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A study on energy expenditure in different running distances through physiological indicators

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Abstract

This study aimed to investigate the physiological variables and total energy expenditure during a race (100m, 400m, 3000m). A portable gas analyzer (K5) was used to measure oxygen uptake (VO_2) of eleven specially trained runners competing on an outdoor track. The tests included (1) 100m, 400m, and 3000m. Blood lactate was analyzed at rest and at 3, 5, and 7 minutes after the end of the two races. All results in the 100m race showed no significant correlation between energy expenditure and physiological variables if they were all ≥ 0.05. While in the 400m race, there was a significant correlation between total energy expenditure and each of the factors (RF, VT, VE, VO_2, VCO_2, VO_2 ml·kg^{-1}·min^{-1}, and MET), where the significance value was ≤ 0.05, while it did not reach the significance value for RQ and HR as the significance values were ≥ 0.05. A significant correlation was found in the 3000m race, where the significance value was ≤ 0.05 between energy expenditure and each of VT, VE, VO_2, VCO_2, RQ, VO_2 ml·kg^{-1}·min^{-1}, and MET, while it did not reach the significance value for RF and HR. In conclusion, the duration and type of activity dictate metabolic dominance (aerobic vs. anaerobic) and influence the relationship between physiological variables and energy expenditure. Aerobic variables (VO_2, VE, VCO_2) are significant for longer activities (>3 minutes), whereas their relevance diminishes in shorter activities. The results have transformative implications for sports science and clinical practice, enabling tailored strategies to optimize athletic performance and metabolic health across diverse athletes.

Keywords: Anaerobic metabolism, EPOC, Oxygen consumption, Physiological variables total energy expenditure.

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1. Introduction

Total energy expenditure (TEE)—the sum of energy utilized by the body for metabolic, physical, and physiological processes—is intricately linked to dynamic interactions between respiratory, cardiovascular, and metabolic systems. Physiological variables such as respiratory rate (Rf), tidal volume (Vt), pulmonary ventilation (Ve), oxygen consumption (VO_2), carbon dioxide production (VCO_2), and heart rate (HR) are critical indicators of energy demand and efficiency during exercise. However, the strength and significance of these relationships depend on the intensity, duration, and metabolic dominance (aerobic vs. anaerobic) of the activity [1].

In short-duration, high-intensity activities (e.g., 100m sprint), energy production relies predominantly on anaerobic pathways (ATP-PCr and glycolysis), with minimal reliance on oxygen-dependent systems. Consequently, traditional physiological metrics like HR and respiratory variables exhibit weak or non-significant correlations with TEE. This is attributed to the delayed rise of HR and pulmonary responses post-exercise (EPOC phase) and the dominance of lactate metabolism over aerobic CO_2 production [2, 3]. Conversely, in prolonged, moderate-intensity activities (e.g., 3000m run), TEE strongly correlates with aerobic variables such as VO_2, Ve, and VCO_2, reflecting the body's reliance on oxidative phosphorylation and steady-state cardiorespiratory adaptation [4].

The respiratory quotient (RQ), which reflects substrate utilization (carbohydrates vs. fats), and metabolic equivalents (METs), which standardize energy expenditure relative to resting metabolism, further illustrate these dynamics. For instance, RQ loses predictive power in anaerobic efforts due to lactate-induced distortions in CO_2 output [5] while METs are validated only in aerobic contexts [6]. Similarly, HR's utility as a TEE proxy diminishes in activities shorter than 30 seconds due to sympathetic response lags [7].

This paper synthesizes evidence from exercise physiology literature to explore how TEE intertwines with cardiorespiratory variables across diverse athletic events, emphasizing the metabolic transitions that govern these relationships. The study by Scott and Kemp [8] examined energy expenditure during and after exercise from both aerobic and anaerobic perspectives, along with the energy needs for aerobic recovery. Current methods for measuring energy expenditure involve assessing oxygen uptake in conjunction with excess post-exercise oxygen consumption (EPOC) or oxygen deficit, alongside oxygen uptake measurements [9]. This research highlights how interpretations of oxygen debt and deficit can influence total energy expenditure calculations. It suggests that while oxygen uptake effectively reflects aerobic metabolism during exercise and recovery, it may not adequately account for anaerobic energy production (fermentation) [10]. In practice, differences in energy expenditure are more realistically observed in high-intensity, intermittent exercises rather than in low-intensity activities.

The study by Scott and Kemp [8] indicates that energy expenditure depends on oxygen uptake during exercise and calculates oxygen consumption through EPOC, which consumes energy following the end of exercise, as well as through blood lactate measurements. The results of this study suggest that both lactate production and rapid glycolytic ATP turnover and lactate oxidation are independently associated with heat production, and thus represent separate and additive components for measuring total energy expenditure during exercise and recovery [8].

In the study by Scott [11] four indirect estimates of anaerobic energy expenditure were measured: (1) oxygen debt ($O2$), (2) oxygen deficit, (3) blood lactate concentration, and (4) increased carbon dioxide production during and after six exercise intervals (2, 4, 10, 15, 30, and 75 seconds) performed at three different intensities (50%, 100%, and 200% of VO2 max). The results of the study indicate that the greatest error occurs in not accounting for ATP turnover at the substrate level in lactate's contribution to calculating total energy expenditure in anaerobic efforts [11].

In Scott [11] titled "Lactate Contribution to Energy Expenditure from Resistance Training," it was found that conventional oxygen uptake measurements do not fully capture the rapid anaerobic ATP turnover that occurs with lactate production. The study compared two weight training protocols: one at 60% of one-repetition maximum (1RM) to failure and another at 80% of 1RM with limited repetitions. The aim was to assess whether blood lactate levels, reflecting rapid substrate-level ATP turnover, significantly enhance the interpretation of total energy expenditure when compared to oxygen uptake measurements alone. The total energy expenditure analysis incorporated blood lactate, oxygen uptake, and post-exercise oxygen consumption (EPOC). When the results were analyzed by gender, blood lactate frequently played a significant role in total energy expenditure during endurance-type training [11].

In the study by Irvine, et al. [12] "Determining Total Energy Expenditure During and After High-Intensity Interval Running," the aim was to examine the variations in the contribution of oxidized O2 and glycolytic analysis during two distinct types of high-intensity interval training, with work ratios of (1:1) and (1:2), namely (30:30) seconds and (15:30) seconds, on a sample consisting of 6 men and 8 women. The researchers measured oxygen consumption (VO2) and carbon dioxide production (VCO2), and the respiratory exchange ratio (RER) to represent the oxidative contribution, along with capillary blood lactate analysis to represent the glycolytic contribution during both high-intensity speed workouts. Post-exercise lactate values showed a significant contribution from the glycolytic system.

Our current study differs from previous studies in the study of physiological variables and their relationship to energy expenditure and the most important physiological factors that determine the total energy expenditure of distance runners (100m, 400m, 3000m).

2. Materials and Methods

2.1. Research Methodology

The researcher used the descriptive approach to suit the research requirements.

2.2. Research Sample

The researcher defined the research population as track and field athletes in the Iraqi university teams participating in the Iraq Athletics Championship for Iraqi universities. The research sample consisted of athletes from the university teams in Nineveh Governorate, totaling 21 players with an average age of 20.03 years. Meanwhile, the main research sample included 11 players with an average age of 20.52 years.

2.3. Devices and Tools Used in the Research

- Electronic Device for Measuring Weight and Height (Type: Detecto).
- Electronic Stopwatches (4 units) for measuring time to the nearest one-hundredth of a second.
- Pulse Measuring Watches.
- Measuring Tape for distances to the nearest centimeter, 40 meters in length.
- K5 Device for measuring CO_2 and O_2.
- Lactate Measuring Device (Lactate PrO2 LT-1730).
- Colored Adhesive Strips for use in tests.
- Chalk in Various Colors for drawing on the ground during pre- and post-tests.

2.4. Measurement of Lactic Acid Concentration in Capillary Blood

The level of lactic acid concentration in capillary blood was measured using the device (Lactate PrO2 LT-1730) five minutes before warm-up. The researcher will then conduct several pilot experiments to measure lactate after aerobic and anaerobic exertion, using strips with a chemical detector that sends an electrical signal in response to the interaction with the blood sample. This signal varies according to the concentration of lactic acid in the tested blood sample.

2.5. Physiological Variables

Energy Expenditure during Aerobic Effort, Energy Expenditure during Anaerobic Effort, Energy Expenditure (EEm) (kcal), Blood Lactate Measurement, Heart rate (HR) (beats/minute), respiratory rate (RR) (1/minute), tidal volume (TV) (liters), pulmonary ventilation ($\dot{V}E$) (liters/minute), oxygen consumption ($\dot{V}O_2$) (liters/minute), carbon dioxide excreted (VCO_2) (liters/minute), respiratory equivalent (RQ), metabolic equivalent (METs).

2.6. Physical Tests

The physical tests will include the following:

- 100-meter run test
- 400-meter run test
- 3000-meter run test

3. Procedures

3.1. Pilot Experiments

The researchers conducted three pilot experiments, the purpose of which was to explain the nature of the test to the sample inside the Northern Technical University stadium. This included explaining how the sample was tested and showing how to connect the K5 device by the assistant team. In addition, the sample became familiar with the face mask while running on the track and received instructions on how to run effectively and evaluate the suitability of the equipment and tools used in the experiment. Tasks were assigned for the procedures for connecting and operating the K5 device to the sample, including entering the names, ages, heights and weights of the sample into the database in preparation for the main experiment. Data from the gas analyzer (K5) was imported into a computer using a program from OMNIA, and then converted to Excel format. In addition to the maximum lactate accumulation time, which was recorded at (3, 5, 7) minutes**.**

3.2. Pre-Measurements

The researchers, along with the assisting team, conducted pre-measurements for the research sample in the Exercise Physiology Laboratory at the College of Basic Education on Tuesday, (date). The measurements included height and mass to input the sample data into the computer, which would be used to assess body composition as well as the functional variables measured using the K5 device for a duration of 5 minutes. This was done to calculate Resting Energy Expenditure (REE), A state of stability must be achieved, clinically defined as a five-minute period where the average $\dot{V}O_2$ and VCO_2 change by less than 10%, and the average RQ changes by less than 5%.

3.3. Main Experiment Procedures

Participants were selected from athletes specializing in athletics (sprinters and endurance runners), ensuring that none had any injuries. All participants underwent a standardized warm-up protocol, which included 10 to 15 minutes of light jogging, followed by stretching and flexibility exercises targeting the lower extremities and trunk. This was complemented by 3 to 4 sprints of 90 to 100 meters, progressively increasing in speed to adequately prepare the muscles. Following the warm-up, a Cosmed K5 device was securely attached to each participant's torso to measure VO_2 (oxygen consumption), VCO_2 (carbon dioxide production), and other physiological variables. The device was calibrated before each trial in accordance with the manufacturer's guidelines and established protocols [13]. A heart rate monitor was affixed via a chest strap to continuously track cardiovascular responses throughout the trial. Timing devices were strategically positioned at the start and finish lines, as well as at designated intervals (e.g., 200 meters for the 400-meter race and 1000 meters for the 3000-meter race), to accurately measure speed and start times. Baseline lactate concentration was assessed through a blood sample taken using a lactate Pro device (TM2 LT). Additional blood samples were collected at 3, 5, and 7-minutes post-race to monitor lactate accumulation and clearance. Participants were instructed to exert maximum effort during the race, initiated by a standardized start signal ("ready, go"). The Cosmed K5 and Polar devices were activated 30 seconds prior to the race start to ensure precise data capture. Athlete data were recorded continuously from the beginning to the end of the race, followed by excess post-exercise oxygen consumption (EPOC) measurements until the athlete's VO2 reached 5 ml/kg/min [11]. Finally, the Cosmed K5 device was disconnected from the participants after data collection.

3.4. Total Energy Expenditure Calculation

Total energy expenditure (TEE) was derived from three components :

(1) energy expended during exercise, (2) excess post-exercise oxygen consumption (EPOC), and (3) energy contribution from lactate metabolism. The calculations were performed as follows:

3.4.1. Exercise Energy Expenditure

Oxygen consumption (VO2) was measured breath-by-breath throughout the trial. All VO2 values (expressed in $mL\cdot kg^{-1}\cdot min^{-1}$) were converted to absolute oxygen consumption ($L\cdot min^{-1}$) using the formula:

Energy expenditure during exercise was then calculated by multiplying absolute VO2 by the energy equivalent of oxygen under aerobic conditions:

Exercise Energy Expenditure (kJ)=VO2 × 21.1

3.4.2. EPOC (Recovery Energy Expenditure)

Post-exercise oxygen consumption (Epoc) was quantified using the same VO2 measurements during the recovery phase, adjusted for the anaerobic contribution via a modified energy equivalent:()

VO2 EPOC(kJ)=VO2 × 19.6

3.4.3. Lactate-Derived Energy Contribution

The rate of lactate accumulation (Δ[La]) was converted to an equivalent oxygen cost using the constant per 1 $mmol\cdot L^{-1}$ increase in blood lactate:

Energy Expenditure (Δ[La]) = Energy Expenditure(Δ[La]) × 3 $mL\cdot kg^{-1}\cdot min^{-1}$)*kg

This value was subsequently converted to energy expenditure using the aerobic energy equivalent:

Lactate Energy (kJ)=Energy Expenditure (Δ[La−])×21.1 (kJ)=

3.4.4. Total Energy Expenditure (TEE)

The cumulative energy expenditure was computed as the sum of the three components:

TEE (kJ)=Exercise Energy+ EPOC+ Lactate Energy [14].

3.4.5. Statistical Methods

Data were statistically processed using computer software, employing statistical programs such as SPSS and Excel. The following statistical methods were utilized :(Mean, Standard deviation., Coefficient of variation., t-test for paired samples, Percentage.)

Table 1.
Shows the relationship between total energy expenditure and physiological variables in the 100m race on the track.

Variables	Unit	Physiology		TEE(kj)		Correlation	Sig
		X	S.D	X	S.D		
RF	Breaths / Min	80.20	17.83	120.74	26.08	0.423	0.195
VT	(L/min)	1.46	0.39	120.74	26.08	0.367	0.267
VE	(L/min)	118.78	31.78	120.74	26.08	0.026	0.941
VO2	mL/min	2534.60	585.16	120.74	26.08	0.370	0.263
VCO2	mL/min	2908.99	620.41	120.74	26.08	0.458	0.157
RQ		1.15	0.11	120.74	26.08	0.195	0.565
VO2/kg	mL/kg/min	37.97	9.48	120.74	26.08	0.330	0.322
METs	mL/kg/min	10.90	2.66	120.74	26.08	0.322	0.334
HR	Beats / minute	128.55	5.72	120.74	26.08	0.483	0.132

4. Results and Discussion

From Table 1, it is clear that the relationship between energy expenditure and all physiological factors (Rf, VT, VE, VO1, VCO2, RQ,

VO2 $ml.kg^{-1}.min^{-1}$, and METs, HR) did not reach the level of significance, with values of (0.195, 0.267, 0.941, 0.263, 0.157, 0.565, 0.322, 0.334, 0.132), respectively. The researchers attribute this to the fact that the effectiveness of the 100m race does not depend on energy expenditure based on oxygen consumption during exercise. Rather, physiological variables remain elevated after the end of the race, forcing reliance on EPOC and expenditures from lactate. The 100m race is a fast-paced event that does not involve a steady-state phase (for physiological variables) during its performance. The researcher also attributes the lack of a significant correlation between energy expenditure and respiratory rate to the short duration. The respiratory system does not play a major role in providing oxygen during the exercise itself due to the short duration (<15 seconds), and the respiratory rate remains elevated until it reaches its peak after the end of the exercise in the EPOC phase (see table). This is consistent with a study by Gastin [2] which indicates that 85% of the energy in short-term activities comes from anaerobic systems, reducing reliance on breathing during exercise. It is also consistent with a study by Åstrand and Rodahl [15] which indicates that an increase in respiratory rate occurs 20 seconds after the exercise, i.e., after the end of the (100) m. As for the lack of a significant correlation between energy expenditure and respiratory volume, the researchers attribute this to the fact that during high-intensity, short-term activities, the body focuses on supplying blood to the working muscles by constricting the blood vessels in non-working organs (such as the digestive system), which limits the increase in respiratory volume. This result is consistent with the A study by Staes, et al. [16] demonstrated that respiratory volume is not directly related to anaerobic activities due to the short duration of the effort.

The results showed no significant correlation with the pulmonary ventilation variable. This is due to the fact that this variable depends on respiratory volume and the number of breaths, which did not show a significant correlation. This explains the weak significant correlation. According to the study by Whipp and Ward [17] pulmonary ventilation is not related to energy expenditure in anaerobic activities because oxygen is not used during the effort itself.

The researcher attributes the lack of a significant correlation between the rate of oxygen consumption (VO_2) and energy expenditure to the short duration of the activity. The aerobic system requires 3-4 minutes to reach a steady state, while the 100-meter activity ends before VO_2 begins to rise. The percentage of oxygen contribution during the (100) meter event is small compared to aerobic events. This was confirmed by the study Parolin, et al. [18] and Saleh, et al. [19] which showed that VO_2 contributes less than (10%) of energy in activities that last less than (30) seconds. Bassett and Howley [4] indicate that VO_2 is measured accurately in long-term aerobic activities. The lack of a significant correlation between VCO_2 production and energy expenditure is attributed to the fact that VCO_2 is usually associated with carbohydrate burning in the aerobic system, while lactate is produced instead in anaerobic activities. Approximately 70% of the lactate produced is recycled by the liver, reducing VCO_2 production. Our current study is consistent with [20] that 70% of lactate is recycled into glucose by the liver, which aids in energy production, reducing VCO_2 production. This is confirmed by Medbø and Burgers [21] who stated that VCO_2 production does not accurately reflect metabolism during anaerobic exercise. The reason for the lack of a significant correlation between the respiratory coefficient (RQ) and energy expenditure is due to the dependence of RQ on VO_2 consumption and VCO_2 production. This reflects the quality of fuel used, but in high-intensity, short-duration activities, the RQ is not accurately represented and loses its reliability. This was confirmed by [5] who stated that the RQ loses its significance in anaerobic activities due to the body not reaching a state of equilibrium. The lack of a significant correlation between metabolic equivalent and energy expenditure is due to the fact that METs (Metabolic Equivalent of Task) depend on VO_2. Since VO_2 is insignificant in the 100 meters, METs also lose their significance, according to Ainsworth, et al. [6]. It should be noted that METs are designed to measure moderate aerobic activity, not maximal anaerobic activity. The researchers also attributed the lack of significant differences between energy expenditure and heart rate (HR) to the fact that heart rate rises rapidly during exercise, but its peak typically occurs after the end of exercise due to a time delay in the sympathetic nervous system's response. Our study is consistent with the results of two studies [22] which demonstrated that HR does not accurately reflect the intensity of effort in activities shorter than 30 seconds, and a study by Buchheit, et al. [7] which demonstrated that HR is not directly related to anaerobic energy. From the current results, we conclude that the lack of statistical significance of traditional physiological variables in the 100-meter event is due to:

1. The dominance of anaerobic systems (ATP-PCr and glucose), which do not depend on oxygen during exercise [23].
2. EPOC (exercise oxygen consumption), which contributes 20-30% of energy expenditure [24].
3. Lactate recycling, which consumes energy after exercise via the Cori cycle [3].

Table 2.
Shows the relationship between total energy expenditure and physiological variables in the 400 m race on the track.

Variables	Unit	Physiology		TEE(kj)		Correlation	Sig
		X	S.D	X	S.D		
RF	Breaths / Min	70.49	12.24	202.24	27.76	0.699	0.017
VT	(L/min)	2.23	0.49	202.24	27.76	0.644	0.032
VE	(L/min)	158.01	50.87	202.24	27.76	0.856	0.001
VO2	mL/min	3850.21	656.80	202.24	27.76	0.759	0.007
VCO2	mL/min	4945.58	1581.91	202.24	27.76	0.774	0.005
RQ		32.68	6.20	202.24	27.76	0.575	0.064
VO2/kg	mL/kg/min	58.53	12.61	202.24	27.76	.685	0.02
METs	mL/kg/min	16.70	3.63	202.24	27.76	.688*	0.019
HR	Beats / minute	156.82	9.14	202.24	27.76	0.261	0.438

From Table 2, it is evident that the relationship between energy expenditure and physiological factors(Rf, VT, VE, VO1, VCO2,VO2 ml.kg^{-1}.min^{-1}, and METs,)was significant, with respective significance values of (0.017, 0.032, 0.001, 0.007, 0.005, 0.064, 0.020, 0.019). In contrast, the correlations for (RQ and HR) were found to be non-significant, with values of (0.064 and 0.438).

Researchers attribute these findings to the fact that the 400-meter event heavily relies on lactate production, with competition times among elite athletes typically ranging from 45 to 60 seconds, which offers greater stability compared to the 100-meter event. This prolonged duration allows for a more consistent physiological response, wherein the respiratory system is sufficiently activated to compensate for oxygen deficits and facilitate carbon dioxide removal, reflecting direct metabolic adaptations.

The significant correlations observed between respiratory factors—such as breathing frequency (Rf), tidal volume (Vt), and pulmonary ventilation (Ve)—and energy expenditure during high-intensity races indicate an increased respiratory effort to counteract oxygen scarcity and expel carbon dioxide. This finding aligns with the research conducted by [1] which underscores the close relationship between pulmonary ventilation, increased oxygen consumption (VO_2), and energy production, particularly in exercises lasting between 1 and 4 minutes.

Moreover, the researchers noted that the increases in VO_2 and carbon dioxide production (VCO_2), along with their significant correlation with energy expenditure, reflect the activation of both aerobic and anaerobic metabolic pathways. Although the 400-meter event predominantly utilizes anaerobic glycolysis (lactate production), the relatively longer duration (45-60 seconds) permits a substantial aerobic contribution. These findings are consistent with those of Bishop, et al. [25] who demonstrated that exercises lasting 30 to 120 seconds exhibit a blending of the aerobic and anaerobic systems, thereby enhancing the correlation between VO_2/VCO_2 and total energy expenditure (TEE).

Significant correlations were also found between energy expenditure and both METs and VO_2/kg. These indicators provide insights into the body's efficiency in utilizing oxygen per kilogram of body weight, suggesting that participants with higher metabolic efficiency were capable of expending greater energy. This is supported by Ainsworth, et al. [6], who state that METs serve as standard measures of energy expenditure, directly proportional to VO_2, indicating that as energy expenditure increases, METs also correspondingly rise, thus contributing to greater energy output.

On the other hand, the study revealed a non-significant correlation between energy expenditure and the respiratory quotient (RQ). RQ, defined as the ratio of VCO_2 to VO_2, is indicative of the type of substrate being oxidized (with fats approximating 0.7 and carbohydrates approximately 1.0). The non-significant value of 0.064 may be attributed to lactate accumulation during anaerobic exercise, which leads to increased CO_2 production as lactate is stored. Furthermore, the short duration of the activity (45-60 seconds) does not allow sufficient time for stabilization of RQ. This is corroborated by the findings of Rogatzki, et al. [26] which link lactate accumulation to an unexpected increase in VCO_2, thereby influencing RQ.

Lastly, the absence of significant correlations between energy expenditure and heart rate (HR) suggests that heart rate does not reach a steady state during activity, with exercise typically concluding before such stabilization can occur. According to Wilmore, et al. [27] HR is considered a less reliable measure of energy expenditure during anaerobic exercise, as it fails to accurately reflect the intensity of effort in such brief activities

Table 3.
Shows the relationship between total energy expenditure and physiological variables in the 3000 m race on the track.

Variables	Unit	Physiology		TEE(kj)		Correlation	Sig
		X	S.D	X	S.D		
RF	Breaths / Min	61.37	13.16	725.87	116.92	0.44	0.176
VT	(L/min)	2.5	0.44	725.87	116.92	0.68	0.027
VE	(L/min)	153	43.11	725.87	116.92	0.81	0.002
VO2	mL/min	4424.8	839.54	725.87	116.92	0.819	0.002
VCO2	mL/min	4577.2	1155.1	725.87	116.92	0.867	0.001
RQ		1.02	0.07	725.87	116.92	0.94	0.001
VO2/kg	mL/kg/min	65.64	9.58	725.87	116.92	0.941	0.001
METs	mL/kg/min	18.75	2.73	725.87	116.92	0.921	0.001
HR	Beats / minute	178.82	14.96	725.87	116.92	0.258	0.444

From Table 3, it is show that the relationship between energy expenditure and physiological factors (VT, VE, VO1, VCO2, RQ,VO2 ml.kg-1.min-1, and METs) was significant, as the p-value was ≤ 0.05. In contrast, the correlations for the (RF and HR) were non-significant, with p-values ≥ 0.05. The researchers attribute this to the fact that the 3000-meter event predominantly relies on aerobic metabolism, with running times typically ranging from 9 to 12 minutes. This allows participants to achieve a steady state, positively influencing respiratory variables and enabling oxygen consumption to reach its maximum during the performance.

The data revealed a strong correlation between VO_2 and energy expenditure, as oxygen consumption serves as a key indicator of the efficiency of the aerobic system, reflecting the body's ability to utilize oxygen for energy production in the mitochondria through oxidative phosphorylation. During the 3000-meter race, the aerobic system reaches its peak efficiency, resulting in increased oxygen consumption proportional to the intensity of the effort. Studies indicate that VO_2 max is one of the fundamental determinants of aerobic performance, with higher aerobic capacity linked to improved performance in sustained activities [4].

The data also indicates that pulmonary ventilation (Ve) has a strong correlation with energy expenditure, highlighting the importance of respiratory efficiency in maintaining high ventilation levels to meet the increasing oxygen demands during the race. As the intensity of aerobic activity increases, pulmonary ventilation rises due to increases in both tidal volume (Vt) and breathing rate (Rf). However, the increase in tidal volume is more significant than the increase in breathing rate for improving ventilation efficiency, as this reduces the work of breathing and enhances oxygen supply [16].

The respiratory quotient (RQ) demonstrated the highest correlation with energy expenditure, as RQ serves as an indicator of the fuel type utilized during exercise. When RQ approaches 1.0, the body predominantly relies on carbohydrates as an energy source. In high-intensity aerobic activities such as the 3000-meter race, the reliance on carbohydrates is substantial, as they provide a rapid and efficient energy source compared to fats [5].

Carbon dioxide production exhibited a strong correlation with energy expenditure, as CO_2 production increases during aerobic exercise due to heightened aerobic metabolism. Studies indicate that increased VCO_2 is directly associated with increased oxygen consumption (VO_2) and energy production demands [27].

The strong relationship between VO_2/kg and energy expenditure underscores the importance of relative aerobic capacity. VO_2/kg is a critical indicator for assessing performance in middle- and long-distance races, as studies show that athletes with higher VO_2/kg values can sustain higher intensities for longer periods [28].

The non-significant relationship between breathing rate and energy expenditure suggests that the breathing rate (Rf) may not be an accurate indicator of ventilation efficiency or energy production. An increase in Rf without a corresponding increase in tidal volume (Vt) may lead to hyperventilation, which does not contribute to performance enhancement [16].

Likewise, the relationship between heart rate (HR) and energy expenditure was found to be non-significant. Although HR rises with increased exercise intensity, reaching a steady state during the 3000-meter race reduces the impact of momentary fluctuations in HR on energy expenditure. Furthermore, HR may be influenced by other factors such as fatigue or psychological stress, making it a less accurate indicator of energy expenditure compared to VO_2 or Ve [29].

In conclusion, the 3000-meter race is classified as a moderate to high-intensity aerobic activity, where a steady state is achieved approximately 2 to 3 minutes after the onset of activity. During this state:

A balance is reached between oxygen consumption and metabolic demand.

Energy production primarily relies on the aerobic system, with reduced reliance on the anaerobic system.

Achieving a steady state enhances the efficiency of both the respiratory and circulatory systems, explaining the strong correlations between energy expenditure and the physiological variables associated with oxygen [28].

5. Conclusion

The results of this study provide valuable insights that advance our understanding of exercise physiology and the assessment of energy expenditure, particularly in the context of high-intensity, mid-range, and specific sports activities. In the 100-meter race, no significant correlations were found between physiological variables and energy expenditure. This reflects the anaerobic dominance of the event, which relies almost entirely on the ATP-PCr and anaerobic glycolysis systems, with oxygen contributing less than 10%.

In contrast, the 400-meter race exhibited significant differences in respiratory frequency (Rf), tidal volume (VT), pulmonary ventilation (VE), oxygen consumption (VO_2), carbon dioxide production (VCO_2), VO_2 in $ml.kg^{-1}.min^{-1}$, and METs, although metabolic equivalents and heart rate (HR) did not reach significance. This indicates a substantial aerobic contribution (30-40%) despite the primary reliance on anaerobic glycolysis.

The results from the 3000-meter race demonstrated a significant correlation between total energy expenditure and variables including VT, VE, VO_2, VCO_2, respiratory quotient (RQ), VO_2 in $ml.kg^{-1}.min^{-1}$, and METs; however, no significant correlation was found with Rf and HR. This indicates a shift towards aerobic dominance, with a metabolic steady state achieved after 2-3 minutes, allowing for accurate measurement of VO_2 max.

Overall, the most important conclusions drawn by the researchers are:

1. The duration and type of activity dictate metabolic dominance (aerobic vs. anaerobic) and influence the relationship between physiological variables and energy expenditure.
2. Aerobic variables (VO_2, VE, VCO_2) are significant for longer activities (>3 minutes), whereas their relevance diminishes in shorter activities.

5.1. Based on These Conclusions, the Researchers Recommend the Following

1. Utilize VO_2/kg and METs as key performance indicators for aerobic activities.
2. Develop lactate tolerance for hybrid events, such as the 400-meter race.
3. Design training programs aimed at improving respiratory efficiency by focusing on increasing tidal volume (VT) rather than respiratory frequency (Rf).

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