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VIEWPOINT

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

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Endurance performance depends on the body's ability to uptake and utilize oxygen to generate energy (4, 10, 12). As such, scientists often determine exercise intensity and predict endurance performance using the percentage of an individual's maximum aerobic capacity (often expressed as $\%\dot{V}O_{2max}$) (4, 10, 12). Scientists calculate $\%\dot{V}O_{2max}$ using an individual's mode-specific, steady-state submaximal $\dot{V}O_2$ (a measure of exercise economy) and $\dot{V}O_{2max}$. However, $\dot{V}O_2$ is only a proxy for the rate of *energy* that an individual can generate via aerobic metabolism, because it does not account for substrate oxidation, which affects the energy yield per volume of O_2 uptake (1, 5, 16). The energy yield per volume of O_2 uptake is ~7% greater for carbohydrate versus fat oxidation (16). Therefore, accounting for substrate oxidation leads to more accurate calculations of the rate of aerobic energy expended during physical activity and exercise. Accordingly, some recent studies have begun expressing exercise economy as the rate of aerobic energy expenditure ($\dot{E}_{aero}$) (e.g., W/kg or $kcal \cdot kg^{-1} \cdot min^{-1}$) rather than $\dot{V}O_2$ (e.g., $ml\ O_2 \cdot kg^{-1} \cdot min^{-1}$) (5, 9, 19, 20).

We propose that exercise economy ($\dot{E}_{aero}$), maximal aerobic capacity ($\dot{E}_{aero\ max}$), and hence intensity ($\%\dot{E}_{aero\ max}$), should be calculated using units of aerobic energy rather than oxygen. As relative aerobic intensity increases, the ratio of oxidized carbohydrates to fats usually rises until carbohydrates constitute nearly 100% of the oxidized substrates (2, 18). Therefore, $\dot{E}_{aero\ max}$ can be calculated using expired gas analysis and the energy yield of oxidized carbohydrates [21.745 $J \cdot ml\ O_2^{-1}$ (16)] when the respiratory exchange ratio (RER) is $\geq$1.0, such as at $\dot{V}O_{2max}$. Subsequently, $\%\dot{E}_{aero\ max}$ can be calculated using submaximal and maximal $\dot{E}_{aero}$.

Compared with relative aerobic intensity expressed as $\%\dot{V}O_{2max}$, $\%\dot{E}_{aero\ max}$ elicits numerically lower relative aerobic intensities when RER is <1.0 and yields the same relative aerobic intensities when RER $\geq$1.0 (Fig. 1). Since there is usually a lower ratio of oxidized carbohydrates to fats at relatively easier workloads/slower movement velocities (2, 18), plots of $\%\dot{E}_{aero\ max}$ versus workload/velocity have greater slopes than plots of $\%\dot{V}O_{2max}$ versus workload/velocity (Fig. 1). Thus, the difference between $\%\dot{E}_{aero\ max}$ and $\%\dot{V}O_{2max}$ is greater at lower relative aerobic intensities (Fig. 1).

Data from Burke et al. (3) provide a clear example of the differences that can occur between the two methods of calculating relative aerobic intensity. They reported $\dot{V}O_2$ and RER for elite race walkers on a high-fat/low-carbohydrate diet across a series of race-walking stages of increasing intensity (3). Our reanalysis shows that across four submaximal race-walking stages, Burke et al.'s participants exercised at mean relative aerobic intensities that were 2.7 to 4.0 percentage points lower using $\%\dot{E}_{aero\ max}$ than using $\%\dot{V}O_{2max}$ (one-way ANOVA, $P < 0.001$) (Fig. 1) (3). The difference between $\%\dot{E}_{aero\ max}$ and $\%\dot{V}O_{2max}$ depended on the race-walking stage (two-way ANOVA interaction effect $P = 0.004$) (Fig. 1) (3), indicating that $\%\dot{E}_{aero\ max}$ and $\%\dot{V}O_{2max}$ have different slopes when plotted against workload or velocity.

Many exercise studies compare individuals at the same relative aerobic intensities (e.g., 40, 60, 80% $\dot{V}O_{2max}$) rather than at task specific mechanical power outputs or velocities (2, 5, 11). Yet, equal $\%\dot{V}O_{2max}$ increments typically yield unequal $\%\dot{E}_{aero\ max}$ increments. Therefore, testing individuals at $\%\dot{E}_{aero\ max}$ increments may be more appropriate than $\%\dot{V}O_{2max}$ for some scientific questions, such as those related to thermoregulation where heat dissipation in addition to oxygen delivery significantly contribute to the physiological responses during physical activity or exercise (11).

Furthermore, the use of $\%\dot{E}_{aero\ max}$ vs. $\%\dot{V}O_{2max}$ may yield different scientific conclusions when comparing individuals across varied diets (3), aerobic training statuses (2), exercise durations (6, 11), altitudes (17), and/or ambient temperatures (11). For instance, in the context of endurance performance, the use of $\%\dot{E}_{aero\ max}$ is more appropriate than the use of $\%\dot{V}O_{2max}$ when comparing individuals that differ in aerobic training status. That is because the point at which the ratio of oxidized carbohydrates to fats begins to rapidly increase (crossover point) occurs at a greater $\%\dot{V}O_{2max}$ in aerobically trained than untrained individuals (2). Hence, the energy yield per volume of O_2 differs between aerobically trained and untrained individuals at the same relative aerobic intensity ($\%\dot{V}O_{2max}$ and $\%\dot{E}_{aero\ max}$).

The use of $\dot{E}_{aero}$ may provide more accurate endurance performance predictions than the use of $\dot{V}O_2$ alone. To illustrate this, we compared Joyner's (12) marathon prediction model using $\dot{V}O_2$ and $\dot{E}_{aero}$. Specifically, Joyner (12) predicted a runner's average marathon running velocity based on their $\dot{V}O_2$ at lactate threshold (LT) (*Eq. 1*). For the comparison, we updated Joyner's equation (*Eq. 1*) to incorporate $\dot{E}_{aero}$ (*Eq. 2*) using a standard conversion (16) and RER values based on the relationship between RER and $\%\dot{V}O_{2max}$ from high-caliber runners (*Eq. 3*) (13).

$$\text{Running velocity (km/h)} = 0.2878 \times \dot{V}O_2(\text{ml } O_2 \cdot kg^{-1} \cdot min^{-1}) \text{ at LT} + 1.5867 \quad (1)$$

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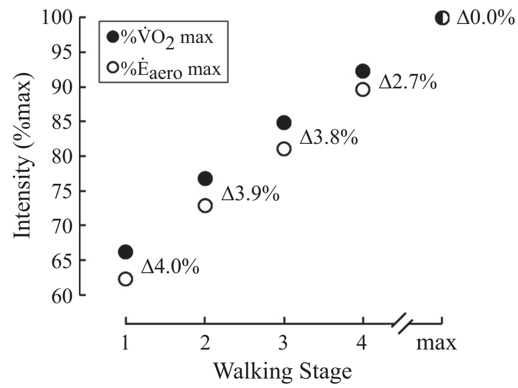

Fig. 1. Mean relative aerobic intensity as $\%\dot{V}O_{2max}$ (●) and as $\%\dot{E}_{aero\ max}$ (○) for elite race walkers on a low-carbohydrate/high-fat diet across 4 submaximal and 1 maximal race-walking stages (3). Δ Indicates a difference in relative intensity percentage points between the 2 calculation methods. Data in this figure are from Table 4 of Burke et al. (3), and $\dot{E}_{aero}$ is determined using the reported $\dot{V}O_2$, RER, and a standard conversion (16). We used the energy equivalent of carbohydrates at Burke et al.'s "max" stage (16). Across walking stages, relative aerobic intensity was statistically lower using $\%\dot{E}_{aero\ max}$ vs. $\%\dot{V}O_{2max}$ (1-way ANOVA, $P < 0.001$). Difference between $\%\dot{E}_{aero\ max}$ and $\%\dot{V}O_{2max}$ depended on the race-walking stage (2-way ANOVA, interaction effect $P = 0.004$) (3), indicating that $\%\dot{E}_{aero\ max}$ and $\%\dot{V}O_{2max}$ have different slopes when plotted against workload or velocity. This figure is created with data adapted from Burke et al. (3) as per the Creative Commons Public License: https://creativecommons.org/licenses/by/4.0/legalcode.

$$\text{Running velocity}(\text{km/h}) = 0.7712 \times \dot{E}_{aero}(\text{W/kg}) \text{ at LT} + 2.2609 \quad (2)$$

$$\text{RER} = 0.00005 \times \%\dot{V}O_{2max}{}^2 - 0.00301 \times \%\dot{V}O_{2max} + 0.87729 \quad (3)$$

Joyner slowed his predicted average marathon running velocities by 10% to account for air resistance (7–8%) and an upward drift in $\dot{V}O_2$ that occurs during prolonged exercise (2–3%) (12). Although the use of $\dot{E}_{aero}$ may eliminate the need to account for $\dot{V}O_2$ drift, we slowed all predicted average marathon running velocities by 10% for consistency. We used a hypothetical runner with a 70 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$ $\dot{V}O_{2max}$, which equates to a 25.6 W/kg $\%\dot{E}_{aero\ max}$ and a lactate threshold that occurs at 80% of $\dot{V}O_{2max}$. Lastly, we predicted the hypothetical runner's average marathon running velocities using $\dot{V}O_2$ (*Eq. 1*) and $\dot{E}_{aero}$ (*Eq. 2*) at "typical" (0.94) (*Eq. 3*), low (0.80) and high (1.00) RERs (13, 15).

Predicted average marathon running velocities using $\dot{V}O_2$ (*Eq. 1*) and $\dot{E}_{aero}$ (*Eq. 2*) can be identical or they can differ by 1 to 3% since the energy yield per volume of O_2 varies depending on the metabolic fuel mixture (1, 5, 16). For our hypothetical runner, using $\dot{V}O_2$ and $\dot{E}_{aero}$ at the typical RER yields the same predicted average marathon running velocity, 15.93 km/h (2:37:18 marathon, hr:min:s). Yet at low and high RERs, the hypothetical runner's $\dot{V}O_2$-based predictions remain the same (15.93 km/h), whereas $\dot{E}_{aero}$-based predictions change to 15.50 km/h (2:41:44 h:min:s) and 16.12 km/h (2:35:28 h:min:s), respectively. Thus, $\dot{E}_{aero}$-based endurance performance predictions are likely more accurate than $\dot{V}O_2$-based predictions because they account for the energy yield per volume of O_2.

While the uptake and presence of oxygen is vital for bodily functions (7, 8, 14, 21), aerobic energy expenditure provides a superior measure of exercise economy and maximal aerobic capacity regarding exercise intensity and endurance performance. Accordingly, we encourage our colleagues to report both maximal aerobic capacity ($\dot{E}_{aero\ max}$) and exercise economy ($\dot{E}_{aero}$) as rates of aerobic energy expenditure to enable the calculation of relative aerobic intensity as $\%\dot{E}_{aero\ max}$. Since $\dot{E}_{aero}$ depends on $\dot{V}O_2$ and substrate oxidation, all studies should at least report $\dot{V}O_2$ and $\dot{V}CO_2$ or RER, enabling readers to calculate $\dot{E}_{aero}$ and compare $\dot{V}O_2$ results to classic studies as desired.

DISCLOSURES

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

AUTHOR CONTRIBUTIONS

O.N.B., S.K., W.C.B., and R.K. conceived and designed research; O.N.B., S.K., W.C.B., and R.K. analyzed data; O.N.B., S.K., W.C.B., and R.K. prepared figures; O.N.B., S.K., W.C.B., and R.K. drafted manuscript; O.N.B., S.K., W.C.B., and R.K. edited and revised manuscript; O.N.B., S.K., W.C.B., and R.K. approved final version of manuscript.

REFERENCES

1. **Brockway JM.** Derivation of formulae used to calculate energy expenditure in man. *Hum Nutr Clin Nutr* 41: 463–471, 1987.
2. **Brooks GA, Mercier J.** Balance of carbohydrate and lipid utilization during exercise: the "crossover" concept. *J Appl Physiol (1985)* 76: 2253–2261, 1994. doi:10.1152/jappl.1994.76.6.2253.
3. **Burke LM, Ross ML, Garvican-Lewis LA, Welvaert M, Heikura IA, Forbes SG, Mirtschin JG, Cato LE, Strobel N, Sharma AP, Hawley JA.** Low carbohydrate, high fat diet impairs exercise economy and negates the performance benefit from intensified training in elite race walkers. *J Physiol* 595: 2785–2807, 2017. doi:10.1113/JP273230.
4. **Costill DL, Fox EL.** Energetics of marathon running. *Med Sci Sports Exerc* 1: 81–86, 1969. doi:10.1249/00005768-196906000-00005.
5. **Fletcher JR, Esau SP, Macintosh BR.** Economy of running: beyond the measurement of oxygen uptake. *J Appl Physiol (1985)* 107: 1918–1922, 2009. doi:10.1152/japplphysiol.00307.2009.
6. **Gimenez P, Kerhervé H, Messonnier LA, Féasson L, Millet GY.** Changes in the energy cost of running during a 24-h treadmill exercise. *Med Sci Sports Exerc* 45: 1807–1813, 2013. doi:10.1249/MSS.0b013e318292c0ec.
7. **Giordano FJ.** Oxygen, oxidative stress, hypoxia, and heart failure. *J Clin Invest* 115: 500–508, 2005. doi:10.1172/JCI200524408.
8. **Goldberg MA, Dunning SP, Bunn HF.** Regulation of the erythropoietin gene: evidence that the oxygen sensor is a heme protein. *Science* 242: 1412–1415, 1988. doi:10.1126/science.2849206.
9. **Hoogkamer W, Kipp S, Frank JH, Farina EM, Luo G, Kram R.** A comparison of the energetic cost of running in marathon racing shoes. *Sports Med* 48: 1009–1019, 2018. doi:10.1007/s4027.
10. **Hoogkamer W, Kram R, Arellano CJ.** How biomechanical improvements in running economy could break the 2-hour marathon barrier. *Sports Med* 47: 1739–1750, 2017. doi:10.1007/s4027.
11. **Jeukendrup AE.** Modulation of carbohydrate and fat utilization by diet, exercise and environment. *Biochem Soc Trans* 31: 1270–1273, 2003. doi:10.1042/bst0311270.
12. **Joyner MJ.** Modeling: optimal marathon performance on the basis of physiological factors. *J Appl Physiol (1985)* 70: 683–687, 1991. doi:10.1152/jappl.1991.70.2.683.
13. **Kipp S.** *Why does metabolic rate increase curvilinearly with running velocity?* (Thesis). Boulder, CO: University of Colorado Boulder, 2017.
14. **Marber MS, Latchman DS, Walker JM, Yellon DM.** Cardiac stress protein elevation 24 hours after brief ischemia or heat stress is associated with resistance to myocardial infarction. *Circulation* 88: 1264–1272, 1993. doi:10.1161/01.CIR.88.3.1264.
15. **O'Brien MJ, Viguie CA, Mazzeo RS, Brooks GA.** Carbohydrate dependence during marathon running. *Med Sci Sports Exerc* 25: 1009–1017, 1993.
16. **Péronnet F, Massicotte D.** Table of nonprotein respiratory quotient: an update. *Can J Sport Sci* 16: 23–29, 1991.
17. **Roberts AC, Butterfield GE, Cymerman A, Reeves JT, Wolfel EE, Brooks GA.** Acclimatization to 4,300-m altitude decreases reliance on fat as a substrate. *J Appl Physiol (1985)* 81: 1762–1771, 1996. doi:10.1152/jappl.1996.81.4.1762.

18. **San-Millán I, Brooks GA.** Assessment of metabolic flexibility by means of measuring blood lactate, fat, and carbohydrate oxidation responses to exercise in professional endurance athletes and less-fit individuals. *Sports Med* 48: 467–479, 2018.
19. **Shaw AJ, Ingham SA, Folland JP.** The valid measurement of running economy in runners. *Med Sci Sports Exerc* 46: 1968–1973, 2014. doi:10.1249/MSS.0000000000000311.
20. **Shaw AJ, Ingham SA, Fudge BW, Folland JP.** The reliability of running economy expressed as oxygen cost and energy cost in trained distance runners. *Appl Physiol Nutr Metab* 38: 1268–1272, 2013. doi:10.1139/apnm-2013-0055.
21. **Todd NV, Picozzi P, Crockard A, Russell RW.** Duration of ischemia influences the development and resolution of ischemic brain edema. *Stroke* 17: 466–471, 1986. doi:10.1161/01.STR.17.3.466.