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WORD COUNT 4112

TIME SUBMITTED 06-JAN-2025 03:38PM

PAPER ID 113884630

Indonesian Journal of Physical Education and Sport Science

IJPESS
Indonesian Journal of Physical Education and Sport Science
p-ISSN 2775-765X | e-ISSN 2776-0200
Volume 5, No. 1, March 2025 Page. 15-24
http://journal.unucirebon.ac.id/index.php ijpess

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Received: 20 November 2024, Approved: 31 December 2024, Published: 30 March 2025

Abstract

Study purpose. This study aims to investigate the effects of non-aerobic (anaerobic) effort accumulation on select functional variables and blood lactate concentrations in middle-distance runners. A diverse cohort of experienced middle-distance runners was recruited for this study.

Materials and methods. The study involved 30 experienced middle-distance runners. The participants engaged in a series of controlled, high-intensity anaerobic exercises to induce the accumulation of anaerobic effort. Following these exercises, we measured a range of functional variables, including maximal oxygen uptake (VO2 max), heart rate, stroke volume, critical indicators of cardiovascular function, and aerobic fitness. Simultaneously, blood samples were drawn from the participants before and after the exercise regimen to quantify blood lactate levels.

Results. The VO2 max showed a slight decline post-exercise (58.7 ± 6.4 mL/kg/min) compared to the baseline measure (61.3 ± 6.7 mL/kg/min). In addition, there was a significant increase in heart rate post-exercise (185.4 ± 8.6 beats/min) compared to pre-exercise (79.2 ± 8.3 beats/min).

Conclusions. The decrease in VO2 max post-exercise indicated a decline in aerobic performance, a typical response to high-intensity exercise. Also, the rise in lactate concentrations post-exercise and the subsequent decrease during recovery provided evidence of anaerobic metabolism during high-intensity exercise and the body's efficient lactate clearance mechanism during recovery. This study contributes to understanding lactate metabolism during and after high-intensity exercise. The findings also contribute to understanding how the body adapts to exercise and have potential implications for designing training and recovery strategies for athletes.

Keywords. Middle Distance Running, Functional Variables, Blood Lactate, Heart Rate, Exercise Physiology, Training Protocols.

DOI: https://doi.org/10.52188/ijpess.v5i1.920

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Introduction

Middle-distance running events ranging from 800 to 5000 meters require athletes to balance their aerobic and anaerobic energy systems. Athletes must have both endurance and the ability to generate speed. Depending on oxygen intake and utilization, aerobic capacity contributes to a runner's endurance (Burke, Castell, Casa, Close, Costa, Desbrow, ... & Stellingwerff, 2019). The more efficiently a runner uses aerobic metabolism, the longer they can sustain submaximal running speeds. However, high-intensity intervals and surges in pace also require anaerobic metabolism, which breaks down fuels without oxygen. These anaerobic bursts are powered by two systems: the phosphagen system utilizes ATP and creatine phosphate for short bursts of up to 10 seconds, while glycolysis breaks down stored glycogen into lactate to fuel speeds up to 2 minutes (Frivold, 2021).

The optimal blend of aerobic endurance and anaerobic power allows middle-distance runners to run fast while sustaining near-maximal or maximal effort for the duration of the race. Developing both energy systems is vital, as aerobic capacity provides the foundation for race pace. At the same time, anaerobic power enables surges and kicks to out-split competitors in the later stages of the race (Girard, Brocherie, & Millet, 2017). Through training, middle-distance runners can improve their balance of aerobic and anaerobic capabilities to achieve peak performance over their specific race distances (Stellingwerff, Maughan, & Burke, 2013). Anaerobic energy systems are vital for success in middle-distance track events. Runners rely on their anaerobic capacity to produce the high-intensity bursts of speed needed to finish strong and out-kick their competitors. However, using anaerobic energy has drawbacks that runners must manage (Greene & Pate, 2014).

Anaerobic glycolysis, which provides energy when the oxygen supply is insufficient, powers surges in pace during the later stages of middle-distance races (Kwon, Lee, Park, & Johnson, 2019). The "anaerobic kick" in the final 400 meters can be the difference between a win and a loss. Runners training for these events must develop a high anaerobic capacity to execute decisive finishing moves (Maglischo, 2012).

However, excessive or prolonged anaerobic effort takes a toll on performance. Glycolysis produces lactate as a byproduct, and as lactate builds up in the muscles and bloodstream, it can interfere with muscle contractions, damage cells, and cause fatigue (Smith, Scott, Girard, & Peiffer, 2022). Middle-distance runners aim to sustain a threshold of anaerobic effort that maximizes the benefits of anaerobic speed while limiting the detrimental effects of metabolic waste accumulation (MacDougall, MacDougall, & Sale, 2014).

Proper pacing and race strategy can help runners manage their anaerobic contributions optimally. Training focuses on improving lactate threshold and clearance, allowing for higher-intensity bursts before fatigue sets in. Thus, aerobic development acts as a foundation (Yang & Chang, 2023), while targeted anaerobic training empowers runners to execute the speed necessary to achieve peak performance over middle-distance events (Blagrove, Howatson & Hayes, 2018). The lactate threshold protocol is essential for enhancing endurance athletes' training and performance. It is considered a crucial physiological indicator that characterizes the change in metabolism during exercise from aerobic to anaerobic. During lactate threshold training, increased lactate clearance rates postpone the onset of tiredness, especially when running longer distances. Additionally, it results in changes to the patterns of muscle fiber activation, which enhances endurance performance. By understanding the lactate threshold and how it affects long-distance running performance, coaches and athletes may create training plans that precisely target and maximize this crucial physiological parameter (Vijay, Sivakumar, Kumar, Muralidharan, Rajkumar, Kannan, ... & Anand, 2024).

The impact of anaerobic effort on physiological variables is that anaerobic effort in middle-distance running impacts multiple physiological factors that influence performance. Understanding how anaerobic contributions affect variables like VO2 max, heart rate, and stroke volume can offer valuable insights into the demands of these events and guide training (Shete, Bute, & Deshmukh, 2014; Al-Rashidi & Al-Hayali, 2024).

Maximal oxygen uptake (VO2 max) represents an athlete's aerobic capacity and limits their sustainable running speed. While aerobic fitness primarily depends on VO2 max (Kamarudin, Sasmarianto, & Rahmalia, 2024), repeated bursts of anaerobic work can also impact it. Some research suggests brief high-intensity intervals may help boost VO2 max over time by promoting adaptations that enhance oxidative enzyme activity and capillary density within muscles (Kurtz, VanDusseldorp, Doyle, Otis, 2021). However, prolonged anaerobic effort before complete recovery can inhibit VO2 max by increasing blood lactate (Laursen, Jenkins, 2002).

Heart rate and stroke volume also change in response to anaerobic efforts during middle-distance running. Heart rate rises with increasing intensity while stroke volume—the amount of blood pumped per beat—plateaus and then decreases at high intensities (Tanaka, Seals, 2008). Heart rate and stroke volume influence cardiac output, a key determinant of aerobic performance (Laursen, Buchheit, 2019).

Understanding how anaerobic contributions impact key variables like VO2 max, heart rate, and stroke volume allows coaches and athletes to fine-tune training. Balancing aerobic development with targeted anaerobic training can optimize these physiological factors to improve performance over middle-distance race distances (Barwood, Weston, Thelwell, Page, 2009).

The study's objective: This study aims to investigate the effects of non-aerobic (anaerobic) effort accumulation on select functional variables and blood lactate concentrations in middle-distance runners. The results could significantly contribute to the body of knowledge in exercise physiology and potentially inform future training strategies for middle-distance runners.

Materials and Methods

Participants

The study involved a group of 30 experienced middle-distance runners (15 males, 15 females), ranging in age from 18 to 35 years, with at least two years of competitive experience. The sample size is 30 participants (15) female and (15) male, and they were matched by age and (body mass index), which is a substitute for weight and is more accurate than weight and the maximum value of relative oxygen consumption, which depends on body weight. Participants were excluded if they had any known cardiovascular, respiratory, or metabolic diseases, or if they were on any medication that could affect their physiological responses to exercise. Written informed consent was obtained from all participants prior to their involvement in the study, following the principles outlined in the Declaration of Helsinki.

Experimental Design

The study used a within-subjects design, with each participant serving as their own control. Each runner completed a series of controlled, high-intensity anaerobic exercises to induce the accumulation of anaerobic effort. Prior to the exercise regimen, baseline measures of functional variables and blood lactate levels were taken. Post-exercise measurements were collected immediately after the exercise regimen and at 30-minute intervals for 2 hours.

Exercise Protocol

The anaerobic exercise protocol consisted of repeated 200-meter sprints on an outdoor 400-meter track, with each sprint followed by a 200-meter walking recovery period. The intensity of the sprints was set to elicit a near-maximal effort, with runners instructed to complete each sprint as fast as they could. The number of sprints completed was individualized based on each runner's anaerobic capacity, as determined by a prior maximal anaerobic running test (MART) (Achten, Jeukendrup, 2003). The researchers determined periods starting from 30 min to 120 min, with an increase of 30 min between the race and the next. The recovery period was calculated based on positive rest (walking), and the distance was used as intensity instead of time, which is the practice in sports training in determining the intensity, whether it is from the pulse intensity or time or from the intensity of the exercise (distance covered).

Measurement of Functional Variables

Maximal oxygen uptake (VO2 max), heart rate, and stroke volume were measured before and after the exercise regimen. VO2 max was estimated using a graded exercise test on a treadmill. Heart rate was assessed using a heart rate monitor, and stroke volume was calculated using Doppler echocardiography.

Blood Lactate Measurement

Blood samples were drawn from the participants' fingertips before the exercise, immediately after, and at 30-minute intervals for 2 hours post-exercise. Blood lactate levels were determined using a portable lactate analyzer (Bassett, Howley, 2000).

Statistical Analysis

Paired t-tests were used to compare pre-and post-exercise measures of functional variables and blood lactate levels. Repeated measures ANOVA was used to analyze changes in these measures over the 2-hour post-exercise period. Statistical significance was set at $p < 0.05$.

Results

Participant Demographics

Thirty middle-distance runners (15 male and 15 female) participated in the study. Table 1 summarizes the participant demographics.

Table 1. Participant Demographics

Demographic	**Mean ± SD**
Age (years)	24.8 ± 4.2
BMI (kg/m2)	21.5 ± 1.8
VO2 max at baseline (mL/kg/min)	61.3 ± 6.7

Functional Variables

Maximal Oxygen Uptake (VO2 max)

The VO2 max showed a slight decline post-exercise (58.7 ± 6.4 mL/kg/min) compared to the baseline measure (61.3 ± 6.7 mL/kg/min), indicating a -4.2% change. The decrease in VO2 max post-exercise suggests a decline in aerobic performance.

Heart Rate

There was a significant increase in heart rate post-exercise (185.4 ± 8.6 beats/min) compared to pre-exercise (79.2 ± 8.3 beats/min), indicating a +134.2% change.

Stroke Volume

Stroke volume remained relatively unchanged post-exercise (70.3 ± 9.2 mL/beat) compared to pre-exercise (71.1 ± 10.1 mL/beat), indicating a -1.1% change.
Changes in these functional variables are summarized in Table 2.

Table 2. Changes in functional variables pre- and post-exercise

Variable	Pre-Exercise (mean ± SD)	Post-Exercise (mean ± SD)	Change %
VO2 max (mL/kg/min)	61.3 ± 6.7	58.7 ± 6.4	-4.2
Heart Rate (beats/min)	79.2 ± 8.3	185.4 ± 8.6	+134.2
Stroke Volume (mL/beat)	71.1 ± 10.1	70.3 ± 9.2	-1.1

The significant increase in heart rate and unchanged stroke volume post-exercise suggests that the body's cardiac response to exercise primarily involves increasing the heart rate rather than the stroke volume.

Blood Lactate Concentrations

The rapid increase in blood lactate concentrations post-exercise and subsequent gradual decrease during recovery provide clear evidence of anaerobic metabolism during high-intensity exercise and the body's ability to clear lactate during recovery.

Changes Over Time

Blood lactate concentrations increased significantly post-exercise and showed a gradual decrease over the 2-hour recovery period. The changes in blood lactate concentrations over time are summarized in Table 3.

Table 3. Changes in Blood Lactate Concentrations Over Time

Time Point	Lactate Concentration (mmol/L) (mean ± SD)
Pre-Exercise	1.3 ± 0.4

Post-Exercise	9.3 ± 2.1
30 min post-exercise	7.1 ± 1.8
60 min post-exercise	3.8 ± 1.3
90 min post-exercise	2.3 ± 0.9
120 min post-exercise	1.7 ± 0.6

Comparison between Males and Females

A separate analysis was conducted to compare lactate concentrations between male and female participants. This comparison is summarized in Table 4.

Table 4. Comparison of Blood Lactate Concentrations between Males and Females

Time Point	Males (mmol/L) (mean ± SD)	Females (mmol/L) (mean ± SD)
Pre-Exercise	1.2 ± 0.3	1.4 ± 0.5
Post-Exercise	9.5 ± 2.3	9.1 ± 1.9
30 min post-exercise	7.3 ± 1.6	6.9 ± 1.9
60 min post-exercise	3.9 ± 1.2	3.7 ± 1.4
90 min post-exercise	2.2 ± 0.8	2.4 ± 1.0
120 min post-exercise	1.6 ± 0.5	1.8 ± 0.7

The comparable changes in lactate concentrations in males and females suggest that gender does not significantly affect lactate metabolism during and after high-intensity exercise. The statistical analysis results, conducted using paired t-tests and repeated measures ANOVA, are summarized in Table 5.

Table 5. Statistical Analysis Results

Variable	Pre-post exercise t-test (p-value)	ANOVA (p-value)
VO2 max	0.021	0.035
Heart Rate	< 0.001	< 0.001
Stroke Volume	0.23	0.21
Lactate Concentration	< 0.001	< 0.001

Discussion

The main objective of this study was to investigate the physiological changes that occur in the body during and after high-intensity exercise, with a particular focus on lactate concentrations. The results showed significant changes in certain physiological parameters post-exercise, providing insights into how the body responds to high-intensity exercise.

Several physiological mechanisms enhance rate and pulse volume during high-intensity exercise to ensure efficient oxygen delivery. For example, during exercise, the amount of blood returning to the heart increases, leading to increased ventricle filling. Also, increasing exercise intensity leads to more blood pumping, which helps increase the grip size. In addition, as the intensity of exercise increases, heart rates and blood flow increase, which helps improve players' performance (McArdle, Katch, Katch, 2010). In addition, during intense exercise, blood is preferentially directed toward active muscles and away from less important areas (such as the gastrointestinal tract and other organs), ensuring that oxygen is efficiently delivered where it is most needed.

As appeared in Table 2, the decrease in the mean value in VO2 max post-exercise to 58.7 from 61.3 in pre-exercise was an anticipated outcome aligned with previous research that reported a similar trend (Smith et al., 2018). It reflects the body's exhaustion after high-intensity exercise, indicating the limit of its ability to uptake, transport, and utilize oxygen during progressively increased exercise intensity (Bassett & Howley, 2000). Low VO2 max can be attributed to several factors, including fatigue and exhaustion that the body suffers from, which causes a decrease in VO2 max. In addition to depleting muscle glycogen stores due to long periods of exercise, which affects oxygen consumption. Also, recovery time and insufficient time between training and recovery or rest periods decrease VO2 max (Rosenblat, Granata, Thomas, 2022).

The increase in heart rate post-exercise (mean value is increased from 79.2 to 185.4 for pre and post-exercise, respectively), as shown in Table 2, is a common physiological response. It helps to meet the body's increased oxygen and nutrient demand during exercise (Achten & Jeukendrup, 2003). The fact that stroke volume remained nearly unchanged may be attributed to the high-intensity nature of the exercise, which is often associated with a plateau in stroke volume, a phenomenon referred to as the "stroke volume paradox" (Gledhill, Cox, & Jamnik, 1994).

Table 3 shows that the increase in lactate concentrations post-exercise (mean value = 9.3) is a clear indication of anaerobic metabolism. During high-intensity exercise, the body's demand for energy exceeds the supply available from aerobic metabolism, causing a shift towards anaerobic glycolysis, resulting in lactate production (Brooks, 2009). The subsequent decrease in lactate during recovery from 7.1 to 1.7 indicates the body's ability to clear lactate through various mechanisms, including conversion back to glucose in the liver through the Cori cycle (Gladden, 2004; Saghiv & Sagiv, 2020).

The results in Table 4 show that the lack of significant gender differences in lactate concentrations is consistent with the existing literature. Several studies have reported similar lactate responses to exercise in males and females (Heck et al., 1985). This suggests that gender does not significantly affect lactate metabolism during and after high-intensity exercise. Conversely, some studies have shown that the anaerobic performance of male and female athletes, such as in swimming or track and field, shows some differences related to gender, with a difference of up to 20% in favor of males, as found in the results of the study (Reaburn, Dascombe, 2009). In addition, this change is attributed to some differences in physiology and muscle strength in addition to oxygen consumption (Landen, Hiam, Voisin, Jacques, Lamon, Eynon, 2023). As a result, some training strategies show specificity due to gender, including strength training for men, which focuses on muscle growth and hypertrophy, and endurance training for women, as women are characterized by endurance and fatigue resistance through the use of high-intensity training that relies on periods interspersed with rest periods (Hunter, 2016)

Conclusions

In conclusion, the decrease in VO2 max post-exercise indicated a decline in aerobic performance, a common response to high-intensity exercise. The increased heart rate and unchanged stroke volume post-exercise suggested that the body's primary cardiac response to exercise is an increased heart rate. The rise in lactate concentrations post-exercise and the subsequent decrease during recovery provided evidence of anaerobic metabolism during high-intensity exercise and the body's efficient lactate clearance mechanism during recovery. No significant gender differences were observed in lactate responses, indicating that sex did not significantly influence lactate metabolism during and after high-intensity exercise. This study provided a comprehensive analysis of the physiological responses to high-intensity exercise, particularly the changes in lactate concentrations.

While this study provides valuable insights into the physiological responses to high-intensity exercise, it has several limitations. For instance, the sample size was relatively small, which may affect the generalizability of the results. In addition, the study did not account for individual fitness levels, which could significantly influence the physiological responses to exercise.

This study provides valuable insights into the physiological responses to high-intensity exercise, which can help inform the design of effective training programs and recovery strategies for athletes. Additionally, the study contributes to the existing body of knowledge on exercise physiology, particularly understanding lactate metabolism during and after high-intensity exercise. Future research should address these limitations and may also explore the genetic and molecular mechanisms underlying the observed physiological responses.

Acknowledgment

Thank you to all parties who have helped the author in completing this research.

Conflict of interest

All authors stated that there was no internal conflict

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Cite this article as: Gorgees, Shtha Hazim. (2024). The Effect of Accumulation of Non-aerobic Effort on Some Functional Variables and Blood Lactate for Middle Distance Runners. *Indonesian Journal of Physical Education and Sport Science (IJPESS)*, *5*(1), 15-24. https://doi.org/10.52188/ijpess.v5i1.920

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