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VIEWPOINT

Commentaries on Viewpoint: Use aerobic energy expenditure instead of oxygen uptake to quantify exercise intensity and predict endurance performance

COMMENTARY ON VIEWPOINT: USE AEROBIC ENERGY EXPENDITURE INSTEAD OF OXYGEN UPTAKE TO QUANTIFY EXERCISE INTENSITY AND PREDICT ENDURANCE PERFORMANCE

TO THE EDITOR: The issue of defining and expressing exercise economy is not a new issue (1) but has taken on increasing consideration in recent years (3–5). Running economy (RE) is traditionally represented by the oxygen demand for a given velocity of submaximal running that reflects the metabolic, biomechanical, and neuromuscular components of running without consideration for what portion of that $\dot{V}O_2$ is a function of good or bad mechanics as opposed to being related to differences in metabolism that may exist in different athletes or under different conditions (1). Accordingly, the traditional measure of RE is flawed, as it is determined by multiple variables that are not based on oxygen consumption alone.

We agree that expressing RE as aerobic energy expenditure at least accounts for differences in substrate oxidation within and between subjects. As such, researchers can also determine with greater precision the true magnitude of change in RE related to metabolic vs. biomechanical or neuromuscular adaptations. This is particularly relevant in longitudinal studies where multiple adaptations may occur and acute intervention studies (2) that are unlikely to affect substrate utilization but often result in changes in RE. Still, depending on the equation used to calculate energy expenditure, results can vary by >5% (5) making comparisons between studies challenging. Therefore, it is encouraged that studies report VO_2 and VCO_2 or RER, thereby enabling readers to calculate RE using a common equation (5) as well as allowing comparison of VO_2 results to traditional studies and existing normative data (1, 3).

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QUANTIFICATION OF EXERCISE INTENSITY AS ENERGY EXPENDITURE: RELIABILITY AND UNITS OF MEASUREMENT

TO THE EDITOR: The Viewpoint (1) offered by Beck and colleagues is timely and to be commended given the high number of investigations that utilize oxygen uptake-related outcome measures. When study participants are compared across different time points, for example in a crossover or intervention study design, it is typical to request that a similar diet and exercise regimen are adopted in the 48 h preceding each physiological assessment; however, in reality this may be impractical to monitor accurately. Accounting for substrate utilization within a calculation of metabolic cost therefore probably provides a more valid strategy to quantify exercise intensity (5). We also recently showed that energy cost is a more reliable metric for quantification of running economy compared with oxygen cost in high-performing adolescent distance runners (2). The authors (1) identify that energy expenditure should be quantified as a ratio to body mass, which is also typical in the literature, but as a method of normalization for body size has been criticized (3, 4). We would therefore advocate that wherever possible an appropriate scaling exponent for the population of individuals under investigation, based upon a larger cohort of homogeneous participants (4, 5), is likely to further enhance the validity of energy expenditure measurement. Furthermore, steady-state conditions are a prerequisite for measuring EE_{aero}; too often these are assumed rather than checked (2). Finally, we would recommend that energy cost of exercise is quantified in the international standard (SI) unit for energy, kilojoules, rather than watts or kilocalories.

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COMMENTARY ON VIEWPOINT: USE AEROBIC ENERGY EXPENDITURE INSTEAD OF OXYGEN UPTAKE TO QUANTIFY EXERCISE INTENSITY AND PREDICT ENDURANCE PERFORMANCE

TO THE EDITOR: Beck et al. (1) raise an important point in the use of caloric expenditure to quantify movement economy ($kcal \cdot km^{-1} \cdot kg^{-1}$ instead of $ml \cdot km^{-1} \cdot kg^{-1}$) and thus to predict performance and evaluate determinants. However, the calculated caloric equivalent (E_{aero}) for (sub)maximal oxygen uptake ($\dot{V}O_2$) values would not solve the common problems associated with prescribing exercise (training) intensities based on percentages of maximal $\dot{V}O_2$ (%$\dot{V}O_{2max}$) or maximal heart rate (%HR_{max}) (2). A given (%$\dot{V}O_{2max}$), but also % of maximal E_{aero}, can result in a high interindividual variance in metabolic stress, given that the relative intensity at which the exercise thresholds (gas exchange threshold and critical power) occur is not fixed and differs between individuals (4). Therefore, an intensity expressed relative to $\dot{V}O_{2max}$ or maximal E_{aero}, can be above critical power for one subject and below critical power for another. Since critical power is considered as the boundary between the heavy and severe intensity domain, exercise below this threshold results in steady-state responses in $\dot{V}O_2$ and blood lactate concentration, whereas this is not the case for exercise above critical power, where theoretically these values evolve to maximal values (3). Using % of maximal E_{aero} would not solve this problem. It can be assumed that prescribing exercise intensities relative to the exercise thresholds would induce a more comparable metabolic and respiratory response between individuals and possibly could account in some part of the strong interindividual differences in the adjustments to a similar training program (2).

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EXERCISE INTENSITY SHOULD BE QUANTIFIED RELATIVE TO THE ANAEROBIC THRESHOLD, RATHER THAN MAXIMAL OXYGEN UPTAKE

TO THE EDITOR: Oxygen uptake ($\dot{V}O_2$) measurement permits estimation of the energy cost of exercise. Beck et al. (1) criticize the common practice of reporting $\dot{V}O_2$ and support the return to calculating the energy cost as we have proposed (2). We demonstrated that expression of running economy as an energy cost is sensitive to changes in speed and is a more valuable expression of running economy than is $\dot{V}O_2$ (2). This approach avoids the necessity of comparing everyone at the same speed, allowing comparison at a speed relative to lactate threshold. Beck et al. also recommend replacing expression of relative maximal $\dot{V}O_2$ with % maximal aerobic energy supply (%$\dot{E}_{aero\ max}$). However, there is a better solution for expression of relative intensity of exercise. The proposed expression (%$\dot{E}_{aero\ max}$) does not recognize the anaerobic threshold (AnT), a factor related to regulation of substrate variability and above which aerobic energy does not account for all energy (4). We suggest quantifying exercise intensity relative to the energy cost at anaerobic threshold (%$\dot{E}_{aero\ AnT}$), estimated as lactate threshold, critical power, or ventilatory threshold (4). Variability in substrate use is less than when %$\dot{V}O_2$ is used. It is also clear that at intensities above 100%$\dot{E}_{aero\ AnT}$, anaerobic energy needs to be accounted for by quantifying lactate accumulation (3). Precision of measurement is improved when $\dot{V}O_2$ is used to estimate energy equivalent below AnT. We encourage our colleagues to calculate energy cost and promote the use of energy cost measured relative to %$\dot{E}_{aero\ AnT}$ rather than at a common %$\dot{V}O_{2max}$.

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COMMENTARY ON VIEWPOINT: USE AEROBIC ENERGY EXPENDITURE INSTEAD OF OXYGEN UPTAKE TO QUANTIFY EXERCISE INTENSITY AND PREDICT ENDURANCE PERFORMANCE

TO THE EDITOR: We appreciate the Viewpoint of Beck et al. (1) providing information about the use of aerobic energy expenditure to quantify exercise intensity in endurance performance. The use of energy cost of running (kcal or $kJ \cdot kg^{-1} \cdot km^{-1}$) has grown because it is well known that this method is more sensitive to changes in speed than oxygen uptake (3).

Recently, we evaluated the Skyrunner World Series's female winner in 2016 (unpublished data) in our laboratory. The oxygen and energy cost of running were measured during seven workloads (9–15 km/h; <1.00 RER) on treadmill, showing different slopes against workload when plotted. The oxygen cost of running exhibited a linear increase (30.87, 34.72, 35.90, 38.77, 43.06, 47.87, 50.22 $ml \cdot kg^{-1} \cdot min^{-1}$), while the energy cost of running exhibited a U-shape curve (4.33, 4.30, 4.06, 4.02, 4.13, 4.29, 4.23 $kj \cdot kg^{-1} \cdot km^{-1}$). During the intermediate workloads, the substrate oxidation remained constant while the oxygen cost increased (0.90, 0.93, 0.93, 0.93, 0.94, 0.96, 0.99 RER). Therefore, the energy cost decreased in these workloads, showing more economical intensities compared with the previous and later workloads. These economical intensities are similar to the competition and also to the majority of training intensities carried out by our subject. These results allow hypothesizing that runners are more economical at the speed they tend to train (2, 4). Definitely, we recommend like Beck et al. (1) to report $\dot{V}O_2$, $\dot{V}CO_2$, and RER values to a better comprehension about the results and conclusions of the future studies.

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CAN AEROBIC ENERGY EXPENDITURE BE USED INSTEAD OF OXYGEN UPTAKE TO BETTER PREDICT ENDURANCE PERFORMANCE?

TO THE EDITOR: We agree with Beck et al. (1) that aerobic energy expenditure has the potential to provide a superior prediction of performance than $\dot{V}O_2$ alone, due to the consideration of energy yield per liter of O_2. Therefore, given our interest in cycling efficiency and the fact that Beck et al. (1) use hypothetical data within their Viewpoint, we decided to test their proposition using data we collected in a previous study (2). Our study investigated the relationship between cycling efficiency and 1 h cycling time trial performance in trained cyclists. Within our study we also measured lactate threshold using an incremental cycling test. Using this data and the $\dot{E}_{aero}$ equation provided by Beck et al. (1), we sought to predict our cyclist's 1 h time trial performance from both the $\dot{V}O_2$ (ml $O_2 \cdot kg^{-1} \cdot min^{-1}$) at LT, and aerobic energy expenditure. $\dot{E}_{aero}$ (J/ml O_2) was significantly positively correlated with mean 1-h cycling time trial performance (239 ± 39 W; $r = 0.71$; $P = 0.007$), explaining ~51% of the variation between cyclists. However, in our data, $\dot{E}_{aero}$ was not able to predict performance to any greater extent than the $\dot{V}O_2$ at LT ($r = 0.73$; $P = 0.005$), explaining ~53% of the variance. Therefore, although we agree with the approach taken by Beck et al. (1) and support the view that aerobic energy expenditure might be a better measure of exercise intensity and endurance performance, our data do not support the proposition that it provides a *better* prediction of performance than $\dot{V}O_2$ at LT.

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SUPERIOR BUT STILL LIMITED METRICS

TO THE EDITOR: Beck et al. (1) provide a clear and compelling rationale to progress beyond the use of oxygen consumption (its maximal rate, sustainable fraction) or economy (cost per unit distance) as primary indicators of absolute and relative exercise intensity and to use an energetic approach in explanatory perspectives of exercise capacity and performance.

Quantifying economy using energy units has been popular in research on prolonged exercise and has allowed for the characterization of the small, near-constant increases in running economy up to marathon distance (2). However, the wide range of changes in running economy observed in ultramarathons (low to high decreases or even improvements) suggests neuromuscular and muscle ultrastructural factors, among others, may confound the magnitude of the measured cardiorespiratory alterations (3).

Recommendations to determine relative exercise intensities as a percentage of the maximum rate of energy expenditure are novel. Although we concur that these metrics could be used to better characterize true physiological capacity in some situations (setting intensity as a percentage of maximum), they would still need to be used in conjunction with relevant turnpoints (thresholds; including respiratory gas exchange) and are associated with the same limitations as oxygen consumption based calculations when applied to any ultraendurance exercise.

Overall, sufficient detail in primary (oxygen consumption, ventilation) and secondary [respiratory exchange ratio, or ventilatory efficiency ($\dot{V}_E \div \dot{V}O_2$)] cardiorespiratory variables should still be provided to allow researchers to interpret and compare findings from laboratory and field studies in the context of inherent differences in pacing strategies, environmental conditions, and training status.

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USE AEROBIC ENERGY EXPENDITURE INSTEAD OF OXYGEN UPTAKE TO QUANTIFY METABOLIC RATE AND COST OF EXERCISE: INTENSITY MATTERS

TO THE EDITOR: Since the classical and seminal study of Margaria (4), the energy expenditure of locomotion (i.e., running and walking at different speeds and gradients) was expressed in kilocalories per minute (i.e., metabolic rate or metabolic power). By using indirect calorimetry, the oxygen uptake assessed during the exercise steady state, was then transformed from ml O_2/min into kcal/min, taking into account the energy equivalent of 1 liter of oxygen. The results of this precursor study showed that the net energy cost of level walking (i.e., the energy spent per unit of distance covered) was ~0.5 $kcal \cdot kg^{-1} \cdot km^{-1}$ and the net energy cost of level running was ~1 $kcal \cdot kg^{-1} \cdot km^{-1}$. According to Beck et al. (1), the metabolic rate or energy cost of exercise should be expressed in units of aerobic energy rather than oxygen to take into account difference in substrate utilization during exercise. For instance, this may be very important when comparing, at the same relative exercise intensities, lean and obese individuals for whom the substrate oxidation during exercise differs (3). However, although indirect calorimetry is extensively used to assess energy expenditure during exercise, changes in the size of the bicarbonate pools may interfere with the calculation of substrate oxidation and thus energy expenditure at high exercise intensities (2). Therefore, it should be limited to exercise intensities lower than the 85% of the maximal oxygen uptake (5). For this reason, we are more skeptical to report maximal aerobic capacity and exercise intensity using units of aerobic energy as suggested by Beck et al. (1).

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RELATIVE EXERCISE INTENSITY SHOULD BE QUANTIFIED BY PHYSIOLOGICAL AND MECHANICAL THRESHOLDS

TO THE EDITOR: Defining relative exercise intensity is a pertinent issue raised by Beck et al. (2). However, the proposed method (2), while appropriate for *intra*-individual comparison, does not sufficiently address *inter*-individual differences. We propose relative exercise intensity is better quantified using individual physiological thresholds, namely lactate threshold (LT) and maximal lactate steady state (MLSS), alongside the mechanical anaerobic speed reserve (ASR) (5), or the work rate range from maximum oxygen uptake ($\dot{V}O_{2max}$) to maximum sprint speed (MSS) or power. Indeed, these parameters can be used effectively in endurance sport to ensure training sessions evoke a given physiological stress and are conducted according to the desired training intensity distribution. For instance, specific low-intensity training sessions are prescribed below LT such that they can be sustained for long periods and elicit low physiological stress. It is this point—that exercise is below the individual's LT—that defines the exercise as low intensity. Where LT exists as a $\%\dot{V}O_{2max}$, or $\%\dot{E}_{aero\ max}$, varies between individuals (1). Therefore, exercise at 60% $\dot{V}O_{2max}$ or $\dot{E}_{aero\ max}$ may be <LT in one athlete, but LT in another, and thus of different physiological stress and relative intensity. Similarly, defining high-intensity exercise (>MLSS) as a $\%\dot{V}O_{2max}$ or $\%\dot{E}_{aero\ max}$ assumes uniform *inter*-individual mechanical ability at supramaximal workloads, but the individual's ASR may define this competence (4). Indeed, ASR effectively explains inter-individual variation in time-to-exhaustion at >90% $\dot{V}O_{2max}$ (3) and therefore the individualized relative exercise intensity. Thus, to ensure the relative exercise intensity is consistent between and within individuals, use of individual physiological and mechanical thresholds seems most appropriate.

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COMMENTARY ON VIEWPOINT: USE AEROBIC ENERGY EXPENDITURE INSTEAD OF OXYGEN UPTAKE TO QUANTIFY EXERCISE INTENSITY AND PREDICT ENDURANCE PERFORMANCE

TO THE EDITOR: As discussed in the current Viewpoint (1), aerobic energy expenditure may be more accurate in endurance performance prediction as well as quantification of exercise intensity, compared with the commonly use method of percentage of maximal oxygen uptake (%$\dot{V}o_{2max}$). Although the authors should be commended for raising discussions around established methodologies in exercise physiology, the practical relevance of their argument for the use of percentage of maximal aerobic energy expenditure (%$\dot{E}_{aero\ max}$) needs to be better defined. The authors used a marathon athlete prediction model with respiratory exchange ratios of 0.80, 0.94, and 1.00. Arguably, a competitive endurance athlete (particularly a marathon runner) will be running close to 1.00 for the entirety of the race (~0.97). The relationship between RER and anaerobic threshold has been discussed by Goedecke et al. (2) and in numerous other studies. Consequently, the predictive difference between %$\dot{V}o_{2max}$ and %$\dot{E}_{aero\ max}$ using Joyner's (3) equations when accounting for a relatively steady-state RER of ~0.97 would be trivial. Although there is potential merit to the use of %$\dot{E}_{aero\ max}$, more research needs to be done before stimulating a paradigm shift of current methods.

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COMMENTARY ON VIEWPOINT: USE AEROBIC ENERGY EXPENDITURE INSTEAD OF OXYGEN UPTAKE TO QUANTIFY EXERCISE INTENSITY AND PREDICT ENDURANCE PERFORMANCE

TO THE EDITOR: The energy-oxygen equivalent is very important for assessing metabolic demand and, as pointed out by Beck et al. (1), it should be always used in running (and all other activities) or at least RER should be presented together with $\dot{V}o_2$. However, it seems not necessary to introduce a new index or definition in the scientific community since it seems only a synonymous of a long-standing, worldwide accepted and used concept in locomotion physiology and biomechanics: the energy cost (C, $J \cdot kg^{-1} \cdot m^{-1}$). The energy cost of running, i.e., the (net) energy needed to move one kilogram of body mass along one meter, was extensively studied by Margaria in 1938 (2); in a later paper, Margaria and colleagues (3) showed that trained athletes have a lower energy cost than untrained subjects, thus C is able to detect performance levels. C already includes the energy equivalent of oxygen consumption, which depends on the substrate oxidized and is expressed in joules (or kJ) that is the unit of the Systéme Interantional d'Unités (SI). Moreover, if running metabolic demand is expressed as cost, the locomotion efficiency can be computed as the ratio between the total mechanical work and the energy cost (4), another useful parameter for performance. As regarding endurance prediction, the di Prampero model of best performance already includes C (5). There are many valid reasons to account for the oxidised substrate, as many as to keep using the energy cost (C, $J \cdot kg^{-1} \cdot m^{-1}$).

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EXERCISE INTENSITY AND ENDURANCE PERFORMANCE: IS AEROBIC ENERGY EXPENDITURE THE BEST CHOICE?

TO THE EDITOR: Endurance performance depends on the body's ability to uptake and utilize oxygen to generate energy. $\dot{V}o_{2max}$ is the most commonly used variable to estimate individual cardiorespiratory capacity (3). However, it becomes questionable when it comes to the intensity and volume of exercise to calculate the aerobic energy expenditure, because its calculation disregards the basal energetic metabolism and the substrate oxidation (2). There is a preference of different energy sources according to intensities of aerobic exercise. At low intensity there is a predominance of greater oxidation of lipids compared with the carbohydrate, and as relative

Table 1. *Results of 10,000 simulations and resulting distribution for prediction error of $\dot{V}O_2$ and EE*

		Simulated Distribution Mean	Simulated Distribution Median	Simulated Distribution Standard Deviaion	Coefficient of Variation, %	ΔError for EE vs. $\dot{V}O_2$, %
$\dot{V}O_2$ = 0.5, l/min	$\dot{V}O_2$	0.50	0.50	0.03	5.2	+2.6
RER = 0.85	EE[a], kJ	10.21	10.20	0.79	7.8	
$\dot{V}O_2$ = 1.0, l/min	$\dot{V}O_2$	1.0	1.00	0.03	2.0	+4.3
RER = 0.93	EE[a], kJ	20.79	20.78	1.44	6.9	
$\dot{V}O_2$ = 1.5, l/min	$\dot{V}O_2$	1.50	1.50	0.03	2.0	+4.8
RER = 0.97	EE[a], kJ	31.43	31.45	2.15	6.8	
$\dot{V}O_2$ = 2.0, l/min	$\dot{V}O_2$	2.00	2.00	0.07	3.2%	+4.0
RER = 1.00	EE[a], kJ	42.19	42.21	3.05	7.2	
	EE[b], kJ	43.9	43.44	2.44	5.6	+2.4

[a]Using Brockway equation and assuming constants have a "standard" normal distribution (i.e. ± 1 SD). [b]Using the author-specified equation when RER ≥1.0: EE = $\dot{V}O_2$ × 21.745. Assuming a "standard" normal distribution around constant.

aerobic intensity increases, the ratio of oxidized carbohydrates to lipids increases until carbohydrate oxidation constitute almost 100% of consumed substrates (1, 2). Due to the biochemical differences in the composition of carbohydrates and lipids, different amounts of oxygen are required for complete oxidation. Therefore, accounting for substrate oxidation leads to more accurate calculations of the rate of aerobic energy expended during exercise (2, 4). Aerobic energy expenditure provides a better measure of exercise economy and maximal aerobic capacity over exercise intensity and resistance performance. The exercise economy ($\dot{E}_{aero}$), maximal aerobic capacity ($\dot{E}_{aero\ max}$), and hence intensity (%$\dot{E}_{aero\ max}$) are probably more accurate to predict the performance of resistance than predictions based on $\dot{V}O_2$ because it accounts for the energy yield per volume of O_2 (2). Therefore, a reformulation of the variables used is important to determine workloads (intensity and volume) and thus allowing greater fidelity to the presented data.

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CONVERTING OXYGEN UPTAKE TO ENERGY EXPENDITURE SUBSTANTIALLY INCREASES PREDICTION ERROR

TO THE EDITOR: The authors' proposal to use energy expenditure (EE) instead of oxygen uptake ($\dot{V}O_2$) to express exercise intensity (1) is an interesting proposition; however, the appropriateness of this data conversion is highly dependent upon the research question. We need to stress that this data conversion introduces assumptions and a substantial increase in predictive error. Modeling indirect calorimetry error via Tenan's method (4) and Macfarlane et al.'s data (3), we simulated the error from $\dot{V}O_2$ alone. Since the author's do not directly specify the equation for converting $\dot{V}O_2$ to EE (except at RER ≥1.0), we used the Brockway equation (2), with no protein contribution (an added assumption): EE (kJ) = 16.58 × $\dot{V}O_2$ + 4.15 × $\dot{V}CO_2$.

As Brockway notes, numerous "fudge factors" exist in the equation, such as assuming 100% of carbohydrate metabolism is starch, as opposed to glucose or glycogen. We therefore apply a reasonable assumption that each constant arises from a standard normal distribution (mean ± SD). As Table 1 shows, the conversion to EE more than doubles the resultant error in many instances. There are undoubtedly instances where the conversion of $\dot{V}O_2$ to EE is necessary, but converting a "measured" variable into a "predicted" variable increases both error and additional assumptions that need to be carefully considered when undertaking such studies.

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COMMENTARY ON VIEWPOINT: USE AEROBIC ENERGY EXPENDITURE INSTEAD OF OXYGEN UPTAKE TO QUANTIFY EXERCISE INTENSITY AND PREDICT ENDURANCE PERFORMANCE

TO THE EDITOR: We agree with Beck et al. (1) that $\dot{E}_{aero}$ may be more representative of aerobic exercise intensity than $\dot{V}O_2$, because it accounts for substrate oxidation. However, factors that affect the calculation of $\dot{E}_{aero}$ should be carefully considered before adopting this measure in place of $\dot{V}O_2$. Since $\dot{E}_{aero}$ is inferred at the level of the mouth using the respiratory exchange ratio (RER), conditions that affect $\dot{V}CO_2$, independent of $\dot{V}O_2$, may affect the calculation of $\dot{E}_{aero}$. One such condition is hypoxia; to illustrate this, we use data from a sample subject in our laboratory who exercised at the same absolute submaximal workload in both hypoxia and normoxia (running speed 13.0 km/h). In both conditions, $\dot{V}O_2$ was 3.38 l/min, corresponding to 70% of normoxic $\dot{V}O_{2max}$. In contrast, hypoxia resulted in a higher $\dot{V}CO_2$ (2.84 vs. 2.77 l/min) and therefore greater RER (0.84 vs. 0.82). Thus, despite the mechanical workload remaining the same, $\dot{E}_{aero}$ in this subject was increased in hypoxia (70.79 vs. 70.46 kJ/min, or 65.4% $\dot{E}_{aero\ max}$ vs. 65.1%) (2), suggesting that running economy was lower in hypoxia when measured by $\dot{E}_{aero}$, but not by $\dot{V}O_2$. Therefore, it is possible that *1*) $\dot{E}_{aero}$ may be more sensitive to changes in economy in specific situations such as hypoxia and/or *2*) $\dot{E}_{aero}$ may need to be interpreted more cautiously in situations where $\dot{V}CO_2$ is altered independently of $\dot{V}O_2$. In conclusion, $\dot{E}_{aero\ max}$ is a potentially useful measure of aerobic exercise intensity, but must be interpreted cautiously until it is fully validated across various populations and conditions.

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