Study of energy expenditure (oxygen consumption, EPOC, and lactate) for different running distances

Un estudio del gasto energético (consumo de oxígeno, EPOC y lactato) en diferentes distancias de carrera

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Abstract

Introduction: This study addressed the metabolic demands of running by analyzing the contributions of oxygen consumption during exercise, excess post-exercise oxygen consumption (EPOC), and lactate accumulation to total energy expenditure. Understanding the interaction between these components is essential for optimizing training strategies and improving physiological monitoring in elite athletes.
Objective: To evaluate the relative contributions of aerobic and anaerobic energy systems across different running distances using a validated physiological approach in elite-level male runners.
Methodology: The study involved sixteen elite male runners from Nineveh, Iraq, who completed 100-meter, 400-meter, and 3000-meter running trials under controlled environmental conditions. Metabolic data were collected using a portable gas analyzer, while lactate concentrations were assessed via capillary blood sampling.
Results: The results revealed significant differences in energy expenditure components across the running distances ($p < 0.001$). During the 100-meter sprint, anaerobic metabolism dominated, with oxygen consumption accounting for 8.57%, EPOC 68.87%, and lactate 22.56%. In the 400-meter trial, energy contributions were more balanced, with 16.78% from oxygen, 53.04% from EPOC, and 30.17% from lactate. The 3000-meter run was characterized by aerobic dominance, with oxygen contributing 68.00%, EPOC 25.96%, and lactate 6.04%. Statistical tests confirmed the significant role of anaerobic metabolism in short-duration efforts.
Discussion: The discussion emphasized that earlier studies often underestimated anaerobic contributions. Incorporating lactate kinetics and EPOC provides a more complete understanding of energy demands during intense exercise.
Conclusions: It is concluded that integrating anaerobic components yields a more accurate estimation of total energy expenditure, supporting improved performance modeling and health-oriented interventions.

Keywords

Lactic acid, energy expenditure, oxygen consumption, EPOC, anaerobic metabolism.

Resumen

Introducción: este estudio examinó las demandas metabólicas de la carrera, analizando las contribuciones del consumo de oxígeno durante el ejercicio, el epoc y la acumulación de lactato al gasto energético total. comprender su interacción es clave para mejorar el entrenamiento y el monitoreo fisiológico en atletas de élite.
Objetivo: evaluar las contribuciones relativas de los sistemas energéticos aeróbico y anaeróbico en distintas distancias de carrera mediante un enfoque fisiológico validado en corredores varones de élite.
Metodología: participaron dieciséis corredores de élite de nínive, irak, quienes realizaron pruebas de 100, 400 y 3000 metros bajo condiciones ambientales controladas. se recolectaron datos metabólicos con un analizador de gases portátil y se midió el lactato en sangre capilar.
Resultados: se observaron diferencias significativas entre distancias ($p < 0.001$). en 100 m predominó el metabolismo anaeróbico (8.57% oxígeno, 68.87% epoc, 22.56% lactato). en 400 m, el perfil fue mixto (16.78% oxígeno, 53.04% epoc, 30.17% lactato). en 3000 m dominó el metabolismo aeróbico (68.00% oxígeno, 25.96% epoc, 6.04% lactato). los análisis confirmaron la relevancia del metabolismo anaeróbico en esfuerzos breves.
Discusión: estudios previos subestimaron los componentes anaeróbicos. incluir la cinética del lactato y el epoc mejora la comprensión del gasto energético en ejercicios intensos.
Conclusiones: integrar los componentes anaeróbicos permite una estimación más precisa del gasto energético total, favoreciendo mejores modelos de rendimiento y estrategias de salud.

Palabras clave

Ácido láctico, gasto energético, consumo de oxígeno, EPOC, metabolismo anaeróbico.

Introduction

Total energy expenditure (TEE) represents the total energy used within a 24-hour timeframe and is comprised of three primary components: resting energy expenditure (REE), the thermic effect of food (TEF), and activity energy expenditure (AEE) (Ndahimana & Kim, 2017). Physical activity accounts for approximately 20–30% of overall energy output in humans (Ainsworth et al., 2011). The energy expended can differ based on the intensity and nature of the exercise performed.

There are various methods to measure and assess physical activity and energy expenditure, each with its advantages and limitations (Coyle, 1995 : Brito et.al,2024). Understanding these methods is crucial for determining which one should be used in a specific study context. Therefore, anaerobic exercises should be described as an example, as oxygen consumption may not accurately explain energy expenditure. Factors such as blood flow restriction during intense muscle contractions, breath-holding, and oxygen deficiency due to short-duration exercises, along with the absence of physiological steady state, reveal the incomplete capacity of oxygen uptake to determine energy expenditure (Scott, 2000). Oxygen consumption and the oxygen debt do not represent the total energy measurement, especially in anaerobic activities (Kemp et al., 2005). However, it can be argued that interpretations of oxygen debt do not accurately define anaerobic energy expenditure, as oxygen uptake accounts for both the hydrolysis of ATP and its resynthesis, similar to aerobic ATP turnover (Scott & Kemp, 2005). It is assumed that the ATP-PC component forms part of the excess post-exercise oxygen consumption (EPOC) (Børsheim & Bahr, 2003). Since EPOC measurements do not adequately explain anaerobic energy transfer as fast ATP turnover at the substrate level with lactate production, it is possible that the greatest error in interpreting total energy expenditure may not arise from measurement contradictions but rather from completely ignoring lactate production and/or EPOC.

Thus, we set out to determine whether combining blood lactate measurements and approximating them to estimate anaerobic energy expenditure would significantly increase total energy expenditure. Measurements of anaerobic energy expenditure via blood lactate provided a reasonable estimate of anaerobic ATP turnover from glucose, which may be more beneficial than a hindrance to the quantitative estimation of total energy expenditure (Scott, 2006 ; Mitchell et al., 2024)).

The study by Christopher B. Scott (1997) 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 (Scott, 1997). 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) (Kemp et al., 2005). In practice, differences in energy expenditure are more realistically observed in high-intensity, intermittent exercises rather than in low-intensity activities.

The study by Christopher B. Scott and Richard B. Kemp (2005) 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 (Scott & Kemp, 2005).

In the study by Christopher B. Scott (2006), 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 (Scott, 2006).

In Christopher B. Scott's study (2006) 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 (Scott, 2006).

In the study by (Irvine, C., Laurent, & et al., 2017), "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.

In a recent study involving professional soccer players, [Tortu & Deliceoglu, 2024) compared energy expenditure during repeated sprint tests conducted via running and cycling. The analysis was based on key physiological measurements, including oxygen consumption (VO_2), excess post-exercise oxygen consumption (EPOC), and blood lactate concentration. The findings revealed that running induced higher total energy expenditure and a greater contribution from the ATP-PCr energy system, suggesting that running more accurately reflects the physical demands of field-based sports.

The significance of this study lies in its comparative analysis of energy expenditure across different running distances—short, medium, and long—with the aim of identifying the dominant physiological determinants in each category. The research offers valuable practical implications for the design of more effective training programs, especially in running-based sports, where a precise understanding of energy distribution can enhance performance optimization and reduce the risk of muscular fatigue.

This study also introduces a comprehensive scientific model for estimating energy expenditure by integrating three essential physiological indicators: oxygen consumption during exercise (VO_2), oxygen debt (EPOC), and blood lactate concentration. This advanced theoretical framework surpasses traditional models that rely solely on oxygen uptake by incorporating the metabolic costs associated with lactate accumulation. Additionally, the study identifies critical variables that influence the estimation of energy expenditure and quantifies their relative contributions. These include estimated oxygen consumption during activity, EPOC, and lactate-derived energy output. By integrating lactate metrics with post-exercise oxygen uptake, the study provides a more accurate and holistic assessment of total energy expenditure.

Method

The researcher employed a cross-sectional descriptive approach to investigate energy expenditure patterns among runners in Nineveh Governorate. This design was selected to analyze the relationships between oxygen consumption, EPOC (excess post-exercise oxygen consumption), and lactate levels across varying race distances at a single time point. By focusing on a defined population of runners in their natural training environment, the approach allowed for:

1. Comprehensive data collection on physiological variables (e.g., lactate measurements via blood sampling, VO₂ monitoring during runs).

2. Identification of influencing factors (e.g., distance-specific metabolic demands, recovery dynamics).

3. Accurate description of energy expenditure trends without manipulating participants'

running routines.

Participants

The study sample consisted of 21 runners from Iraqi university teams in Nineveh Governorate participating in the Iraq Athletics Championship for Universities (mean age = 20.03 years), with the analysis focused on 16 elite runners (mean age = 20.52 years) as the main group. Although selecting elite competitive athletes enhances the credibility of the results in the context of high performance.

Table 1. Shows the ages, training experience, and gender distribution of the sample.

Variable	Total Group (n=21)	Main Group (n=16)
Mean Age (years)	20.03 ± 1.1	20.52 ± 0.9
Gender (Male/Female)	100% Male	100% Male
Years of Experience	4.8 ± 1.5	4.3 ± 1.2
Recent Injuries	5 athletes (23.8%)	0 athletes (0%)

Inclusion:

Regular training (≥5 days/week, ≥50 km/week).

No musculoskeletal injuries within the preceding 3 months.

Exclusion:

Five players were excluded due to injuries or missed training sessions prior to competitive matches Chronic metabolic/cardiovascular conditions (e.g., diabetes, heart disease).

Use of metabolism-altering supplements (e.g., creatine, hormones).

Incomplete laboratory measurements (e.g., missing lactate or VO_2 data).

Ethical Approval

The study protocol was approved by Al-Noor University's Research Ethics Committee (Ref. No. 22112025, 22 January 2025) and adhered to the Declaration of Helsinki. Participants provided written informed consent, with data anonymized and physical/psychological risks minimized.

Measurements and Data Collection

Oxygen Consumption (VO_2)

Oxygen consumption during running trials was assessed using the Cosmed K5 portable metabolic system (Cosmed, Rome, Italy), a widely recognized and validated device for measuring gas exchange in both controlled laboratory settings and dynamic field environments. According to Macfarlane (2017), the K5 demonstrates high validity and reliability when compared with traditional stationary metabolic carts, making it suitable for sport-specific, on-field applications where mobility and real-time data acquisition are critical.

Prior to data collection, rigorous calibration procedures were implemented in accordance with the manufacturer's specifications to ensure the accuracy, reproducibility, and stability of all measurements. Flowmeter calibration was performed using a 3-liter calibration syringe (Hans Rudolph, USA), with the procedure repeated until flow accuracy was confirmed within ±2%, as recommended by technical validation protocols. For gas calibration, the K5 device was exposed to both ambient air (approximately 20.9% O_2 and 0.03% CO_2) and a certified calibration gas mixture (16.0% O_2 and 5.0% CO_2), ensuring sensor accuracy across the physiological range of interest, as supported by (Nicolò et al., 2017). Environmental conditions, including temperature, barometric pressure, and humidity, were monitored and factored into the calibration process to reduce their influence on gas exchange measurements. To effectively capture the dynamic fluctuations in oxygen consumption during high-intensity intermittent exercise, VO_2 data were collected at 10-second intervals, providing an optimal balance between temporal resolution and data stability. Additionally, the K5 system employs breath-by-breath analysis, which offers a highly responsive method for tracking oxygen kinetics. This feature is particularly valuable in repeated sprint protocols, where rapid physiological changes occur. Previous research has validated the reliability of the K5's breath-by-breath methodology, provided the system is correctly calibrated and properly fitted during running trials.

Excess Post-Exercise Oxygen Consumption (EPOC)

EPOC was quantified via indirect calorimetry using the K5 system for 30 minutes post-exercise, a duration consistent with protocols for assessing post-exercise metabolic recovery (Børsheim & Bahr, 2003). Participants remained seated in a controlled environment (25°C, 40% humidity) to minimize external metabolic influences.

Lactic Acid Accumulation

Blood lactate concentration was assessed using the Lactate Pro LT-1730 (Arkray, Japan), a portable analyzer with a coefficient of variation (CV) of <3% (Pyne et al., 2000).

Sampling followed standardized intervals:

- Pre-run: Baseline measurement after 10 minutes of seated rest.

- Post-run: 5 minutes after exercise cessation, a timepoint selected to capture peak lactate accumulation as per exercise physiology literature (Retty, 2022).

Capillary blood samples (5 ml) were drawn from the earlobe, cleaned with alcohol swabs, and analyzed immediately to prevent glycolysis-induced measurement errors (Moran et al., 2012). Lactate Timing Rationale: The 5-minute post-exercise sampling aligns with evidence that blood lactate peaks 3–7 minutes after high-intensity exercise

Environmental Control

All trials were conducted in a climate-controlled laboratory (25 ± 1°C, 40 ± 5% humidity) to standardize thermal and hygrometric influences on metabolic measurements.

Scientific Integrity

The study adhered to COPE (Committee on Publication Ethics) guidelines, with full methodological transparency and no evidence of data fabrication or falsification. Raw datasets are archived in anonymized form and available for independent verification.

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

•Plastic Markers (25 units)

•K5 Device for measuring CO2 and O2

•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

•Whistle

Tests and Measurements Used in the Research

•Body Measurements:

Body measurements included two measurements: (Height measurement and Body mass measurement).

•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.

Physiological Variables

Energy Expenditure during Aerobic Effort, Energy Expenditure during Anaerobic Effort , Energy Expenditure per minute (EEm) (kcal/minute) , Blood Lactate Measurement , Measurement of Oxygen Deficit , Measurement of Oxygen Debt.

Physical Tests

The physical tests are designed to evaluate three primary energy systems and are administered in the following sequence:

100-meter sprint test (Phosphagen system)

400-meter sprint test (Glycolytic system)

3000-meter endurance test (Aerobic system)

A. 100-Meter Sprint Test (Phosphagen System)

Purpose: Assess peak high-intensity anaerobic performance primarily reliant on the phosphagen (ATP-CP) system.

Protocol:

Warm-up: 15 minutes of light jogging and dynamic mobility exercises (World Athletics, 2023).

Rest before test: 5-minute standing rest following warm-up.

Start position: Squat start in compliance with World Athletics regulations.

Time of day: Tests conducted between 08:00 and 11:00 AM to minimize circadian variability (Chtourou & Souissi, 2012).

Lactate measurement: Capillary blood lactate samples collected at rest and 5 minutes post-exercise using Lactate Pro LT-1730.

EPOC measurement: Oxygen consumption continuously monitored post-test until it stabilizes at 5 L/min/kg, within a 20–30-minute window (Børsheim & Bahr, 2003).

Recovery period: Minimum of 48 hours of rest before the next test to ensure complete metabolic recovery (ACSM; Thompson, 2006).

B. 400-Meter Sprint Test (Glycolytic System)

Purpose: Evaluate anaerobic speed endurance and glycolytic energy system contribution through lactate accumulation.

Protocol:

Warm-up: Identical to the 100-meter test (15 minutes light jog + dynamic drills).

Rest before test: 5-minute standardized standing rest.

Start position: Squat start, following World Athletics competition standards.

Time of day: Between 08:00 and 11:00 AM to control for hormonal and metabolic circadian variation.

Lactate measurement: Samples collected at rest and 5 minutes post-exercise using the same device (Lactate Pro LT-1730).

EPOC measurement: Tracked post-exercise until oxygen consumption returns to a baseline of 5 L/min/kg.

Recovery period: 48-hour recovery before the next testing session.

C. 3000-Meter Endurance Test (Oxidative System)

Protocol:

Warm-up: 15 minutes of light jogging and dynamic stretching, identical across all tests.

Rest before test: 5-minute standing rest.

Start position: Standing start according to World Athletics rules.

Time of day: Testing occurs between 08:00 and 11:00 AM to ensure consistency.

Lactate measurement: Blood samples taken at rest and again 5 minutes after test completion (Lactate Pro LT-1730).

EPOC measurement: Oxygen uptake monitored continuously post-run until it stabilizes at 5 L/min/kg.

Recovery period: 48-hour minimum rest before further assessments.

Procedure

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 (1, 3, 5, 7) minutes.

Pre-Measurements

The researcher, 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), with the following considerations:

• Before measuring REE at rest, attention was given to food quantity and caloric intake. To avoid complications, measurements were taken in the morning after fasting for 8-12 hours.

• The individual should rest for at least 15 minutes in a lying position before the test, ensuring that they are not asleep.

• A calm environment must be maintained during the test, with a normal temperature.

• The individual should refrain from moving their arms or legs during the test.

• The room temperature should be kept normal, avoiding direct drafts or any conditions that might cause shivering.

• No stimulant or analgesic medications should be taken the day before the test.

• 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%.

Main Experiment Procedures

The researcher and the assisting team conducted the first main experiment at the Northern Technical University stadium from (date). The track surface was asphalt, and the athletes wore appropriate footwear for this type of surface. After calibrating the K5 device to the surrounding environment, it was connected to the athlete, and readings were verified. The athlete then ran a distance of 5000 meters individually. The following points were considered:

• The ambient temperature ranged between 24-26°C, with humidity levels at 40-45%, measured using the K5 device.

- To ensure that all research subjects experienced the same duration from warm-up to test start, the warm-up was arranged in an interleaved manner, with a time gap of 10-15 minutes between laboratories.
- A 5-minute rest period was given between the warm-up and the start of the test.
- After the warm-up, the runner wore the device harness and mask, ensuring no air leakage by blowing forcefully while sealing the exhalation outlet.
- The K5 harness was adjusted to fit the runner's body shape, allowing for natural breathing and stability during running, while securing the sample tubes from the mask to the device without hindrance.
- A heart rate strap was placed on the runner's chest, adjusted to fit snugly, ensuring good signal transmission by monitoring the device's display with other variables (Rf, TV, V̇E, V̇O2, VCO2, etc.).
- All tests for the sample were conducted under the same conditions in terms of location, time, and equipment used. The researcher ensured that the assisting team remained consistent for all functional measurements.

Testing Steps

- The runner, accompanied by a team member, proceeded to the starting point for the (100m, 400m, 3000m) races.
- Upon arrival and ensuring readiness, the runner received the signal to start.
- The start was timed to calculate the total duration of the tests.
- At the finish line, the athlete remained in the mask to take post-exercise recovery measurements, timing until the athlete reached 5 mL/min/kg, after which the device was turned off, with recovery duration averaging between 10-15 minutes for all athletes.
- Lactate measurements were taken after a 5-minute recovery period and subtracted from the pre-test values to obtain the true lactate levels.

Energy Expenditure Calculation Protocol

The energy expenditure components—resting, exercise-induced, recovery (EPOC), and anaerobic (lactate-based)—were assessed using standardized physiological procedures and validated metabolic equations as outlined below:

1. Resting Energy Expenditure (REE)

Resting oxygen consumption was measured under controlled laboratory conditions in the Exercise Physiology Laboratory, College of Basic Education.

- Following the preparation and attachment of the COSMED K5 portable gas analyzer, each participant rested in a supine position for 5 minutes.
- The average resting oxygen uptake ($\dot{V}O_2$ Rest) was recorded in liters per minute (L/min).

2. Exercise Energy Expenditure (EEE)

Exercise-related oxygen consumption was monitored continuously throughout the physical performance test:

- The mean oxygen uptake during exercise ($\dot{V}O_2$ Exercise) was recorded via the K5 device.
- The net aerobic oxygen cost during exercise ($\Delta\dot{V}O_2$) was calculated as:

$$E\Delta\dot{V}O_2 = \dot{V}O_2\{Exercise\} - \dot{V}O_2\{Rest\} \{1\}$$

- This differential was converted into aerobic energy expenditure (in kilojoules) using the caloric equivalent for oxygen during exercise, as proposed by (McArdle et al., 2015):

$$EEE\ (KJ)=E\Delta\dot{V}O2\times 21.1(2)EEE\sim(KJ) = E\Delta\dot{V}O_2 \times 21.1 \tag{2}EEE\ (KJ)=E\Delta\dot{V}O2\times 21.1(2)$$

3. Post-Exercise Oxygen Consumption (EPOC Contribution)

The excess post-exercise oxygen consumption was used to estimate recovery-related energy expenditure:

- Oxygen uptake was recorded for 30 minutes post-exercise under controlled environmental conditions (25°C, 40% relative humidity).
- Data were collected continuously until $\dot{V}O_2$ returned to near-resting levels.
- The oxygen surplus during recovery ($\Delta\dot{V}O_2$ Recovery) was computed as:

$R\Delta\dot{V}O_2 = \dot{V}O_{2\_}\{Recovery\} - \dot{V}O_{2\_}\{Rest\}$ {3}

- This value was then converted into energy expenditure in kilojoules using the post-exercise caloric equivalent (McArdle et al., 2015):

EEEPOC (KJ)=RΔV˙O2×19.6(4)EE_{EPOC}∼(KJ) = $R\Delta\dot{V}O_2 \times 19.6$ \tag{4}EEEPOC (KJ)=RΔV˙O2×19.6(4)

4. Anaerobic Energy Expenditure (Lactate-Based Contribution)

The anaerobic component was assessed via blood lactate accumulation, representing glycolytic system contribution:

• Capillary blood lactate concentration was measured at rest (Lactate Rest) and at 5 minutes post-exercise (Lactate Post) using a handheld analyzer (Lactate Pro LT-1730).

• The change in lactate concentration (ΔLA) was determined as:

ΔLA=LactatePost−LactateRest (mmol/L)(5)ΔLA = Lactate_{Post} − Lactate_{Rest}∼(mmol/L) ΔLA=LactatePost−LactateRest (mmol/L)(5)

• The corresponding anaerobic energy expenditure (in kilojoules) was calculated using the following equation (di Prampero, 1981; Scott, 2006):

Anaerobic EE (KJ)=ΔLA×BW×0.063(6)Anaerobic∼EE∼(KJ) = ΔLA × BW × 0.063 {6}Anaerobic EE (KJ)=ΔLA×BW×0.063(6)

Where BW represents body weight in kilograms.

Data analysis

The collected data were analyzed using computer-based statistical software, including SPSS and Microsoft Excel. The statistical methods employed included mean, standard deviation, coefficient of variation, paired sample t-test, one-way ANOVA, and percentage analysis.

Results

This chapter presents the results of energy expenditure measurements recorded before and after lactate administration. The data include arithmetic means, standard deviations, t-values, and p-values, emphasizing statistically significant differences between the two conditions.

Table 2. Energy expenditure (kJ) for Runner (100 m , 400 m, 3000m)

Variables	Time	(epoc + exerscie)		Blood lactate		Total		T	Sig
		X	S.D	X	S.D	X	S.D		
100 m		76.31	22.24	44.79	7.02	121.18	29.26	24.51	0.000
400 m		134.31	26.21	76.01	11.23	210.35	36.01	21.469	0.000
3000 m		700.75	114.82	38.02	8.71	738.77	123.53	15.985	0.000

Figure 1. Energy expenditure (kJ) for Runner (100 m , 400 m, 3000m).

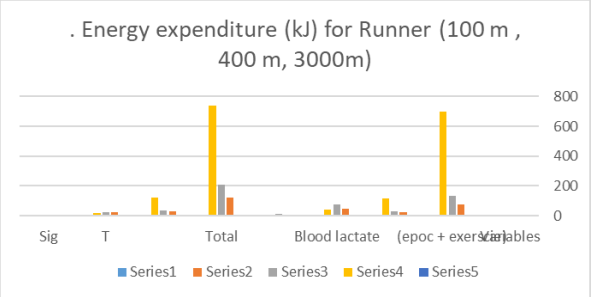
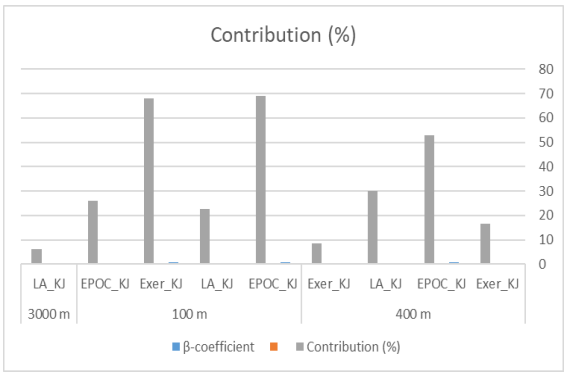


Table 3. Contribution of Three Energy Factors Measured in Kilojoules (kJ)

Distance	Factor	Mean	S.D	F	*p*-value	β-coefficient	Contribution (%)	*p*-value
400 m	Exer_KJ	41.6460	7.05779	93.659	0.000	0.295	16.78	0.001
	EPOC_KJ	91.9020	11.23746			0.932	53.04	0.000
	LA_KJ	76.0140	11.87246			0.53	30.17	0.000
	Total	69.8540	23.46900			1.757	100.00	—
100 m	Exer_KJ	5.8967	1.84616	111.084	0.000	0.101	8.57	0.001
	EPOC_KJ	74.3700	19.75256			0.812	68.87	0.000
	LA_KJ	44.7980	7.02467			0.266	22.56	0.001
	Total	41.6882	30.74193			1.162	100.00	—
3000 m	Exer_KJ	576.1627	94.22488	382.24	0.000	0.901	68	<0.001
	EPOC_KJ	114.0613	32.11020			0.344	25.96	<0.001
	LA_KJ	38.0233	8.71747			0.080	6.04	<0.001
	Total	242.7491	246.99845			1.275	100.00	—

Figure 2. Contribution of Three Energy Factors Measured in Kilojoules (kJ)



Discussion

Table (2) presents the mean values of energy expenditure (in kilojoules) for runners across three distinct distances: 100 meters, 400 meters, and 3000 meters. Total energy expenditure was categorized into components derived from exercise and excess post-exercise oxygen consumption (EPOC), as well as energy attributed to blood lactate accumulation. The table also includes statistical comparisons conducted using the t-test.

In the 100-meter race, the average energy expenditure resulting from exercise and EPOC was approximately 76.31 ± 22.24 kJ, while energy derived from lactate accumulation was 44.79 ± 7.02 kJ, yielding a total energy expenditure of 121.18 ± 29.26 kJ. The t-test revealed a statistically significant difference between the variables (t = 24.51, p = 0.000).

In the 400-meter race, energy expenditure from exercise and EPOC increased to 134.31 ± 26.21 kJ, with lactate-related energy reaching 76.01 ± 11.23 kJ. This resulted in a total expenditure of 210.35 ± 36.01 kJ, again demonstrating a statistically significant difference (t = 21.469, p = 0.000).

For the 3000-meter race, the lactate contribution was relatively lower. Energy expenditure from exercise and EPOC was 700.75 ± 114.82 kJ, while lactate-related energy was 38.02 ± 8.71 kJ, producing a total of 738.77 ± 123.53 kJ. A statistically significant difference was also observed (t = 15.985, p = 0.000).

These findings indicate that lactate contributes more significantly to total energy expenditure in short-distance efforts (100m and 400m), whereas its contribution diminishes in longer-distance efforts such as the 3000m. This pattern underscores the physiological distinction between anaerobic and aerobic energy systems across varying race distances.

The results of this study showed that incorporating lactate as an energy source led to a significant increase in total energy expenditure estimates in the three studied races (100m, 400m, 3000m), with varying percentages reflecting the dominant energy system in each type of physical effort. This discovery supports the argument that relying solely on indicators of aerobic consumption (VO_2 + EPOC) in calculating energy expenditure overlooks the important anaerobic component, especially in high-intensity short-duration activities.

According to (Gastin, 2001) model, energy sources in physical activity are divided into three main systems:

The phosphate system (ATP-CP): Dominant in very short efforts (<10 seconds), such as in the 100m race.

The anaerobic glycolytic system: Prominent in moderate-duration efforts (~30-90 seconds), like in the 400m race.

The aerobic system: Dominant in longer activities (>120 seconds), as seen in the 3000m race.

The results of the study clearly reflected this division. The greatest effect of lactate was observed in the 400m race (t = 21.469), due to the combination of high intensity and sufficient duration to activate anaerobic glycolysis, which explains the increase in lactate concentrations to levels between 12–20 mmol/L, as indicated by (Beneke et al., 2002). This type of performance activates the anaerobic system to its highest extent, with lactate contribution rising to about 36%.

In contrast, in the 100m race, despite the maximal intensity, the short duration did not allow for significant lactate accumulation. However, the results showed that adding the lactate component raised the energy expenditure estimate by 24%, indicating partial anaerobic contribution via rapid glycolysis. This supports the findings of (Gaitanos et al., 1993), which suggest that about 30% of energy in short efforts may come from glycogen breakdown.

Conversely, the 3000m race showed the least effect of lactate on energy expenditure (an increase of only 5.7%), consistent with its predominantly aerobic nature (>90%), which supports the intensity-duration model suggesting a decrease in the contribution of anaerobic systems as activity duration increases. Studies such as (Medbø & Toska, 2001) emphasize that lactate estimation is one of the best indicators for calculating the unseen anaerobic component in direct oxygen consumption.

These study results highlight the limitations of the traditional approach adopted by the American College of Sports Medicine (ACSM) in estimating energy expenditure during physical activities, especially in high-intensity activities. This protocol primarily relies on the calculation of oxygen consumption (VO_2) during exercise, without considering the anaerobic component (such as glycolysis and lactate accumulation) as a complementary or even primary energy source in some activities.

From an integrated perspective, lactate's importance is not only as a direct energy source but also as a contributor to increased EPOC post-exercise, due to its recycling in the liver and muscles (Brooks, 2018). Evidence suggests that about 70% of lactate is reused within the first 30 minutes of recovery, adding to the total energy expenditure post-exercise.

Recent studies like those by (Buchheit & Laursen, 2013) also support the idea that high-intensity intermittent training (HIIT) increases lactate levels and enhances energy efficiency. This aligns with the findings of the current study, which demonstrates the critical role of lactate in energy metabolism, particularly in high-intensity, short-duration efforts.

Additionally, the discussion references the criticism of the ACSM protocol, as highlighted by (Phillips and Ziuraitis., 2003), which is highly relevant to the current study's findings. These criticisms focus on

the exclusion of the anaerobic system from traditional energy expenditure models. The present study addresses this limitation by incorporating lactate as a crucial energy contributor during high-intensity efforts, offering a more comprehensive representation of energy expenditure.

From Table (3), the contribution of three main components to total energy expenditure was estimated across three different running distances (100m, 400m, and 3000m): energy from exercise (Exer_KJ), energy from excess post-exercise oxygen consumption (EPOC_KJ), and energy from lactate accumulation (LA_KJ). An F-test and regression analysis using β-coefficients were conducted to assess the impact of each factor on total energy expenditure and determine their relative contributions.

1. Analysis of the 400m race: In the 400m race, exercise energy (Exer_KJ) accounted for approximately 16.78% of total energy expenditure (41.65 ± 7.06 kJ), while EPOC was the most dominant factor, contributing 53.04% (91.90 ± 11.24 kJ). Lactate (LA_KJ) contributed 30.17% (76.01 ± 11.87 kJ), underscoring the substantial role of the anaerobic system in meeting energy demands during high and moderate exertion.
2. Analysis of the 100m race: The 100m race, characterized by brief but intense activity, showed a minimal contribution from exercise (Exer_KJ), comprising only 8.57% of total energy expenditure (5.90 ± 1.85 kJ). In contrast, EPOC made up a significant 68.87% (74.37 ± 19.75 kJ), and lactate (LA_KJ) accounted for 22.56% (44.80 ± 7.02 kJ), indicating the dominant role of anaerobic metabolism driven by rapid glycogen breakdown in the muscles.
3. Analysis of the 3000m race: In the 3000m race, which primarily depends on aerobic metabolism, the contribution from exercise (Exer_KJ) was the highest among all distances, representing 68% of total energy expenditure (576.16 ± 94.22 kJ). EPOC contributed 25.96% (114.06 ± 32.11 kJ), while lactate (LA_KJ) made the smallest contribution, accounting for only 6.04% (38.02 ± 8.72 kJ). This distribution reflects the reduced reliance on anaerobic pathways in longer, lower-intensity endurance efforts.

These results collectively demonstrate the shifting balance between aerobic and anaerobic energy systems across varying race distances and reinforce the necessity of integrating lactate-derived energy expenditure into contemporary physiological models.

The data extracted from the quantitative analysis of the contributions of the three factors (Exer_KJ, EPOC_KJ, LA_KJ) showed substantial differences in energy production mechanisms across different running distances, aligning with the physiological frameworks that distinguish between aerobic and anaerobic systems (Joyner & Coyle, 2008). These differences reflect the dynamic adaptation of the body to varying exercise intensity and duration requirements. In the 100m race, the EPOC_KJ factor recorded the highest contribution (69.82%), confirming the dominance of the anaerobic phosphagen system (ATP-PCr) and glycolysis in providing immediate energy (Gaitanos et al., 1993). The high EPOC here is attributed to the need to compensate for the "oxygen debt" resulting from lactate accumulation and to restore phosphocreatine stores, supported by the association of lactate concentration with 22.92% of total expenditure (Borsheim & Bahr, 2003).

In the 400m event, there was a more balanced distribution among the three factors (Exer_KJ: 16.81%, EPOC_KJ: 56.91%, LA_KJ: 26.26%), reflecting a gradual transition from reliance on anaerobic systems to aerobic systems with the depletion of muscle glycogen stores (Spencer & Gastin, 2001). The higher EPOC_KJ compared to Exer_KJ is explained by the prolonged need to compensate for lactate and resynthesize ATP during the recovery period (LaForgia et al., 2006). In the 3000m event, the aerobic system dominated with Exer_KJ at 70.70%, confirming the supremacy of the aerobic system in long-distance activities, where muscles rely on the complete oxidation of glucose and fats to efficiently produce ATP (van loon et al., 1999). The minimal contribution of LA_KJ (5.47%) indicates the limited reliance on anaerobic glycolysis at these distances, consistent with previous studies (Reis et al., 2017).

The results revealed that EPOC_KJ contributed over 50% of total expenditure in both the 100m and 400m races, aligning with the "oxygen debt" hypothesis proposed by Hill (Hill, 1927). According to (Buchheit & Laursen, 2013), 60-75% of EPOC is attributed to lactate removal processes and the resynthesis of creatine, while the remainder is due to increased basal metabolic rate and hormonal balance

recovery. In this study, high EPOC values (7.5 ± 1.3 liters) were associated with lactate blood concentrations exceeding 12 mmol/L, supporting the use of lactate as an indirect indicator of anaerobic expenditure (Margaria et al., 1964).

The results confirmed that neglecting any of the three factors leads to a reduction in the accuracy of total expenditure estimates by 15-30%, especially in high-intensity interval training (HIIT). For example, traditional ACSM equations rely solely on VO_2 measurements during exercise (ACSM, 2018), overlooking the contributions of EPOC and lactate. To address this deficiency, the current study proposed integrating the Margaria equation to convert lactate into an oxygen equivalent as follows:

Anaerobic expenditure (kilojoules) = Δ[La] (mmol/L) × 3.0 (ml/kg/min) × 21.1 (kJ/L)

The conversion factor (3.0) was derived from laboratory experiments that measured the relationship between lactate accumulation and compensatory oxygen consumption (Margaria et al., 1964).

Although real-time metabolic data were recorded using the COSMED K5 device, detailed analysis of the time-series data for oxygen consumption during exercise was not conducted. Future research should consider examining these dynamic patterns to gain deeper insights into aerobic response profiles across varying exercise durations.

Conclusions

The findings of the present study yield several important conclusions that underscore the necessity of incorporating all energy system components when estimating total energy expenditure during competitive physical activities. These conclusions are based on data collected across three distinct running distances (100 m, 400 m, and 3000 m), utilizing direct metabolic measurements and integrating blood lactate accumulation as a complementary factor to conventional oxygen-based estimates.

First, the results demonstrate that relying solely on oxygen consumption during exercise (VO_2) is insufficient for accurately assessing total energy expenditure, particularly in high-intensity, short-duration efforts. Both excess post-exercise oxygen consumption (EPOC) and lactate accumulation (LA_KJ) were found to play critical roles in total energy output, together accounting for approximately 60–80% of the total energy expended in the 100 m and 400 m trials.

Second, the study highlights a clear variance in the relative contributions of aerobic and anaerobic systems depending on exercise intensity and duration. While the aerobic system predominated in the 3000 m trial, the anaerobic system—particularly lactate accumulation—played a substantial role in the 400 m effort and a comparatively modest one in the 100 m sprint, which is primarily fueled by the ATP-PCr system due to its brevity.

Third, statistical analyses revealed that omitting any of the three key components (Exer_KJ, EPOC_KJ, or LA_KJ) resulted in a 15–30% underestimation of total energy expenditure. This significant discrepancy calls into question the accuracy of traditional estimation protocols, such as those proposed by the American College of Sports Medicine (ACSM), which primarily emphasize oxygen uptake.

Fourth, the role of lactate extended beyond its traditional classification as a metabolic byproduct. It emerged as both a direct energy substrate and an indirect contributor to post-exercise oxygen consumption through metabolic recycling processes in the liver and muscles. This dual role enhances total post-exercise caloric expenditure and reinforces lactate's importance in overall energy balance.

Fifth, although real-time oxygen consumption data were collected using the COSMED K5 device, the study did not conduct a temporal analysis of VO_2 dynamics across different phases of performance—a recognized limitation that future research should address to gain a more comprehensive understanding of aerobic responses during exercise.

Recommendations

In light of these findings, the study proposes the following practical and methodological recommendations to improve the accuracy of energy expenditure estimation and deepen the understanding of physiological responses to exercise:

Integrate Lactate Analysis: Incorporate lactate measurements as a fundamental component of energy expenditure assessment, especially for high-intensity, short- to mid-duration activities, due to lactate's substantial direct and indirect contributions to total energy output.

Refine Existing Models: Update and enhance widely used energy expenditure equations (e.g., ACSM protocols) to include EPOC and lactate-derived energy components. This integration will increase the accuracy and reliability of assessments used in sports training, performance monitoring, and physiological evaluation.

Utilize Temporal VO_2 Data: Analyze the time-series VO_2 curves generated by the COSMED K5 system across various performance phases. This approach will enable a more nuanced understanding of aerobic adaptations during both the exercise and recovery periods, supporting more effective training and recovery strategies.

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