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4 authors:

Erik Andersson
Mid Sweden University

Thomas Stöggl
University of Salzburg

Philipp Bachl
University of Salzburg

John O. Osborne
UiT The Arctic University of Norway

The effect of exercise hyperpnea on gross efficiency and anaerobic capacity estimates during a 3-min cycle time trial

Erik P. Andersson[1,2*], Thomas L. Stöggl[3,4], Philipp Bachl[1,3], and John O. Osborne[2]

[1]Swedish Winter Sports Research Centre, Department of Health Sciences, Mid Sweden University, Östersund, Sweden.

[2]School of Sport Sciences, Faculty of Health Sciences, UiT The Arctic University of Norway, Tromsø, Norway.

[3]Department of Sport and Exercise Science, University of Salzburg, Salzburg, Austria.

[4]Red Bull Athlete Performance Center, Salzburg, Austria.

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Corresponding author:

Dr. Erik Andersson

School of Sport Sciences, Faculty of Health Sciences

UiT The Arctic University of Norway

Hansine Hansens veg 18

9019 Tromsø, Norway

E-mail: erik.andersson@uit.no

Telephone: +46 10-1428863

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Abstract

This study aimed to analyze the effect of exercise-induced hyperpnea on gross efficiency (GE) and anaerobic capacity estimates during a self-paced 3-min supramaximal cycle time trial (TT). Fourteen highly-trained male cyclists performed 7×4-min submaximal stages, a 6-min passive rest, a 3-min TT, a 5-min passive rest, and a 6-min submaximal stage. Three models were based on the 7×4-min linear regression extrapolation method, using (1) the conventional model (7-Y_{LIN}); (2) the same 7-Y_{LIN} model but correcting for the additional ventilatory cost (i.e., hyperpnea) (7-$Y_{LIN\text{-}V\text{-}cor}$); and, (3) accounting for linearly declining GE during the TT (7-$Y_{LIN\text{-}D}$). The other three models were based on GE from the last submaximal stage, using the conventional model (GE_{LAST}) and the same modifications as described for 7+Y_{LIN}, i.e., (1) GE_{LAST}, (2) $GE_{LAST\text{-}V\text{-}cor}$, and (3) $GE_{LAST\text{-}D}$. The GE_{LAST} model generated 18% higher values of anaerobic capacity than the 7-Y_{LIN} model ($P<0.05$). During the TT, the hyperpnea corrected model (i.e., 7-$Y_{LIN\text{-}V\text{-}cor}$ or $GE_{LAST\text{-}V\text{-}cor}$) generated, compared to the respective conventional model (i.e., 7-Y_{LIN} or GE_{LAST}), ~0.7 percentage points lower GE and ~11% higher anaerobic capacity (all, $P<0.05$). The post-TT GE was 1.9 percentage points lower ($P<0.001$) and the 7-$Y_{LIN\text{-}D}$ or $GE_{LAST\text{-}D}$ model generated, compared to the respective conventional model, a lower GE (~1.0 percentage points) and ~17% higher anaerobic capacity during the TT (all, $P<0.05$). In conclusion, the correction for a declining GE due to hyperpnea during a supramaximal TT resulted in an increased required total metabolic rate and anaerobic energy expenditure compared to the conventional models.

NEW & NOTEWORTHY

This study demonstrates that GE declines during a 3-min supramaximal cycle TT, which is possibly related to the hyperpneic response during supramaximal exercise. The finding from this study also provides novel insight into how the increased ventilatory energy cost from exercise-induced hyperpnea contributes to decreased GE, increased required total metabolic rate, and increased anaerobic energy expenditure during supramaximal exercise. Therefore, conventional linear models for estimating anaerobic capacity are likely to generate underestimated values.

Keywords: endurance exercise, energetics, oxygen deficit, supramaximal exercise, ventilation rate

INTRODUCTION

Two common approaches for estimating the metabolic requirement and anaerobic capacity during supramaximal exercise are the linear regression method, usually referred to as the maximal accumulated oxygen deficit method, and the gross efficiency (GE) method (1, 2). An alternative version of the conventional maximal accumulated oxygen deficit method uses a linear relationship between power output and metabolic rate (i.e., a PO-MR linear-regression method) during submaximal steady-state exercise to estimate the instantaneous required total metabolic rate (i.e., the sum of the aerobic and anaerobic metabolic rates) during supramaximal exercise by extrapolation (3-5). Such a linear relationship can also be used to estimate instantaneous GE during supramaximal exercise, which is of interest when comparing anaerobic capacity estimates generated by different computational models (3, 5). When estimating the required total metabolic rate using the GE method, GE is usually determined during a single submaximal bout at a relatively high exercise intensity (~70-80% of maximum oxygen uptake [$\dot{V}O_{2max}$]), which is used to determine the required total metabolic rate during a subsequent supramaximal effort (2-4). For both the PO-MR linear-regression method and the GE method, the accumulated anaerobic energy expenditure is calculated as the difference between the estimated required total metabolic rate and measured aerobic metabolic rate, integrated over time. For a linear regression between power output and metabolic rate with a positive Y-intercept value, GE increases hyperbolically with increasing power output (6, 7). However, when using the GE method, a fixed value of GE is used, i.e., GE is not assumed to increase with higher power output. Due to these differences, the conventional GE method would likely generate higher values of anaerobic capacity during cycle-ergometry exercise than the linear regression method.

Yet both of these methods have been criticized as potentially too simplistic, following observations of a decline in GE after prolonged (~60 min at 60% of $\dot{V}O_{2max}$) submaximal-intensity exercise (8) and/or supramaximal-intensity exercise (9-11). To account for these variations in GE, de Koning et al. (12) suggested a method where GE measured post-exercise could be back-extrapolated to the end of the high-intensity exercise, with the decline in GE from pre-to-post high-intensity exercise being assumed to be proportional with the minute ventilation (i.e., the hyperpneic response). This back-extrapolation of GE has been utilized to estimate anaerobically attributable work in some recent studies (10, 12, 13), with demonstrable differences between the two calculation methods for constant, or declining, GE. Since instantaneous GE can also be calculated during supramaximal exercise by using the linear regression method based on power output and metabolic rate (3, 5), a similar method to the one proposed by de Koning et al. (12) that accounts for a declining GE could potentially also be used in connection with the linear regression method used for determining anaerobic capacity.

Yet the back-extrapolation GE method also introduces additional potential confounding factors that may influence the veracity of the estimated GE during supramaximal exercise. For example, excess post-exercise oxygen consumption (EPOC), or recovery oxygen uptake, following a supramaximal exercise task will likely induce some confounding to calculated GE, potentially affecting back-extrapolation and the computed anaerobic contribution to external work (or power output) (14, 15). In addition, non-linear kinetics of carbon dioxide ($\dot{V}CO_2$) elimination by ventilation during and after supramaximal exercise will influence the respiratory exchange ratio (RER), and so may not reflect the actual substrate utilization (11, 16, 17). Therefore, quantification of anaerobic capacity (or anaerobic work capacity) during high-intensity exercise using back-extrapolated GE may prove erroneous due to the influence of the stated confounding factors.

An alternative method to account for the potential decline in GE during high-intensity/supramaximal-intensity exercise may be to consider the additional metabolic requirement associated with higher ventilation, i.e., exercise-induced hyperpnea (18). During incremental submaximal exercise up to a ventilation rate of ~105 L min^{-1} (~75% of $\dot{V}O_{2max}$ in endurance-trained males (5)), the oxygen cost of ventilation as a fraction of the oxygen uptake remains relatively constant at ~4% (18). However, due to the exponential rise in the energy cost per liter of ventilation and/or the higher ventilatory equivalent for oxygen, the relative oxygen cost of ventilation may increase to ~15% of $\dot{V}O_{2max}$ during high-intensity or supramaximal-intensity exercise (18-21). The exponential increase in the oxygen cost of hyperpnea has been proposed to be the main factor for a declining GE during supramaximal exercise (12). Therefore, research where this aspect (i.e., hyperpnea) is integrated into the estimation of GE during high-intensity and/or supramaximal-intensity exercise would be of particular interest to many athletes, coaches, and sports scientists, as this information could be utilized in a variety of different ways (e.g., used for optimizing ventilation patterns, refining pacing strategies, and/or targeting appropriate nutritional needs, etc.). As the oxygen cost of hyperpnea increases exponentially from high-intensity submaximal to supramaximal exercise, failure to integrate this additional oxygen cost during supramaximal exercise would result in an underestimation of the required total metabolic rate, the estimated anaerobic metabolic rate, and the accumulated anaerobic energy expenditure. Yet, to the best of our knowledge, no previous study has considered the effect of the additional metabolic requirement of hyperpnea on GE and anaerobic capacity estimates during supramaximal exercise.

Therefore, the current study was designed to analyze, for the first time, the effect of exercise hyperpnea on GE and anaerobic capacity estimates during a self-paced 3-min supramaximal cycle time trial (TT) using the two common methods for calculating anaerobic capacity (i.e., a PO-MR linear regression method [$7\text{-}Y_{LIN}$] and a GE method [GE_{LAST}]) with three different variations for each method (i.e., [1] the standard model; [2] with additional ventilation cost during the supramaximal exercise; and [3] accounting for a declining GE), which resulted in a total of six different models. Specifically, the two different calculation methods would be first tested using their default conventional equations (i.e., $7\text{-}Y_{LIN}$ and GE_{LAST}); then both corrected for the additional metabolic cost of ventilation (i.e., $7\text{-}Y_{LIN\text{-}V\text{-}cor}$ and $GE_{LAST\text{-}V\text{-}cor}$); and finally, accounting for a linearly declining GE during the TT ($7\text{-}Y_{LIN\text{-}D;}$ $GE_{LAST\text{-}D}$).

The hypotheses of the current study were as follows: 1) the anaerobic capacity estimate would be higher for the GE_{LAST} than the $7\text{-}Y_{LIN}$ model, and 2) the anaerobic capacity estimate would be higher for each of the respective hyperpnea-corrected models (i.e., $7\text{-}Y_{LIN\text{-}V\text{-}cor}$ and $GE_{LAST\text{-}V\text{-}cor}$) compared to the respective conventional model.

METHODS

Participants

Fourteen highly-trained male cyclists (mean ± SD: age: 26.2 ± 3.7 years, body mass: 74.7 ± 5.9 kg, stature: 180.5 ± 6.0 cm) participated in this study (Tier 3–4, McKay et al. (22)). The ethical review board of the University of Salzburg approved the study (EK-GZ: 05/2020). All participants were fully informed about the nature of the study and provided written consent to participate. The participants regularly competed in cycling events and had previously undergone a laboratory performance test on a bike. A criterion for exclusion was a $\dot{V}O_{2max}$ of < 55 $ml \cdot kg^{-1} \cdot min^{-1}$. On the day of laboratory testing, participants were instructed to have their last regular meal 3-h pre-test and refrain from ingesting caffeine. All participants were familiar with submaximal and maximal cycle ergometry tests.

Equipment and testing procedures

The participant's stature and body mass were measured pre-test (Seca 764, Hamburg, Germany). Each participant used their cycling gear (e.g., shoes, cleats, pedals, and clothes) during testing and a Monark LC7TT time-trial bike (Monark Exercise AB, Vansbro, Sweden) was set to the participant's preferences. The LC7TT time-trial bike was equipped with road race handlebars and standard shifting mechanics (Shimano Ultegra 11 Speed, Shimano Inc., Osaka, Japan). Cycling power output was logged continuously as second-by-second data. Respiratory variables were measured using a Cosmed Quark CPET mixing chamber system (Cosmed srl, Rome, Italy) with data as 10-s values. This setup was used to provide valid and reliable metabolic measurements, especially at high ventilation rates in highly trained athletes (23, 24). The gas analyzers were calibrated prior to each test using a known reference gas containing 15.0% O_2 and 5% CO_2 (UN 1950 Aerosols, Cortex Biophysik GmbH, Leipzig, Germany) and ambient air. The flowmeter was calibrated with a 3-L syringe (M9424; Medikro Oy, Kuopio, Finland). Blood lactate concentration was determined from an earlobe blood sample (20 μL) and analyzed with a Biosen S-line (EKF diagnostic GmbH, Magdeburg, Germany), which was calibrated with a standard solution of 12 mmol L^{-1}. Heart rate was monitored using a chest strap (Wahoo Kickr, Wahoo Fitness, Atlanta, Georgia, United States) that was connected to the ANT+ receiver of the Cosmed system and synchronously stored with ergospirometry data.

A 6-min warm-up was performed at ~37% of peak oxygen uptake ($\dot{V}O_{2peak}$) and was directly followed by a 7 × 4-min submaximal protocol, at intensities corresponding to ~37-70% (~5.5% increments) of $\dot{V}O_{2peak}$ and power outputs were determined based on previous test results. After the submaximal protocol, a 6-min passive rest was given to the participant followed by a self-paced 3-min TT that was performed at a maximal effort. Following completion of the TT, the participants passively rested for 5-min, whereafter a 6-min submaximal stage was performed at the same power output as the final submaximal stage prior to the TT. For the warm-up and submaximal stages, the power output was fixed and cadence independent whereas, for the TT, the power output was regulated freely by the athlete via the bike's shifters and was cadence dependent. During all testing, cadence was self-selected by the participant. The cadence for the submaximal exercise was determined as the average of the final minute of each stage.

The self-paced 3-min TT was performed with no visible information available regarding physiological response or performance (i.e., heart rate, oxygen uptake, and power output). Participants were instructed to generate the highest possible average power output throughout the

TT, with verbal encouragement and information about elapsed time every half minute provided by the test leaders. Blood lactate concentration was measured 5 min into the warm-up, at the end of the 7 × 4-min submaximal stages, 1 min before the start of the TT, and 2 min after completion of the TT.

Processing of respiratory data

Respiratory and heart rate data were collected continuously during the submaximal exercise and TT. During the submaximal exercise, data from the last minute of each submaximal stage was used for analyzes. To enable a more dynamic respiratory response during the TT, raw respiratory 10-s data from the TT were interpolated second-by-second using piecewise constant interpolation for each 10-s average and smoothed using a 9-s counterbalanced moving average (i.e., using a ±4-s time window for smoothing), which was conducted twice as described by Lidar et al. (25). The $\dot{V}O_{2peak}$ and peak ventilation rate were determined as the respective highest 20-s moving average during the TT, as based on the raw 10-s respiratory data, while peak heart rate was obtained as the highest 10-s average value. Peak RER was taken over the same period as the $\dot{V}O_{2peak}$.

Calculations

Submaximal exercise

Energy expenditure was calculated from oxygen uptake ($\dot{V}O_2$) and RER ($\dot{V}CO_2 \cdot \dot{V}O_2^{-1}$) according to the equation introduced by Weir (26) and then converted into a metabolic rate that was based on the average $\dot{V}O_2$, in L·min^{-1}, and RER values (≤ 1.00) during the final minute of each stage of the submaximal exercise protocol.

$$MR\ [W] = \frac{4184(\dot{V}O_2(1.1RER+3.9))}{60} \qquad \text{(Eq. 1)}$$

GE was calculated as:

$$GE = \frac{PO\ [W]}{MR\ [W]} \qquad \text{(Eq. 2)}$$

Where PO is the power output on the bike.

During the submaximal exercise following the TT, the MR was based on the average $\dot{V}O_2$ in L·min^{-1} during the final minute and using the RER value from the last submaximal stage prior to the TT. This was because RER measured following supramaximal exercise was not considered to reflect the actual substrate utilization due to EPOC and ventilatory dynamics (14, 16, 17). The GE for the submaximal exercise following the TT was calculated as in Eq. 2.

The estimation of anaerobic capacity

A linear relationship between PO (W) and metabolic rate (W) during the final minute of each of the 7 × 4-min submaximal stages was derived for each participant and referred to as the 7-Y_{LIN} model (Figure 1). The 7-Y_{LIN} regression equation was used to estimate the required instantaneous metabolic rate during the TT (MR_{TT_req}) at each 1-s time-point. Submaximal GE based on the last submaximal stage (GE_{LAST}) was also used to estimate the MR_{TT_req} at each 1-s time-point of the TT, with MR_{TT_req} calculated by dividing instantaneous PO with GE_{LAST}. The instantaneous s-by-s GE values during the TT were also calculated for the 7-Y_{LIN} model (GE_{REG}) as instantaneous PO divided by the instantaneous MR calculated from the regression equation.

A model was developed to correct for a changing GE during the TT based on the difference in GE between the last submaximal stage (i.e., GE_{LAST}) and GE measured following the TT (GE_{TTpost}). To reflect the relative decline in GE at the end-point of the TT (i.e., at 180 s), a ratio between GE_{TTpost} and GE_{LAST} was used, whereas the GE ratio was set to 1 at the start of the TT. A linear regression was fitted through the GE ratio at the start of the TT (i.e., 1) and the GE ratio at the end-point of the TT (i.e., GE_{TTpost} divided by GE_{LAST}). The regression equation was used to determine the GE ratio at each 1-s time-point (*t*) of the TT (GE_{RATIO}). The correction for a declining ($_D$) GE during the TT was applied to the original 7-Y_{LIN} and GE_{LAST} models and then referred to 7-$Y_{LIN\text{-}D}$ and $GE_{LAST\text{-}D}$. The MR_{TT_req} at each 1-s time-point (*t*) of the TT was calculated for 7-$Y_{LIN\text{-}D}$ as:

$$MR_{TT\_req,t}[W] = \frac{PO_{TT,t}\,[W]}{GE_{REG,t} \times GE_{RATIO,t}} \quad \text{(Eq. 3)}$$

For $GE_{LAST\text{-}D}$, the MR_{TT_req} at each 1-s time-point (*t*) of the TT was calculated similarly as in Eq. 3, but with the exception that GE_{REG} was changed to GE_{LAST}.

For the four models (i.e., 7-Y_{LIN}, GE_{LAST}, 7-$Y_{LIN\text{-}D}$, and $GE_{LAST\text{-}D}$), the instantaneous anaerobic metabolic rate (MR_{AN}) at each 1-s time-point (*t*) of the TT could then be expressed as:

$$MR_{AN,t}[W] = MR_{TT_{req},t}[\mathrm{W}] - MR_{AE,t}[W] \quad \text{(Eq. 4)}$$

where MR_{AE} is the aerobic metabolic rate calculated according to Eq. 1 and using an RER of 1.00 (i.e., assuming 100% carbohydrate utilization during the TT).

For all four models, the total anaerobic energy expenditure (E_{AN}) was calculated by integrating MR_{AN} over the 3-min TT.

The estimation of the metabolic requirement for ventilation

Based on the non-linear relationship for minute ventilation versus respiratory oxygen cost for exercise hyperpnea reported by Dempsey et al. (18), a polynomial third-order equation was constructed but with the oxygen cost of ventilation converted to an energy cost in Joules per liter of ventilation (V_E), assuming 100% carbohydrate utilization and an energy equivalent of 20.92 $J \cdot mL[VO_2]^{-1}$. The equation was expressed as:

$$VE_{E-COST}[J \cdot L^{-1}\, V_E] = -1.05217 \times 10^{-5} \times VE^3 + 5.74842 \times 10^{-3} \times VE^2 - 0.520568 \times VE + 48.8437 \quad \text{(Eq. 5)}$$

where $VE_{E\text{-}COST}$ is the ventilatory energy cost in Joules per liter of V_E.

The metabolic requirement for ventilation (MR_{VE} [in W]) was calculated as the product of $VE_{E\text{-}COST}$ ($J \cdot L^{-1}$, calculated as in Eq. 5) and respiratory rate ($L \cdot s^{-1}$). The metabolic requirement for ventilation was also expressed as (1) a fraction of the metabolic rate during the submaximal stages; (2) as a fraction of the average aerobic metabolic rate during the TT; and (3) as a fraction of $\dot{V}O_{2peak}$ at the ventilation rate associated with $\dot{V}O_{2peak}$ (calculated by converting $\dot{V}O_{2peak}$ to a peak aerobic metabolic rate [Eq. 1] using an RER of 1.00).

The ventilatory corrected models for estimating anaerobic capacity

Eq. 5 was used for estimating the additional metabolic requirement during the TT caused by exercise hyperpnea as described in Figure 2. The increase in $VE_{E\text{-}COST}$ with increasing hyperpnea during exercise is shown in Figure 2A. The $VE_{E\text{-}COST}$ above that associated with the last submaximal stage was then added to the metabolic requirement estimated during the TT with the 7-Y_{LIN} and GE_{LAST} models and were then referred to as the 7-$Y_{LIN\text{-}V\text{-}cor}$ and $GE_{LAST\text{-}V\text{-}cor}$ models.

The additional instantaneous metabolic requirement for ventilation (AMR_{VE}) at each 1-s time-point (*t*) of the TT was calculated as:

$$AMR_{VE,t}[W] = (VE_{E-COST_{TT},t} - VE_{E-COST_{SUB7}}[J \cdot L^{-1}V_E]) \times TT_{VE,t}[L \cdot s^{-1}] \quad \text{(Eq. 6)}$$

where $TT_{VE,t}$ is the instantaneous ventilation rate during the TT; $VE_{E-COST_{TT},t}$ is the instantaneous VE_{E-COST} during the TT; and $VE_{E-COST_{SUB7}}$ is the VE_{E-COST} associated with the last submaximal stage (*SUB7*).

$AMR_{VE,t}$ was only calculated for ventilation rates higher than the ventilation rate at the last submaximal stage.

The $AMR_{VE,t}$ was added to the $MR_{TT\_req,t}$ estimated with the 7-Y_{LIN} and GE_{LAST} models and thereafter referred to as the 7-$Y_{LIN\text{-}V\text{-}cor}$ and $GE_{LAST\text{-}V\text{-}cor}$ models (i.e., the ventilatory corrected [V-cor] models).

The instantaneous anaerobic metabolic rate for the 7-$Y_{LIN\text{-}V\text{-}cor}$ and $GE_{LAST\text{-}V\text{-}cor}$ models was calculated as in Eq. 4 and the E_{AN} was calculated by integrating MR_{AN} over the 3-min TT.

The estimation of GE and anaerobic work capacity during supramaximal exercise

The instantaneous GE at each 1-s time-point (*t*) of the TT ($GE_{TT,t}$) was calculated as:

$$GE_{TT,t} = \frac{PO_{TT,t}[W]}{MR_{TT,t}\,[W]} \quad \text{(Eq. 7)}$$

where $MR_{TT,t}$ is the model-specific instantaneous required metabolic rate. This calculation was performed for the 7-Y_{LIN}, 7-$Y_{LIN\text{-}V\text{-}cor}$, $GE_{LAST\text{-}V\text{-}cor}$, 7-$Y_{LIN\text{-}D,}$ and $GE_{LAST\text{-}D}$ models. The calculation was redundant for the GE_{LAST} model as that assumes a constant GE (i.e., the same GE as for the last submaximal stage).

Anaerobic PO contribution (PO_{AN_cont}) (i.e., PO attributable to MR_{AN}) at each 1-s time-point (*t*) of the TT was calculated for the 7-Y_{LIN}, GE_{LAST}, 7-$Y_{LIN\text{-}V\text{-}cor}$, $GE_{LAST\text{-}V\text{-}cor}$, 7-$Y_{LIN\text{-}D}$, and $GE_{LAST\text{-}D}$ models as:

$$PO_{AN_{cont},t}[W] = PO_{TT,t}[W] - (MR_{AE,t}[W] \times GE_{TT,t}) \quad \text{(Eq. 8)}$$

where $PO_{TT,t}$ is the PO during the TT and $MR_{AE,t}$ is the aerobic metabolic rate.

The anaerobic work capacity in Joules was calculated for the six models by integrating the model-specific PO_{AN_cont} (W) over the TT duration (s).

The estimated relative effect of hyperpnea on the change in GE between pre- and post-TT measures

To calculate a GE value for the post-TT submaximal bout that was independent of a changing MR_{VE} ($GE\_IND_{MR\_VE}$), the following equation was used:

$$GE\_IND_{MR_{VE}} = \frac{PO_{SUB}[W]}{MR_{SUB\_post} - \left(MR_{VE_{post}} - MR_{VE_{pre}}\right)[W]} \quad \text{(Eq. 9)}$$

Where PO_{SUB} is the submaximal power output (was the same for pre-and post-TT measures of GE), MR_{SUB_post} is the post-TT submaximal metabolic rate (in W), MR_{VE_post} is the post-TT metabolic requirement for ventilation (in W), and MR_{VE_pre} is the pre-TT metabolic requirement for ventilation (in W).

The percentage point difference in GE between SUB7 and GE_{TTpost} was compared with the percentage point difference in GE between SUB7 and $GE\_IND_{MR\_VE}$. Based on these data the relative effect of exercise hyperpnea on the change in GE from pre-to-post TT submaximal exercise could be evaluated.

Statistics

Data were checked for normality by visual inspection of Q-Q plots and histograms together with the Shapiro-Wilks analysis and are presented as mean ± standard deviation (SD), except in the case of RPE and peak heart rate where data are presented as median and interquartile range (IQR). The linear relationship between power output and metabolic rate was assessed using linear regression analysis. A one-way repeated measures ANOVA test was used to compare GE between the seven submaximal stages. The six different model-specific estimated values of GE, required metabolic rate, anaerobic capacity, and anaerobic work capacity associated with the TT were also compared with one-way repeated measures ANOVA tests. In addition, the methodological error was evaluated via the overall standard error of measurement (SEM) calculated as the square root of the within-subjects mean square error term in the repeated-measures ANOVA. For the ANOVA tests, the assumption of sphericity was tested using Mauchly's test and for violated sphericity, Greenhouse-Geisser correction of the degrees of freedom was used (epsilon was ≤ 0.75). Eta squared effect size (η^2) was also reported for the ANOVA tests. Bonferroni α corrections were applied to all ANOVA tests. A paired *t*-test was used to compare physiological responses, GE, and perceived effort associated with submaximal exercise during the seventh submaximal stage prior to the TT versus the same submaximal exercise after the TT. The mean difference ± 95% limits of agreement for the respective pair-wise comparisons of the six anaerobic capacity estimates were evaluated by using Bland-Altman calculations (27). The pair-wise mean difference was also tested with a paired-sample *t*-test. In addition, the absolute typical error for the comparisons was computed, which was also expressed as a percentage (i.e., relative to the grand mean). For the paired *t*-tests, the standardized mean difference (Hedges' g_{av}, effect size [ES_{Hg_av}]) was computed according to the equations presented by Lakens (28). All statistical tests were processed using Office Excel 2016 (Microsoft Corporation, Redmond, WA, USA) and the Statistical Package for the Social Sciences (SPSS 25, IBM Corp., Armonk, NY, USA). The level of statistical significance was set at $\alpha \leq 0.05$.

RESULTS

The submaximal power outputs, cadences, physiological responses, and GE associated with the seven submaximal stages (SUB_{1-7}) of cycle ergometry exercise, and the post time trial submaximal bout are shown in Table 1. The GE was shown to be power output dependent as revealed by the significant differences between the seven submaximal stages ($F_{2,28} = 18.8$, $P < 0.001$, $\eta^2 = 0.591$) with significant pairwise differences being indicated in Table 1. The blood lactate concentrations 1 min prior to the first submaximal stage (after a 5-min warm-up) and immediately after the seventh submaximal stage were 0.9 ± 0.1 and 2.2 ± 0.8 $mmol \cdot L^{-1}$, respectively. The average metabolic rates for the 7-Y_{LIN} model are displayed in Figure 1A and GE values are presented in Figure 1B.

The 3-min TT was completed at an average power output of 399 ± 42 W at an average cadence of 93 ± 11 rev·min^{-1}. The average $\dot{V}O_2$ was 50 ± 4 ml·kg^{-1}·min^{-1} (3.8 ± 0.5 L·min^{-1}) and the $\dot{V}O_{2peak}$ was 66 ± 6 ml·kg^{-1}·min^{-1} (4.9 ± 0.6 L·min^{-1}, 1.71 ± 0.22 kW) at an RER of 1.11 ± 0.08. The peak ventilation rate and peak heart rate were 183 ± 26 L·min^{-1} and 181 (IQR = 179-183) beats·min^{-1}, respectively. The blood lactate concentrations 1 min pre and 2 min post the TT were 1.9 ± 0.5 and 10.9 ± 2.0 mmol·L^{-1}, respectively. The median RPE measured immediately after the TT was 19 (IQR = 19-20). Respiratory responses and the estimated ventilatory energy cost per liter of ventilation as well as the estimated metabolic rate required for ventilation during the TT are shown in Table 1. The ventilation rate at $\dot{V}O_{2peak}$ was 181 ± 27 L·min^{-1}, which resulted in an estimated ventilatory energy cost of 81 ± 14 J·L[V_E]$^{-1}$ and an estimated metabolic rate required for ventilation of 250 ± 80 W, which was equivalent to 14.4 ± 3.4% of $\dot{V}O_{2peak}$.

The difference in physiological responses between the last submaximal stage prior to the TT, and the submaximal stage following the TT, are shown in Table 1. For the same power output (3.30 ± 0.30 W·kg^{-1}), the physiological responses were higher for all variables except for RER, whereas GE was 1.9 percentage points lower than prior to the TT. Approximately one-third (29%) of the 1.9 percentage point decline in GE could be related to the higher ventilatory energy expenditure due to the 27% higher ventilation rate and the 20% higher ventilatory energy cost per liter of ventilation.

Figure 2A shows the relationship between ventilation rate (L·min^{-1}) and ventilatory energy cost (J·L [V_E] $^{-1}$) adapted from Dempsey et al. (1996). Figure 2B shows the average instantaneous ventilation rate during the TT and Figure 2C shows the additional instantaneous metabolic requirement for respiration that was added to the required metabolic rate estimated with the 7-Y_{LIN} and GE_{LAST} models, and thereafter referred to as the 7-$Y_{LIN\text{-}V\text{-}cor}$ and $GE_{LAST\text{-}V\text{-}cor}$ models.

Figure 3 shows the average effect on the required total metabolic rate, GE, and anaerobic metabolic rate when the estimated additional metabolic rate due to hyperpnea was added to the 7-Y_{LIN} and GE_{LAST} models, i.e., the results for the two ventilation corrected models (7-$Y_{LIN\text{-}V\text{-}cor}$ and $GE_{LAST\text{-}V\text{-}cor}$).

When comparing the 7-Y_{LIN} versus the GE_{LAST} model, the 7-Y_{LIN} model resulted in a 0.9 percentage point higher GE associated with the TT, a 5% lower required total metabolic rate, a 15% lower anaerobic capacity, and an 11% lower anaerobic work capacity (see Table 2). The correction for an increased metabolic requirement due to hyperpnea (i.e., the 7-$Y_{LIN\text{-}V\text{-}cor}$ and $GE_{LAST\text{-}V\text{-}cor}$ models) resulted in ~0.7 percentage points lower GE, ~3% higher required total metabolic rate, ~11% higher anaerobic capacity, and ~9% higher anaerobic work capacity for the 7-$Y_{LIN\text{-}V\text{-}cor}$ and $GE_{LAST\text{-}V\text{-}cor}$ models combined versus the GE_{LAST} and 7-Y_{LIN} models combined. The mean differences, limits of agreement, and typical errors for the pair-wise comparisons of the six various models are presented in Figure 4.

DISCUSSION

This study has systematically analyzed the effect of exercise hyperpnea on GE and anaerobic capacity estimates during a self-paced 3-min supramaximal cycle TT. For the two conventional models that were compared, the GE_{LAST} model generated higher values of anaerobic capacity than the 7-Y_{LIN} model, due to the positive Y-intercept value for the 7-Y_{LIN} model, which assumes an increasing GE with higher power outputs for the 7-Y_{LIN} model. When correcting for hyperpnea during the TT (i.e., 7-$Y_{LIN\text{-}V\text{-}cor}$ and $GE_{LAST\text{-}V\text{-}cor}$), GE values were ~0.7 percentage points lower than for the conventional models (i.e., 7-Y_{LIN} and GE_{LAST}), which resulted in significantly higher values of the required metabolic rate (~3.2%) and anaerobic capacity (~11%) during the TT. The GE measured after the TT was 1.9 percentage points lower than prior to the TT.

The significantly higher values of anaerobic capacity (18%) observed with the GE_{LAST} than $7\text{-}Y_{LIN}$ model confirmed the study hypothesis. This finding was explained by the positive Y-intercept in the $7\text{-}Y_{LIN}$ regression (Figure 1A) and the increasing GE with higher power output (Figure 1B), which is contrary to the GE_{LAST} model that assumes a constant GE. On average, this resulted in a 0.9 percentage point higher GE during the TT for the $7\text{-}Y_{LIN}$ than the GE_{LAST} model. This finding differs from the results of previous studies that utilized different exercise modalities, such as diagonal-stride roller-skiing or running on a treadmill, where a linear regression model (power output/speed versus metabolic rate) without a baseline (i.e., "resting") value of metabolic rate generated similar values of anaerobic capacity as a model based on a fixed value of GE and/or gross energy cost (4, 5, 29). This was due to the close-to-zero average Y-intercept value for the respective linear regression model in these previous studies.

A novel aspect of the current study was the inclusion of an estimated additional metabolic cost of ventilation for exercise intensities that were above the exercise intensity of the last submaximal stage; as demonstrated in Figure 2. Thus, the additional instantaneous metabolic rate due to hyperpnea during the TT was calculated and added to the total metabolic requirement generated by the $7\text{-}Y_{LIN}$ and GE_{LAST} models (Figure 2C) with the average effect presented in Figure 3. Due to the ventilatory response during the TT (see Figures 2B-C), the instantaneous GE started to decline after approximately the first minute of exercise and continued to gradually decline throughout the TT (see Figures 3C-D). This resulted in a higher anaerobic metabolic rate for each respective ventilatory-corrected model, compared to each respective conventional model, during the last two minutes of exercise (Figures 3E-F). When correcting for hyperpnea during the TT, the GE was, on average, ~0.7 percentage points lower compared to the conventional model (i.e., 7-Y_{LIN} or GE_{LAST}), and anaerobic capacity values were ~11% higher (or 0.14 kJ·kg^{-1} higher). As shown in Figures 4E and 4H, the higher anaerobic capacity estimates due to hyperpnea ranged between 0.05-0.27 kJ·kg^{-1}, indicating considerable inter-participant variation. This is not a surprising result as the magnitude of additional ventilatory energy cost is related to the absolute ventilation rate during exercise (Figure 2A), which has also been considered in previous studies (18, 21).

To account for a declining GE during supramaximal cycle exercise, de Koning et al. (12) suggested an alternative back-extrapolation approach compared to the conventional GE method. However, this back-extrapolated approach has some methodological issues and requires several problematic assumptions. For example, oxygen uptake recovery (also known as EPOC) after a high-intensity/supramaximal-intensity effort is curvilinear due to the respective fast and slow components (14, 15). Also, the nonlinear $\dot{V}CO_2$ kinetics after maximal exercise is likely to generate a post-exercise RER that does not reflect actual substrate utilization (11, 14, 17). For example, in the current study, the RER measured during the submaximal bout after the TT was 0.80, which was substantially lower than the RER of 0.90 that was measured prior to the TT (see Table 1). However, it is highly unlikely that substrate utilization shifts towards a higher relative fat utilization after a supramaximal TT, indicating that the measured RER did not accurately reflect the true substrate utilization. Due to these aforementioned problems, GE in the current study was measured during the final minute of a 6-min submaximal stage that started 5 min after the TT. Since the RER measured during the submaximal exercise following the TT was not considered to reflect substrate utilization, the RER value from the same steady-state submaximal exercise prior to the TT (i.e., the seventh submaximal stage) was used in the calculation of metabolic rate and GE. It should be acknowledged that the revised models of the present study are based on theoretical constructs, and are thus unlikely to calculate the exact quantity of anaerobic capacity, due to the complex physiological systems. However, this caveat is also pertinent to the original models and should be considered an inherent flaw in all anaerobic capacity calculations.

Similar to previous research (10-13), GE was found to be lower during the submaximal exercise that followed the supramaximal TT than before. Interestingly, a considerable part of this 1.9-percentage-point lower GE could be related to the increased metabolic requirement for ventilation due to the ~25 $L{\cdot}min^{-1}$ higher ventilation rate and the estimated ~20% higher energy cost per liter of ventilation. Other potential factors to the lower GE after the supramaximal TT could have been attributed to impaired muscle contractility and/or altered muscle recruitment patterns (11, 30). One major factor for the higher ventilation rate during the submaximal exercise bout that followed the TT, than prior to the TT, was likely mainly related to an increased ventilatory drive, i.e., lower ventilatory recruitment threshold of the ventilatory response, caused by lower blood pH (acidosis) due to anaerobic glycolysis from the prior 3-min supramaximal TT (16). Both the 7-$Y_{LIN\text{-}D}$ and 7-$Y_{LIN\text{-}V\text{-}cor}$ models generated higher values of anaerobic capacity than the conventional 7-Y_{LIN} model (Figures 4D, E), a result that also was similar to the GE method-based models (Figures 4G, H). One clear difference between the 7-Y_{LIN} and GE_{LAST} models is presented in Figure 1, where the 7-Y_{LIN} model assumes a slightly increasing GE with higher power outputs, whereas the GE_{LAST} model assumes a constant GE during the TT based on the GE value from the seventh submaximal stage. Due to the decline in GE during supramaximal exercise, the 7-Y_{LIN} likely underestimated anaerobic capacity. In contrast, the GE_{LAST} model may have provided a more valid estimate due to the lower GE value used for calculating the required metabolic rate (see Figures 3C-D). The corrections made for a declining GE during the TT in connection with the 7-Y_{LIN} model, i.e., the 7-$Y_{LIN\text{-}V\text{-}cor}$ and 7-$Y_{LIN\text{-}D}$ models, probably generated more valid estimates of anaerobic capacity compared to the conventional 7-Y_{LIN} model. On the other hand, the corrections made for a declining GE during the TT in connection with the GE_{LAST} model, i.e., the $GE_{LAST\text{-}V\text{-}cor}$ and $GE_{LAST\text{-}D}$, may have overestimated the anaerobic capacity.

From these observations, we conclude that GE declines during a 3-min supramaximal cycle TT. A major cause of this decline is likely related to the concave-upward relationship of ventilation rate versus ventilatory energy cost (see Figure 2A) and the ventilatory response during supramaximal exercise with a higher ventilatory equivalent for oxygen. Therefore, conventional linear regression models that do not account for a declining GE during supramaximal cycle-ergometry exercise may underestimate the total metabolic requirement and, thus, the accumulated anaerobic energy expenditure. In the current study, the relationship between ventilation rate and ventilatory energy cost was adapted from data presented by Dempsey et al. (18) and was assumed to remain consistent across participants, i.e., no inter-participant variation. We recognize that this assumption was a simplification of the probable individual variation, as a high individual variation in this relationship has been previously observed (21). Based on the results presented in Table 1 and Figure 2A, a very minor part of the increased requirement for ventilation was likely already included in the 7-Y_{LIN} model. This is because the estimated relative metabolic rate required for ventilation increased from 4.5% at the first submaximal stage to 5.4% at the last submaximal stage (see Table 1). Nevertheless, this part is likely to be very marginal as the ventilatory equivalent for oxygen increased substantially during the TT and so did also the ventilatory energy cost per liter of ventilation (see Table 1). Due to these issues, a more refined methodology would include a separate test to establish the individual polynomial relationships between ventilation rate and ventilatory oxygen cost (or estimated energy cost) (18, 19, 21). For example, a participant could mimic different exercise ventilation rates during rest, i.e., different levels of enforced hyperventilation at rest using a CO_2-enriched gas mixture to avoid the participant from fainting (21). Such an analysis would also allow for a more holistic understanding of the importance of respiratory energy/oxygen cost on exercise performance. For instance, the method provided in this study would make it possible to estimate the individual effect of hyperpnea on GE (or gross energy cost), which is an important performance factor in many sports (31). In addition, different ventilation strategies/patterns, pacing strategies, and/or altitudes may potentially induce different hyperpneic responses that could result in altered metabolic requirements for ventilation which in turn could influence GE and exercise performance. Further studies could potentially determine the specific effect(s) of respiratory training and/or respiratory muscle fatigue on high-intensity endurance performances (32, 33). Other areas of interest could be to analyze the potential effect of exercise-induced hyperpnea, and/or respiratory muscle fatigue (18, 34, 35), on the $\dot{V}O_2$ slow component during high-intensity submaximal exercise (11, 35, 36).

CONCLUSIONS

The current study shows that for the two conventional models that were compared, the GE_{LAST} model generated higher values of anaerobic capacity than the $7\text{-}Y_{LIN}$ model, an effect caused by the different GE assumptions during supramaximal exercise. The two hyperpnea corrected models (i.e., $7\text{-}Y_{LIN\text{-}V\text{-}cor}$ and $GE_{LAST\text{-}V\text{-}cor}$) generated, on average, a 0.7 percentage point lower GE estimate during the TT, which resulted in an 11% higher anaerobic capacity estimate compared to the respective conventional models. In addition, a substantial part of the decline in GE after the TT was estimated to be caused by the higher ventilation rate, and, thus, the increased metabolic requirement for ventilation, that followed the supramaximal exercise. Therefore, these findings suggest that the conventional linear model (i.e., 7-Y_{LIN}) for estimating anaerobic capacity is likely to generate underestimated values.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

E.A. designed the study whereas P.B. and T.S. were responsible for the data collection. E.A. analyzed and interpreted the data. E.A. and J.O. wrote the first draft of the article. All listed authors drafted the manuscript, revised the manuscript and approve the final version to be published and agree to be accountable for all aspects of the work.

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FIGURE CAPTIONS

Figure 1. (A) The average metabolic rates associated with the seven stages of submaximal exercise (Sub stages 1-7) and the extrapolated average total metabolic rate for the supramaximal

self-paced 3-min time trial (TT_{AVG}). The black line represents the linear regression line (7-Y_{LIN}) based on the average data with the dotted lines representing the ± SD for the linear regression line. (B) The gross efficiencies for the seven stages of submaximal exercise (yellow tilted squares) and the average gross efficiency for the TT_{AVG} as calculated from the regression equation in A (i.e., power output divided by the total metabolic rate during the TT). The black line (in B) represents the gross efficiency relationship calculated from the linear regression equation presented in A with the dotted lines representing the ± SD.

Figure 2. (A) The effect of an increased ventilation rate on the energy cost of ventilation (VE_{E-COST}). The relationship was adapted from Dempsey et al. (16) with further details provided in the methods. The dashed green vertical lines indicate the average ventilation range for the seven submaximal stages in the current study. The dashed red horizontal line is based on the average ventilation rate associated with the last submaximal stage and represents the average boundary for additional metabolic requirement due to exercise hyperpnea during the supramaximal time-trial (TT) effort (i.e., the TT average cut off). (B) The average instantaneous second-by-second ventilatory response during the 3-min supramaximal TT. (C) The average additional instantaneous metabolic rate due to hyperpnea during the TT, calculated as VE_{E-COST} above the last submaximal stage multiplied by the ventilation rate in liters per second (see the methods for further details). The estimated additional instantaneous MR due to hyperpnea during the TT was added to the total metabolic requirement generated by the 7-Y_{LIN} and GE_{LAST} models and then referred to as the 7-$Y_{LIN-V-cor}$ and $GE_{LAST-V-cor}$ models (i.e., the ventilatory corrected [V-cor] models).

Figure 3. The power output and the estimated required total metabolic rates (MR_{REQ}) for (A) GE_{LAST} and $GE_{LAST\text{-}V\text{-}cor}$, and (B) 7-$Y_{LIN}$ and 7-$Y_{LIN\text{-}V\text{-}cor}$ models during the 3-min self-paced cycle time trial (TT). The 7-Y_{LIN} is the linear model based on seven submaximal stages and the GE_{LAST} is the model based on the GE value from the last submaximal stage. The 7-$Y_{LIN\text{-}V\text{-}cor}$ and $GE_{LAST\text{-}V\text{-}cor}$ are the same models but with the estimated additional metabolic rate due to hyperpnea added to the 7-Y_{LIN} and GE_{LAST} models. (C-D) The instantaneous second-by-second gross efficiency values for the different models during the TT. (E-F) The instantaneous second-by-second aerobic metabolic rate (MR_{AE}) and the estimated anaerobic metabolic rate (MR_{AN}) as based on the different models during the TT. The presented data are based on group-average values.

Figure 4. Bland-Altman plots for the six various models of estimating anaerobic capacity (AnC) associated with the 3-min self-paced cycle time trial. Bland-Altman plots represent the mean difference ($MEAN_{DIFF}$) in the AnC ± 95% (1.96 SD) limits of agreement between the methods. Abbreviations: AnC_{DIFF}, the difference in AnC; TE, typical error (in parenthesis: typical error expressed as a percentage of the grand mean); ES, Hedges's g_{av} effect size (Hg_{av}), 7-Y_{LIN}, the 7 × 4-min linear regression model; GE_{LAST}, the gross efficiency model based on the last submaximal stage; 7-$Y_{LIN\text{-}V\text{-}cor}$, the exercise hyperpnea corrected 7-Y_{LIN} model; $GE_{LAST\text{-}V\text{-}cor}$, the exercise hyperpnea corrected GE_{LAST} model; 7-$Y_{LIN\text{-}D}$, the 7-Y_{LIN} model corrected for a declining GE; $GE_{LAST\text{-}D}$, the GE_{LAST} model corrected for a declining GE.

Table 1. Mean ± SD values of power outputs, physiological responses, and gross efficiencies associated with the seven submaximal stages (SUB_1-SUB_7), the 3-min supramaximal time trial (TT), and the post-time-trial submaximal stage (SUB_{TTpost}) of cycle ergometry exercise.

	SUB_1	SUB_2	SUB_3	SUB_4	SUB_5	SUB_6	SUB_7	TT	SUB_{TTpost}	ES
Power output ($W \cdot kg^{-1}$)	1.54 ± 0.14	1.84 ± 0.16	2.13 ± 0.19	2.42 ± 0.22	2.72 ± 0.24	3.01 ± 0.27	3.30 ± 0.30	5.34 ± 0.43	3.30 ± 0.30	-
Cadence ($rev \cdot min^{-1}$)	69 ± 5	71 ± 5	74 ± 5	77 ± 5	80 ± 5	83 ± 5	86 ± 5	93 ± 11	87 ± 7	0.3
Heart rate (% of TT_{peak})	60 ± 6	64 ± 6	67 ± 6	72 ± 6	77 ± 5	82 ± 5	86 ± 5	-	91 ± 4$^{\$}$	0.9
MR_{AE} ($W \cdot kg^{-1}$)	8.3 ± 1.2	9.4 ± 1.3	10.6 ± 1.3	11.8 ± 1.6	13.1 ± 1.6	14.4 ± 1.6	15.8 ± 1.7	17.7 ± 1.4	17.4 ± 1.7$^{\$}$	0.9
MR_{AE} (% of MR_{AE_peak})	36 ± 6	42 ± 7	47 ± 7	52 ± 8	58 ± 9	64 ± 9	69 ± 9	-	76 ± 9$^{\$}$	0.7
$\dot{V}_E$ ($L \cdot min^{-1}$)	45.6 ± 8.2	50.9 ± 9.7	57.3 ± 10.3	64.3 ± 10.3	72.5 ± 11.2	81.0 ± 12.9	90.7 ± 15.6	130.5 ± 23.1	115.6 ± 20.6$^{\$}$	1.3
$VE_{E\text{-}COST}$ ($J \cdot L[V_E]^{-1}$)	36 ± 1	36 ± 1	36 ± 1	37 ± 1	38 ± 2	39 ± 3	42 ± 4	61 ± 9	50 ± 8$^{\$}$	1.2
MR_{VE} ($W \cdot kg^{-1}$)	0.4 ± 0.1	0.4 ± 0.1	0.5 ± 0.1	0.5 ± 0.1	0.6 ± 0.1	0.7 ± 0.1	0.9 ± 0.2	2.0 ± 0.6	1.3 ± 0.4$^{\$}$	1.4
MR_{VE_rel} (% of MR_{AE})	4.5 ± 0.3	4.3 ± 0.3	4.4 ± 0.3	4.5 ± 0.3	4.7 ± 0.4	4.9 ± 0.5	5.4 ± 0.9	10.2 ± 2.4	7.5 ± 1.9$^{\$}$	1.3
$\dot{V}_E \cdot \dot{V}O_2^{-1}$	24.6 ± 1.7	24.0 ± 1.7	24.1 ± 1.5	24.5 ± 1.6	24.8 ± 1.3	25.2 ± 1.5	26.0 ± 2.2	34.8 ± 3.5	30.3 ± 3.2$^{\$}$	1.5
$\dot{V}_E \cdot \dot{V}CO_2^{-1}$	28.6 ± 2.1	28.1 ± 2.3	28.0 ± 2.2	28.1 ± 2.5	28.3 ± 2.3	28.4 ± 2.3	28.9 ± 2.9	33.5 ± 3.1	37.5 ± 4.4$^{\$}$	2.2
RER ($\dot{V}CO_2 \cdot \dot{V}O_2^{-1}$)	0.86 ± 0.04	0.86 ± 0.04	0.86 ± 0.05	0.87 ± 0.04	0.88 ± 0.05	0.89 ± 0.05	0.90 ± 0.05	1.03 ± 0.09	0.80 ± 0.04$^{\$}$	-2.1

Gross efficiency (%)	18.8 ± 2.0$^{c\text{-}g}$	19.7 ± 2.1^{d}	20.2 ± 1.8	20.7 ± 1.8	20.8 ± 1.4	20.9 ± 1.3	21.0 ± 1.3	-	19.1 ± 1.2$^{\$}$	-1.4

Abbreviations: ES, effect size; TT_{peak}, TT peak value; MR_{AE}, aerobic metabolic rate; MR_{AE_peak}, peak aerobic metabolic rate from the TT; $\dot{V}_E$, ventilation rate; $VE_{E\text{-}COST}$, ventilatory energy cost; V_E, ventilation volume; MR_{VE}, the estimated metabolic rate required for ventilation (i.e., $VE_{E\text{-}COST}$ [$J \cdot L^{-1}$] × $\dot{V}_E$ [$L \cdot s^{-1}$]); MR_{VE_rel}, the estimated metabolic rate required for ventilation expressed as a fraction of the MR_{AE}; $\dot{V}_E \cdot \dot{V}O_2^{-1}$, ventilatory equivalent for oxygen; $\dot{V}_E \cdot \dot{V}CO_2^{-1}$, ventilatory equivalent for carbon dioxide; RER, respiratory exchange ratio. Statistical comparisons were performed between SUB_{TTpost} and SUB_7. $^{\$}P < 0.001$ versus SUB_7. Hedges' g_{av} ES (Hg_{av}) was presented for the respective pair-wise comparisons. A one-way repeated measures ANOVA was used to compare the gross efficiency values for the seven submaximal stages. $^{c\text{-}g}$Significantly different from SUB_3, SUB_4, SUB_5, SUB_6, and SUB_7, all $P < 0.01$. ^{d}Significantly different from SUB_4, $P = 0.01$.

Table 2. Mean ± SD values of the gross efficiency, metabolic requirement, anaerobic capacity, anaerobic work capacity, and relative anaerobic energy contribution during the 3-min cycle time trial (TT) for the six different calculation models.

	Model of calculation									
	$7\text{-}Y_{LIN}$	$7\text{-}Y_{LIN\text{-}V\text{-}cor}$	$7\text{-}Y_{LIN\text{-}D}$	GE_{LAST}	$GE_{LAST\text{-}V\text{-}cor}$	$GE_{LAST\text{-}D}$	F-value	*P*-value	η^2	SEM
GE_{TT_avg} (%)	$21.9 \pm 1.4^{b\text{-}f}$	$21.2 \pm 1.3^{e,f}$	20.9 ± 1.3^{f}	$21.0 \pm 1.3^{e,f}$	20.4 ± 1.3	20.0 ± 1.2	$F_{2,21} = 23.4$	< 0.001	0.643	0.89
MR_{TT_req} ($W \cdot kg^{-1}$)	$24.3 \pm 1.9^{b\text{-}f}$	$25.1 \pm 2.0^{e,f}$	25.4 ± 2.2^{f}	$25.5 \pm 2.4^{e,f}$	26.3 ± 2.6	26.6 ± 2.7	$F_{5.65} = 21.8$	< 0.001	0.627	0.66
MR_{TT_req} (% of MR_{ae_peak})	$106 \pm 4^{b\text{-}f}$	$110 \pm 4^{e,f}$	111 ± 5^{f}	$111 \pm 6^{e,f}$	115 ± 6	116 ± 6	$F_{5.65} = 24.1$	< 0.001	0.650	2.72
AnC ($kJ \cdot kg^{-1}$)	$1.19 \pm 0.27^{b\text{-}f}$	$1.33 \pm 0.25^{e,f}$	1.41 ± 0.32^{f}	$1.40 \pm 0.31^{e,f}$	1.54 ± 0.31	1.63 ± 0.36	$F_{5.65} = 23.6$	< 0.001	0.645	0.12
AnWC ($kJ \cdot kg^{-1}$)	$0.26 \pm 0.05^{b\text{-}f}$	$0.29 \pm 0.05^{e,f}$	0.30 ± 0.06^{f}	$0.29 \pm 0.06^{e,f}$	0.32 ± 0.05	0.33 ± 0.06	$F_{2.22} = 25.0$	< 0.001	0.658	0.03
AN_{rel} (% of total)	$27 \pm 5^{b\text{-}f}$	$29 \pm 4^{e,f}$	31 ± 5^{f}	$30 \pm 5^{e,f}$	32 ± 4^{f}	34 ± 5	$F_{2,20} = 27.6$	< 0.001	0.680	3.01

Abbreviations: $7\text{-}Y_{LIN}$, the 7 × 4-min linear regression model; GE_{LAST}, the gross efficiency model based on the last submaximal stage; $7\text{-}Y_{LIN\text{-}V\text{-}cor}$, the exercise hyperpnea corrected $7\text{-}Y_{LIN}$ model; $GE_{LAST\text{-}V\text{-}cor}$, the exercise hyperpnea corrected GE_{LAST} model; $7\text{-}Y_{LIN\text{-}D}$, the $7\text{-}Y_{LIN}$ model corrected for a declining GE; $GE_{LAST\text{-}D}$, the GE_{LAST} model corrected for a declining GE; SEM, standard error of measurement; GE_{TTavg}, average GE during the TT; MR_{TTreq}, required total metabolic rate during the TT; MR_{ae_peak}, peak aerobic metabolic rate during the TT; AnC, anaerobic capacity; AnWC, anaerobic work capacity; AN_{rel}, relative anaerobic energy contribution. F-values, *P*-values, and eta squared effect size (η^2) were obtained by a one-way ANOVA. [b]Statistically significantly different from 7-

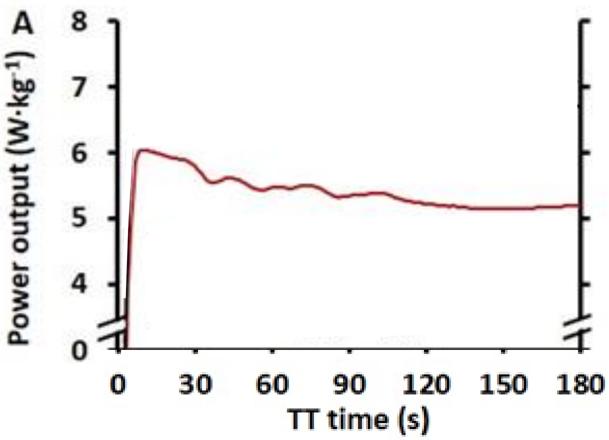
$Y_{LIN\text{-}V\text{-}cor}$ ($P < 0.05$). [c]Statistically significantly different from 7-$Y_{LIN\text{-}D}$ ($P < 0.05$). [d]Statistically significantly different from GE_{LAST} ($P < 0.05$). [e]Statistically significantly different from $GE_{LAST\text{-}V\text{-}cor}$ ($P < 0.05$). [f]Statistically significantly different from $GE_{LAST\text{-}D}$ ($P < 0.05$).

The effect of exercise hyperpnea on gross efficiency and anaerobic capacity estimates during a 3-min cycle time trial

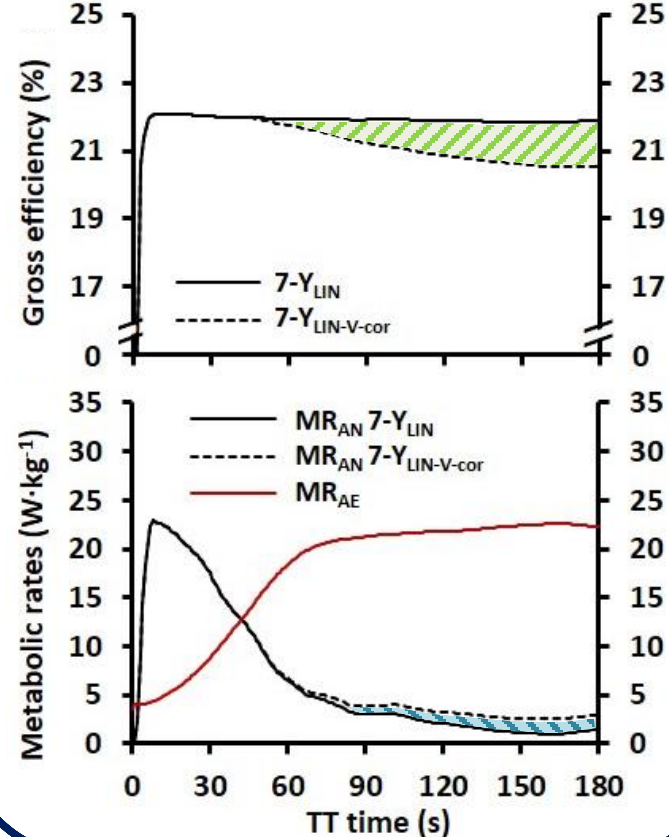
METHODS

n=14
Highly-trained cyclists

3-min
Time trial

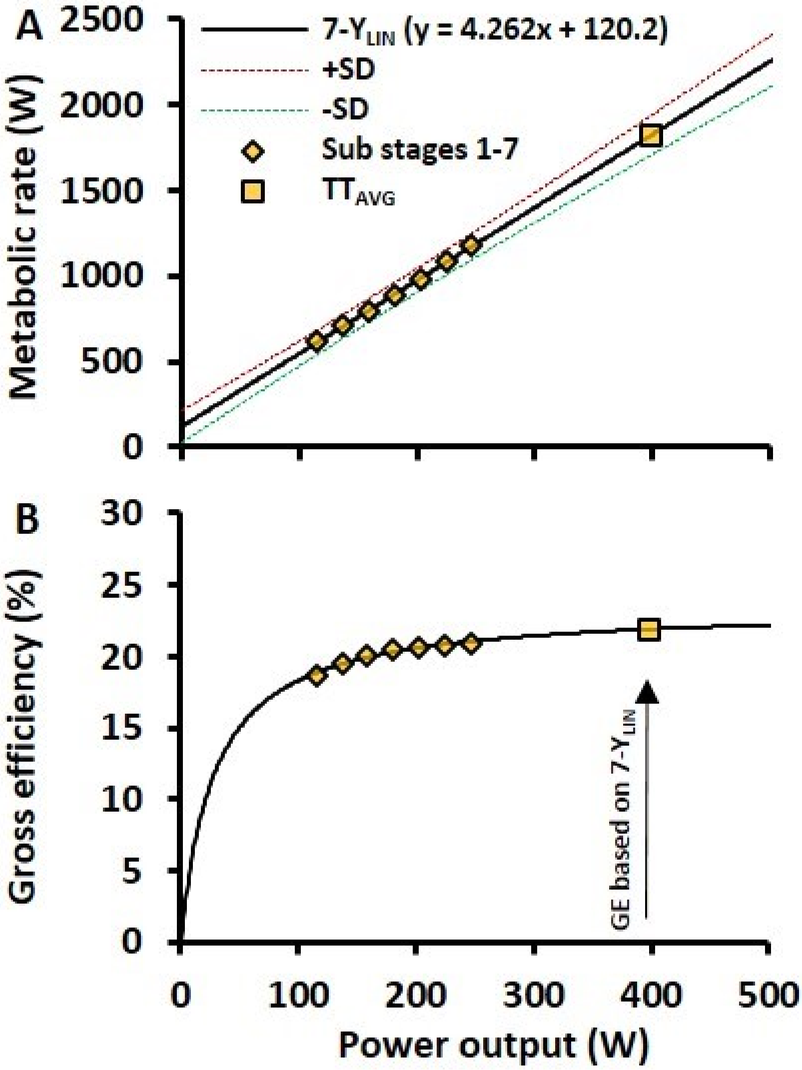


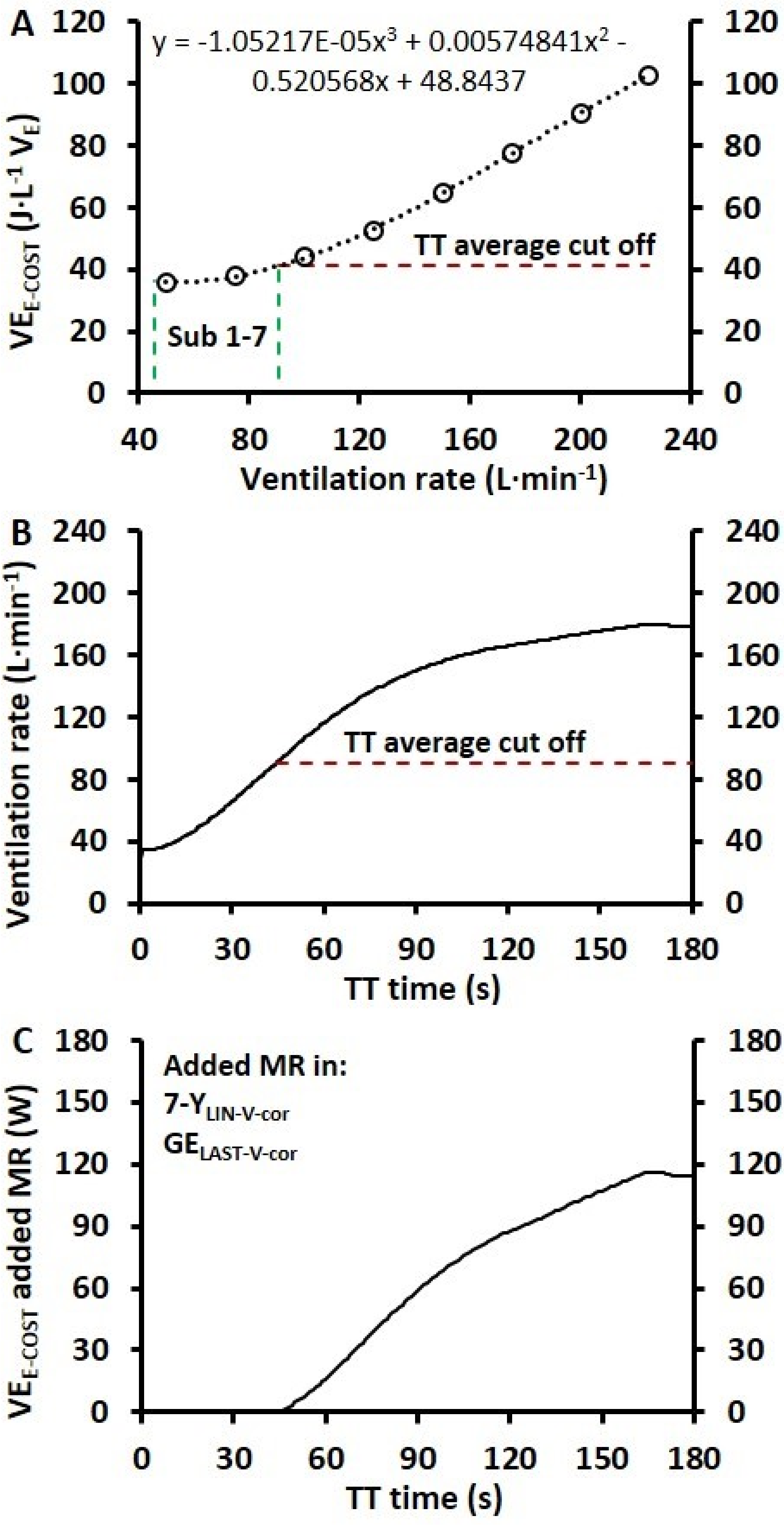
OUTCOME

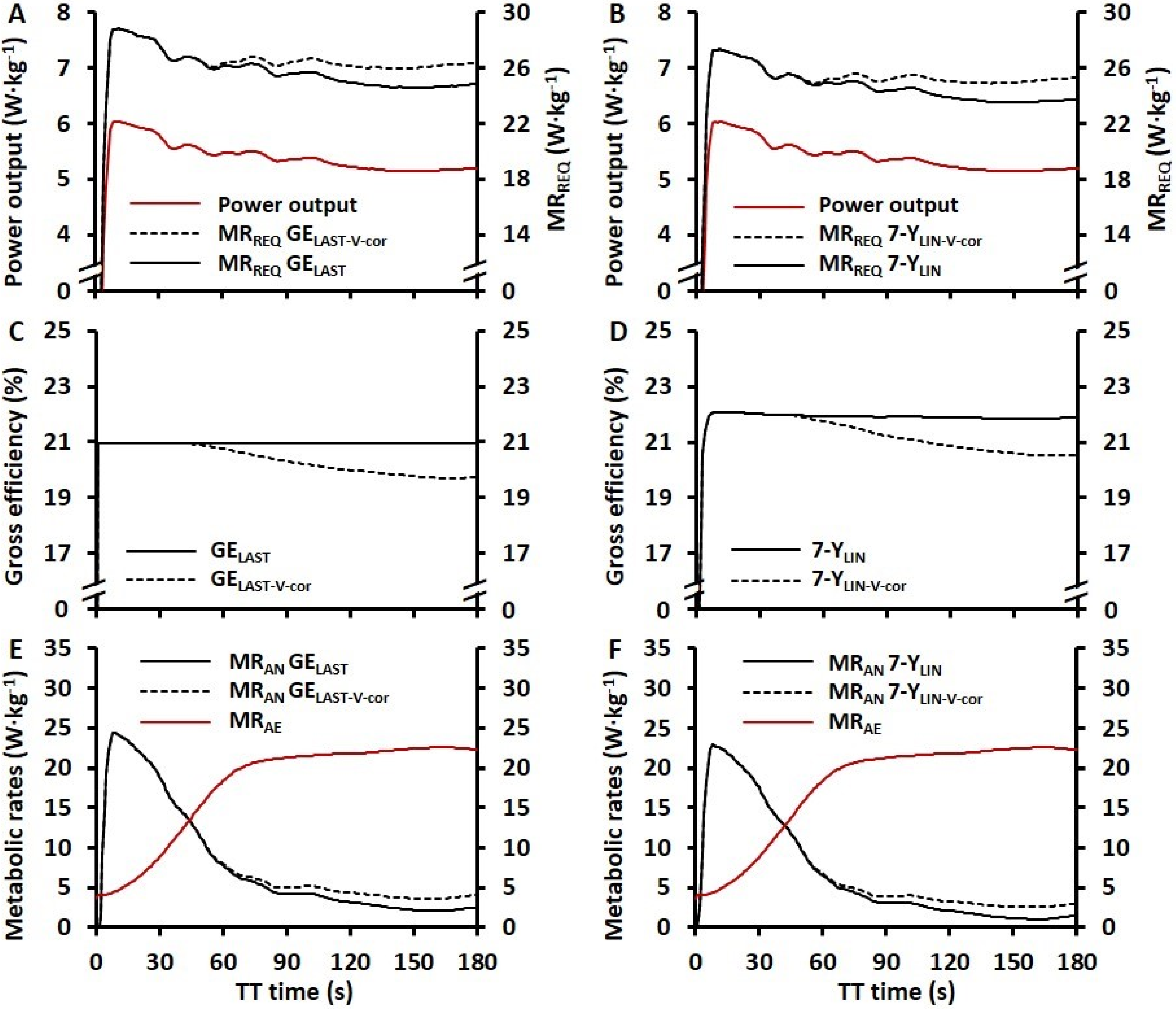


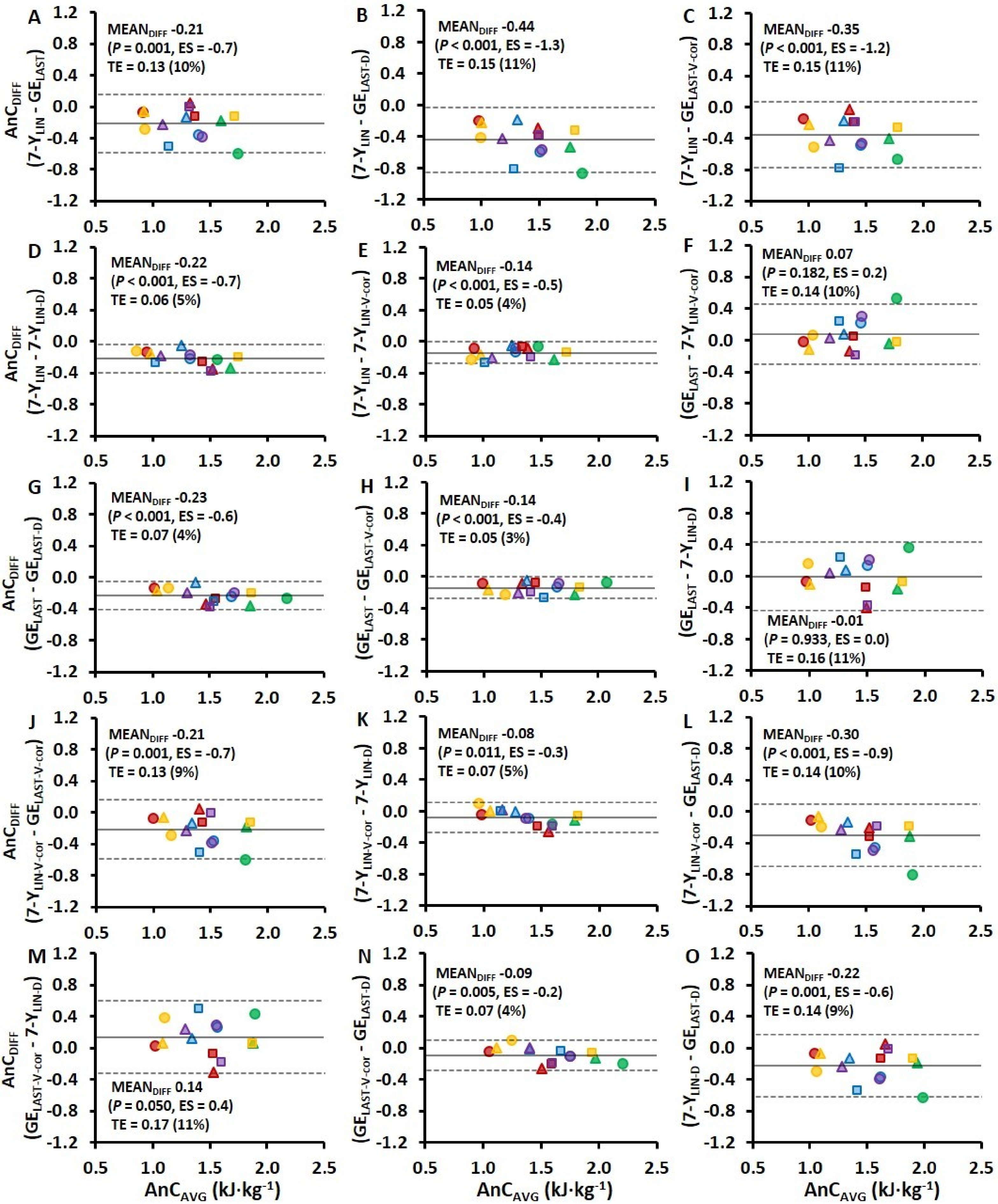
CONCLUSION

Exercise-induced hyperpnea decreased gross efficiency and increased required total metabolic rate and anaerobic energy expenditure during supramaximal exercise. Estimation models should include the additional energy cost from increased ventilatory energy requirements.


A
B
7-Y_LIN (y = 4.262x + 120.2)
+SD
-SD
Sub stages 1-7
TT_AVG
Metabolic rate (W)
0
500
1000
1500
2000
2500
Gross efficiency (%)
0
5
10
15
20
25
30
GE based on 7-Y_LIN
0
100
200
300
400
500
Power output (W)


A
y = -1.05217E-05x³ + 0.00574841x² - 0.520568x + 48.8437
TT average cut off
Sub 1-7
VE_E-COST (J·L⁻¹ V_E)
Ventilation rate (L·min⁻¹)
B
TT average cut off
Ventilation rate (L·min⁻¹)
TT time (s)
C
Added MR in:
7-Y_LIN-V-cor
GE_LAST-V-cor
VE_E-COST added MR (W)
TT time (s)


A
B
C
D
E
F
Power output (W·kg-1)
MRREQ (W·kg-1)
Power output
MRREQ GELAST-V-cor
MRREQ GELAST
MRREQ 7-YLIN-V-cor
MRREQ 7-YLIN
Gross efficiency (%)
GELAST
GELAST-V-cor
7-YLIN
7-YLIN-V-cor
Metabolic rates (W·kg-1)
MRAN GELAST
MRAN GELAST-V-cor
MRAE
MRAN 7-YLIN
MRAN 7-YLIN-V-cor
TT time (s)


A
MEAN$_{DIFF}$ -0.21
(P = 0.001, ES = -0.7)
TE = 0.13 (10%)
AnC$_{DIFF}$
(7-Y$_{LIN}$ - GE$_{LAST}$)
B
MEAN$_{DIFF}$ -0.44
(P < 0.001, ES = -1.3)
TE = 0.15 (11%)
(7-Y$_{LIN}$ - GE$_{LAST-D}$)
C
MEAN$_{DIFF}$ -0.35
(P < 0.001, ES = -1.2)
TE = 0.15 (11%)
(7-Y$_{LIN}$ - GE$_{LAST-V-cor}$)
D
MEAN$_{DIFF}$ -0.22
(P < 0.001, ES = -0.7)
TE = 0.06 (5%)
AnC$_{DIFF}$
(7-Y$_{LIN}$ - 7-Y$_{LIN-D}$)
E
MEAN$_{DIFF}$ -0.14
(P < 0.001, ES = -0.5)
TE = 0.05 (4%)
(7-Y$_{LIN}$ - 7-Y$_{LIN-V-cor}$)
F
MEAN$_{DIFF}$ 0.07
(P = 0.182, ES = 0.2)
TE = 0.14 (10%)
(GE$_{LAST}$ - 7-Y$_{LIN-V-cor}$)
G
MEAN$_{DIFF}$ -0.23
(P < 0.001, ES = -0.6)
TE = 0.07 (4%)
AnC$_{DIFF}$
(GE$_{LAST}$ - GE$_{LAST-D}$)
H
MEAN$_{DIFF}$ -0.14
(P < 0.001, ES = -0.4)
TE = 0.05 (3%)
(GE$_{LAST}$ - GE$_{LAST-V-cor}$)
I
MEAN$_{DIFF}$ -0.01
(P = 0.933, ES = 0.0)
TE = 0.16 (11%)
(GE$_{LAST}$ - 7-Y$_{LIN-D}$)
J
MEAN$_{DIFF}$ -0.21
(P = 0.001, ES = -0.7)
TE = 0.13 (9%)
AnC$_{DIFF}$
(7-Y$_{LIN-V-cor}$ - GE$_{LAST-V-cor}$)
K
MEAN$_{DIFF}$ -0.08
(P = 0.011, ES = -0.3)
TE = 0.07 (5%)
(7-Y$_{LIN-V-cor}$ - 7-Y$_{LIN-D}$)
L
MEAN$_{DIFF}$ -0.30
(P < 0.001, ES = -0.9)
TE = 0.14 (10%)
(7-Y$_{LIN-V-cor}$ - GE$_{LAST-D}$)
M
MEAN$_{DIFF}$ 0.14
(P = 0.050, ES = 0.4)
TE = 0.17 (11%)
AnC$_{DIFF}$
(GE$_{LAST-V-cor}$ - 7-Y$_{LIN-D}$)
N
MEAN$_{DIFF}$ -0.09
(P = 0.005, ES = -0.2)
TE = 0.07 (4%)
(GE$_{LAST-V-cor}$ - GE$_{LAST-D}$)
O
MEAN$_{DIFF}$ -0.22
(P = 0.001, ES = -0.6)
TE = 0.14 (9%)
(7-Y$_{LIN-D}$ - GE$_{LAST-D}$)
1.2
0.8
0.4
0.0
-0.4
-0.8
-1.2
0.5
1.0
1.5
2.0
2.5
AnC$_{AVG}$ (kJ·kg^{-1})