Substrate-Corrected VO_2 Models for Improved Interpretation of Movement Economy

Technical Report

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Abstract

Introduction: Movement economy is a core metric in endurance performance, yet conventional interpretation overlooks substrate-specific oxygen costs. Elevated oxygen consumption (VO_2) is often misclassified as reduced efficiency when it may instead reflect adaptive increases in fat oxidation. This report introduces and evaluates normalization approaches designed to yield more physiologically valid interpretations of oxygen consumption.
Methods: This conceptual, simulation-based, and secondary data analysis developed two substrate-corrected VO_2 models: (1) the RER-Based Energy Equivalent (RER-EE) model, which adjusts VO_2 for varying caloric yields per liter of oxygen across RER values, and (2) the RER-Based Substrate Partitioning with Substrate Correction Ratio (RER-SP+SCR) model, which partitions VO_2 by substrate and corrects the fat-derived fraction for its lower ATP yield per O_2. Both were applied to previously published datasets from endurance athletes under diverse metabolic conditions.
Results: Both models produced appreciably different normalized VO_2 values compared to traditional methods, particularly under high-fat oxidation conditions. The largest corrections occurred during prolonged submaximal efforts, such as 13KM and 25KM trials, reducing bias that would otherwise misclassify fat-adapted athletes as less economical.
Conclusions: Substrate-corrected normalization provides a physiologically valid framework for interpreting oxygen consumption, enhancing research and applied assessments of endurance performance, training adaptation, and metabolic health.

Key Words: Oxygen Consumption, Energy Metabolism, Substrate Utilization

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Introduction

Movement economy (ME) is a widely used metric in endurance performance, yet its conventional interpretation overlooks the substrate-dependent variability in oxygen cost during ATP resynthesis. It is typically calculated as the volume of oxygen consumed (VO_2) per unit of mechanical output, with lower VO_2 values interpreted as greater metabolic efficiency. The concept of ME emerged from early work on muscle energetics by A.V. Hill in the 1920s and was later refined by di Prampero[4], Margaria[6], and Taylor[12]. While ME remains foundational in endurance performance evaluation, its reliance on raw VO_2 assumes a fixed relationship between oxygen uptake and efficiency, an oversimplification that limits its utility in modern contexts.

This assumption overlooks the physiological variability in substrate oxidation profiles across individuals with different adaptive states. Training, environmental stressors, or chronic dietary adaptations can substantially alter substrate utilization during exercise, even at a fixed workload, thereby affecting oxygen consumption. (Péronnet and

Massicotte[9]). In such cases, elevated VO_2 may reflect adaptive changes in substrate utilization, rather than diminished mechanical or metabolic efficiency. When account is not taken of these shifts, traditional ME metrics may misrepresent an individual's true energy efficiency or endurance potential.

This paper addresses the need for updated analytical methods or interpretive methods that better capture the complexity of human metabolism during exercise. It introduces and evaluates two normalization strategies that adjust VO_2 interpretation based on underlying substrate use, enabling more reliable assessments of metabolic efficiency and movement economy across diverse metabolic conditions. These approaches aim to improve the relevance and applicability of ME as a performance metric, particularly when evaluating individuals with nonstandard or highly adaptive physiological profiles.

Methods

To examine how normalization alters the interpretation of VO_2 across varying metabolic states, we reanalyzed published exercise physiology datasets using two substrate-aware correction models. This approach illustrates the extent to which apparent differences in movement economy are influenced by substrate-specific oxygen cost rather than true variations in mechanical efficiency.

We applied both normalization models to eight datasets extracted from four prior studies involving athletes under diverse metabolic conditions, including ketogenic adaptation and carbohydrate-fed states (Burke et al.[2]; Burke et al.[3]; Prins et al.[10]; Prins et al.[11]). Supplemental data is available. These studies, which included race walkers, runners, and triathletes, were selected based on (1) their variation in substrate utilization profiles and (2) the availability of VO_2 and RER data at matched workloads, both necessary for model application. The objective was not to assess training effects, but rather to isolate the influence of substrate utilization on oxygen consumption and its interpretation in the context of movement economy.

Participants

The analyzed cohorts included trained race walkers, distance runners, and triathletes, all of whom were experienced endurance athletes. This diversity enabled assessment of substrate utilization effects across a range of locomotor patterns and endurance-specific performance demands.

Exercise Conditions

We analyzed VO_2 data across both maximal efforts (TTE/Peak) and submaximal race segments (i.e., 1KM, 13KM, 25KM), allowing for comparisons across exercise intensities and durations. This comparison enabled evaluation of whether normalization effects varied by exercise duration and intensity. The TTE/Peak VO_2 was measured at the end of a time-to-exhaustion or peak-intensity test, representing maximal or near-maximal oxygen uptake. Then, 1KM, 5KM, 13KM, 25KM VO_2 was measured during steady-state efforts at fixed race distances, reflecting sustained submaximal exercise at defined intensities.

Normalization Methods

The two VO_2 normalization methods proposed here aim to correct for substrate-dependent differences in the oxygen cost of ATP resynthesis. By adjusting VO_2 values according to substrate utilization, these methods allow for more physiologically grounded comparisons of movement economy across individuals or states with differing fat and carbohydrate oxidation profiles. They also better reflect the true metabolic cost of oxygen consumption by incorporating changes in the respiratory exchange ratio (RER).

Method 1: RER-Based Energy Equivalent Normalization (RER-EE)

This normalization adjusts absolute VO_2 (L/min) to account for differences in substrate-specific caloric yield. Since fat oxidation yields fewer kilocalories per liter of oxygen than carbohydrate oxidation, absolute VO_2 reflects both mechanical workload and the substrate composition of energy metabolism. The RER-EE method corrects for this by converting measured absolute VO_2 into an equivalent value that assumes 100% carbohydrate oxidation, enabling standardized comparisons across varying RER values.

It should be noted that this approach normalizes VO_2 based on caloric energy expenditure (kcal/L O_2), not on biochemical ATP yield per mole of O_2 and thus represents a conservative correction relative to more mechanistic oxygen cost models.

Derivation of RER-EE: This method applies the well-established relationship between respiratory exchange ratio (RER) and the caloric equivalent of oxygen consumption, originally described by Weir[14] and later refined by Péronnet and Massicotte[9].

$$\text{kcal/L } O_2 = 3.815 + 1.232 \times \text{RER}$$

This equation describes the caloric value of oxygen across a range of RER values (0.70 to 1.00), reflecting mixed substrate oxidation. This formula was not derived from new regression analyses in the present study. It is directly adopted from established stoichiometric models widely used in indirect calorimetry.

$$\text{RER-EE Normalization Formula: } VO_2 \text{ Normalized} = \text{Absolute } VO_2 \text{ x } [(3.815 + 1.232 \text{ x RER}) / 5.05 \text{ kcal/L}]$$

The component variables in the RER-EE normalization formula each play a specific role in interpreting oxygen consumption. Absolute VO_2 refers to the measured oxygen uptake during a given exercise intensity and represents the unadjusted metabolic volume in liters per minute. The term 3.815 + 1.232 × RER estimates the caloric equivalent of oxygen consumption at the observed RER, reflecting the proportion of carbohydrate and fat being oxidized based on established combustion chemistry rather than regression modeling. RER itself is the respiratory exchange ratio, a key indicator of substrate use during exercise. Finally, 5.05 represents the caloric value of oxygen in kilocalories per liter when oxidation is derived entirely from carbohydrates (RER = 1.00) and serves as the normalization reference point for converting oxygen consumption into a standardized unit.

Example:

Given: Absolute VO_2 = 3.42 L/min; RER = 0.85

$$VO_2 \text{ Normalized} = 3.42 \text{ L/min x } [(3.815 + 1.232 \text{ x RER}) / 5.05 \text{ kcal/L}]$$

$$VO_2 \text{ Normalized} = 3.42 \text{ L/min x } [(4.86 \text{ kcal/L}) / 5.05 \text{ kcal/L}]$$

$$VO_2 \text{ Normalized} = 3.29 \text{ L/min}$$

Rationale: This normalization applies an energy expenditure correction derived from the empirically established relationship between respiratory exchange ratio (RER) and the caloric equivalent of oxygen consumption (Péronnet & Massicotte[9]; Weir[14]). While both VO_2 and RER are routinely measured via indirect calorimetry, full substrate oxidation calculations (i.e., estimating grams per minute of fat and carbohydrate oxidation) require additional assumptions and computations. The RER-EE approach simplifies this by using RER directly as a surrogate to estimate the effective caloric yield per liter of oxygen, without the need for detailed substrate partitioning calculations. By applying a single scalar correction based on RER, this method provides a simplified yet physiologically grounded adjustment for interpreting VO_2 across mixed substrate conditions.

While the RER-EE model provides a simplified correction based on caloric yield, the following method offers a more physiologically detailed normalization based on substrate-specific ATP efficiency.

Method 2: RER-Based Substrate Partitioning with SCR Normalization (RER-SP+SCR)

This method utilizes established RER-to-substrate conversion tables to estimate the proportion of energy (ATP) derived from fat and carbohydrate oxidation at a given RER. The measured VO_2 is then partitioned into fat- and carbohydrate-derived components, and a Substrate Correction Ratio (SCR) is applied to the fat-derived portion to account for its lower ATP yield per unit of oxygen compared to carbohydrate.

The derivation of the RER-SP+SCR method uses standard non-protein RER tables to estimate the proportion of ATP production derived from fat and carbohydrate oxidation relative to oxygen consumption. Once these fractional contributions are determined, a substrate correction ratio (SCR) is applied specifically to the fat-derived portion of VO_2 to account for its lower ATP yield per liter of oxygen, which is based on established mitochondrial oxidative phosphorylation data. These stoichiometric values, calculated under standard conditions and excluding protein contributions, show that carbohydrate oxidation produces approximately 5.2 molecules of ATP per molecule of oxygen, while fat oxidation produces about 4.4 molecules of ATP per molecule of oxygen consumed.

As with RER-EE, no empirical modeling was used to derive this coefficient; it is grounded in well-established stoichiometric principles and reflects the consistent difference in oxidative ATP yield between carbohydrate and fat substrates.

Substrate Correction Ratio (SCR): (SCR is a constant)

$$SCR = ATP/O_2^{(Fat)} \; / \; ATP/O_2^{(Carbs)}$$
$$SCR = 4.4 / 5.2$$
$$SCR = .846$$

RER-SP+SCR Normalization Formula: VO_2 Normalized = (Absolute VO_2 x Carb%) + (Absolute VO_2 x Fat% x SCR)

The component variables in the RER-SP+SCR normalization model each serve a specific role in accurately interpreting oxygen consumption. Absolute VO_2 represents the measured oxygen uptake in liters per minute during exercise. Carb% refers to the fractional contribution of carbohydrate oxidation, expressed as a unitless value, and is estimated using standard non-protein RER-to-substrate conversion tables such as those developed by Péronnet and Massicotte (1991). Fat% represents the fractional contribution of fat oxidation, also unitless and derived from the same conversion tables, indicating the proportion of total energy produced from fat metabolism. Finally, SCR, or Substrate Correction Ratio, is a unitless coefficient (.846) that adjusts the fat-derived portion of VO_2 to account for its lower ATP yield per liter of oxygen relative to carbohydrate oxidation.

Example:

Given: Absolute VO_2 = 3.42 L/min, RER = 0.85 (Fat% = 51.2%, Carb% = 48.8%)

VO_2 Normalized = (3.42 L/min x .488) + (3.42 L/min x .512 x .846)

VO_2 Normalized = (1.78) + (1.75 x .846)

VO_2 Normalized = (3.14 L/min)

This value reflects what VO_2 would be if fat were as oxygen-efficient as carbohydrate, enabling a more balanced comparison across fuel states.

Rationale: Unlike the RER-EE method, which applies a single energy-equivalent correction to total VO_2, the RER-SP+SCR approach separately estimates fat and carbohydrate contributions and applies a correction only to the fat-derived fraction. A correction factor (Substrate Correction Ratio, SCR) is then applied exclusively to the fat-derived portion to reflect its lower oxygen efficiency (ATP/O_2). This method provides improved physiological specificity, particularly at lower RER values where fat oxidation predominates, and enhances interpretive accuracy across differing substrate utilization conditions.

While both methods use RER to adjust VO_2 for substrate use, RER-EE applies a single energy-equivalent correction to the entire VO_2 value, whereas RER-SP+SCR separates substrate fractions and applies a correction only to the fat-derived portion. This distinction gives RER-SP+SCR greater physiological specificity, particularly in fat-dominant states where traditional models tend to overestimate inefficiency.

Results

Across datasets, absolute VO_2 was generally higher in fat-adapted (ketogenic) conditions than in carbohydrate-fed states, particularly among race walkers. For example, Burke et al.[2] observed a 0.54 L/min higher VO_2 at 13KM in the ketogenic group compared to the carbohydrate-fed group. Without normalization, this difference would traditionally be interpreted as a reduction in movement economy for the fat-adapted group.

RER values revealed clear differences in substrate use across conditions. Carbohydrate-fed athletes exhibited consistently high RER values (mean = 0.99), indicative of near-exclusive carbohydrate oxidation. In contrast, fat-adapted athletes exhibited lower RER values (mean = 0.86), corresponding to a mean fat oxidation of 50.75% compared to 17.08% in carbohydrate-fed athletes. Carbohydrate oxidation was also higher in carbohydrate-fed athletes (82.93%) compared to fat-adapted athletes (49.25%), consistent with their RER profiles.

Seven of the eight pre-normalization VO_2 differences fell within the pooled standard deviation of the respective group comparisons. This suggests that much of the apparent inefficiency attributed to fat-adapted athletes may instead reflect normal biological variability. However, even when differences exceed this threshold, normalization provides a means to distinguish true mechanical inefficiency from substrate-related differences in oxygen cost.

RER-EE Normalization

The RER-EE normalization model adjusts VO_2 values according to the caloric equivalent of oxygen at a given respiratory exchange ratio (RER), thereby accounting for differences in substrate-specific energy yield. This model was applied to eight datasets extracted from published studies involving elite race walkers, runners, and triathletes under diverse dietary and training conditions. The exercise conditions included maximal effort (TTE/Peak) and steady-state segments at fixed distances (1KM, 5KM, 13KM, 25KM). These datasets enabled comparison across both high-intensity and prolonged submaximal efforts in carbohydrate-fed and fat-adapted conditions.

Application of the RER-EE model consistently reduced apparent VO_2 differences between carbohydrate-fed and fat-adapted conditions across all eight datasets. Before normalization, fat-adapted athletes exhibited higher absolute VO_2, with a mean difference of −0.31 L/min compared to carbohydrate-fed athletes at matched workloads. This uncorrected difference would conventionally be interpreted as reduced movement economy in the fat-adapted state. After normalization for RER-based caloric equivalence, the mean VO_2 difference narrowed to −0.19 L/min.

Across datasets, normalization reduced the observed VO_2 difference by an average of -0.09 L/min. In every dataset, normalized VO_2 values for the fat-adapted group moved closer to those of the carbohydrate-fed group. This pattern demonstrates that much of the elevated VO_2 observed in fat-adapted athletes reflects the higher oxygen cost of fat oxidation, rather than a true decline in movement economy. The RER-EE model reduces this interpretive bias by correcting for substrate-specific differences in energy yield per liter of oxygen.

Table 1. Reanalyzed VO_2 (L/min) Data Using RER-EE Normalization

Study	Sport	Exercise Condition	Carb-Fed (Uncorrected)	Carb-Fed (Normalized)	Fat-Adapted (Uncorrected)	Fat-Adapted (Normalized)
Burke et al., 2020	Race Walking	TTE/Peak	3.64	3.64	4.07	3.86
Burke et al., 2017	Race Walking	TTE/Peak	4.20	4.20	4.56	4.49
Burke et al., 2017	Race Walking	1KM	3.13	3.05	3.60	3.16
Burke et al., 2017	Race Walking	13KM	3.09	2.98	3.63	3.15
Burke et al., 2017	Race Walking	25KM	3.13	2.95	3.59	3.10
Prins et al., 2019	Runners	TTE/Peak	4.30	4.30	4.30	4.30
Prins et al., 2019	Runners	5KM	3.40	3.33	3.70	3.43
Prins et al., 2025	Triathletes	TTE/Peak	3.23	3.01	3.18	2.88
Overall Mean			3.52	3.43	3.83	3.55

This table presents absolute oxygen consumption (VO_2, L/min) and corresponding RER-Based Energy This table presents absolute oxygen consumption (VO_2, L/min) and corresponding RER-Based Energy Equivalent (RER-EE) normalized VO_2 values from eight datasets spanning carbohydrate-fed and fat-adapted metabolic states (Burke et al.[2]; Burke et al.[3]; Prins et al.[10]; Prins et al.[11]). RER-EE normalization adjusts VO_2 values based on the caloric equivalent of oxygen at each respiratory exchange ratio (RER), enabling standardized comparisons across different substrate utilization profiles. The data illustrates how normalization reduces apparent inefficiencies in fat-adapted athletes by correcting for the higher oxygen cost of fat oxidation.

Column definitions: Study indicates the source; Sport refers to the athlete population studied; Exercise Condition specifies the point at which VO_2 was measured (i.e., TTE/Peak, 13 km); Uncorrected (Carb-Fed or Fat-Adapted) reports uncorrected, absolute oxygen consumption; Normalized (Carb-Fed or Fat-Adapted) reflects substrate-adjusted values based on RER.

RER-SP+SCR Normalization

The RER-SP+SCR normalization model refines VO_2 interpretation by accounting for both substrate partitioning and the lower ATP yield associated with fat oxidation. We applied this model to eight datasets from studies involving elite race walkers, runners, and triathletes tested under carbohydrate-fed and fat-adapted conditions. The exercise conditions included TTE/Peak efforts and steady-state trials at 1KM, 5KM, 13KM, and 25KM distances, allowing for comparison across a range of intensities and durations.

Before normalization, fat-adapted athletes exhibited higher VO_2, with a mean difference of −0.31 L/min compared to carbohydrate-fed athletes at matched workloads. After normalization, the mean VO_2 difference narrowed to −0.12 L/min. This shift suggests that much of the observed variation in oxygen cost reflects substrate-specific effects rather than true mechanical inefficiency. Across all datasets, normalization reduced VO_2 by an average of -0.18 L/min in the fat-adapted group. The most substantial adjustments were observed during prolonged submaximal efforts, consistent with greater reliance on fat oxidation at lower intensities.

These results demonstrate that the RER-SP+SCR model enables more physiologically valid comparisons of VO_2 by correcting for differences in oxygen cost between carbohydrate and fat oxidation. Without such correction, assessments of movement economy are likely to overstate inefficiencies in fat-adapted athletes, particularly during endurance performance. By integrating substrate-specific oxygen demands, this model reveals that perceived reductions in movement economy under fat-adapted conditions are largely artifacts of measurement, not actual performance deficits.

Table 2. Reanalyzed VO_2 (L/min) Data Using RER-SP+SCR Normalization

Study	Sport	Exercise Condition	Carb-Fed (Uncorrected)	Carb-Fed (Normalized)	Fat-Adapted (Uncorrected)	Fat-Adapted (Normalized)
Burke et al., 2020	Race Walking	TTE/Peak	3.64	3.72	4.07	3.97
Burke et al., 2017	Race Walking	TTE/Peak	4.20	4.29	4.56	4.52
Burke et al., 2017	Race Walking	1KM	3.13	3.09	3.60	3.40
Burke et al., 2017	Race Walking	13KM	3.09	3.04	3.63	3.41
Burke et al., 2017	Race Walking	25KM	3.13	3.04	3.59	3.36
Prins et al., 2019	Runners	TTE/Peak	4.30	4.44	4.30	4.33
Prins et al., 2019	Runners	5KM	3.40	3.36	3.70	3.57
Prins et al., 2025	Triathletes	TTE/Peak	3.23	3.13	3.18	3.04
Overall Mean			3.52	3.51	3.83	3.70

This table displays absolute oxygen consumption (VO_2, L/min) and RER-Based Substrate Partitioning with Substrate Correction Ratio (RER-SP+SCR) normalized values from eight datasets across carbohydrate-fed and fat-adapted states (Burke et al.[2]; Burke et al.[3]; Prins et al.[10]; Prins et al.[11]). The RER-SP+SCR model partitions VO_2 by substrate and applies a correction to the fat-derived fraction to reflect its lower ATP yield, enhancing physiological specificity. These results demonstrate how normalization reduces misinterpretation of elevated VO_2 in fat-adapted athletes, enabling more valid comparisons of movement economy across metabolic states.

Column definitions: Study indicates the source; Sport refers to the athlete population studied; Exercise Condition specifies the point at which VO_2 was measured (i.e., TTE/Peak, 13 km); Uncorrected (Carb-Fed or Fat-Adapted) reports uncorrected, absolute oxygen consumption; Normalized (Carb-Fed or Fat-Adapted) reflects substrate-adjusted values based on RER.

Both normalization methods substantially alter the interpretation of VO_2 across the analyzed datasets, especially in conditions where substrate utilization varied due to dietary interventions. As shown in Tables 1 and 2, uncorrected VO_2 values often suggested reduced movement economy in fat-adapted athletes due to elevated oxygen uptake. Normalization consistently attenuated these differences, indicating that much of the observed variation was attributable to the higher oxygen cost of fat oxidation rather than to true performance impairments. Most normalized VO_2 differences fell within the pooled standard deviation, with the largest residuals observed in race walking datasets during prolonged submaximal efforts. This suggests that elevated VO_2 in fat-adapted states reflects the use of metabolic substrates rather than mechanical inefficiency.

Table 3 summarizes the impact of normalization across all eight datasets for both RER-EE and RER-SP+SCR models. The table compares absolute VO_2 differences, post-normalization differences, and the resulting correction magnitude. While both models corrected for substrate-driven discrepancies, the RER-SP+SCR method consistently produced larger adjustments, particularly during longer-duration, submaximal efforts. This reinforces the importance of accounting for fuel-dependent oxygen costs when assessing movement economy, particularly in athletes undergoing dietary or metabolic interventions. Together, these findings underscore the value of normalization in generating more physiologically accurate assessments of performance and energy expenditure.

Table 3. Normalization Effect on Reanalyzed Data

Study	Absolute VO2 Difference	Normalized VO2 Difference	Normalization Effect	Normalization Method
Burke et al., 2020	-0.43	-0.25	-0.18	RER-EE
Burke et al., 2017	-0.36	-0.23	-0.13	RER-EE
Burke et al., 2017	-0.47	-0.31	-0.16	RER-EE
Burke et al., 2017	-0.54	-0.37	-0.17	RER-EE
Burke et al., 2017	-0.46	-0.32	-0.14	RER-EE
Prins et al., 2019	0.00	0.12	0.12	RER-EE
Prins et al., 2019	-0.30	-0.21	-0.09	RER-EE
Prins et al., 2025	0.05	0.09	0.04	RER-EE
Burke et al., 2020	-0.43	-0.22	-0.21	RER-SP+SCR
Burke et al., 2017	-0.36	-0.29	-0.07	RER-SP+SCR
Burke et al., 2017	-0.47	-0.12	-0.35	RER-SP+SCR
Burke et al., 2017	-0.54	-0.18	-0.36	RER-SP+SCR
Burke et al., 2017	-0.46	-0.15	-0.31	RER-SP+SCR
Prins et al., 2019	0.00	0.00	0.00	RER-SP+SCR
Prins et al., 2019	-0.30	-0.10	-0.20	RER-SP+SCR
Prins et al., 2025	0.05	0.13	0.08	RER-SP+SCR
Overall Mean	-0.31	-0.12	-0.18	

This table summarizes the effect of two normalization methods, RER-Based Energy Equivalent (RER-EE) and RER-Based Substrate Partitioning with Substrate Correction Ratio (RER-SP+SCR), on VO_2 differences between carbohydrate-fed and fat-adapted athletes across eight datasets. For each dataset, the absolute VO_2 difference, normalized VO_2 difference, and the normalization effect (defined as the reduction in difference after correction) are reported. Both models reduced the apparent inefficiency in fat-adapted states, with the RER-SP+SCR model producing larger corrections in prolonged submaximal trials.

These findings demonstrate that normalizing VO_2 for substrate use provides a more physiologically grounded basis for comparing energy expenditure across diverse metabolic states. By mitigating biases in standard movement economy models, these approaches enhance the interpretation of dietary interventions, training adaptations, and metabolic health evaluations, offering a refined framework for exercise physiology research.

Discussion

Traditional movement economy (ME) metrics treat oxygen consumption as a valid proxy for metabolic efficiency, regardless of the substrate fueling exercise. However, the physiological cost of ATP production varies depending on which substrates are oxidized. As training or adaptive states shift fuel reliance, especially toward greater fat oxidation, VO_2 may rise without reflecting a true decline in mechanical efficiency.

This discrepancy stems from two interrelated issues: (1) the increased oxygen demand of fat oxidation across various metabolic adaptations, and (2) the failure of conventional ME models to partition VO_2 by substrate source (i.e., fat vs. carbohydrate). Together, these factors introduce a systematic misclassification of efficiency in individuals with altered metabolic function. Just as VO_2 max is often expressed relative to body weight to account for size differences, substrate-aware VO_2 normalization adjusts for the differing oxygen costs of carbohydrate and fat oxidation (Millet et al.[7]). This ensures that differences in oxygen consumption due to varying fuel sources do not confound the interpretation of movement economy or metabolic efficiency. The following sections outline the physiological mechanisms underlying this bias and present the physiological rationale for substrate-corrected VO_2 models, as well as their implications for interpreting movement economy.

Increased fat oxidation

In certain adaptive states, energy production during exercise shifts toward a distinctly different fuel profile, marked by an increased reliance on fat oxidation as a primary aerobic substrate. This shift is commonly observed in individuals who have undergone long-term endurance training or other systemic adaptations. These changes include mitochondrial biogenesis, enhanced capillary density, upregulation of β-oxidation enzymes, enhanced fatty acid transport, and greater intramuscular lipid availability, which support a more prominent role for fat as a working substrate during exercise (Horowitz and Klein[5]; van Loon et al.[13]).

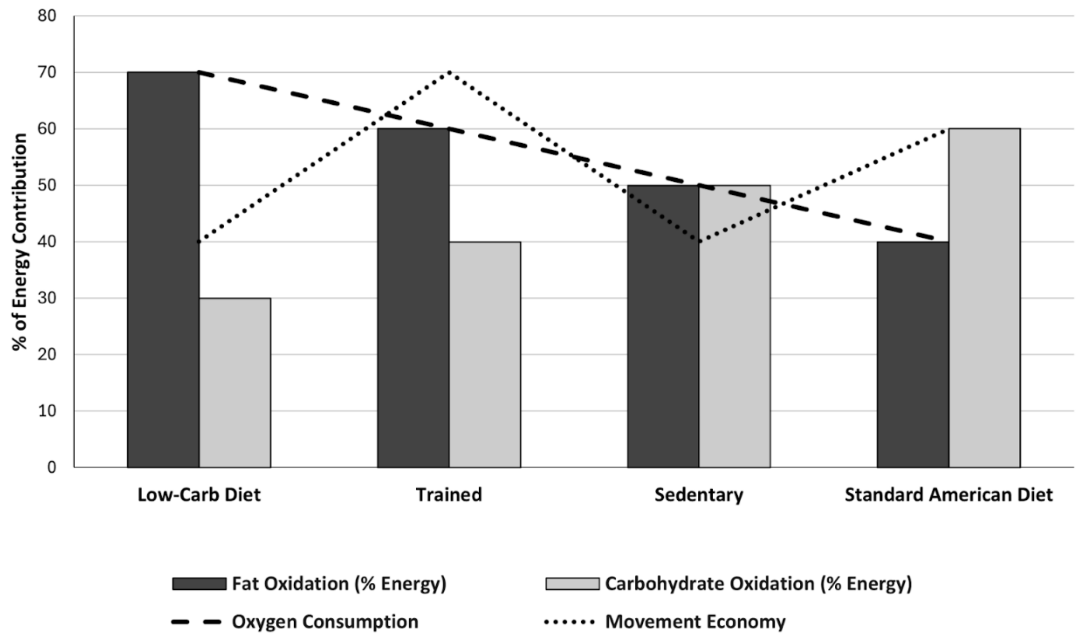
This altered substrate profile confers several endurance-relevant benefits, including glycogen preservation, reduced lactate accumulation, more stable blood glucose levels, improved metabolic flexibility, and prolonged energy availability (Nordby et al.[8]; Yeo et al.[15]). However, despite these physiological advantages, individuals with elevated fat oxidation are often misrepresented as less efficient due to elevated VO_2 rather than due to measured deterioration in mechanical or metabolic inefficiency. These models interpret increased oxygen consumption (VO_2) as reduced movement economy, without recognizing that the shift in substrate use reflects a fundamentally different fuel strategy, not necessarily an impaired performance capacity.

A central limitation of ME is its inability to distinguish elevated VO_2 due to improved cardiovascular or muscular adaptations from those elevations caused by shifts in substrate oxidation. Increases due to cardiovascular or muscular improvements, such as enhanced cardiac output, plasma volume, or oxygen extraction, are typically regarded as signs of positive adaptation. Yet, when similar VO_2 elevations result from a shift in substrate use, particularly increased fat oxidation, they are often misclassified as a reduction in mechanical efficiency (Bassett and Howley[1]).

As illustrated in Figure 1, both endurance training and low-carbohydrate nutrition increase fat oxidation, a physiological adaptation associated with improved metabolic flexibility and endurance capacity. Yet, despite eliciting similar metabolic shifts in substrate use, the interpretations of these adaptations diverge depending on their origin.

When increased fat utilization occurs due to training, it is regarded as a marker of enhanced performance and efficiency. In contrast, when the same adaptation results from a nutritional intervention, such as a low-carbohydrate diet, it is often viewed as detrimental to performance. This inconsistency reveals a bias in how ME and VO_2 are interpreted. Conceptually, individuals on a standard high-carbohydrate diet may exhibit the lowest VO_2 at a given workload due to near-exclusive carbohydrate oxidation. In contrast, endurance-trained or low-carb-adapted individuals exhibit elevated VO_2 not because they are less efficient, but because fat oxidation is increased as a result of these metabolic adaptations. The mismatch where nutrition-driven fat adaptation is penalized while training-driven adaptation is described as beneficial, highlights a flaw in our current evaluation tools. Without accounting for substrate use, metrics like VO_2 and ME risk mislabeling beneficial adaptations as performance deficits simply because they alter fuel consumption rates.

Figure 1. Fat Oxidation Bias in Movement Economy Interpretation.



A conceptual model illustrating the relationship between substrate oxidation (bars), oxygen consumption (dashed line), and movement economy (dotted line) across four metabolic states: Low-carbohydrate diet, Trained, Sedentary, and Standard American diet. Although both endurance training and low-carbohydrate adaptation increase fat oxidation, only the former is typically interpreted as improving efficiency. In contrast, elevated oxygen consumption associated with dietary fat adaptation is often misclassified as inefficiency by traditional VO_2-based metrics. This figure is conceptual and not derived from empirical data; oxygen consumption and movement economy are normalized for illustrative purposes.

VO_2 substrate partitioning

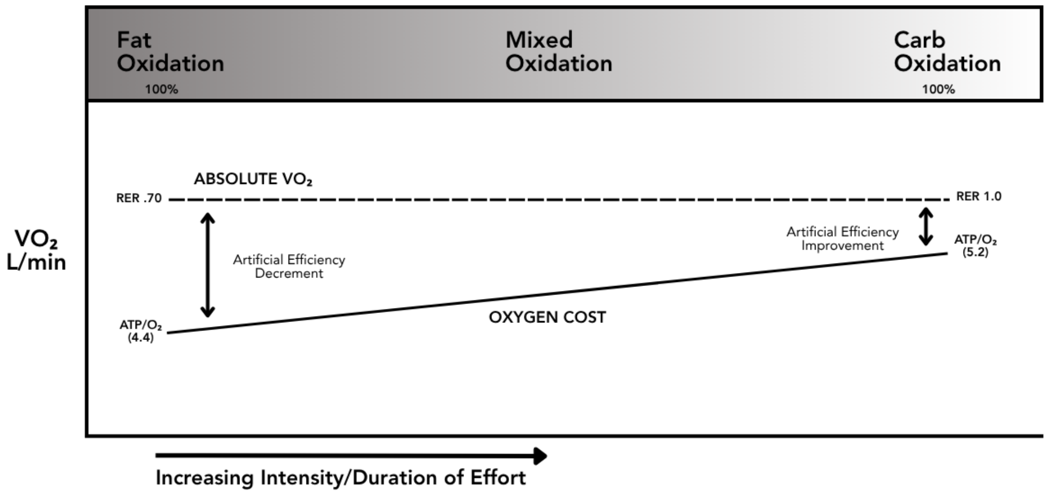
This refers to estimating the proportion of energy derived from fat versus carbohydrate oxidation during exercise. This partitioning is typically inferred from the respiratory exchange ratio (RER), which represents the ratio of carbon dioxide produced to oxygen consumed. As RER decreases, indicating a shift toward greater fat oxidation, the energy yield per liter of oxygen declines, as fat yields ~13% less energy per liter of O_2 than carbohydrates (Péronnet and Massicotte[9]).

This variation increases the oxygen cost of ATP production even when the mechanical workload remains unchanged. Traditional movement economy (ME) metrics do not account for these stoichiometric differences and assume a uniform energy yield per unit of oxygen consumption (VO_2). As a result, they may incorrectly attribute elevated VO_2 to inefficiency when in fact it reflects substrate-driven metabolic adaptation.

The discrepancy becomes more pronounced as fat oxidation increases, introducing systematic bias into ME assessments if substrate use is not considered. Individuals with these adaptations may be misclassified as less economical when evaluated using uncorrected VO_2 values. Without adjusting for substrate partitioning, ME cannot reliably distinguish between oxygen use associated with improved metabolic function and that resulting from true mechanical inefficiency, a distinction illustrated conceptually in Figure 2.

To address these limitations, this paper introduces two VO_2 normalization methods that incorporate substrate-specific oxygen costs derived from RER and known bioenergetic constants. The RER-Based Energy Equivalent Normalization (RER-EE) and the RER-Based Substrate Partitioning with Substrate Correction Ratio (RER-SP+SCR) integrate RER data with established bioenergetic constants to generate adjusted VO_2 values. These methods provide a physiologically grounded approach for evaluating metabolic efficiency under varying substrate utilization conditions. The following section outlines the rationale, equations, and implementation for each approach.

Figure 2. Conceptual Model of Substrate Partitioning and Misinterpretation of VO_2



A conceptual illustration of how traditional interpretations of absolute oxygen consumption (VO_2) can lead to misleading conclusions about metabolic efficiency across varying respiratory exchange ratios (RER). The dashed line represents observed VO_2 across increasing RER values, while the solid line reflects the true oxygen cost per unit of ATP, accounting for substrate-specific differences in oxidative efficiency. The vertical gap between the two lines represents the interpretive error introduced by failing to account for substrate use. As RER increases (and carbohydrate oxidation predominates), traditional VO_2-based models underestimate the true cost of work, creating a false appearance of improved efficiency. This figure is conceptual and not based on empirical data

Limitations

At respiratory exchange ratio (RER) values above 1.00, the fundamental assumptions underlying RER-based modeling no longer hold true, as excess carbon dioxide produced from acid-base buffering artificially elevates RER. This leads to an overestimation of the caloric equivalent of oxygen and renders substrate partitioning calculations invalid, meaning normalization models should not be applied in this range. For instance, when RER is 1.09 and absolute VO_2 is 3.42 L/min, the RER-EE method yields a normalized VO_2 of 3.49 L/min, while the RER-SP+SCR method yields 3.42 L/min. At RER values exceeding 1.00, the caloric equivalent per liter of oxygen becomes artificially high, substrate partitioning breaks down as fat oxidation approaches zero and carbohydrate contribution cannot exceed 100%, and the increase in RER is driven primarily by acid-base compensation rather than actual changes in substrate utilization.

Even at RER values below 1.00, exercise intensities near or above the ventilatory threshold may introduce additional errors in substrate estimation. Ventilatory compensation elevates CO_2 output disproportionately, causing RER values to rise independently of substrate oxidation. This leads to an underestimation of fat oxidation and overestimation of carbohydrate oxidation using standard gas exchange equations. While both normalization models adjust VO_2 based on observed RER, caution is warranted at higher intensities, where ventilatory buffering alters gas exchange dynamics and skews substrate estimates.

For exercise intensities that result in RER values greater than 1.00, it is recommended to report absolute VO_2 in liters per minute without applying any normalization, as the assumptions behind substrate-based calculations are no longer valid. It is also important to note that RER values above 1.00 reflect non-metabolic CO_2 contributions from acid-base buffering, which invalidate substrate utilization estimates. In these cases, using lactate measurements or ventilatory thresholds provides a more accurate context for interpreting metabolic efficiency during high-intensity exercise.

Additional Considerations
While this paper has contrasted normalized and absolute VO_2 to highlight the effects of substrate correction, the central aim is not comparison; it is to advocate for replacing traditional VO_2 as the primary metric for evaluating movement economy and metabolic efficiency. The true value of normalization lies not in how it compares to raw VO_2, but in its ability to yield physiologically valid and consistent insights across various testing conditions, time points, and metabolic states. In this sense, normalized VO_2 is not simply a complementary analysis; it is a necessary evolution of the metric itself.

Traditional VO_2 measures overlook substrate-dependent variations in oxygen cost, introducing systematic error when evaluating individuals with differing fuel utilization. This limitation is most problematic in contexts involving ketogenic adaptation, endurance training, nutritional interventions, or prolonged exercise, situations where substrate shifts are expected and physiologically meaningful.

In contrast, normalized VO_2 provides three core advantages in the assessment and interpretation of metabolic efficiency. First, it eliminates substrate bias, enabling valid comparisons between individuals or across different metabolic states regardless of variations in fuel utilization. Second, it allows for consistent longitudinal tracking of metabolic adaptations over time, offering clearer insights into physiological changes. Third, it enhances interpretive accuracy by distinguishing genuine physiological adaptations from the variability introduced by differences in the oxygen costs of fat and carbohydrate oxidation.

The critical comparison is not normalized versus traditional VO_2; it is normalized VO_2 across varying conditions, where substrate use changes over time, across diets, or between individuals. This enables a shift in focus, from crude oxygen consumption to meaningful bioenergetic insight. Normalized VO_2 should not be treated as a secondary adjustment. In any context involving variable substrate use, whether due to diet, training, or exercise duration, it should be considered the standard for interpreting oxygen consumption and movement economy.

Importantly, both normalization models rely solely on VO_2 and RER, metrics already collected in standard indirect calorimetry protocols. As a result, both approaches are immediately implementable without requiring additional equipment or procedures.

Future Research
These normalization models do not introduce new metabolic theory but instead represent a novel application of established biochemical constants to address a fundamental limitation of traditional movement economy metrics: their failure to account for substrate-dependent differences in oxygen cost. Although grounded in robust stoichiometric and physiological principles, these models require empirical validation. Future research comparing normalized VO_2 values to gold-standard methods, such as ^{13}C-labeled substrate oxidation, stable isotope tracers, or whole-body calorimetry, will be critical for assessing their accuracy across different populations, metabolic states, and exercise conditions.

Application
The two normalization models differ in both complexity and physiological specificity, giving users flexibility to choose the most appropriate approach based on research context and interpretive goals. Rather than functioning as competing methods, each provides a unique perspective for evaluating metabolic efficiency and offers a more accurate alternative to uncorrected VO_2-based assessments. Although both approaches adjust for substrate-specific oxygen costs, they are not analytically interchangeable and produce distinct interpretations due to their underlying bioenergetic assumptions. The RER-EE method is best suited for applied settings such as field testing, athlete monitoring, or performance tracking, where quick implementation and a more conservative correction are preferred. In contrast, the RER-SP+SCR method is ideal for research applications, detailed metabolic efficiency analyses, and clinical settings where substrate-specific precision is essential.

The two models yield different normalized VO_2 values depending on substrate mix, reflecting their different interpretive units: caloric energy versus biochemical ATP. Neither model is universally superior; each offers utility depending on the physiological question being addressed. Each provides a context-sensitive lens that highlights different facets of metabolic performance. Both models converge at shared RER values for substrate partitioning and remain valid within physiologically relevant ranges.

Researchers and practitioners should explicitly disclose their chosen normalization method, as it directly influences conclusions about metabolic efficiency and substrate use. Refer to Table 4 for key considerations when selecting the appropriate method for normalizing VO_2. Whether the intended use is clinical, performance, or scientific, users must balance the tradeoff between methodological simplicity and physiological specificity. By presenting both methods and their comparative behaviors, this work offers a flexible yet rigorous framework for assessing oxygen consumption across diverse metabolic contexts.

Table 4. Practical Comparison of RER-EE and RER-SP+SCR Normalization Methods

Criteria	RER-EE Method	RER-SP+SCR Method
Conceptual Basis	Uses caloric equivalent per L O_2 based on RER (via Weir equation)	Calculates substrate% % from RER, applies correction only to Fat-derived O2 using SCR
Main Output	Normalizes VO_2 based on the Caloric energy per liter O_2	Normalizes VO_2 based on Substrate specific ATP yield
Complexity	Simple: single-step formula	Moderate: requires RER-to-substrate conversion +duel step correction
Anchoring Reference	5.05 kcal/L O_2 at RER = 1.0 (100% carbohydrate)	ATP yield of glucose as baseline (SCR = 1.00); fat adjusted to 0.846
Accuracy at RER = 1.0	High	High
Accuracy at RER < 0.85	Moderate: may under correct	High: (models true fat oxidation cost)
Risk of Overcorrection	Low	Medium: if fat% is overestimated
Physiological Specificity	General estimate of caloric output	Models true oxidative substrate use
Assumptions Required	Linear kcal/O_2 relationship with RER	Valid RER-to-substrate mapping; fixed ATP/O_2 yield ratios
Data Required	VO_2 and RER	VO_2, RER, and substrate fraction estimate (table or equation)
Sensitivity to RER Range	Moderate	High: adapts with substrate mix
Mixed Substrate Resolution	Indirectly reflects via RER	Directly models fat vs. carbohydrate effects

Best Use Case	Field testing, athlete monitoring, applied research	Laboratory studies, metabolic efficiency frameworks, fuel-specific comparisons
Limitations	Doesn't model ATP yield; conservative at lower RER	Fat% estimation errors can affect precision
Strengths	Simplicity, fast implementation, conservative baseline	Precision, substrate specificity, physiologically grounded
Recommended Use	Practical assessment, sport science, VO2 comparisons	Research, clinical analysis, or diet/metabolism studies

Summary of conceptual differences, physiological assumptions, data requirements, and use-case applications for two VO_2 normalization models: RER-Based Energy Equivalent (RER-EE) and RER-Based Substrate Partitioning with Substrate Correction Ratio (RER-SP+SCR). Each method offers distinct advantages based on context, complexity, and interpretive goals.

Conclusion

Conventional assessments of movement economy rely on absolute oxygen consumption as a proxy for efficiency, implicitly assuming uniform substrate oxidation across individuals and conditions. This approach introduces systematic bias when substrate utilization shifts, particularly in contexts where fat oxidation increases due to dietary adaptation, training, or prolonged exercise. The normalization methods presented in this work address this limitation by incorporating substrate-specific oxygen cost into VO_2 interpretations, thereby providing a more physiologically valid framework for evaluating energy efficiency. By integrating respiratory exchange ratio data with established bioenergetic properties of carbohydrate and fat oxidation, both normalization approaches improve the interpretation of oxygen consumption across diverse metabolic states and enable valid comparisons between individuals with differing fuel utilization profiles.

The adoption of these substrate-adjusted normalization models can enhance both research precision and applied assessments of endurance performance, nutritional interventions, and metabolic health, providing a more accurate foundation for evaluating performance, adaptation, and metabolic function across diverse fuel utilization states. As the field increasingly recognizes the limitations of interpreting VO_2 without regard to substrate mix, incorporating normalized VO_2 may represent a significant step forward in assessing endurance and metabolic efficiency.

Conflict of Interest.

The authors do not have any conflicts of interest to report.

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