~~<~~ 0.01). Using a declining GE from the BE method, there was a 44% greater anaerobic contribution compared to assuming a constant GE during 4 min HIE at 100%$_{MAP}$.

Conclusion: HIE acutely reduced B~~E~~GE at 100%$_{MAP}$. A greater anaerobic contribution to exercise as well as excess post oxygen consumption at 100%$_{MAP}$ may contribute to this decline in efficiency. The BE method may be a reliable and valid tool in both estimating GE during HIE and calculating aerobic and anaerobic contributions.

Keywords: anaerobic capacity, excess post-exercise oxygen consumption, pacing strategy, performance, maximal exercise

Introduction

Gross efficiency (GE) is defined as the ratio of work generated to the metabolic energy cost, and has been shown to be a key component of cycling performance.[1,2] The calculation of GE is conventionally determined from steady state measures where energy expenditure from purely aerobic processes can be accounted for via expired gases measured at the mouth.

However, during high-intensity exercise (HIE) with a significant anaerobic energy contribution, $\dot{V}O_2$ measured at the mouth cannot be used to estimate the total energy expenditure. Therefore, conventional measurement of GE during submaximal exercise may not be a valid estimate of GE during HIE. A novel approach to estimate GE during high intensity exercise has recently been proposed.[3] This method uses linear regression of post-HIE GE values and back extrapolates these values to estimate GE at the end of the HIE-bout. Using this back-extrapolation (BE) method, de Koning et al.[3] found GE declined by 2.5% during 4 minutes of cycling at $100\%_{MAP}$. As a result, the calculated anaerobic contribution to their HIE bout was 32% larger when assuming a declining vs constant GE (23.7kJ vs 17.9kJ).[3]

The BE method has previously been used to investigate the impact of GE on high intensity cycling performance.[4] It has been demonstrated that the estimated anaerobic contribution to cycling time trial performance is 30% larger during time trials of less than 4000m when a declining rather than constant GE is assumed.[4] A declining GE and a higher anaerobic contribution could therefore have important implications for both pacing strategy and performance. However, the reliability and validity of the BE method in estimating GE during HIE has not previously been assessed.

There is also debate in the literature regarding possible physiological factors that might be influential in the reduction of GE seen following both prolonged submaximal[5,6,7,8] and high intensity[9,10] bouts of exercise. Near-infrared spectroscopy (NIRS) has previously been used to investigate changes in muscle oxygen consumption during a bout of prolonged constant load cycling. It has been shown that 90 mins of cycling at 60% maximal minute power resulted in an increased muscle oxygen consumption, and reduction in whole body GE.[8] Whether the same relationships are seen during short duration high intensity cycling is yet to be elucidated.

The purpose of this study is: 1) to assess the reliability and validity of measuring whole body GE in HIE calculated using the BE method, compared to traditional submaximal methods 2) to investigate the relationship between changes in whole body GE and NIRS parameters from high intensity exercise.

Methods

Subjects

Thirteen trained male (mean ± SD: age 35 ± 5 yr, mass 75 ± 7 kg, $\dot{V}O_{2max}$ 63± 7 $ml \cdot kg^{-1} \cdot min^{-1}$, Maximal Aerobic Power (MAP) 389 ± 46 W) and 2 female (age 25 ± 5 yr, mass 60 ± 1 kg, $\dot{V}O_{2max}$ 50 ± 2 $ml \cdot kg^{-1} \cdot min^{-1}$, MAP 272 ± 39 W) participants who trained for a minimum of 6 hours per week volunteered to participate in the study. The study was conducted with full university ethical approval and after obtaining informed written consent from all participants.

Experimental design

Participants attended the exercise testing laboratory on four separate occasions. Visit 1 consisted of a maximal incremental exercise test to determine $\dot{V}O_{2max}$ and MAP. On 2~~3~~ subsequent visits participants completed 2 high intensity bouts in the same order.~~; one bout at 80%$_{MAP}$, 30-min rest, followed by a bout at 100%$_{MAP}$~~ Each HIE bout was preceded and followed with a submaximal exercise bout at 50%$_{MAP}$. One HIE was performed at 80%$_{MAP}$, and the second HIE bout at 100%$_{MAP}$. All tests were performed on an electromagnetically braked ergometer (Schoberer Rad Messtechnik, Germany). Handlebar and saddle height were adjusted for each individual during visit 1, and then replicated for each subsequent visit. Participants used their own clipless pedals. Respiratory exchange data was collected on a breath-by-breath basis during each visit using an online gas analyser (Metalyser 3B; CORTEX Biophysik GmbH, Germany).

Maximal Incremental Exercise Test

Upon reporting to the laboratory, body mass was measured to the nearest 0.1 kg using beam balance scales (Seca, Germany), and stature was measured to the nearest 0.5 cm using a stadiometer (Seca, Germany). Participants undertook a maximal incremental cycling test to ascertain their $\dot{V}O_{2max}$ and MAP. The test started with a 10-min warm up at 100W. After a 1-min rest the cycling output increased by 5 W every 15 s until the participant reached volitional exhaustion (defined as a cadence of <60 revolutions/minute despite strong verbal encouragement). $\dot{V}O_{2max}$ was determined as the highest measured 60 s $\dot{V}O_2$ achieved during the incremental test. MAP was calculated as the average power output over the final minute of the ramp test.

High Intensity Exercise Tests

Participants completed two HIE 4-min bouts of exercise in the same order per visit, the first HIE bout at 80%$_{MAP}$ (P1) and the second HIE bout at 100%$_{MAP}$ (P2) (see Figure 1).~~ Bouts were separated by 30 minutes recovery.~~ Each HIE bout was preceded by 6-min cycling at 50%$_{MAP}$ and 2-min at 25 W,and followed by 1-min at 25 W and 10-min at 50%$_{MAP}$. P1 and P2 were separated by 30 minute rest. Participants were instructed to maintain a cadence of 80 rev·min^{-1} throughout the testing protocols.

INSERT FIGURE 1 HERE

Muscle oxygenation was measured continuously throughout the trials via near-infrared spatially resolved dual-wavelength spectrometry (Portamon, Artinins Medical Systems, Netherlands), emitting light at 760 nm and 850 nm wavelengths. The device was placed on the right thigh over the belly of the vastus lateralis muscle, 10cm proximal to the knee joint. Relative concentration changes in deoxygenated haemoglobin (HHb) were calculated from an arbitrary baseline value taken for 2-min prior to the start of each exercise protocol. An absolute measure of tissue oxygen saturation (TSI%) was also recorded throughout the exercise trial. Skinfold thickness was measured at the site of the NIRS device over the vastus lateralis muscle in the seated position using Harpenden skinfold calipers (British Indicators Ltd, Burgess Hill, UK). Adipose tissue thickness (ATT) was calculated by taking the median of three skinfold measurements and dividing the skinfold thickness by two with a mean value of 6.8 ± 2.5 mm.

Blood lactate was taken via a finger-prick blood sample immediately prior to the start and immediately at the end of the trial (Biosen C-Line analyser, EKF diagnositics, Wales).

Data analysis

Expired gas data measured at steady state during the last 3-min of the $50\%_{MAP}$ bouts[11] prior to, and after, HIE ($Pre50\%_{MAP}$ and $Post50\%_{MAP}$ respectively) was used to calculate GE conventionally with equations 1 and 2:

GE (%) = (Power input (W) / Energy expenditure (W)) x 100 (1)

Energy expenditure = (VO_2) x (RER x 4904) +16040)/60) (2)

VO_2 in equation 2 is expressed in L·min^{-1}. VO_2 data points in the last 3 minutes that had an RER >1.0 were excluded.

B~~E~~GE was calculated by fitting a linear regression to the GE~~VO_2~~ data points in the last 8-min of the $Post50\%_{MAP}$ bout; only data points ~~-~~with an RER < 1.0 were included in this 8-min period. These values were then back-extrapolated to the end of the HIE bout to give an estimation of the change of GE.[3] The decline in GE during the HIE bout was subsequently calculated by plotting a linear relationship between GE during $Pre50_{\%MAP}$ and calculated B~~E~~GE values. Whilst, Mulder et al. (2015) found that a linear relationship can be used for short bouts of HIE, an exponentional relationship should be used for HIE of longer duration.[4] Total work, aerobic work and anaerobic work were estimated by calculating the total power output, aerobic power and anaerobic power over time during HIE in P1 and P2 as previously described elsewhere. [3,4,12]

Statistical analysis

Shapiro-Wilk tests were conducted to assess for normality of distribution. To assess validity of B~~E~~GE, the relationship between submaximal GE and B~~E~~GE was assessed using a partial correlation controlling for Pre50% efficiency. The magnitude thresholds to assess the strength of the validity correlation are based on Cohen's effect sizes.[13] To assess the reliability of GE, B~~E~~GE, HHb and TSI, data from all three visits were used. Within-subject variation across the three repeated visits was calculated using Coefficient of Variation (CV) and 95% limits of agreement.[14] A repeated measures ANOVA was conducted to assess differences between the repeated visits in terms of GE, B~~E~~GE, TSI and HHb. Statistical significance was set at P <0.05. All values are presented as mean ± SD unless otherwise stated.

Results

All participants completed the P1 HIE bouts at all visits. Three participants failed to complete the P2 HIE bout on two or all three visits; therefore, their P2 GE data were excluded from the analyses.

Reliability of conventional and back-extrapolation GE methods

A mean CV of 7.8% (95% CL: 5.9 – 11.7%) for P1 and 9.8% (95% CL: 7.3 – 15.1%) in P2 B~~E~~GE was found. For GE $Pre50\%_{MAP}$ there was a mean CV of 7.6% (95% CL: 5.8 – 11.6%) for P1 and 8.8% (95% CL: 6.8%– 12.9%) in P2. For GE $Post50\%_{MAP}$ a mean CV of 6.2% (95% CL: 4.4 – 10.8%) for P1 and 6.8% (95% CL: 5.3 – 10.6%) in P2 was found. The mean limits of agreement in relative

GE percentage point units were ± 3.6% for Pre50%MAP and ± 3.74% for B~~E~~GE in P1, and ± 4.2% for Pre50%MAP and ± 4.1% for B~~E~~GE in P2.

Figure 2 illustrates the limits of agreement between the three repeated visits for P1 and P2 using Pre50$\%_{MAP}$ and B~~E~~GE.

INSERT FIGURE 2 HERE

Reliability of GE change

There was a mean CV of 0.86% (95% CL: 0.66 -1.23%) for the change in GE observed between Pre50%MAP and BGE in P1 and 0.99% (95% CL: 0.74 – 1.59%) for the change observed between Pre50%MAP and B~~E~~GE in P2.

Reliability of anaerobic contribution to high-intensity exercise

The mean CV for the anaerobic contribution using a constant GE in P1 were 3.5% (95% CL: 2.6-5.5 %) vs 2.9% (95% CL: 2.2-4.4%) using B~~E~~GE. The mean CV for the anaerobic contribution using a constant GE in P2 were 6.8% (95% CL: 5.2-10.8%) vs 5.0% (95% CL: 3.9-7.1%) using B~~E~~GE.

NIRS reliability analysis

Mean CVs were calculated for the 4-min HIE bout at both intensities. A mean CV of 6.9% (95% CL: 5.5 – 9.8%) for P1 TSI and 9.7% (95% CL: 7.8 – 13.9%) in P2 TSI was found. For HHb there was a mean CV of 19.4% (95% CL: 15.5 – 27.11%) for P1 and 17.3% (95% CL: 13.8% – 23.8%) in P2.

Physiological responses to high-intensity exercise

Mean blood lactate concentration was significantly different pre- vs post-HIE (1.49 ± 1.05 vs. 3.06 ± 0.57 mmol·L^{-1} ; P<0.05) in P1, and also in P2 (2.06 ± 0.73 vs. 5.52 ±1.73 mmol·L^{-1}; P <0.05) There was a significant interaction effect between intensity and timepoint (P=~~<~~0.006).

Figure 3 shows the calculated GE Pre50$\%_{MAP}$, B~~E~~GE and GE Post50$\%_{MAP}$ in both P1 and P2. B~~E~~GE was significantly correlated with GE Post50$\%_{MAP}$ in P1 (r = 0.98; P = 0.01) and in P2 (r = 0.80; P = 0.01) (figure 4a and 4b). Repeated measures ANOVA demonstrated that there was no significant difference between P1 GE Pre50$_{\%MAP}$ and P1 B~~E~~GE (21.1% vs 20.9%; P = 0.29). P1 GE Pre50$\%_{MAP}$ and GE Post50$\%_{MAP}$ were not significantly different (21.1% vs. 21.0%; P = 0.65). A greater reduction in B~~E~~GE is seen following HIE from P2 compared to P1 (-3.0% vs 0.27%, absolute GE units, figure 5a). HIE in P2 resulted in a significantly lower B~~E~~GE compared to P2 GE Pre50$_{\%MAP}$ (18.1 ± 1.6% vs 21.1 ± 2.2%; P =0.01), and P2 GE Post50$_{\%MAP}$ (20.3 ± 1.7% P= 0.01). P2 Post50$\%_{MAP}$ GE was also significantly different than P2 Pre50$\%_{MAP}$ GE (20.3 ± 1.7 vs 21.1% ± 2.2%)

INSERT FIGURE 3 HERE

INSERT FIGURE 4 HERE

Mean total energy expenditure during the 4-min HIE bouts were 72.8kJ in P1 and 92.5 kJ in P2. Calculated anaerobic contribution at the end of the 4min HIE bout in both P1 and P2 were higher at the end of the HIE bout using the BE method compared to assuming a constant GE from the Pre50%$_{MAP}$ bout (P1 = 6.8 kJ vs 6.1kJ, P = ~~<~~0.89~~05~~; P2 = 20.9kJ vs 11.8kJ, P = ~~<~~0.034~~5~~). This resulted in a 9% and 44% difference in anaerobic work contributions at the end of the 80%$_{MAP}$ (P1) and 100%$_{MAP}$ (P2) bouts respectively (figures 5c and d).

INSERT FIGURE 5 HERE

INSERT FIGURE 6 HERE

A typical NIRS trace for TSI and HHb is shown in figure 6a and 6b, respectively. Table 1 presents mean data and changes from baseline for TSI and HHb for both P1 and P2 before the HIE, during HIE, at 5-min after HIE (post5), and at 10-min after HIE (post10). There were no significant differences across all TSI timepoints in P1. However, there was a significant difference in TSI between 4-min HIE vs Post5 (P = 0.02), and Post5 vs Post10 (P = 0.02) in P2. There were no significant differences across all HHb timepoints in P1. However, there was a significant difference between Post5 vs Post10 (P = 0.009) in P2.

INSERT TABLE 1 HERE

Discussion

The main findings of this study are 1) the BE method is valid and reliable to estimate GE during HIE; 2) using the BE method, GE declines during HIE accompanied by a significant reduction in TSI~~ and increase in HHb~~; 3) assuming a declining GE during HIE, resulted in a larger calculated anaerobic contribution compared to using an assumed constant GE.

B~~E~~GE was significantly correlated with GE Post50%$_{MAP}$ in both P1 ($r = 0.63$; $P = 0.01$), and in P2 ($r = 0.85$; $P = 0.002$). The "r medium-large" correlation[13] between conventional GE and B~~E~~GE measured in P1 and P2 suggests that B~~E~~GE is a valid measure of GE during high intensity exercise such as that used in the current study.

The total within-subject variation in GE using the Douglas bag method has previously been reported to be as low as 1.5% during submaximal exercise.[15] However, in line with the current study, previous research using breath-by-breath online gas analysers have reported higher mean CVs of 3.2- 6.4%; closer to that of the current study.[11,16] Moreover, the mean bias of all trials using Pre50%$_{MAP}$ GE and B~~E~~GE were almost zero, indicating a similar level of repeatability for both methods. By assessing reliability, the smallest important difference (SID) in GE can also be ascertained. This is calculated by square rooting the difference between the observed standard deviation of the difference scores, by the typical error.[17] This measure is useful in monitoring any beneficial or detrimental changes in an individual's GE. SID values for GE Post50%$_{MAP}$ compared to B~~E~~GE were 0.29 and 0.27 ~~relative~~ absolute GE units in P1, and 0.30 and 0.10 ~~relative~~absolute GE units and P2, respectively. This suggests that B~~E~~GE may be a more sensitive method in detecting important differences from high intensity work rates.

The decline in GE of 2.5% seen during 4-min at $100\%_{MAP}$ in de Koning et al.[3] is comparable to the 3% seen at the same intensity (P2) in the present study. As illustrated in Figure 3, the differential effects of the two different HIE protocols on GE (using both conventional and the BE methods) suggests that its determining mechanisms are intensity dependent. Indeed, GE has been shown to be decreased as a result of both HIE[3,4,9], and prolonged exercise. [8,18] However, this study is the first to demonstrate that the relative intensity of HIE may play a major role in the observed decrease in GE. Specifically, the present study demonstrated that B~~E~~GE was significantly lower in P2, but not P1 where GE was not different across the measurement time points (Figure 3).

In agreement with previous work using B~~E~~GE,[3,4] the current study demonstrates a larger anaerobic work contribution during the 4-min HIE bout at $100\%_{MAP}$ results in a reduction in GE. However, as indicated by similar calculated energetic contributions using conventional and B~~E~~GE methods, cycling for 4-min at an intensity of $80\%_{MAP}$ does not appear to have a large reliance on anaerobic metabolism (figure 5c and 5d), and hence does not result in a reduction in GE. Moreover, the current study demonstrates a greater decrease in the TSI in P2 compared to P1 (Table 1), accompanied by a corresponding significant reduction in B~~E~~GE. It is likely that these changes in TSI when cycling at an intensity of $100\%_{MAP}$ arise from the greater metabolic demand than oxidative supply, and therefore greater anaerobic energy contribution to power production, compared to $80\%_{MAP.}$

It is important to note that part of the estimated GE using BE may be affected by recovery processes that increase VO_2 post-HIE. Whilst there were no significant differences in P1 GE or NIRS parameters, the reduction of B~~E~~GE in P2 was accompanied by significant differences in P2 GE and TSI and HHb at both Post5 and Post10 timepoints (see table 1). This suggests that exercise at $100\%_{MAP}$ may create a larger oxygen deficit as well as a greater excess post-exercise oxygen consumption where there is an increase in adenosine triphosphate and creatine phosphate re-synthesis, as well as increased lactate removal. Thus, at supramaximal intensities, or longer durations of HIE[17], there may be greater reductions in calculated B~~E~~GE leading to greater calculated anaerobic contribution and a prolonged period of recovery. ~~From a practical perspective, our data suggests that performing short duration HIE during a bicycle race may involve a large anaerobic energy expenditure, which will subsequently reduce GE. However, should the intensity drop post-HIE sufficiently for the oxygen deficit to be repaid, then GE will likely recover. The mechanisms causing reductions in GE after short duration HIE seem to be driven by a transient recovery related process. By comparison, previous research has suggested changes in GE during prolonged submaximal exercise may be driven by progressive reductions in mitochondrial/contractile efficiency of the working muscle.[8] Therefore, in bicycle races combining high-intensity and prolonged duration (e.g. criteriums, stage races) there may be reductions in GE through a combination of both recovery related processes and reductions in muscle contraction-coupling efficiency. Consequently, optimal pacing strategy may have to be modified to ensure that GE declines at a rate that doesn't negatively affect performance, or to allow GE to recover adequately between HIE efforts.~~

Practical applications

From a practical perspective, our data suggests that performing short duration HIE ~~during a bicycle race may~~ involvinge a large anaerobic energy expenditure, ~~which~~ will subsequently reduce GE. However, should exercise~~the~~ intensity ~~drop post-HIE~~reduce sufficiently for the oxygen deficit to be repaid, ~~then~~ GE will likely recover. Therefore, in bicycle races combining high-intensity exercise and prolonged duration (e.g. criteriums, stage races) there may be reductions in GE through a combination of both recovery related processes and reductions in muscle contraction-coupling efficiency.[8] ~~(Ronnestad et al., 2011, Hopker et al., 2013).~~ Consequently, ~~optimal pacing strategy~~competition or pacing strategy may have to be modified to minimize the negative impact of

~~ensure that~~ reductions in GE ~~declines at a rate that does not negatively affect~~on performance~~, or to allow GE to recover adequately between HIE efforts~~.

Conclusion

This study demonstrates that the BE method to estimate GE during HIE is a valid and reliable measure. Assuming a declining GE during short duration HIE at an intensity of $100\%_{MAP}$ there is a significantly greater anaerobic contribution compared to cycling at $80\%_{MAP,}$ leading to a larger O_2 deficit, and thus contributing to a reduction in GE. Following short-duration HIE, GE may recover if the intensity is sufficiently low enough to allow the oxygen debt to be repaid. Further work is needed to characterise changes in GE during prolonged exercise interspersed with HIE.

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References

[1] Joyner MJ, Coyle EF. Endurance exercise performance: the physiology of champions. *J Appl Physiol.* 2008;586(1):35-44. doi:10.1113/jphysiol.2007.143834.

[2] Hopker JG, Coleman DA, Gregson HC, et al. The influence of training status, age, and muscle fiber type on cycling efficiency and endurance performance. *J Appl Physiol*. 2013;115(5):723-729. doi:10.1152/japplphysiol.00361.2013.

[3] de Koning JJ, Noordhof DA, Uitslag TP, Galiart RE, Dodge C, Foster C. An approach to estimating gross efficiency during high-intensity exercise. *Int J Sports Physiol Perform*. 2013;8(6):682-684.

[4] Mulder RCM, Noordhof DA, Malterer KR, Foster C, de Koning JJ. Anaerobic Work Calculated in Cycling Time Trials of Different Length. *Int J Sports Physiol Perform*. 2015;10(2):153-159. doi:10.1123/ijspp.2014-0035.

[5] Hagberg JM, Mullin JP, Nagle FJ. Oxygen consumption during constant-load exercise. *J Appl Physiol Respir Environ Exerc Physiol.* 1978;45(3):381-384. doi:10.1152/jappl.1978.45.3.381.

[6] Hagan RD, Weis SE, Raven PB. Effect of pedal rate on cardiorespiratory responses during continuous exercise. *Med Sci Sports Exerc.* 1992;24(10):1088-1095

[7] Coyle EF, Sidossis LS, Horowitz JF. Cycling efficiency is related to the percentage of type I muscle fibers. *Med Sci Sports Exerc.* 1992;24:782-8.

[8] Hopker JG, O'Grady C, Pageaux B. Prolonged constant load cycling exercise is associated with reduced gross efficiency and increased muscle oxygen uptake. *Scand J Med Sci Sports.* March 2016:n/a–n/a. doi:10.1111/sms.12673.

[9] Noordhof DA, Mulder RCM, Malterer KR, Foster C, de Koning JJ. The Decline in Gross Efficiency in Relation to Cycling Time-Trial Length. IJSPP. 2015;10(1):64-70. doi:10.1123/ijspp.2014-0034.

[10] Vanhatalo A, Poole DC, DiMenna FJ, Bailey SJ, Jones AM. Muscle fiber recruitment and the slow component of O 2uptake: constant work rate vs. all-out sprint exercise. AJP: Regulatory, Integrative and Comparative Physiology. 2011;300(3):R700-R707. doi:10.1152/ajpregu.00761.2010..

[11] Noordhof DA, de Koning JJ, van Erp T, et al. The between and within day variation in gross efficiency. *Eur J Appl Physiol.* 2010;109(6):1209-1218. doi:10.1007/s00421-010-1497-4.

[12] Serresse O, Lortie G, Bouchard C, Boulay M. Estimation of the Contribution of the Various Energy Systems During Maximal Work of Short Duration. *Int J Sports Med.* 2008;09(06):456-460. doi:10.1055/s-2007-1025051.

[13] Cohen J. *Statistical power analysis for the behavioural sciences.* 2nd ed. New Jersey, Lawrence Erlbaum, 1988.

[14] Hopkins WG. Measures of Reliability in Sports Medicine and Science. *Sports Med.* 2000;30(1):1-15. doi:10.2165/00007256-200030010-00001.

[15] Hopker JG, Jobson SA, Gregson HC, Coleman D, Passfield L. Reliability of Cycling Gross Efficiency Using the Douglas Bag Method. *Med Sci Sports Exerc*. 2012;44(2):290-296. doi:10.1249/MSS.0b013e31822cb0d2.

[16] Moseley L, Jeukendrup AE. The reliability of cycling efficiency. *Med Sci Sports Exerc*. 2001:621-627. doi:10.1097/00005768-200104000-00017.

[17] Hopkins WG. Measures of Reliability in Sports Medicine and Science. Sports Med. 2000;30(1):1-15. doi:10.2165/00007256-200030010-00001.

[18] Passfield L, Doust JH. Changes in cycling efficiency and performance after endurance exercise. *Med Sci Sports Exerc*. 2000;32(11):1935-1941. doi:10.1097/00005768-200011000-00018.

Figure Legends:

Figure 1. High intensity exercise protocols with 4-min HIE at 80%$_{MAP}$ during P1 and 100%$_{MAP}$ during P2

Figure 2. Bland Altman plots with 95% LOA for GE across all three trials for each HIE protocol a) P1 Pre50%$_{MAP}$ GE b) P1 B~~E~~GE c) P2 Pre50%$_{MAP}$ GE d) P2 B~~E~~GE

Figure 3. Mean GE changes (with 95% CIs) at 80$_{\% MAP}$ (solid line, circle) and 100$_{\% MAP}$ (dotted line, square) calculated Pre and Post 4 min HIE and using the back-extrapolation method to the end of the 4min-HIE bout. a = significant difference from Pre50$_{\%MAP}$ (P = <0.05). β = significant difference from B~~E~~GE (P=<0.05).

Figure 4. Linear partial correlation using GE residuals between Post50 and B~~E~~GE in (a) P1 and (b) P2

Figure 5. (a) Mean change in GE calculated using back extrapolation during the 4 min HIE bout at 80% MAP (solid line, squares) and 100% MAP (dotted line, circles). (b) Mean BE values from the end of P1 (solid line) and P2 (dotted line) from the end of the 10 min post HIE recovery to the end of the 4 min HIE bout. Mean aerobic (Paer) and anaerobic (Pan) power contributions during 4 min HIE bout at (c) 80%$_{MAP}$ and (d) 100%$_{MAP}$ using a constant Pre50% MAP GE (solid line, circle) and a variable BE50 GE (dotted line, triangle).

Figure 6. (a) A typical TSI (%) and (b) HHb concentration changes for P1 (dotted line) and P2 (solid line)

	Pre50	Δbaseline	4min HIE	Δbaseline	Post5	Δbaseline	Post10	Δbaseline
P1								
TSI(%)	68.6 (±1.0)	-3.8 (±0.4)	68.5 (±3.8)	-8.7 (±0.8)	69.2 (±1.2)	-5.9 (±0.3)	68.6 (±1.0)	-5.1 (±0.3)
HHb (μm)	10.2 (±1.1)	9.1 (±0.6)	9.9 (±4.9)	11.8 (±1.2)	9.9 (±1.0)	4.9 (±0.3)	9.7 (±1.4)	6.7 (±0.4)
P2								
TSI(%)	67.8 (±1.0)	-3.5 (±0.2)	66.6 (±4.4)	-10.3 (±1.3)	70.0 (±2.0) *	-7.9 (±0.6)	68.6 (±2.0) §	-8.1 (±0.8)
HHb (μm)	9.7 (±1.2)	10.3 (±0.3)	10.8 (±4.6)	10.4 (±0.7)	11.0 (±1.7)	8.9 (±0.3)	9.8 (±1.7) §	7.2 (±0.2)

Table 1. TSI and HHb NIRS response during Pre50, 4-min HIE, Post5 and Post10. Values are mean response and Δbaseline. *significantly different to 4-min HIE (P = 0.02). § significantly different to Post5 (P = 0.009)

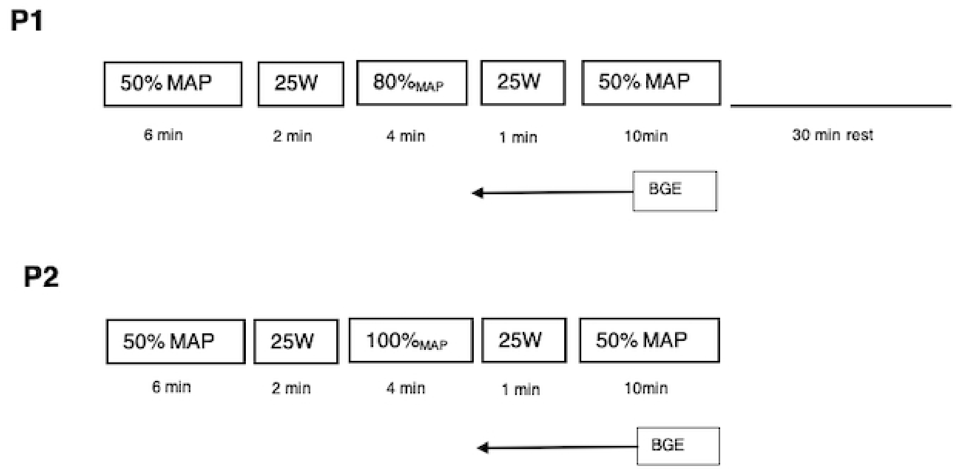

Figure 1. High intensity exercise protocols with 4-min HIE at 80%MAP during P1 and 100%MAP during P2

228x119mm (72 x 72 DPI)

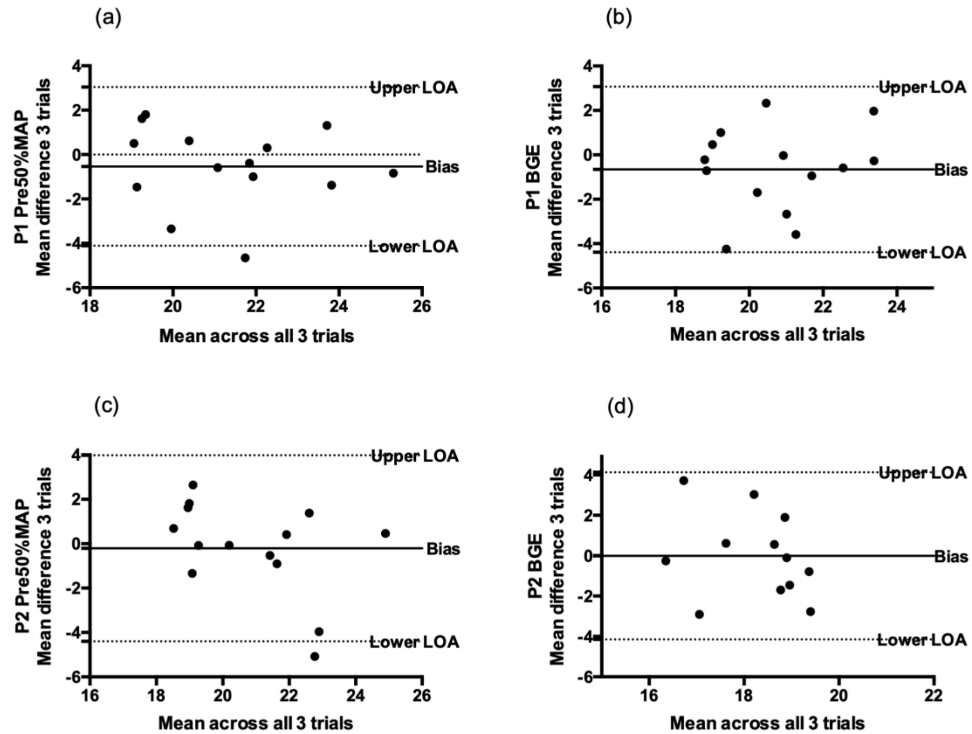

Figure 2. Bland Altman plots with 95% LOA for GE across all three trials for each HIE protocol a) P1 Pre50%MAP GE b) P1 BEGE c) P2 Pre50%MAP GE d) P2 BEGE

165x127mm (300 x 300 DPI)

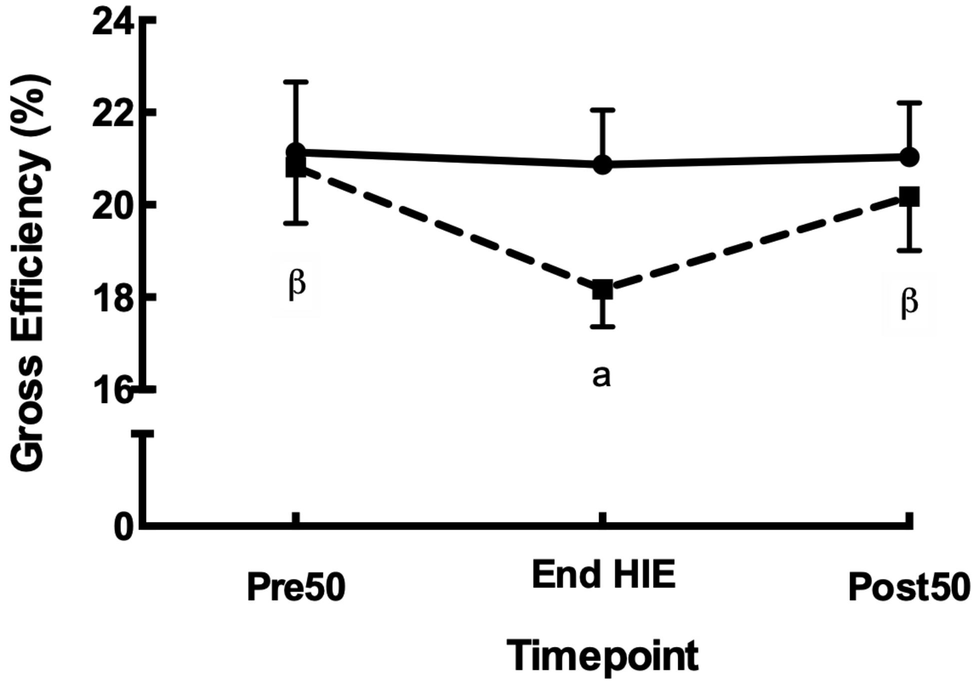

Figure 3. Mean GE changes (with 95% CIs) at 80% MAP (solid line, circle) and 100% MAP (dotted line, square) calculated Pre and Post 4 min HIE and using the back-extrapolation method to the end of the 4min-HIE bout. a = significant difference from Pre50%MAP (P = <0.05). B = significant difference from BEGE (P=<0.05).

99x71mm (300 x 300 DPI)

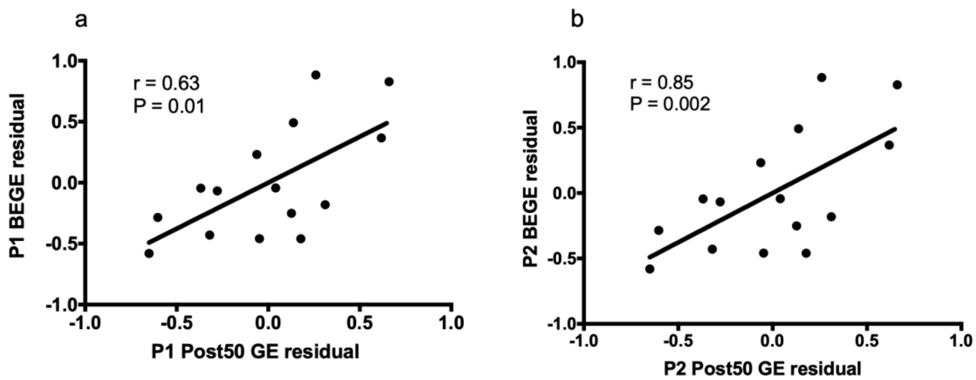

Figure 4. Linear partial correlation using GE residuals between Post50 and BEGE in (a) P1 and (b) P2

165x66mm (300 x 300 DPI)

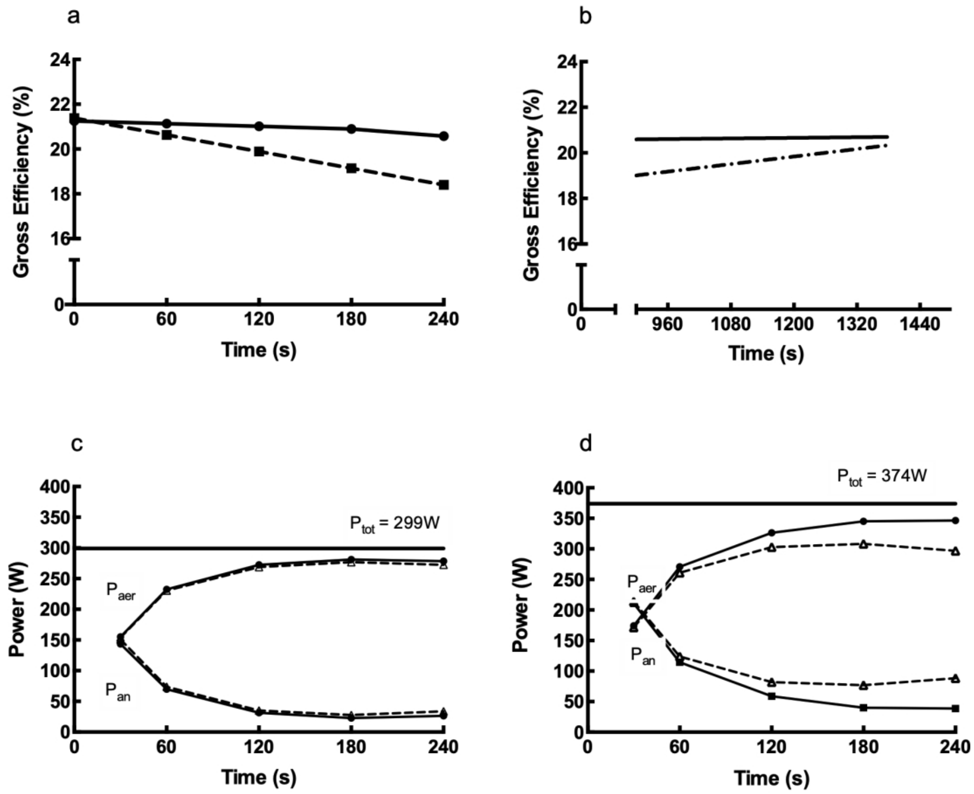

Figure 5. (a) Mean change in GE calculated using back extrapolation during the 4 min HIE bout at 80% MAP (solid line, squares) and 100% MAP (dotted line, circles). (b) Mean BE values from the end of P1 (solid line) and P2 (dotted line) from the end of the 10 min post HIE recovery to the end of the 4 min HIE bout. Mean aerobic (Paer) and anaerobic (Pan) power contributions during 4 min HIE bout at (c) 80%MAP and (d) 100%MAP using a constant Pre50% MAP GE (solid line, circle) and a variable BE50 GE (dotted line, triangle).

166x138mm (300 x 300 DPI)

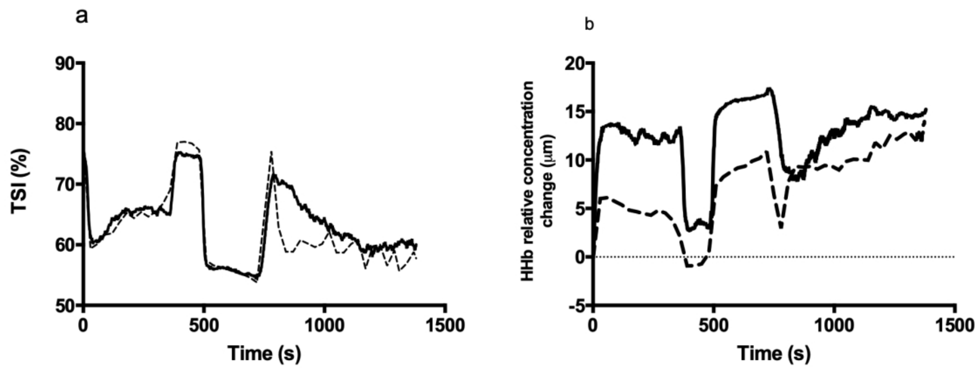

Figure 6. (a) A typical TSI (%) and (b) HHb concentration changes for P1 (dotted line) and P2 (solid line)

166x66mm (300 x 300 DPI)