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EFFECTS OF ENDURANCE, STRENGTH, AND SPEED TRAINING MODALITIES ON PHYSIOLOGICAL, HAEMATOLOGICAL AND PERFORMANCE DETERMINANTS INFLUENCING ELITE ETHIOPIAN MIDDLE AND LONG-DISTANCE ATHLETES

BY

NIGATU WORKU

A DISSERTATION SUBMITTED TO THE COLLEGE OF EDUCATION AND LANGUAGE STUDIES OF ADDIS ABABA UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN SPORT SCIENCE (EXERCISE PHYSIOLOGY)

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This is to certify that the dissertation prepared by **Nigatu Worku**, entitled **'Effects of Endurance, Strength and Speed Training Modalities on the Physiological, Hematological and Performance Determinants Influencing Elite Ethiopian Meddle and Long-Distance Athletes'** and submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy in Sport Science (Exercise Physiology) complies with the regulations of Addis Ababa University and meets the accepted standards with respect to originality and quality.

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DEDICATION

This dissertation is dedicated to my parents, whose support and encouragement made this work possible.

STATEMENT OF AUTHOR

I, Nigatu Worku, declare that this dissertation, titled "**EFFECTS OF ENDURANCE, STRENGTH, AND SPEED TRAINING MODALITIES ON PHYSIOLOGICAL AND HAEMATOLOGICAL DETERMINANTS OF MIDDLE AND LONG-DISTANCE ELITE ATHLETES' PERFORMANCE**," is my own original work. It has not been submitted for any degree or examination in any other university, and all sources of material used for the dissertation have been duly acknowledged.

Signature: _________________________

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Date: _______________

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LIST OF ABBREVIATIONS

AAU	Addis Ababa University
ANOVA	Analysis of Variance
Hgb	Haemoglobin
Hrmax	Maximal Heart Rate
Htc	Haematocrit
Hct	Hematocrit
HIIT	High-Intensity Interval Training
LDH	Lactate Dehydrogenase
LT	Lactate Threshold
MAOD	Maximal Accumulated Oxygen Deficit
MCV	Mean Corpuscular Volume
RE	Running Economy
RFD	Rate of Force Development
RBC	Red Blood Cell
RDW	Red Cell Distribution Width
RHR	Resting Heart Rate
SD	Standard Deviation
tHgb-mass	Total Haemoglobin Mass
VO_2 max	Maximal Oxygen Uptake
WBC	White Blood Cell

ABSTRACT

Middle- and long-distance running performance is influenced by a complex interplay of aerobic and anaerobic determinants, haematological and physiological factors, anthropometric characteristics, diet, genetics, and various training modalities. While the efficacy of endurance, strength, and speed training modalities has been widely studied, their effects on haematological and physiological determinants in the context of Ethiopian middle- and long-distance athletes remain underexplored. This study aimed to investigate the impact of endurance, strength, and speed training modalities on physiological and haematological determinants of performance among elite Ethiopian athletes. A quasi-experimental design was employed, involving 20 elite middle- and long-distance athletes from the Ethiopian Adidas team. The athletes underwent 6-week blocks of endurance, strength, and speed training interventions, with pre- and post-tests conducted to assess changes in selected physiological (VO2 max, resting heart rate, energy expenditure) and haematological (hemoglobin, hematocrit, RBC, WBC) determinants. Performance was evaluated through event-specific time trials, 400-meter sprint tests, and indirect VO2 max tests. Haematological assessments were conducted using complete blood chemistry laboratory tests. This thesis, structured as an article-compilation, presents four distinct studies. Each Study details the specific adaptations in physiological, haematological, and performance measures resulting from the respective training modality. The first study examines the effects of the endurance training intervention on key physiological and haematological determinants of performance. The second study investigates the effects of the strength training block. The third study analyzes speed training and, the final study examine the combined effects of these training interventions on physiological, haematological and performance determinants among elite Ethiopian athletes. The final chapter synthesizes the combined effects of these training interventions, draws overall conclusions, and offers practical recommendations for coaches and athletes, as well as directions for future research. Endurance training increased VO_2 max (+6.20 ml/kg/min, $p<0.001$), reduced resting heart rate (-3.80 bpm, $p<0.001$), elevated haemoglobin (+0.5 g/dL, $p<0.05$) and hematocrit (+4.35%, $p<0.001$), and improved 5000m time (-18 s, $p<0.01$). Strength training enhanced 400m speed (-1.21 s, $p<0.001$), running economy (-4.2% oxygen cost, $p<0.01$), and 5000m time (-6 s, $p<0.05$). Speed training improved 400m performance (-1.0 s, $p<0.001$), anaerobic capacity (+8.7%, $p<0.01$), VO_2 max (+0.7 ml/kg/min, $p<0.05$), and enhanced 5000m time (-9 s, $p<0.01$). The illustrative findings across the four studies suggest that each training modality elicits unique and significant benefits. Endurance training enhanced VO_2 max and haematological markers. Strength training improved running economy and muscular power without compromising aerobic or haematological status. Speed training boosted anaerobic capacity, 400m performance, and also contributed to VO_2 max improvements. Collectively, these results indicate that a periodized and integrated approach, incorporating all three training modalities, is optimal for enhancing the performance of elite Ethiopian middle- and long-distance runners.

Keywords: Performance, Physiology, Haematology, Training Modality, Endurance Training, Strength Training, Speed Training, Ethiopian Athletes, Hemoglobin, Hematocrit, VO2 max, Running Economy

CHAPTER 1: INTRODUCTION

1. Background and Justification

Middle- and long-distance running events, ranging from 800 metres to marathons, are amongst the most demanding competitions in track and field, requiring a unique combination of speed, strength, and endurance (Ingham *et al*., 2008; Brisebois *et al*., 2018). These events are predominantly aerobic, with performance influenced by a complex interplay of physiological, haematological, and anthropometric factors. Key physiological determinants such as running economy (RE), maximal oxygen uptake (VO_2 max), cardiovascular dynamics, neural recruitment patterns, muscle bioenergetics, and skeletal muscle acid-base status have been identified as critical to success in middle- and long-distance events (Saunders *et al*., 2004; van der Zwaard *et al*., 2021). Additionally, haematological variables, including haemoglobin (Hgb), haematocrit (Htc), red blood cell (RBC) count, total Hgb mass, and blood volume, play a pivotal role in oxygen transport and utilisation, directly affecting endurance performance (Habte *et al*., 2015; Hu & Lin, 2012; Wilber & Pitsiladis, 2012).

Training modalities encompassing endurance, strength, and speed have long been recognised as essential strategies for enhancing these physiological and haematological determinants amongst elite athletes (Joyner & Coyle, 2008; Bassett & Howley, 2000). Endurance training improves aerobic capacity and VO_2 max, strength training enhances muscular power and running economy, and speed training boosts anaerobic threshold and neuromuscular efficiency (Laursen, 2010). However, the specific effects of these training interventions on elite middle- and long-distance runners, particularly in unique environmental conditions such as high altitudes, remained underexplored prior to this study.

High-altitude training, conducted at elevations ranging from 2,001 to 4,000 metres, offers physiological advantages such as increased total haemoglobin mass (tHgb-mass) and enhanced oxygen utilisation, which are critical for endurance performance (Schmidt & Prommer, 2008; Levine & Stray-Gundersen, 1997). These adaptations are particularly pronounced in athletes training at moderate (2,001–3,000 m) or high (3,001–4,000 m) altitudes, where classical training methods such as living and training at altitude and the live-high-train-low (LHTL) approach have been employed to circumvent limitations on training intensity (Wehrlin *et al*., 2006, 2016).

Ethiopian athletes have consistently demonstrated world-class performance in middle- and long-distance running, often attributed to a combination of genetic predisposition, favourable physiological adaptations, and high-altitude training environments (Wilber & Pitsiladis, 2012; Tucker *et al*., 2013). Many of these athletes train in regions such as Addis Ababa, at elevations between 2,100 and 3,500 metres, where the hypoxic conditions stimulate erythropoiesis and increase RBC production, thereby enhancing oxygen-carrying capacity (Levine & Stray-Gundersen, 1997). Despite this, the precise impact of structured endurance, strength, and speed training modalities on the physiological and haematological profiles of Ethiopian elite runners remained poorly understood.

Previous research highlighted the dominance of East African athletes, including Ethiopians, but lacked detailed investigations into how specific training interventions at high altitudes influenced haematological variables such as Hgb, Htc, and RBC count, as well as physiological determinants critical to performance (Prommer *et al*., 2008; Koç *et al*., 2018). This gap in the literature underscored the need for a targeted study to examine the effects of these training modalities on elite Ethiopian middle- and long-distance runners.

Prior to this research, there were no published data specifically addressing whether haematological determinants such as Hgb, Htc, mean corpuscular volume (MCV), red cell distribution width (RDW), white blood cell count (WBC), and monocyte and lymphocyte percentages were unique to Ethiopian endurance runners or how they responded to different training interventions (Wilber & Pitsiladis, 2012; Lobigs *et al*., 2018). Furthermore, whilst studies had explored the general benefits of altitude training and the physiological adaptations associated with endurance performance, few had systematically investigated the differential effects of endurance, strength, and speed training on performance outcomes in this population (McLean *et al*., 2013).

The Adidas track team, comprising some of Ethiopia's most elite athletes and training in high-altitude environments around Addis Ababa, presented an ideal context to address these gaps and provide evidence-based insights for optimising athletic performance. By focusing on the Adidas track team, the research aimed to contribute to the global understanding of athletic training, offering practical recommendations for coaches and sports scientists whilst shedding light on the unique adaptations of Ethiopian athletes in high-altitude settings.

The impact of endurance, strength, and speed training on the physiological and hematological determinants of performance among elite Ethiopian middle- and long-distance runners. By focusing on the Adidas track team, the research aimed to contribute to the global understanding of athletic training, offering practical recommendations for coaches and sports scientists while shedding light on the unique adaptations of Ethiopian athletes in high-altitude settings.

2. Literature Review

2.1. Introduction

This chapter provides a comprehensive review of the existing literature relevant to the effects of endurance, strength, and speed training modalities on the physiological and haematological determinants of performance in middle- and long-distance elite athletes. The review aims to establish the theoretical and empirical foundation for the current study, identify gaps in the existing knowledge, and justify the research questions and hypotheses. It explore the distinct and combined impacts of different training approaches, the key physiological and haematological factors crucial for endurance performance, and the specific context of high-altitude training, particularly concerning Ethiopian athletes.

2.2. Theoretical Framework

This study's conceptual framework is built upon the foundational principles of exercise physiology, theories of training, and the concept of adaptation. It suggests that targeted training stimuli, specifically endurance, strength, and speed trigger distinct physiological and haematological adaptations, which subsequently shape athletic performance.

Endurance performance is a multifaceted construct influenced by aerobic capacity (VO2 max), running economy, lactate threshold, and fuel utilization (Joyner & Coyle, 2008). Haematological factors, particularly Hgb mass and blood volume, are critical for oxygen transport and are significantly influenced by altitude exposure and training (Saunders *et al*., 2006a; Wilber & Pitsiladis, 20127). Traditional endurance training, involving continuous running at varying intensities and durations, is known to improve VO2 max, enhance cardiovascular function, increase mitochondrial density, and improve metabolic efficiency (Hawley, 2002). In elite athletes, further improvements often require meticulous manipulation of training volume, intensity, and frequency. Haematologically, endurance training, especially at altitude, can stimulate erythropoiesis, leading to increased red blood cell count and Hgb concentration (Levine & Stray-Gundersen, 2005). Several key theories inform this framework:

General Adaptation Syndrome (GAS): Originating from Hans Selye's work, this theory outlines the body's three-stage response to stress, which encompasses the stress induced by physical training. Training serves as a stressor, initiating an alarm phase, followed by a resistance phase where adaptation occurs, and potentially an exhaustion phase if overtraining takes place. The goal of properly periodized training is to optimize adaptation within the resistance phase.

Specificity of Training Principle: This principle asserts that physiological adaptations are directly related to the specific type of training undertaken. For instance, endurance training primarily bolsters aerobic capacity, strength training enhances muscular strength and power, and speed training focuses on developing anaerobic power and neuromuscular coordination.

Progressive Overload Principle: To elicit ongoing adaptations, the training stimulus must be systematically and gradually increased over time. This can be achieved by augmenting the volume, intensity, or frequency of training sessions.

Oxygen Transport and Utilization Cascade: Performance in events requiring endurance is critically linked to the body's capacity to effectively take up, transport, and utilize oxygen. This intricate process involves the respiratory, cardiovascular, and muscular systems, along with haematological elements such as Hgb concentration and overall blood volume.

This study investigates how various training modalities affect different points within this oxygen transport and utilization cascade, as well as other physiological systems pertinent to performance.

2.3. Endurance Training: Physiological and Haematological Impacts

Endurance sports involve prolonged physical activity across long distances, demanding that athletes sustain a particular velocity or power output for extended durations (McCormick, 2016). Success in these events predominantly depends on the aerobic resynthesis of ATP. This, in turn, requires efficient oxygen delivery from the atmosphere to cytochrome oxidase located in the mitochondrial electron transport chain, coupled with a sufficient supply of fuels like carbohydrates and lipids (Sloth *et al*., 2013). Significant adaptations throughout the pulmonary, cardiovascular, and neuromuscular systems are induced by endurance training, which also enhances mitochondrial function and metabolic regulation within muscle cells (Teo *et al*., 2011).

Extensive research indicates that rigorous training can cause considerable changes in athletes' physiological and biochemical conditions (Wallace & Slattery, 2007). Nevertheless, the correlation between training stress and performance results is intricate and displays individual variability (Clemente-Suarez, 2014).

2.3.1. Physiological Adaptations to Endurance Training

Key physiological adaptations resulting from endurance training encompass:

(i) Increased VO_2 max: As the maximal rate of aerobic energy expenditure, VO_2 max is a vital determinant of success in endurance sports. Elite endurance athletes generally possess high VO_2 max levels, which are significantly influenced by genetics but can also be improved via structured training (Bassett & Howley, 2000). Both increasing training volume and intensity are effective strategies for enhancing VO_2 max, especially in individuals who are less fit (Midgley *et al*., 2007).

(ii) *Improved Running Economy (RE):* RE is defined as the oxygen cost associated with running at a specific submaximal velocity. Endurance training can enhance RE through improved biomechanical efficiency, increased mitochondrial density, and better substrate utilization (Saunders *et al*., 2004).

(iii) *Enhanced Lactate Threshold*: The lactate threshold, representing the exercise intensity at which lactate starts to accumulate in the bloodstream, is a robust predictor of endurance performance. Endurance training can elevate the lactate threshold to a higher percentage of VO2 max, enabling athletes to maintain higher intensities for longer periods (Joyner & Coyle, 2008).

(iv) *Cardiovascular Adaptations:* These adaptations include an augmented stroke volume, increased cardiac output, greater capillarization of muscle tissue, and an expansion of plasma volume, all contributing to superior oxygen delivery (Laursen & Jenkins, 2002).

(v) *Muscular Adaptations:* Endurance training promotes an increase in mitochondrial density and oxidative enzyme activity, boosts intramuscular glycogen stores, and encourages a shift towards muscle fiber types that are more resistant to fatigue (Hawley & Burke, 2010).

2.3.2. Haematological Adaptations to Endurance Training

Haematological variables, such as red blood cell (RBC) count, hemoglobin (Hgb) concentration, Hct, and total blood volume, are crucial for endurance performance because of their central role in oxygen transport (Brocherie *et al*., 2015; Wilber & Pitsiladis, 2012).

Hemoglobin, the protein within red blood cells, is tasked with transporting oxygen from the lungs to the body's tissues. Generally, higher Hgb levels correspond to a greater oxygen-carrying capacity and, consequently, improved endurance performance. Endurance training, especially when conducted at altitude, can stimulate erythropoiesis (the production of RBCs), resulting in an increased Hgb mass (Levine & Stray-Gundersen, 2005).

An expansion of plasma volume is one of the earliest adaptations observed with endurance training. Although this can cause a minor reduction in Hct (a condition sometimes termed "sports anemia" or dilutional pseudoanemia), the net effect is often advantageous due to enhanced cardiovascular function and improved thermoregulation (Convertino, 1991).

Intense or extended periods of exercise can lead to temporary fluctuations in WBC counts, which mirror the body's reaction to stress and inflammation. The chronic adaptations in WBCs due to training are not as clearly defined but are significant for monitoring the immune function of athletes (Smith, 2003a).

2.3.3. Endurance Training Impacts on Metabolites

Endurance exercise profoundly affects metabolic processes, and training leads to adaptations that boost metabolic efficiency and resistance to fatigue.

Substrate Utilization: Trained individuals demonstrate a superior ability to oxidize fats at a given absolute exercise intensity, thereby conserving muscle glycogen. This improvement is attributed to increased mitochondrial density, higher oxidative enzyme activity, and larger intramuscular triglyceride stores (Holloszy & Coyle, 1984; Smith, 2003a).

Biomarkers of Muscle Damage and Stress: Variations in biochemical markers like creatinine kinase (CK), lactate dehydrogenase (LDH), urea, and creatinine can signal muscle damage, protein breakdown, and metabolic stress (Smith, 2003b. Endurance training can alter the response of these markers to exercise, frequently resulting in a diminished response over time as the body adapts (Saunders *et al*., 2006a).

Ketone Bodies and Potassium: During prolonged exercise, particularly when carbohydrate reserves are low, ketone bodies can serve as an alternative fuel source. Potassium levels are vital for nerve and muscle function; significant changes can occur during intense exercise and may contribute to fatigue. Training might enhance the body's capacity to regulate potassium homeostasis (Nieman *et al*., 2017).

2.4. Strength Training: Effects on Endurance Athletes

Historically, strength training was often overlooked by endurance athletes due to concerns about increased muscle mass and potential negative impacts on aerobic performance. However, a growing body of evidence demonstrates that concurrent strength training can improve running economy, delay fatigue, enhance maximal speed, and reduce injury risk in distance runners without inducing significant hypertrophy (Rønnestad & Mujika, 2014; Balsalobre-Fernández *et al*., 2016). These benefits are attributed to neuromuscular adaptations, such as increased musculotendinous stiffness and improved motor unit recruitment. The influence of strength training on endurance performance has been a subject of extensive discussion among athletes, coaches, and sports scientists. Nevertheless, a growing collection of evidence indicates that engaging in concurrent strength and endurance training can positively affect performance in middle- and long-distance running across different competitive levels (Denadai *et al*., 2017).

2.4.1. Mechanisms of Improvement

Strength training can augment endurance performance via several pathways:

For instance, strength training, especially heavy resistance and plyometric exercises, can enhance RE by increasing muscular stiffness, improving neuromuscular efficiency, and boosting the rate of force development (RFD). This enables runners to generate the same submaximal force while expending less energy (Balsalobre-Fernández *et al*., 2016; Paavolainen *et al*., 1999).

In similar way, by elevating maximal strength and power, strength training can lessen the relative intensity of submaximal running, potentially postponing the onset of fatigue (Rønnestad & Mujika, 2014). Increased power and RFD can improve performance during sprints or surges within a race and may also refine overall running mechanics (Spurrs *et al*., 2003).

Strength training might lead to an enhanced capacity to recruit fast-twitch muscle fibers, which can be advantageous during high-intensity segments of a race or in a finishing kick (Aagaard *et al*., 2001). Moreover, although not a direct performance enhancer, well-designed strength training can increase the resilience of muscles, tendons, and ligaments, potentially lowering the risk of overuse injuries prevalent among endurance runners (Lauersen *et al*., 2014).

2.4.2. Types of Strength Training for Endurance Athletes

Effective strength training programs include heavy resistance training, plyometric training and concurrent training consideration. Heavy Resistance Training involves lifting heavy loads (e.g., exceeding 80% of 1RM) for a limited number of repetitions. Such training is effective for boosting maximal strength and RFD (Storen *et al*., 2008).

Plyometric training are explosive exercises (e.g., jumps, bounds) that utilize a rapid stretch-shortening cycle. Plyometrics are beneficial for improving reactive strength, power, and RE (Saunders *et al*., 2006b).

In concurrent training considerations**:** When integrating strength and endurance training, meticulous planning is essential to prevent interference effects, where one form of training might diminish the adaptations from the other. It is generally advisable to schedule strength and endurance sessions on separate days or with several hours between them (Fyfe *et al*., 2014).

Improvements have been noted in moderately trained (Albracht & Arampatzis, 2013; Piacentini *et al*., 2013), well-trained (Skovgaard *et al*., 2014; Beattie *et al*., 2017), and highly trained athletes (Saunders *et al*., 2006b), suggesting that runners at all proficiency levels can benefit. For example, studies have demonstrated that incorporating strength training into the routines of endurance runners can enhance time trial performance and RE without a corresponding increase in VO_2 max or body mass (Blagrove *et al*., 2018).

2.5. Speed Training: Relevance for Middle and Long-Distance Runners

Speed training, including high-intensity interval training (HIIT) and sprint training, targets improvements in anaerobic capacity, lactate tolerance, neuromuscular power, and VO2 max (Laursen & Jenkins, 2002; Buchheit & Laursen, 2013). For distance runners, enhanced speed contributes to better performance during surges, breakaways, and finishing kicks. Speed training can also improve running economy at race paces.

Although middle- and long-distance running are primarily aerobic activities, the capacity to maintain high speeds, execute surges, and deliver a powerful finishing kick is vital for competitive success. Speed training, which often includes interval training and sprint training, targets anaerobic energy systems, neuromuscular adaptations, and running mechanics at faster velocities.

2.5.1. Physiological Adaptations to Speed Training

Speed training, particularly high-intensity interval training (HIIT), boosts the capacity of anaerobic glycolysis and the phosphagen system, facilitating greater ATP production during brief, intense efforts (Laursen & Jenkins, 2002). Intense training can enhance the body's ability to buffer and tolerate the buildup of metabolic byproducts, such as hydrogen ions, which contribute to fatigue (Edge *et al*., 2006). Speed training can also result in improved motor unit recruitment, increased firing frequency, and enhanced intermuscular coordination, leading to more efficient and powerful muscle contractions at high speeds (Ross *et al*., 2001).

Moreover**,** training at or above race pace can refine running technique, improve stride length and frequency, and shorten ground contact time, all of which contribute to better speed maintenance (Weyand *et al*., 2000). While primarily aimed at anaerobic systems, certain types of high-intensity interval training can also serve as a strong stimulus for improving VO2 max (Helgerud *et al*., 2007).

2.5.2. Types of Speed Training

Interval Training: This method involves repeated segments of high-intensity exercise interspersed with recovery periods. The duration, intensity, and recovery time of intervals can be varied to target specific physiological adaptations (e.g., short intervals for anaerobic power, longer intervals for aerobic power and VO_2 max).

Repetition Training (Reps): Similar to interval training but generally featuring longer recovery periods, this allows for near-maximal effort during the work bouts. It is often employed to improve speed and running economy at race pace or faster.

Sprint Training: This entails maximal or near-maximal intensity efforts over short distances (e.g., 30-200m) with extended recovery periods, focusing on the development of maximal speed and power.

Speed endurance, defined as the capability to sustain high velocities over prolonged periods, is also critical for endurance athletes, with LDH playing a key role in lactic acid clearance and energy metabolism during high-intensity efforts (McLean *et al*., 2013).

2.6. Combined Effects of Different Training Modalities

Achieving optimal performance in middle- and long-distance running often stems from a well-periodized training program that strategically integrates endurance, strength, and speed training. The main challenge is to balance these varied stimuli to maximize adaptation while minimizing interference or the risk of overtraining.

Periodization: Training is typically structured into cycles (macro-, meso-, micro-cycles) that place varying emphasis on different training modalities. For instance, a base-building phase might prioritize endurance volume, whereas a pre-competition phase might increase the focus on speed and race-specific intensity, with strength training being maintained or tapered (Mujika & Padilla, 2001).

Concurrent Training: As previously noted, combining strength and endurance training necessitates careful planning. Research indicates that high-intensity, low-volume strength training is less prone to interfering with endurance adaptations compared to high-volume, hypertrophy-focused strength work (Hickson, 1980; Baar, 2014).

Synergistic Effects: When combined appropriately, different training modalities can produce synergistic effects. For example, enhanced strength can improve running economy, which in turn allows an athlete to maintain a given pace with less effort, thereby complementing endurance adaptations. Improved speed can enhance the finishing kick, capitalizing on the aerobic base developed through endurance training.

2.7. Physiological Determinants of Middle and Long-Distance Running Performance

Success in middle- and long-distance running is a multifaceted phenomenon, yet several key physiological determinants are consistently highlighted in scientific literature:

*VO_2 max***:** A high VO_2 max establishes the upper boundary for aerobic ATP production and is a characteristic feature of elite endurance athletes (Bassett & Howley, 2000).

Lactate Threshold (LT) / Fractional Utilization of VO_2 max: The capacity to sustain a high percentage of VO_2 max without significant lactate accumulation is crucial. Athletes with a higher LT can run at a faster pace before fatigue ensues (Joyner & Coyle, 2008).

Running Economy (RE): This refers to the oxygen cost of running at a given submaximal speed. Better RE signifies less energy expended to maintain a certain pace, making it a critical factor, particularly in longer events (Saunders *et al*., 2004).

Fuel Utilization: The ability to efficiently use carbohydrates and fats as fuel sources, and to conserve glycogen, is important for sustained performance (Hawley & Burke, 2010).

Thermoregulation: The capacity to dissipate heat and maintain core body temperature during exercise, especially in warm conditions, can significantly affect performance (Cheuvront & Haymes, 2001).

2.8. Haematological Determinants and Adaptations in Elite Athletes

As discussed earlier, haematological determinants are vital for oxygen transport and, consequently, for endurance performance.

Hemoglobin Mass (tHgb-mass): Total hemoglobin mass shows a strong correlation with VO2 max and endurance performance. Adaptations that increase tHb-mass, such as altitude training, are actively pursued by elite athletes (Schmidt & Prommer, 2008).

Blood Volume: Both plasma volume and red cell volume contribute to the overall blood volume. An increased blood volume can enhance cardiac filling and stroke volume (Convertino, 1991).

Iron Status: Sufficient iron stores are essential for Hgb synthesis. Iron deficiency, whether accompanied by anemia or not, can impair endurance performance (Burke, 2015).

Erythropoietin (EPO): This hormone stimulates the production of red blood cells. Its natural production is elevated by hypoxia (e.g., at altitude), and its synthetic version is a prohibited performance-enhancing substance.

2.9. Altitude Training and its Interaction with Training Modalities

Training at high altitude is a prevalent strategy employed by endurance athletes to boost performance, primarily through haematological adaptations (Lundby *et al*., 2012).

Hypoxic Stimulus: The reduced partial pressure of oxygen at altitude stimulates erythropoiesis, leading to an increase in red blood cell mass and Hgb concentration over several weeks (Levine & Stray-Gundersen, 1997).

Live High-Train Low: This model, where athletes reside at altitude to gain haematological benefits but train at lower elevations to preserve training intensity, is regarded as one of the most effective altitude training strategies (Stray-Gundersen & Levine, 2008).

Impact on Training Modalities: Training at altitude can affect the ability to perform high-intensity strength and speed work due to diminished oxygen availability. Consequently, the implementation of different training modalities must be adjusted in altitude environments. Ethiopian athletes, many of whom live and train at natural high altitudes (e.g., Addis Ababa, 2100-3500m), benefit from chronic exposure to hypoxia (Wilber & Pitsiladis, 2012; Tucker *et al*., 2013).

2.10. Gaps in the Literature

Despite comprehensive research on training and endurance performance, several gaps existed prior to studies. While the success of Ethiopian runners is widely acknowledged, there was a scarcity of specific research on how structured interventions involving different training modalities (endurance, strength, speed) precisely influenced their unique physiological and haematological profiles, particularly within their natural high-altitude training settings.

The majority of research on training modalities has been conducted on sea-level athletes or those acutely exposed to altitude. The responses of athletes who are chronically adapted to high altitude, like many Ethiopians, to specific training blocks might differ.

Although general haematological adaptations to altitude are known, the nuanced responses of determinants such as MCV, RDW, and specific WBC differentials to various training types in elite Ethiopian runners were not thoroughly documented.

Few studies had comprehensively investigated the simultaneous impact of distinct training blocks on a broad array of physiological, haematological, and direct performance measures within the same group of elite high-altitude athletes.

The current thesis endeavors to address these gaps by systematically examining the effects of endurance, strength, and speed training on physiological, haematological, and performance variables in elite Ethiopian middle- and long-distance runners.

3. Statement of the Problem

While the general benefits of endurance, strength, and speed training are well-documented, there is a paucity of research specifically investigating the distinct and comparative effects of these training modalities on the physiological and haematological determinants of performance in elite Ethiopian middle- and long-distance athletes. These athletes train and live in a unique high-altitude environment, and their adaptive responses to specific training interventions may differ from those of sea-level athletes or athletes undergoing short-term altitude exposure. Understanding these specific adaptations is crucial for optimizing training programs and maximizing the potential of this globally dominant group of runners. This dissertation aims to address this gap by systematically examining the impact of 6-week training blocks focused on endurance, strength, and speed, respectively, on a cohort of elite Ethiopian athletes.

4. Hypotheses

Based on the existing literature, the following hypotheses were formulated for this dissertation:

For Study 1 (Endurance Training):

H_1: The 6-week endurance training intervention will lead to significant improvements in VO_2max, a decrease in RHR, and positive changes in haematological parameters, resulting in improved event-specific time trial performance.

> **H_1a**: A 6-week endurance training intervention will significantly increase VO2max in elite Ethiopian middle- and long-distance athletes.
>
> **H_1b**: A 6-week endurance training intervention will significantly decrease resting heart rate (RHR) in elite Ethiopian middle- and long-distance athletes.
>
> **H_1c**: A 6-week endurance training intervention will significantly improve running economy (RE) in elite Ethiopian middle- and long-distance athletes.
>
> **H_1d**: A 6-week endurance training intervention will lead to significant increases in hematological parameters, including hemoglobin (Hgb), hematocrit (Htc), and red blood cell count (RBC), while white blood cell count (WBC) may remain stable or decrease slightly due to reduced inflammation.
>
> **H_1e**: A 6-week endurance training intervention will significantly enhance overall running performance (e.g., time trial or race times) in elite Ethiopian middle- and long-distance athletes.

For study 2 (Strength Training):

H_2: The 6-week strength training intervention will lead to significant improvements in RE, strength measures, and event-specific time trial performance, with minimal or non-detrimental changes to VO_2 max and haematological profiles.

H_2a: A 6-week strength training intervention will not significantly change VO2max but may show minor improvements in elite Ethiopian middle- and long-distance athletes.

H_2b: A 6-week strength training intervention will significantly decrease resting heart rate (RHR) through improved cardiovascular efficiency in elite Ethiopian middle- and long-distance athletes.

H_2c: A 6-week strength training intervention will significantly improve running economy (RE) by enhancing muscular efficiency in elite Ethiopian middle- and long-distance athletes.

H_2d: A 6-week strength training intervention will significantly increase strength measures (e.g., maximal force output or power) in elite Ethiopian middle- and long-distance athletes.

H_2e: A 6-week strength training intervention will result in modest changes to hematological parameters, with potential increases in hemoglobin (Hgb), hematocrit (Htc), and red blood cell count (RBC), and stable or slightly elevated white blood cell count (WBC) due to muscle repair processes.

H_2f: A 6-week strength training intervention will significantly improve running performance, particularly in aspects requiring power and efficiency, in elite Ethiopian middle- and long-distance athletes.

For study 3 (Speed Training):

H_3: The 6-week speed training intervention will lead to significant improvements in 400m sprint performance, anaerobic capacity markers, and potentially VO_2max, with stable or adaptive changes in haematological profiles, resulting in improved event-specific time trial performance.

H_3a: A 6-week speed training intervention will significantly increase VO2max through high-intensity adaptations in elite Ethiopian middle- and long-distance athletes.

H_3b: A 6-week speed training intervention will significantly decrease resting heart rate (RHR) due to enhanced cardiovascular recovery in elite Ethiopian middle- and long-distance athletes.

H_3c: A 6-week speed training intervention will significantly improve anaerobic capacity markers (e.g., lactate threshold or maximal sprint speed) in elite Ethiopian middle- and long-distance athletes.

H_3d: A 6-week speed training intervention will lead to hematological adaptations, including increases in hemoglobin (Hgb), hematocrit (Htc), and red blood cell count (RBC) to support oxygen delivery during high-intensity efforts, with potential transient increases in white blood cell count (WBC) from acute stress.

H_3e: A 6-week speed training intervention will significantly enhance running performance, especially in speed-dependent metrics like acceleration and finishing kicks, in elite Ethiopian middle- and long-distance athletes.

For study 4 (Overall Effects):

H_4: Each training modality (endurance, strength, speed) will elicit distinct yet complementary physiological and haematological adaptations, all contributing to enhanced running performance in elite Ethiopian athletes. An integrated approach incorporating all three modalities will be most beneficial for overall performance optimization.

H_{4}a: Endurance training will produce the greatest improvements in aerobic physiological parameters (e.g., VO2max and RE) compared to strength and speed training in elite Ethiopian middle- and long-distance athletes.

H_{4}b: Strength training will yield the most substantial gains in strength measures and muscular efficiency, with moderate effects on hematological parameters, relative to endurance and speed training in elite Ethiopian middle- and long-distance athletes.

H_{4}c: Speed training will result in the largest enhancements in anaerobic capacity markers and high-intensity performance, with comparable or slightly greater hematological adaptations (e.g., Hgb and Htc increases) than the other modalities in elite Ethiopian middle- and long-distance athletes.

H_{4}d: Overall running performance improvements will be similar across all three training modalities, but the mechanisms will differ: endurance via aerobic gains, strength via power and economy, and speed via anaerobic thresholds, in elite Ethiopian middle- and long-distance athletes.

H_{4}e: Hematological responses (e.g., increases in RBC and Hgb) will be most pronounced in endurance and speed training due to higher metabolic demands, compared to strength training, in elite Ethiopian middle- and long-distance athletes.

5. Objectives of the Study

The primary objective of this dissertation is to investigate and compare the effects of 6-week endurance, strength, and speed training interventions on selected physiological, haematological, and performance parameters in elite Ethiopian middle- and long-distance athletes.

6.1. Specific objectives are:

- To determine the effects of a 6-week endurance training program on VO_2max, RHR, RE, Hgb, Htc, RBC, WBC, and running performance.

- To determine the effects of a 6-week strength training program on VO_2max, RHR, RE, strength measures, Hgb, Htc, RBC, WBC, and running performance.

- To determine the effects of a 6-week speed training program on VO_2max, RHR, anaerobic capacity markers, Hgb, Htc, RBC, WBC, and running performance.

- To compare the magnitude and nature of adaptations across the three different training modalities.

- To provide evidence-based recommendations for optimizing training programs for elite Ethiopian middle- and long-distance runners.

6. Significance of the Study

This study holds significant practical and scientific value for Ethiopian coaches and athletes with evidence-based insights into how different training modalities specifically impact performance-related physiological and haematological parameters. This can lead to more targeted and effective training program design. This research will contribute to the body of knowledge specific to Ethiopian athletes, who represent a unique, high-altitude adapted population. It can inform national training strategies and athlete development programs. The study will add to the broader understanding of training adaptations in elite endurance athletes, particularly highlighting responses in a chronically altitude-exposed group. It will offer comparative data on endurance, strength, and speed training effects.

7. Delimitations of the Study

The study was delimited to twenty elite male middle- and long-distance runners from the Ethiopian Adidas team. Athletes training in and around Addis Ababa, Ethiopia (high altitude). Three specific 6-week training intervention blocks (endurance, strength, speed). Selected physiological parameters (VO_2max, RHR, RE, strength/anaerobic markers) and haematological parameters (Hgb, Htc, RBC, WBC).

8. Limitations of the Study

Potential limitations include:

- The quasi-experimental design without a concurrent control group for each intervention block.
- The sample size, though typical for elite athlete studies, is relatively small.

- Reliance on some field-based tests for physiological measures (e.g., estimated VO_2 max) which may be less precise than laboratory gold standards. Performance measures including event-specific time trials and a 400m sprint test.

9. Definition of Terms

- ***Endurance Training*****:** Training designed to improve the body's ability to sustain prolonged aerobic activity.

- ***Strength Training*****:** Training designed to increase muscular force production and power.

- ***Speed Training*****:** Training designed to improve maximal running velocity and anaerobic capacity.

- ***Physiological Parameters*****:** Measurable characteristics of bodily function (e.g., VO_2max, RHR, RE).

- ***Haematological Parameters*****:** Measurable characteristics of the blood (e.g., Hgb, Htc, RBC count).

- ***VO2 max*****:** Maximal oxygen uptake; the maximum rate at which an individual can consume oxygen during intense exercise.

- ***Running Economy (RE)*****:** The oxygen cost of running at a given submaximal velocity.

- ***Elite Athletes*****:** Athletes competing at a national or international level

10. Organization of the Dissertation

This dissertation is organized in an article-compilation format as per the Addis Ababa University guidelines.

- ➔ **Chapter 1 (General Introduction):** Provides the background, literature review, statement of the problem, research questions, hypotheses, objectives, significance, delimitations, limitations, definition of terms, and organization of the dissertation.

- ➔ **Chapter 2 (Study 1):** Presents the first research paper, focusing on the effects of the 6-week endurance training intervention.

- ➔ **Chapter 3 (Study 2):** Presents the second research paper, focusing on the effects of the 6-week strength training intervention.

- ➔ **Chapter 4 (Study 3):** Presents the third research paper, focusing on the effects of the 6-week speed training intervention.

- ➔ **Chapter 5 (Study 4):** Presents the third research paper, focusing on the effects of the 6-week speed training intervention.

- ➔ **Chapter 6 (General Discussion, Conclusions, and Recommendations)** Synthesizes the findings from the three papers, provides an overall discussion, draws general conclusions, and offers practical recommendations and directions for future research.

CHAPTER 2: STUDY 1

PHYSIOLOGICAL AND HAEMATOLOGICAL ADAPTATIONS TO ENDURANCE TRAINING IN ELITE MIDDLE AND LONG-DISTANCE RUNNERS: IMPLICATIONS FOR PERFORMANCE OPTIMIZATION

Abstract

Endurance training (EnT) is a critical component for elite middle and long-distance runners, necessitating a comprehensive examination of the haematological and physiological adaptations that occur throughout a training cycle. This study investigated the effects of EnT on various physiological and haematological factors that influence running performance. A well-structured training program with dynamic intensities and intervals was developed. A quasi-experimental approach was used to conduct pre- and post-tests. The key findings revealed substantial improvements, particularly in erythrocyte volume and hemoglobin (Hgb) mass. Specifically, the RBC count increased significantly from a pre-training mean of 5.18 (±0.40) million/L to 5.45 (±0.39) million/L post-training (t = 5.23, P = 0.001). Furthermore, maximal oxygen consumption (VO_{2max}) demonstrated a marked increase from 71.9 (±1.27) to 78.4 (±2.02) ml/kg/min (t = 16.24), indicating enhanced aerobic capacity. In addition to these improvements, RHR exhibited a significant reduction, decreasing from 57 (±3) to 53 (±4) beats per minute (bpm) (t = 4.48, P = 0.001). Collectively, these physiological enhancements accounted for an impressive explanatory power of 86.9% for performance outcomes, particularly evident in the 5000m time trial (TT). These results underscore the importance of EnT programs in optimizing performance for elite runners, highlighting the need of individualized training regimens that promote the physiological adaptations essential for maximizing athletic potential.

Keywords: Endurance training, Haematological adaptations, physiological adaptations, Oxygen consumption, high-intensity training, Red blood cells

1. INTRODUCTION

Endurance training (ET) is a fundamental component in the development of athletes across diverse sports disciplines, significantly contributing to enhancements in athletic physiology and performance (Mujika, Bourdillon, Zelenkova, Vergnoux, & Millet, 2024a). Attaining elite status as an middle and long-distance athlete (MLDA) necessitates extensive and specialized training, often involving countless hours of dedication and effort (Aagaard & Andersen, 2010; Steiner, Maier, & Wehrlin, 2019). The pathway to success in this field requires an unwavering commitment to hard training regimens, which typically encompass the completion of vast distances annually and the systematic improvement of both physical and technical skills (Joyner & Coyle, 2008). Central to this process is the incorporation of advanced training methodologies and the integration of strength and muscle development techniques focusing on optimizing overall athletic performance (Paquette et al., 2017).

EnT encompasses a multitude of factors that influence athletic performance and general well-being (MacInnis & Gibala, 2017). While the physical dimensions of training are frequently emphasized, the impact of EnT on hematological adaptations (HemA) is equally critical (Tilahun Muche et al., 2021). Endurance MLDA often experience significant alterations in HemA, including RBC counts, Hgb levels, and Htc, all of which play a vital role in performance and overall well-being (Mujika et al., 2024; Schmidt and Prommer, 2008; Shivalingaiah et al., 2015). Recent evidence underscores the importance of high-intensity interval training (HIIT) in modulating these HemA (Koç, Özen, Abanoz, & Pulur, 2018; Stankovic, Djordjevic, Trajkovic, & Milanovic, 2023). By integrating HIIT with traditional EnT methods, both elite and recreational athletes can optimize their athletic outcomes (Nybo et al., 2010; Ramírez-Campillo et al., 2014).

A comprehensive understanding of the effects of various training modalities on HemA is essential for refining training programs and maximizing MLDA potential (Rodríguez Zamora, 2013; Schmidt & Prommer, 2008, 2008). The relationship between ET, HEMA, and athletic performance highlights the necessity for continued research to explain the mechanisms driving these physiological changes (Mancera-Soto, Chamorro-Acosta, Ramos-Caballero, Torrella, & Cristancho-Mejía, 2022). This knowledge is crucial not only for enhancing athletic performance but also for ensuring the long-term well-being of endurance MLDA (Birhanu, Ambelu, Berhanu, Tesfaye, & Woldemichael, 2017; MacInnis & Gibala, 2017).

Physiological adaptations induced by EnT span several domains, including cardiovascular, respiratory, muscular (Campos et al., 2002), and metabolic systems (Mancera-Soto et al., 2022; Montero et al., 2017). These adaptations significantly enhance performance and consistency (Alcaraz-Ibañez & Rodríguez-Pérez, 2018; Barnes & Kilding, 2015). For instance, increased cardiac output, driven by elevated stroke volume and left ventricular hypertrophy, enhances the heart's pumping efficiency (Birhanu et al., 2017; Brugniaux et al., 2006). Elite endurance MLDA often exhibit bradycardia, with RHR below 60 beats per minute, alongside high maximal cardiac output, facilitating superior oxygen delivery and utilization during exertion (MacInnis & Gibala, 2017). Similarly, respiratory adaptations improve pulmonary diffusion capacity and VO_{2max}, which are critical for middle- and long-distance events (Kenney, Wilmore, & Costill, 2022).

Skeletal muscle adaptations resulting from EnT include increased mitochondrial density, enhanced capillarization, and shifts in muscle fiber composition toward oxidative profiles, thereby enabling sustained aerobic metabolism (Alcaraz-Ibañez & Rodríguez-Pérez, 2018). Enhanced oxidative enzyme activity and glycogen storage further extend endurance by delaying the onset of fatigue (Wutzler, Yu, Schrumpf, & Zaehle, 2022). Improvements in neuromuscular coordination reduce energy wastage, while metabolic adaptations facilitate better lipid utilization and lower blood lactate levels during submaximal exercise (Bayati, Farzad, Gharakhanlou, & Agha-Alinejad, 2011). Additionally, hormonal shifts, such as increased insulin sensitivity and modulated catecholamine release, further optimize energy utilization and recovery (Hughes, Ellefsen, & Baar, 2018; Paquette et al., 2017).

Research has emphasized the influence of training load, specificity, age, and baseline fitness on the HemA induced by EnT (Coutts, Wallace, & Slattery, 2007; MacInnis & Gibala, 2017). Key improvements associated with EnT include increased Hgb mass, RBC volume, and white blood cell (WBC) count (Cregg, 2013). However, chronic EnT can also lead to exercise-induced anemia, characterized by reduced Hgb concentration despite increases in total Hgb mass, underscoring the necessity for balanced training protocols (Birhanu et al., 2017; Prommer, Sottas, Schoch, Schumacher, & Schmidt, 2008). Coaches must design training programs that prioritize athlete health and sustainable performance (Nybo et al., 2010).

EnT has been shown to be essential for enhancing cardiovascular fitness, muscular strength, and mental resilience, benefiting MLDA across various disciplines (Cregg, 2013; Jafer, Mondal, & Abdulkedir, 2019). In Ethiopia, research has highlighted the effectiveness of tapering strategies, such as HIIT low-volume and HIIT moderate-volume training, in improving RBC count, Hgb concentration, and Htcs (Htc) (Mujika et al., 2024). Altitude training, which enhances oxygen-carrying capacity (Mujika, Bourdillon, Zelenkova, Vergnoux, & Millet, 2024b), further contributes to improved endurance performance (Boullosa et al., 2020). Additionally, EnT fosters chronic adaptations in thyroid hormone metabolism and other biochemical markers, aiding MLDA in managing competitive stress (Haugen, Sandbakk, Seiler, & Tønnessen, 2022).

The dynamic interplay between ET, HA, and athletic performance underscores the necessity for personalized training strategies that maximize physiological adaptations while safeguarding long-term health (Brisebois, Rigby, & Nichols, 2018). A holistic approach ensures that MLDA can achieve their full potential and excel in their respective disciplines (Haugen et al., 2022). This study aims to investigate the effects of EnT on the physiological and HemA influencing running performance among selected male elite MLDA.

2. METHODS

Study Design

A quasi-experimental research design was employed to examine the effects of EnT protocols on physiological and HemA influencing running performance among elite male Ethiopian endurance MLDA. The study spanned six weeks and utilized systematic data collection methods to ensure reliability and validity.

Participants and Sampling

Twenty-one elite male MLDA specializing in mid-distance (1,500m and 3,000m) and long-distance (5,000m and 10,000m) events were purposefully selected based on their representation in international competitions and their willingness to participate in the study. MLDA with health conditions that could potentially affect study outcomes were excluded from participation.

Ethical Compliance

Prior to participation, all MLDA were thoroughly briefed on the study's objectives and procedures. Informed consent was obtained, and measures to ensure confidentiality and data protection were strictly implemented.

Data Collection Protocols

Blood samples were collected at baseline (pre-test, $test_0$) and after the six-week training intervention (post-test, $test_1$). Participants adhered to a 48-hour period of rest from intense activity and a 12-hour fasting regimen before sampling. Blood samples (10 ml) were drawn from the antecubital vein and analyzed in a hematology laboratory to assess Hgb mass, Htc mass, WBC count, and RBC count.

Key physiological parameters, including indirect VO_{2max}, 400m speed test (ST), and RHR, were measured at both $test_0$ and $test_1$ stages. VO_{2max} data were collected using Garmin devices during event-specific time trials to ensure accuracy. Athletic performance was assessed through standardized time trials conducted on a 400m track, and MLDA provided qualitative feedback on perceived performance improvements during the intervention.

Training Protocol

A structured training regimen with progressive intensity was implemented over the six-week period. Each session commenced with a zero-minute warm-up, followed by 15 minutes of dynamic stretching and mobilization exercises. The main training segment involved continuous running at 70–85% of VO2max, performed as a single 60-minute session, two 30-minute sessions, or three 20-minute intervals at a consistent pace. Training also included a 3km cool-down and 10 minutes of stretching. Weekly training volume began at 80% of the MLDA' baseline and increased incrementally by 10% each week until reaching a maximum of 120 km. This progressive and systematic approach aimed to optimize endurance adaptations while minimizing the risk of overtraining or injury.

Data Analysis

Statistical tools, such as t-test, ANOVA, regression analysis were employed to analyze changes in HA, physiological adaptations, and performance metrics over time at a 95% confidence level. Variation in HA, physiological adaptations, and performance metrics were compared using a one-way repeated measures ANOVA. To test for differences between modalities, two-way repeated measures ANOVA was utilized. Paired t-tests were conducted to compare $test_0$ and $test_1$ values within each group. Principal Component Analysis (PCA) was conducted to evaluate the significant differences between $test_0$ and $test_1$. Regression analysis was employed to evaluate the association of various factors with performance. All analyses were performed using R software (R Core Team, 2022), version 4.2.3.

3. RESULTS

The EnT program resulted in significant improvements across several HA, as detailed in Table 2-1. The RBC count increased from a $test_0$ training mean of 5.18 (±0.40) million/µL to 5.45 (±0.39) million/µL $test_1$ (t = 5.23, $P < 0.001$), demonstrating a strong correlation between $testest_0$ and $test_1$ values (r = 0.81, $P < 0.01$). Notably, RBC counts exhibited a consistent increase across all weight categories, with a mean change of 5.97%.

The mass Hgb also rose significantly, from 15.1 (±1.1) g/dL to 16.0 (±1.1) g/dL (t = 4.92, $P < 0.01$). Heavier MLDA recorded higher mean changes (5.97%). Htc levels demonstrated a highly significant increase, rising from 42.5% (±3.12) to 46.9% (±3.24) (t = 9.86, $P < 0.001$). Similar to Hgb, Htc levels increased across all weight groups (mean change = 10.45%), with heavier MLDA showing higher values (Figure 2-1). In contrast, the mean WBC count exhibited a non-significant increase, from 7.5 (±1.9) to 7.7 (±1.77) (t = -1.58, $P > 0.05$), although a robust correlation was observed between $test_0$ and $test_1$ WBC values (r = 0.99, $P < 0.01$) (Figure 2-9A6).

RHR decreased significantly from 57 bpm (±3) to 53 bpm (±4) $test_1$ (t = 4.48, $P < 0.001$). Additionally, VO_{2max} increased markedly, from 71.9 (±1.27) ml/kg/min to 78.4 (±2.02) ml/kg/min (t = 16.24, $P < 0.001$). VO_{2max} values improved across all weight categories, with heavier individuals generally exhibiting slightly higher VO_{2max} values (mean change = 8.61%, Figure 2-10A7).

Table 2-1: Summary of statistical comparison for HemA and Performance determinant at test0 and test1 (EnT intervention)

Parameter	**Test**	**Max**	**Min**	**Mean ± SD**	**Variance**	**Mean Change ±**	***t-test***	***r***
RBC (million/µL)	t_0	5.84	4.55	5.18 ± 0.40	0.16	-0.28 ± 0.24	5.23**	0.81**
	t_1	6.12	4.81	5.45 ± 0.39	0.15			
WBC(thousand/µL)	t_0	10.6	4.5	7.5 ± 1.9	3.5	-0.1 ± 0.30	-1.58	0.99**
	t_1	9.3	5.92	7.7 ± 1.77	0.15			
Hgb (g/dL)	t_0	17	12.6	15.1 ± 1.1	1.3	-0.88 ± 0.82	4.92**	0.73**
	t_1	17.5	13.8	16.0 ± 1.1	1.2			
Htc(%)	t_0	49	37	42.5 ± 3.12	9.76	-4.4 ± 0.02	9.86**	0.80**
	t_1	53	42	46.9 ± 3.24	10.5			
RHR (bpm)	t_0	60	52	57 ± 3	9	3.8 ± 3.89	4.48**	0.38
	t_1	60	48	53 ± 4	15			
D_{12min} (m)	t_0	3810	3620	3723 ± 57	3201	-29 ± 73.52	17.86**	0.58**
	t_1	4130	3800	4009 ± 90	8146			
VO_{2max} (ml/kg/min)	t_0	73.9	69.6	71.9 ± 1.27	1.6	-6.4 ± 1.7	16.24**	0.57*
	t_1	81	73.7	78.4 ± 2.02	4.06			
Speed test(s)	t_0	61	54	58 ± 2	5	1.19 ± 3.34	1.63	0.12
	t_1	62	52	57 ± 3	8			
TT (min)	t_0	14:13	13:47	14:00 ± 0:07	0:44	0:07 ± 0:05	5.49**	0.71**
	t_1	14:10	13:44	13:53 ± 0:08	1:04			
Race Time (min)	t_0	13:46	12:57	13:18 ± 0:14	3:16	0:02 ± 0:06	1.43	0.89**
	t_1	13:42	12:50	13:16 ± 0:12	1:22			

Notes: t = pre-post tests, *r* = correlation coefficient, SD = Standard deviation. Statistical Significance: $p < 0.05$ = *, $p < 0.01$ = **.

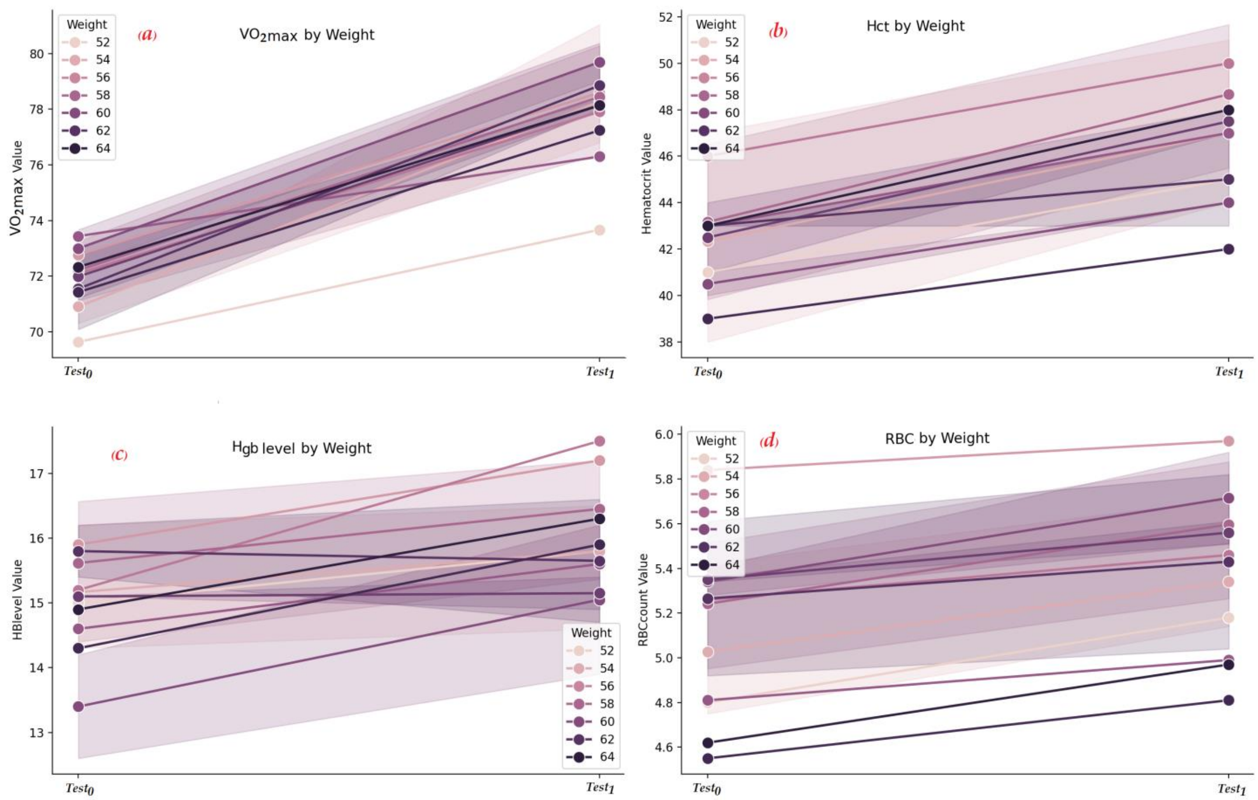

Figure 2-1: Line chart to show the *$test_0$*- *$test_1$* changes for key determinants across different subject weights. "lines highlight the trends in" VO_2 max" (a), "Hct" (b), "Hgb" (c), and "RBC" (d) by weight at *$test_0$* and *$test_1$* intervals.

The D_{12min} improved significantly, increasing from 3723 meters (±57) to 4009 meters (±90) (t = 17.86, P < 0.001). Similarly, the TT improved from 14:00 minutes (±7 seconds) to 13:53 minutes (±8 seconds) (t = 5.49, P < 0.001) (Figure 2.2). Conversely, the ST exhibited a non-significant decrease from 58 seconds (±2) to 57 seconds (±3). A strong correlation was observed between improvements in VO_{2max} and D_{12min} (r = 0.92) (Figure 2-3a).

Although the scatter plot in Figure 3b illustrates the regression model of *$test_1$* VO_{2max} values, the model did not fit the data well (-0.097). Regression analyses identified predictors of performance improvements. Model 1, which included RHR, ST times, and D_{12min}, explained 58.9% of the variance in $test_1$ training performance ($R^2 = 0.59$, $P = 0.001$). The addition of endurance-specific metrics in Model 2 improved the explanatory power to 86.9% ($R^2 = 0.87$, $P < 0.001$). The inclusion of HemA in Model 3 yielded marginal gains, achieving an R^2 of 0.87 ($P = 0.001$). Principal component analysis (PCA) revealed that the first three components accounted for 59% of the variance in the data, while five components explained 76%. The inclusion of eight components captured over 90% of the dataset's variability.

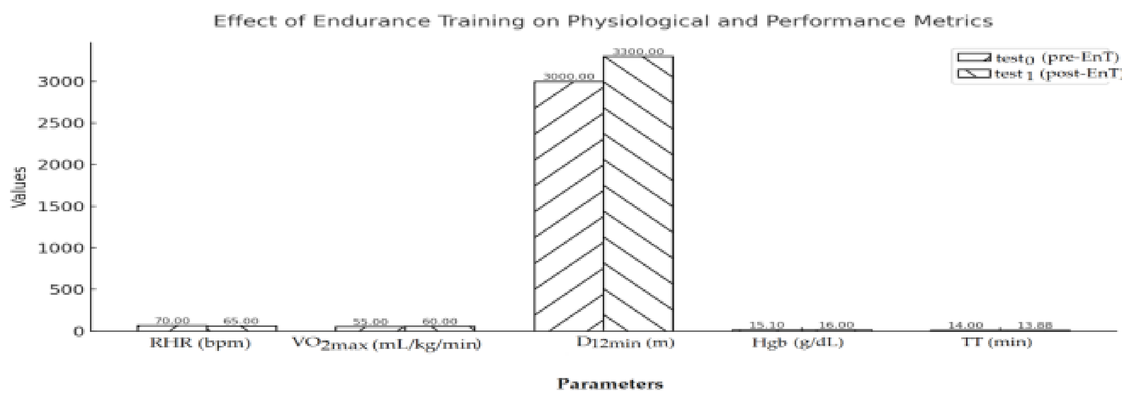

Figure 2-2: Graph to show analysis result of performance over all improvement from $test_0$ to $test_1$ (intervention)

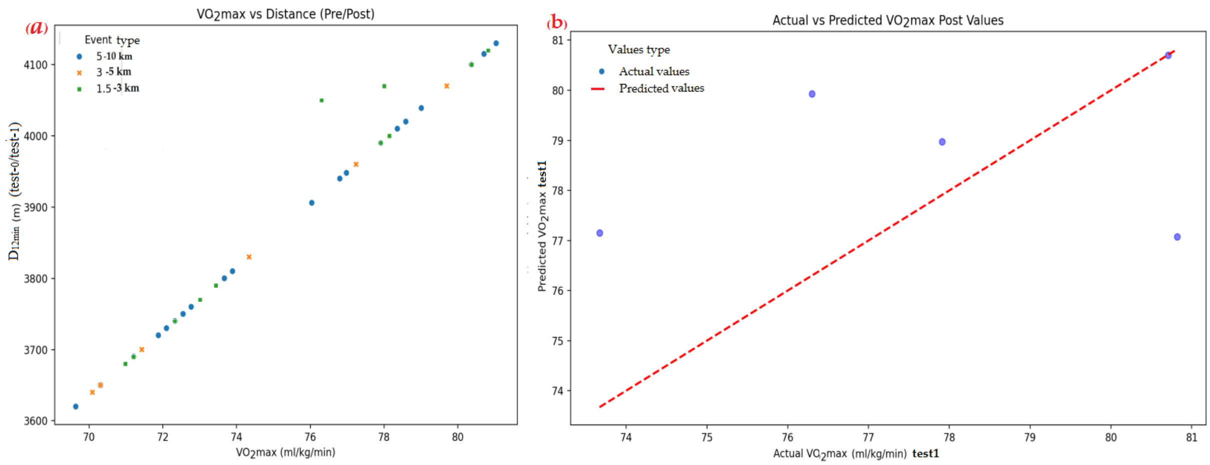

Figure 2-3: (a).VO_{2max} trend chart to explain VO_{2max} by D_{12min} correlation (r = 0.92) across event; and (b) actual with predicted VO_{2max} scatter plot to show actual and predicted VO_{2max} $test_1$ values with regression line in red color. Each blue dot represents an individual data point comparing actual and predicted values. The red dashed line is the line of equality, where predicted values match actual values exactly.

Key contributors to variance included $test_0$ VO_{2max} and D_{12min}, which exhibited strong loadings on the first principal component (PC1). RHR negatively loaded on PC2, while subject weight exhibited a positive loading. Age demonstrated a notable negative loading on PC3. These findings underscore the significant roles of aerobic capacity and demographic factors in performance outcomes (Figure 2-7A4**)**.

4. DISCUSSION

Post-Endurance Training Haematological Adaptations

The findings indicate that EnT effectively enhanced erythropoiesis among elite male MLDA, consistent with previous studies that reported increased RBC counts as an adaptation to elevated oxygen demands during exercise (Sheykhlouvand *et al*., 2018; Tilahun Muche *et al*., 2021). The observed increases in RBC count, Hgb mass, and Htc align with existing literature indicating that EnT enhances the oxygen-carrying capacity of the blood (Sheykhlouvand *et al*., 2018). The modest change in RBC count suggests that while MLDA maintained overall health, there was no significant alteration in immune response attributable to prolonged EnT (Mujika *et al*., 2024b). Furthermore, the minimal variability in WBC count, coupled with a strong correlation between $test_0$ and $test_1$ WBC measurements, supports the notion that WBC counts are less sensitive to EnT adaptations compared to RBC-related determinants (Billat, 2001; Mancera-Soto *et al*., 2022). Variations in the magnitude of these HemA can be attributed to factors such as altitude and training intensity (Mujika *et al*., 2024b). This study underscores the significant impact of EnT on physiological adaptations, particularly focusing on HemA and their implications for athletic performance.

The increase in Hgb mass supports the hypothesis that EnT improves the oxygen transport capacity of MLDA. The observed increment in Htc highlights training-induced adaptations that enhance blood viscosity and oxygen delivery mechanisms. The increase in Hgb and RBC volume corroborates previous research emphasizing the role of EnT in promoting erythropoiesis (Montero *et al*., 2017). Comparative studies emphasize that increased erythropoiesis contributes to improved oxygen delivery, which is crucial for sustaining prolonged exercise (Montero *et al*., 2017). Our findings also align with those of Corsetti *et al*. (2012), who reported similar adaptations in elite cyclists. The significant increases in Hgb mass and erythrocyte volume observed in our study suggest that EnT induces substantial HemA that enhances aerobic capacity. This is further supported by

(Steiner *et al*. (2019), who noted that EnT promotes erythropoiesis and optimizes oxygen transport.

Physiological Adaptations of Endurance Training

The results regarding RHR and VO_{2max} (Figure 2-6A3**)** reflect improved cardiovascular efficiency, enhanced aerobic capacity, and increased autonomic control over heart function, alongside augmented endurance potential. The significant increase in VO_{2max} and the reduction in RHR are consistent with expected outcomes of EnT (Prommer *et al*., 2008; Steiner *et al*., 2019). However, the extent of VO_{2max} improvement observed in this study is particularly noteworthy, potentially attributable to the unique physiological characteristics of Ethiopian MLDA (Tilahun Muche *et al*., 2021). The reduction in RHR indicates enhanced cardiovascular efficiency, while the increase in VO_{2max} signifies improved oxygen utilization during HIIT efforts (Mancera-Soto *et al*., 2022). Research involving European and North American MLDA reports lower baseline VO_{2max} levels and smaller increments $test_1$, even under rigorous training conditions. This discrepancy may be linked to genetic factors, as studies by Larsen have highlighted that East African MLDA, particularly those of Ethiopian and Kenyan descent, possess unique physiological traits, such as a higher percentage of slow-twitch muscle fibers and an efficient running economy, which may predispose them to superior endurance performance (Larsen, 2003).

The physiological improvements observed in this study, including enhanced VO_{2max} and improved running performance, are consistent with adaptations described by Moxnes and Hausken (2012). These studies highlight that EnT leads to notable gains in cardiovascular efficiency and muscular adaptations, collectively enhancing overall performance (Figure 2-4A1).

Athletic Performance Enhancement

The findings from the ST suggest that while overall endurance has improved, enhancements in speed may require a more specialized training approach. The lack of significant improvement in ST indicates that the training program may need to incorporate more speed-focused elements to enhance short-distance performance (Stankovic *et al*., 2023). This highlights the importance of a balanced training approach that addresses both endurance and speed. Moreover, the study suggests that performance metrics related to endurance are paramount in predicting race outcomes, indicating a potential need for targeted speed training. This result aligns with findings from Chen *et al*. (2023) and Mujika *et al*., (2024), who reported that altitude training and HIIT improve both HemA and performance metrics (Stankovic *et al*., 2023). This suggests that the observed improvements in performance are not solely attributable to increased RBC mass but also to enhanced cardiovascular and muscular efficiency (Carroll, 2018). The improved results in D_{12min} further highlight the effectiveness of the training regimen in significantly enhancing endurance capacity.

The improvement in TT performance indicates a favorable impact of EnT on overall race performance (Figure 2-5A2). The observed enhancements in TT align with findings from other studies on elite EnT (Paquette *et al*., 2017).

The study also highlights the importance of HIIT in maximizing endurance performance. demonstrated that HIIT can lead to significant improvements in both aerobic and anaerobic capacities, which are crucial for endurance MLDA (Boullosa *et al*., 2020). Our findings support these conclusions, indicating that incorporating HIIT into training regimens can yield substantial performance benefits.

Practical Aspects

The results contribute to the growing body of literature on the physiological adaptations induced by ET, particularly in the context of elite endurance MLDA. The insights gained from this research not only enhance our understanding of the mechanisms underlying athletic performance but also provide practical implications for coaches and MLDA seeking to optimize training strategies. Future research should continue to explore the interplay between various training modalities and performance outcomes, with a focus on personalized approaches that maximize both endurance and speed while ensuring the long-term health and well-being of MLDA

5. References

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6. Additional files

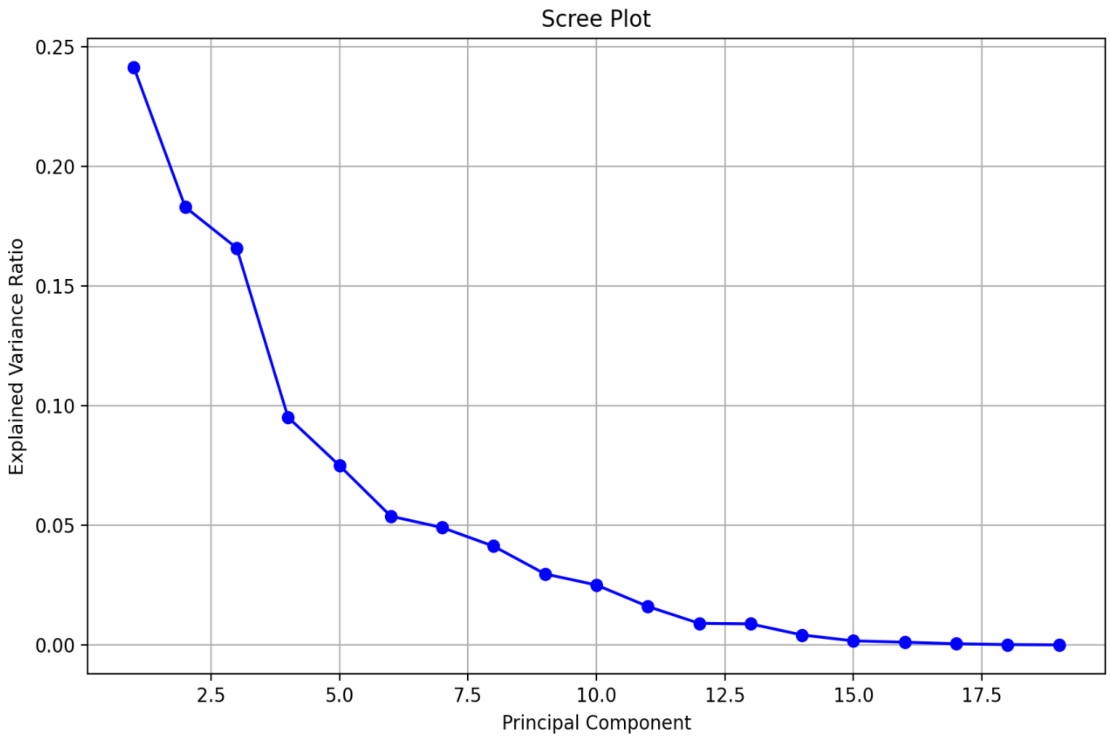


Figure 2- 4A1: The PCA analysis reveals the key findings how much of the total variance in the dataset is explained by the principal components (PCs).

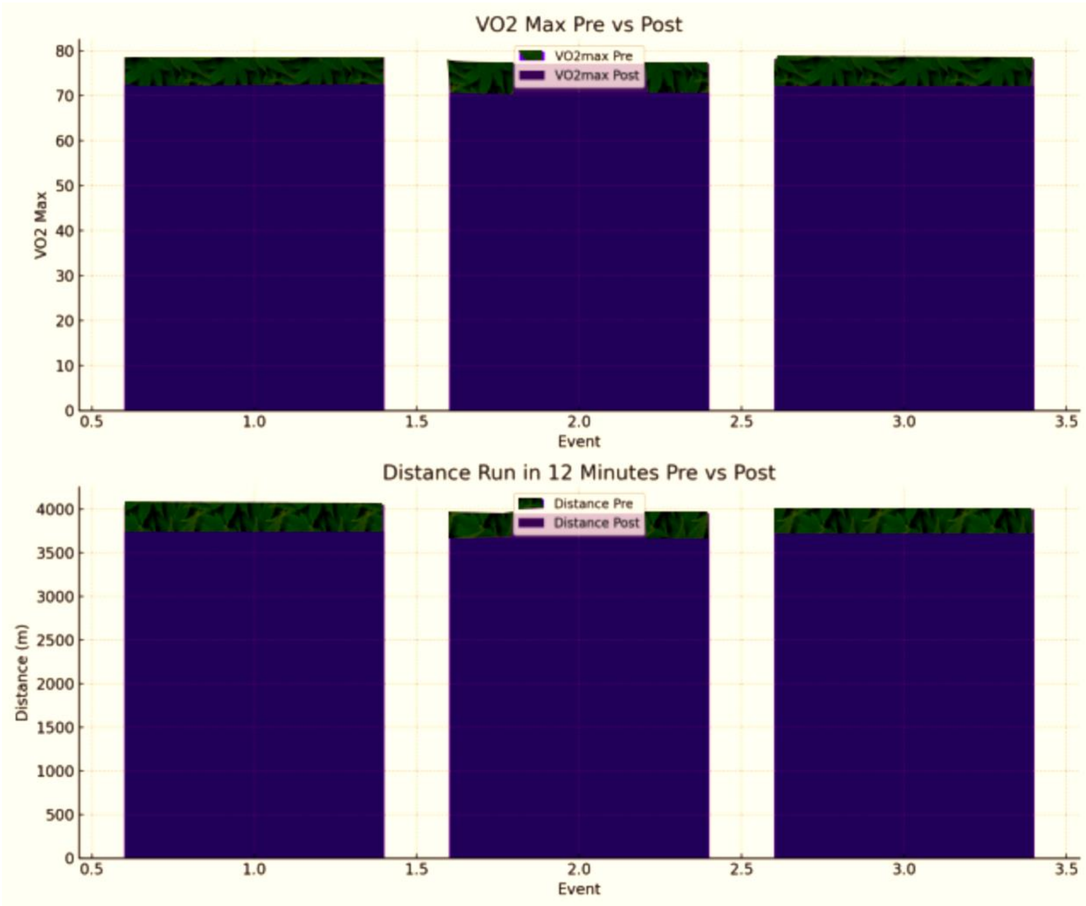


Figure 2-5A2: The analysis VO_2max and 12 minutes run along event (in km) that showed significant difference from pre and post training intervention.

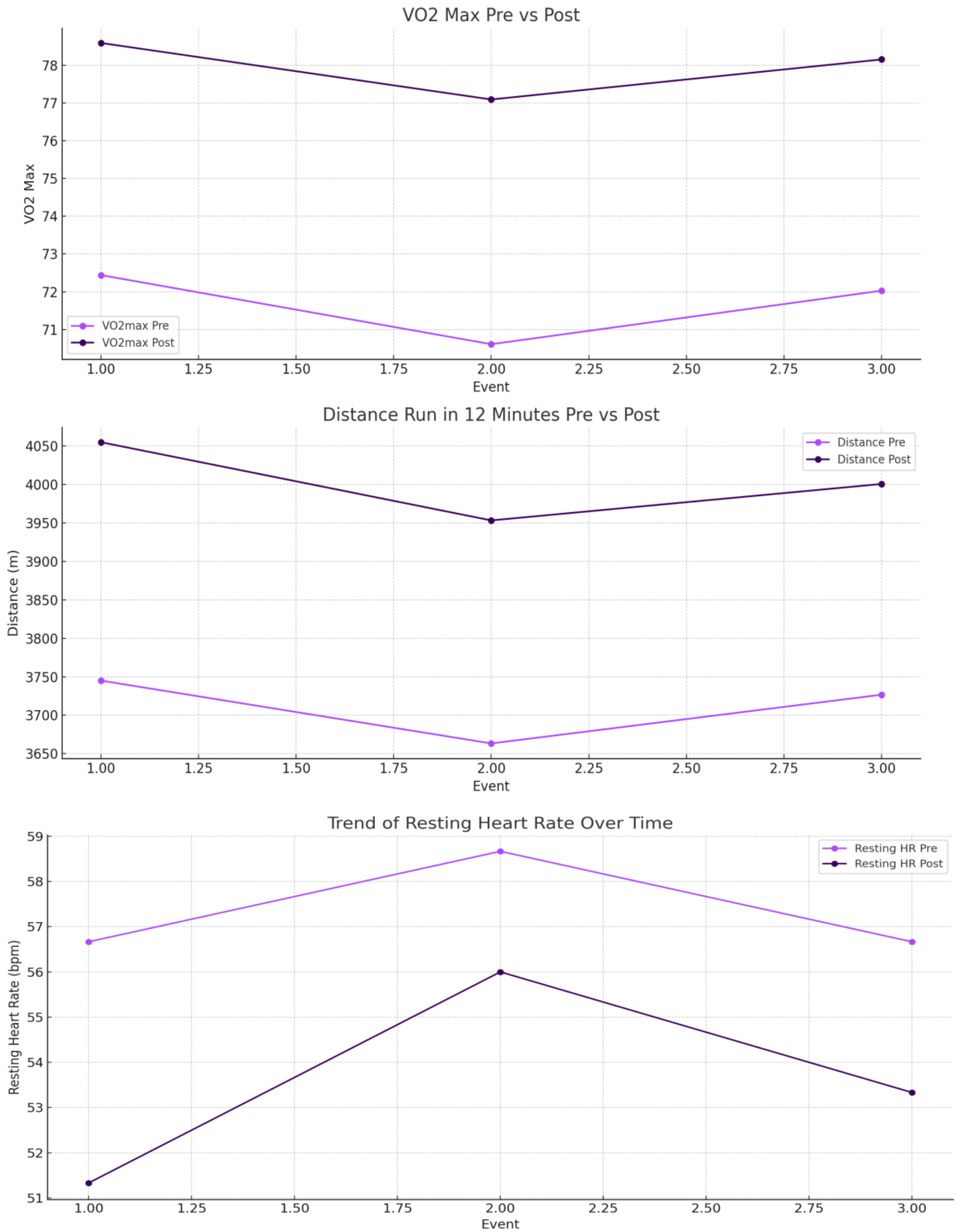


Figure 2-6A3: The line chart visualizing the changes in VO2 max, distance run in 12 minutes and The trend of Resting Heart Rate over time from pre-test to post-test for each event.

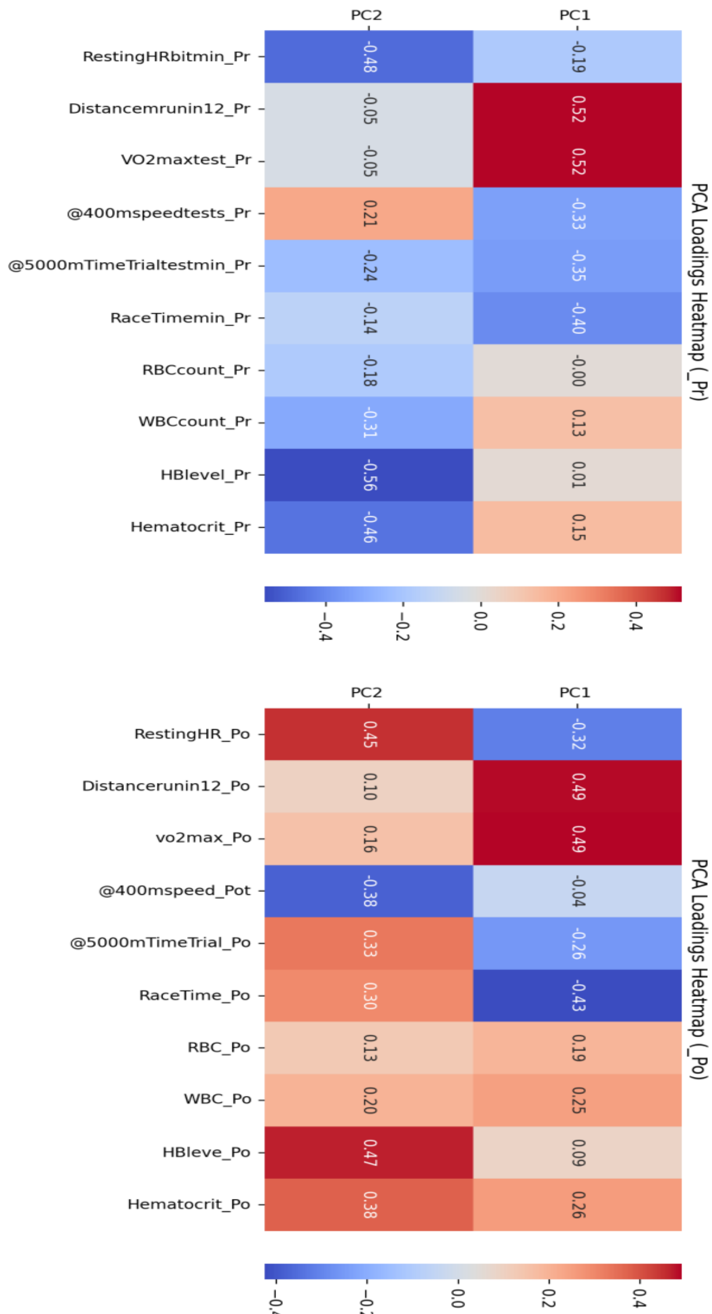


Figure 2- 7A4: The PCA analysis of heatmap shows the strength and direction of each variable's contribution to the principal components. For Pre-training (_Pr) data: First two components explain about 51% of variance (33% + 18%), and for Post-training (_Po) data: First two components explain about 55% of variance (30% + 25%)

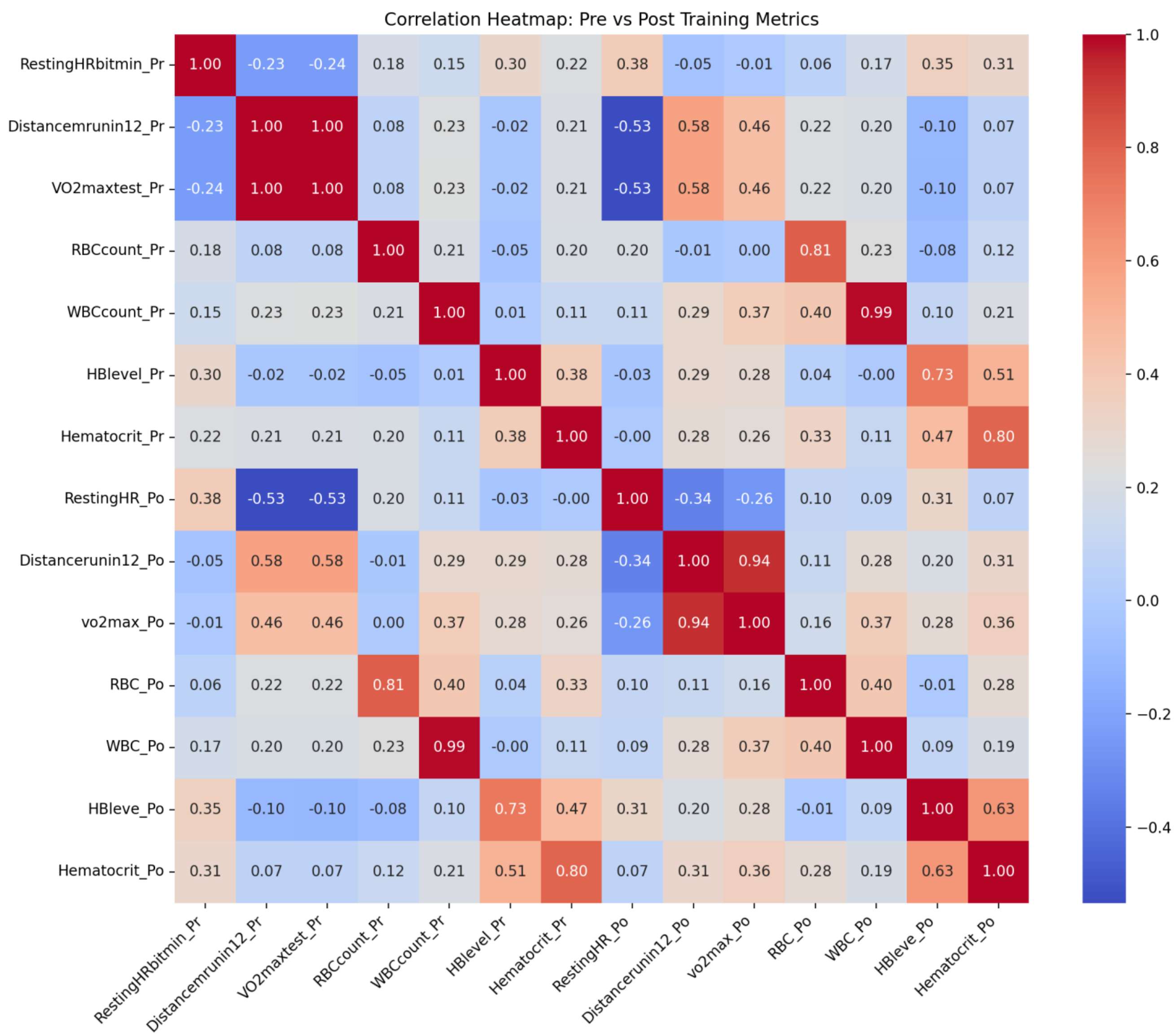


Figure 2- 8A5: The correlation heatmap shows the strength and direction of each variable's contribution to the principal components.

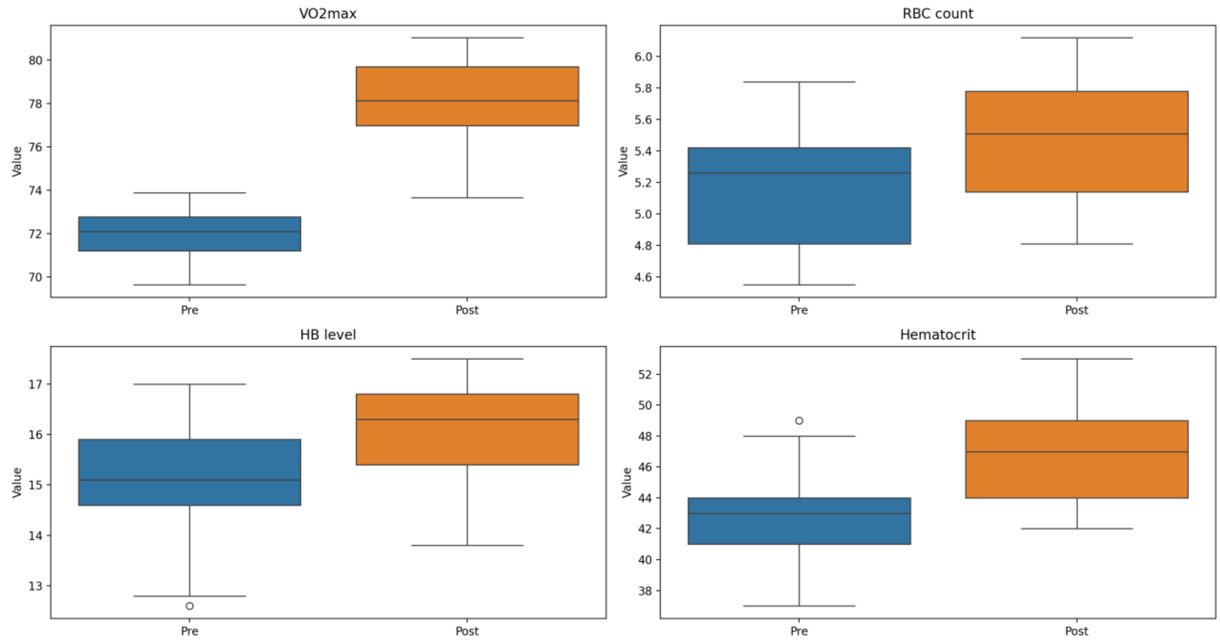


Figure 2-9A6: The box-plot results show significant improvements ($p<0.001$) across all measured determinants, with notable increases in VO_{2max} (8.60%) and Hct (10.30%).

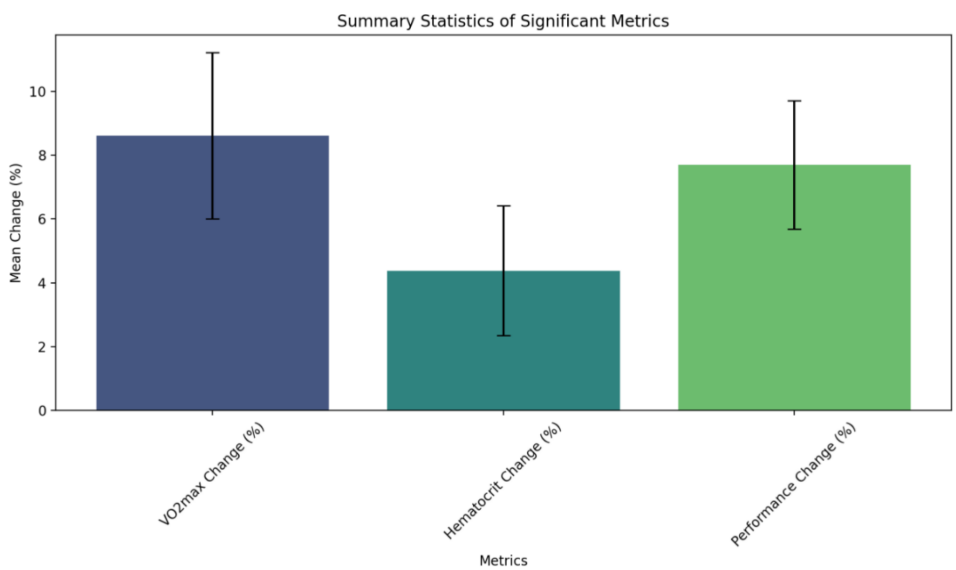


Figure 2-10A7: Bar chart showing the mean, SD, and range of significant metrics (VO_{2max}, Hct, and Performance changes).

Table 2-2: Statistics analysis of the regression model summaries, demonstrating the

Model	R	R^2	Adjusted R^2	Change Statistics				
				R^2 Change	F Change	df1	df2	Sig. F
1	0.77[a]	0.59	0.52	0.59	8.117	3	17	0.001
2	0.93[b]	0.87	0.81	0.28	9.975	3	14	0.001
3	0.93[c]	0.87	0.76	0.001	0.025	3	11	0.994

a. Predictors: (Constant), Distance run in 12' Post, 400m speed test Post, RHR Post

b. Predictors: (Constant), Distance run in 12' Pot, 400m speed test Post, RHR Post, 5000m Time Trial test (min) Pre, 5000m Time Trial Post, Race Time (min) Pre

c. Predictors: (Constant), Distance run in 12' Pot, 400m speed Post, RHR Post, 5000m Time Trial test (min) Pre, 5000m Time Trial Post, Race Time (min) Pre, RBC Post, Hb_{mass} Post, WBC Postd. Dependent Variable: Race Time Post of three models.

model predication

Table 2-3: Summary of the ANOVA results, demonstrating the model's predictive power.

Model		**Sum of Squares**	**df**	**Mean²**	**F**	***p*.**
1	Regression	6844062	3	2281354	8.117	0.001[b]
	Residual	4777766	17	281045		
	Total	11621828	20			
2	Regression	10099045	6	1683174	15.475	0.000[c]
	Residual	1522783	14	108770		
	Total	11621828	20			
3	Regression	10109279	9	1123253	8.169	0.001[d]
	Residual	1512549	11	137504		
	Total	11621828	20			
Note: a. Dependent Variable: Race Time Post, b. Predictors: (Constant), Distance run in 12' Post, 400m speed test Post, RHR Post						
c. Predictors: (Constant), Distance run in 12' Pot, 400m speed test Post, RHR Post, 5000m Time Trial test (min) Pre, 5000m Time Trial Post, Race Time (min) Pre						
d. Predictors: (Constant), Distance run in 12' Pot, 400m speed Post, RHR Post, 5000m Time Trial test (min) Pre, 5000m Time Trial Post, Race Time (min) Pre, RBC Post, Hbmass Post, WBC Post						

Table 2-4: Statistical Analysis Results of Intervention

	Descriptive					Paired comparison			
	Max	Mini	Mean ±St. D		Var.	Corr.	Mean ±Std. D		t
RBC_{Pre}	5.84	4.55	5.18	± 0.40	0.16	0.81**	-0.28	± 0.24	5.23**
RBC_{Post}	6.12	4.81	5.45	± 0.39	0.15				
WBC_{Pre}	10.6	4.5	7.5	± 1.9	3.5	0.99**	-0.1	± 0.30	-1.58
WBC_{Post}	9.30	5.92	7.70	± 1.77	.15				
HB_{Pre}	17.0	12.6	15.1	± 1.1	1.3	0.73**	-.88	± 0.82	4.92**
HB_{Post}	17.5	13.8	16.0	± 1.1	1.2				
Hem_{Pre}%	49	370	42.5	± 3.12	9.76	0.80**	-4.4	± 0.02	9.86**
Hem_{Post}%	53	42	46.9	± 3.24	10.5				
RHR_{Pre} (bit/min)	60	52	57	± 3	9	0.38	3.8	± 3.89	4.48**
RHR_{Post} (bit/min)_Po	60	48	53	± 4	15				
Run (m) dist. $12'_{Pre}$	3810	3620	3723	± 57	3201	0.58**	-29	± 73.52	17.86**
Run (m) dist. $12'_{Post}$	4130	3800	4009	± 90	8146				
VO_2 max_{Pre}	73.9	69.6	71.9	± 1.27	1.60	0.57*	-6.4	± 1.7	16.24**

CHAPTER 3: STUDY 2

IMPACT OF STRENGTH TRAINING ON HEMATOLOGICAL PROFILES, PHYSIOLOGICAL ADAPTATIONS, AND PERFORMANCE METRICS IN ELITE MID-TO-LONG DISTANCE RUNNERS

ABSTRACT

This study examined the effects of a 6-week strength training (StT) program on elite middle- to long-distance runners (1500m–10,000m). While strength training is recognized for improving athletic performance, its specific impact on physiological and haematological determinants in Ethiopia remains unclear. Twenty-one elite athletes underwent pre- and post-training assessments, measuring resting heart rate (RHR), maximal oxygen consumption (VO_2 max), 5000m race time, 400m speed, and haematological markers, including red blood cell (RBC) count, white blood cell (WBC) count, hemoglobin (Hgb), and hematocrit (Hct). Results showed that 5000m performance significantly improved ($p < 0.001$), demonstrating the positive effect of StT on endurance. Regression and ANOVA analyses revealed strong predictive relationships for VO_2 max ($R^2 = 0.304$, $p = 0.010$), 5000m time ($R^2 = 0.719$, $p < 0.001$), 400m speed ($R^2 = 0.784$, $p < 0.001$), and Hct levels ($R^2 = 0.894$, $p < 0.001$). No significant changes were found in RBC, WBC, or Hb levels. These findings suggest strength training enhances endurance performance without significantly affecting haematological determinants, emphasizing the need for further research on long-term haematological adaptations. This research contributes valuable insights into the effectiveness of strength training interventions for enhancing athletic performance.

Key words: Exercise therapy, strength training, Haematologic tests, Sport performance, Physiological processes, Endurance running

1. INTRODUCTION

Strength training (StT) has long been debated as a tool for improving endurance performance, particularly in middle- and long-distance athletes (MLDA)(Tomschi, Bloch, & Grau, 2018). Recent studies suggest that StT can significantly enhance running performance by improving key factors such as running economy, power, and endurance capacity (Gill, Williams, & Reifsteck, 2017). StT works by overloading the neuromuscular system, leading to better motor unit recruitment, increased firing frequency, musculotendinous stiffness, and improved intramuscular coordination, all of which contribute to enhanced running efficiency and performance metrics (Siddique *et al*., 2020; Škarabot, Brownstein, Casolo, Del Vecchio, & Ansdell, 2021).

Different modalities of StT, such as explosive and heavy StT, target various physiological adaptations. Explosive StT which includes bodyweight jumping and plyometric exercises, improves the rate of motor unit activation and muscular power (Liao *et al*., 2022). Although, heavy StT enhances anaerobic capacity and maximal speed is particularly useful for sprinting in competitive events (Gäbler, Prieske, Hortobágyi, & Granacher, 2018). These adaptations help delay fatigue and increase the MLDA's ability to sustain lower levels of exertion over time, which is critical for long-distance events (Midgley, McNaughton, & Jones, 2007).

Additionally, StT has been shown to improve haematological profiles, which are critical for endurance performance. Specifically, StT can increase red blood cell (RBC) counts, Hb, and Hct, all of which are essential for efficient oxygen delivery to working muscles (Ahmadizad & El-Sayed, 2005). While endurance training traditionally focuses on improving aerobic capacity, integrating StT offers a complementary approach, potentially boosting both muscular and haematological adaptations (Tomschi *et al*., 2018).

However, the specific effects of StT on the haematological profiles of elite runners remain underexplored (Zachár y *et al*., 2023). Existing research suggests that StT may positively influence these determinants, but further investigation is required to fully understand its impact, particularly in high-level MLDA (Tomschi *et al*., 2018). This study aims to fill this gap by examining how a structured StT program affects the haematological profiles, physiological adaptations, and overall performance of elite mid-to-long distance runners (Boullosa *et al*., 2020).

The study also explores the predictive role of pre-intervention Hb levels on post-StT outcomes, offering insights into how baseline physiological metrics may influence the effectiveness of StT interventions(Steiner, Maier, & Wehrlin, 2019). By addressing these factors, this research seeks to optimize training regimens for elite endurance MLDA, contributing to a more nuanced understanding of the relationship between ST, haematological adaptation, and performance improvement (Best, 2021; Mujika, Bourdillon, Zelenkova, Vergnoux, & Millet, 2024).

The effects of StT on endurance athletic performance have long been the subject of debate among athletes, coaches, and sports scientists. StT has a positive impact on middle- and long-distance running performance and its key determinants for different competitive levels (Blagrove, Howatson, & Hayes, 2018). StT modalities have been shown to elicit performance improvements in moderately-trained (Albracht & Arampatzis, 2013), well-trained (Alcaraz-Ibañez & Rodríguez-Pérez, 2018; Mujika *et al*., 2024), and highly-trained participants (Boullosa *et al*., 2020). This suggests that runners of any training status can benefit from ST.

StT provides an overload to the neuromuscular system, improving motor unit recruitment, firing frequency, musculotendinous toughness, and intramuscular coordination, potentially providing distance runners with a approach to enhance their RE and event-specific muscular power elements {Formatting Citation}. StT includes both explosive and heavy ST, which promote different training adaptations (Aagaard & Andersen, 2010). Explosive StT involves bodyweight jumping exercises (Blagrove *et al*., 2018) and plyometric exercises, commonly used to increase short-tempered strength through the stretch-shortening cycle (Iaia & Bangsbo, 2010). This leads to adaptations such as an increased rate of activation of motor units (Coutts, Wallace, & Slattery, 2007).

StT contributes to enhancing endurance performance by improving the economy of movement, delaying fatigue, improving anaerobic capacity, and enhancing maximal speed. In running, the combination of these changes can provide an MLDA with tactical advantages, such as in attacks or final sprints, while also potentially affecting indices of aerobic capacity (Chen *et al*., 2023). Additionally, strength exercises that enhance endurance capacities are imperative in improving competitive running performance (Siddique *et al*., 2020; Škarabot *et al*., 2021).

The integration of StT into the regimen of endurance MLDA, particularly MLDA, has gained considerable attention due to its potential to enhance performance (Alcaraz-Ibañez & Rodríguez-Pérez, 2018; Mujika *et al*., 2024). StT not only augments muscular power and endurance but also induces beneficial physiological and haematological adaptations (Barnes & Kilding, 2015; Montero *et al*., 2017). Haematological determinants such as increased Hb concentration and RBC count have been associated with improved endurance capacity (Alcaraz-Ibañez & Rodríguez-Pérez, 2018; Schumacher, Schmid & Bültermann, 2002). The aim of this study is to examine the impact of a structured StT program on the haematological profiles, physiological adaptations, and performance metrics of elite mid-to-long distance runners. This study hypothesizes that StT modalities will show significant changes in MLDA haematological, physiological, and performance determinants, with RHR being the most affected physiological determinant. By addressing this gap in the literature, the study aims to provide a comprehensive understanding of how StT can be integrated into the training regimens of elite endurance MLDA to optimize performance (Steiner *et al*., 2019; Tomschi *et al*., 2018).

2. MATERIALS AND METHODS

2.1. Description of the sample population

This study was conducted in the Addis Ababa region of Ethiopia, focusing on an elite group of male middle- and long-distance athletes (MLDA) coached by the researcher. Participants were selected from athletes who primarily trained at high-altitude sites, including Intoto, Kenenisa's running tracks, and Dukum sand roads, with elevations ranging from 2,800 to 3,500 meters above sea level. These athletes were chosen due to their competitive status and representation of Ethiopia in international middle- and long-distance running events (1,500m to 10,000m).

2.2. Research design

This study employed a quasi-experimental design to investigate the effects of strength training on physiological and haematological factors influencing running performance. A purposive and convenience sampling technique was used to select 21 elite MLDAs who met the inclusion criteria of competing at the national or international level. Following a pre-test assessment, participants underwent a six-week strength training (StT) intervention, after which post-treatment effects on performance-related physiological and haematological determinants were evaluated. Ethical approval for the study was obtained from the AAU College of Natural Sciences Research Ethics Committee. All participants provided written informed consent, and the study adhered to the ethical principles outlined in the Helsinki Declaration for human research.

2.3. Experimental procedure

The intervention consisted of a six-week StT program, with 3–4 sessions per week. The study was conducted in three phases:

- Pre-test phase: Physiological and haematological determinants were assessed after four weeks of pre-intervention training.
- Intervention phase: A six-week StT program was implemented, focusing on endurance, strength, and speed training.
- Post-test phase: The same physiological and haematological determinants were measured immediately after the intervention.

The StT program included three hard training days, one moderate day, two easy days, and one rest day per week. Training variables (type, volume, and intensity) were strictly controlled, while extrinsic and intrinsic factors remained uncontrolled to minimize bias inherent in quasi-experimental designs

2.4. Strength training protocol

The StT program integrated hill running (3 × 200m) as the final station in a circuit of bodyweight exercises. The circuit comprised six sets of eight stations, with each station involving 1–2 minutes of work followed by a one-minute rest. Between sets, participants rested for three minutes. The program targeted muscle groups critical to running performance.

Training sessions were conducted three times per week (Tuesday, Thursday, and Saturday) over six consecutive weeks. Each session included: a 20-minute warm-up, 10 minutes of dynamic mobilization exercises, the main training session (duration determined by individual preliminary tests), and a 10-minute cool-down.

A preliminary test was conducted to establish each participant's workload, set at 60–80% of their one-repetition maximum (1RM). The program followed the principle of progressive overload, with workload increasing by 10% weekly until reaching 80% of 1RM.

2.5. Data collection techniques

Blood samples were collected 48 hours after the final training session of each intervention phase. For the pre-test, participants were advised to refrain from strenuous activity for two days prior to sample collection. A total of 10 mL of blood was drawn from the antecubital fossa vein after a 12-hour fast. Post-StT blood samples were collected following the same procedure. Blood collection and analysis were performed by trained professionals in a certified laboratory. Physiological data were collected through event-specific time trials, indirect VO_2 max tests, 400m speed tests, and RHR measurements. Pre- and post-StT data collection adhered to standard laboratory protocols and established guidelines (Mackenzie, 2005).

2.6. Data analysis

Descriptive statistics, including mean (M), standard deviation (SD), and range, were calculated for pre- and post-StT data to identify general trends. Paired t-tests were conducted to assess statistically significant changes in physiological, performance, and haematological variables from pre- to post-StT.

Correlation analysis was performed to explore relationships between variables, and Analysis of Variance (ANOVA) was used to determine statistically significant differences in dependent variables (e.g., VO_2 max, 400m speed, 5,000m run-time, RBC count, WBC count, Hb, Hct) before and after the StT intervention. Multiple regression analyses were conducted to evaluate the predictive power of pre- and post-StT metrics on post-StT hemoglobin (Hgb) levels. Statistical significance was set at $p < 0.05$.

3. RESULTS

3.1. Physiological adaptations

The analysis of RHR revealed a mean pre-intervention value of 53.14 ± 3.82 beats per minute (bpm). Following the post-strength training intervention (PSTI), the mean RHR increased slightly to 54.10 ± 4.02 bpm. A paired t-test comparing pre- and post-StT RHR values (t = -1.00, $p = 0.33$) indicated no statistically significant change (Table 3-1).

For VO_2 max, the pre-StT mean value was 78.37 ± 2.10 mL/kg/min, which increased marginally to 79.33 ± 4.70 mL/kg/min post-StT. The paired t-test revealed no statistically significant improvement in VO_2 max (t = -1.11, $p = 0.28$) following the intervention (Figure 3-1).

In contrast, the 5000m running performance showed a notable improvement. The average time to complete the 5000m run decreased significantly from 13.78 ± 0.28 minutes pre-StT to 13.51 ± 0.03 minutes post-StT. A paired t-test demonstrated a statistically significant improvement in performance (t = 4.37, $p = 0.0003$), indicating a meaningful enhancement in running efficiency following the intervention.

The analysis of RHR revealed that before the intervention the mean RHR with a standard deviation (SD) was (53.14±3.82) beats per minute (bpm). Post-strength training intervention (PSTI), the mean RHR increased slightly to 54.10 bpm (±4.02). A paired *t*-test comparing pre-and post-StT RHR yielded ($t = -1.00$, $p = 0.33$), indicating no statistically significant change (Table 3-1).

Table 3- 1: The summary table of pre–post analysis

Metric	Pre Mean	Post Mean	Change (%)	*t*	*p*	Cohen's d
Resting Heart Rate (bts/sec)	53.1	54.1	1.79	-1.0	0.33	0.24
12-minute run (m)	4010.5	4017.1	0.17	-0.88	0.39	0.07
VO_2max (mL/kg/min)	78.372	79.3	1.22	-1.11	0.28	0.26
Speed test (sec)	57.079	55.8	-2.24	5.45	0.00**	-0.54
Red Blood Cells (million/µL)	5.447	5.56	2.08	-2.48	0.02*	0.3
White Blood Cells (WBC)	7.428	7.52	1.23	-1.06	0.3	0.05
Hemoglobin (g/dL)	15.94	16.15	1.34	-2.49	0.02*	0.21

For VO_2 max, the pre-StT mean was 78.37 mL/kg/min (±2.10), which increased slightly to (79.33±4.70 mL/kg/min) post-StT. The paired *t*-test resulted in no significant improvement in VO_2 max (t = -1.11, p = 0.28), post-StT (Figure 3-1).

In contrast, the 5000M showed a notable improvement. The average time to complete the 5000m run decreased from 13.78 minutes (±0.28) pre-StT to 13.51 minutes (±0.03) post-StT. A paired *t*-test revealed a statistically significant improvement in performance, (t = 4.37, p = 0.0003).

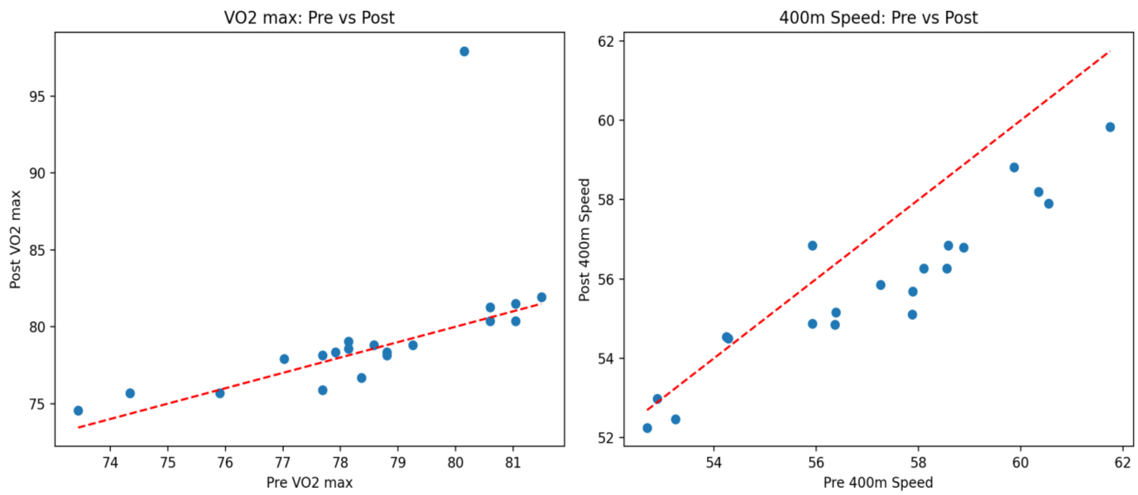


Figure 3-1: Linear regression

3.2. Haematological changes

The intervention influenced several haematological determinants, as analysed through a violin plot (Figure 3-2). The post-StT result exhibited a slightly higher RBC mean count compared to the pre-StT, but with greater variability, as evidenced by the wider distribution. However, the ANOVA test indicated no significant impact of the intervention on RBC ($p = 0.061$).

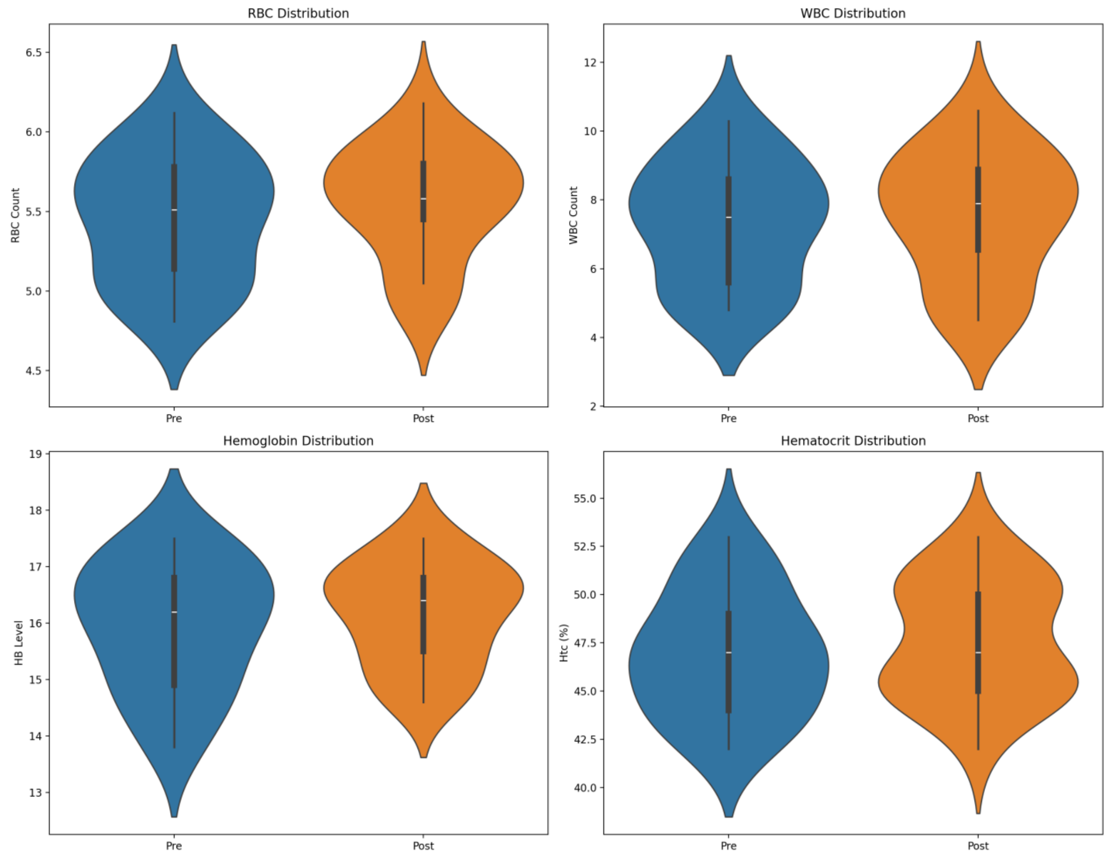


Figure 3-2: Statistical summaries of haematology

PSTI, the Hb level showed a noticeable decline compared to pre-StT, as indicated by the violin plot (Figure 3-2). The variability in Hb levels was slightly lower post-StT. Regression analysis revealed a significant relationship between pre- and post-StT Hb levels ($R^2 = 0.899$, $p < 0.001$), but the ANOVA test confirmed no significant treatment effect ($p = 0.158$, Table 3-1). The mean WBC count remained similar between the pre- and post-StT groups. However, the distribution in the post-StT group was more concentrated around the median, indicating reduced variability.

Regression analysis demonstrated a strong relationship between pre-StT and post-StT WBC counts ($R^2 = 0.892$, $p < 0.001$) and in RBC ($R^2 = 0.848$, $p < 0.001$) (Figure 3-3), but the ANOVA test showed no significant change in RBC ($p = 0.218$, Table 3-1).

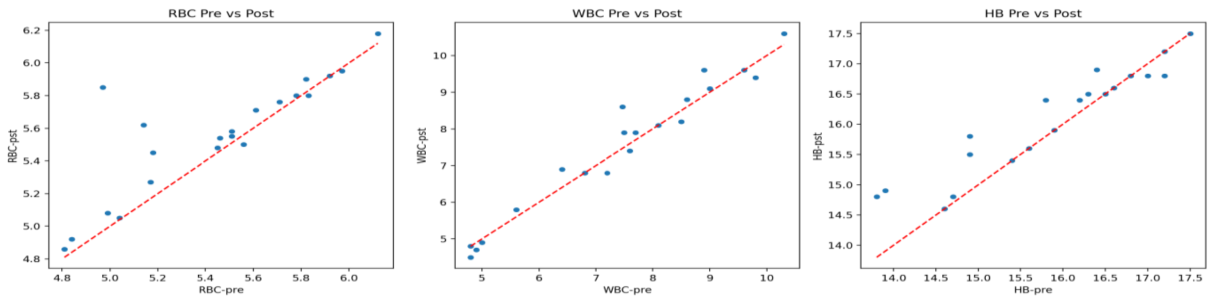


Figure 3-3: Linear regression of pre by post intervention

3.3. Measures of association between anthropometry and strength training intervention (STI)

ANOVA results demonstrated a significant association between RBC count and age ($F = 3.167$, $Eta^2 = 0.68$, $p = 0.03$), with age explaining 19.3% of the variance and linearity being an important factor ($p = 0.02$) (Table 3-2).

No significant effects of age were observed for WBC, Hb, or Hct. RHR by height has high effect sizes ($Eta^2 = 0.76$) but is not statistically significant ($p = 0.10$). Height was marginally associated with RHR ($F = 2.637$, $p = 0.078$), but no significant associations were observed between height and the haematological determinants. WBC by height show moderate effect sizes ($Eta^2 = 0.54$). Similarly, weight showed no significant effects on any of the studied parameters.

Table 3- 2: Summary of Post-Haematological determinants

Parameter	Variable	Between SS	Within SS	Total SS	F-Value	*p*	R^2	Eta²
RBC	Age	3.2	1.5	4.7	3.17	0.03	0.19	0.68
	Height	3.2	1.5	4.7	1.73	0.21	0.13	0.68
	Weight	1.3	3.4	4.7	1.17	0.40	0.06	0.28
WBC	Age	39.9	33.5	73.4	1.79	0.17	0.07	0.54
	Height	25.2	48.2	73.4	0.43	0.90	0.11	0.34
	Weight	18.1	55.3	73.4	0.98	0.50	0.01	0.25
HB	Age	2.7	15.1	17.8	0.27	0.96	0.02	0.15
	Height	12.1	5.8	17.8	1.72	0.20	0.00	0.68
	Weight	1.0	16.8	17.8	0.19	0.96	0.00	0.06
Htc	Age	88.9	97.2	189.0	1.33	0.32	0.06	0.47
	Height	91.8	97.2	189.0	0.77	0.70	0.07	0.49
	Weight	4.7	184.2	189.0	0.08	1.00	0.01	0.03
RHR	Height	247.1	76.7	323.8	2.64	0.10	0.00	0.76
	Weight	108.1	215.7	323.8	1.50	0.25	0.02	0.33

Key: Sum of Squares (SS), degree of freedom (df), Mean Square (M^2), estimated association (Eta),sig. at 95% CI (p)

The data suggest that the intervention had limited significant effects across most determinants. While the 5000M showed a marked improvement, the haematological determinants and VO_2 max remained largely unchanged. We found strong negative correlation (-0.71) between VO_2 max and TT, Figure 3-4.

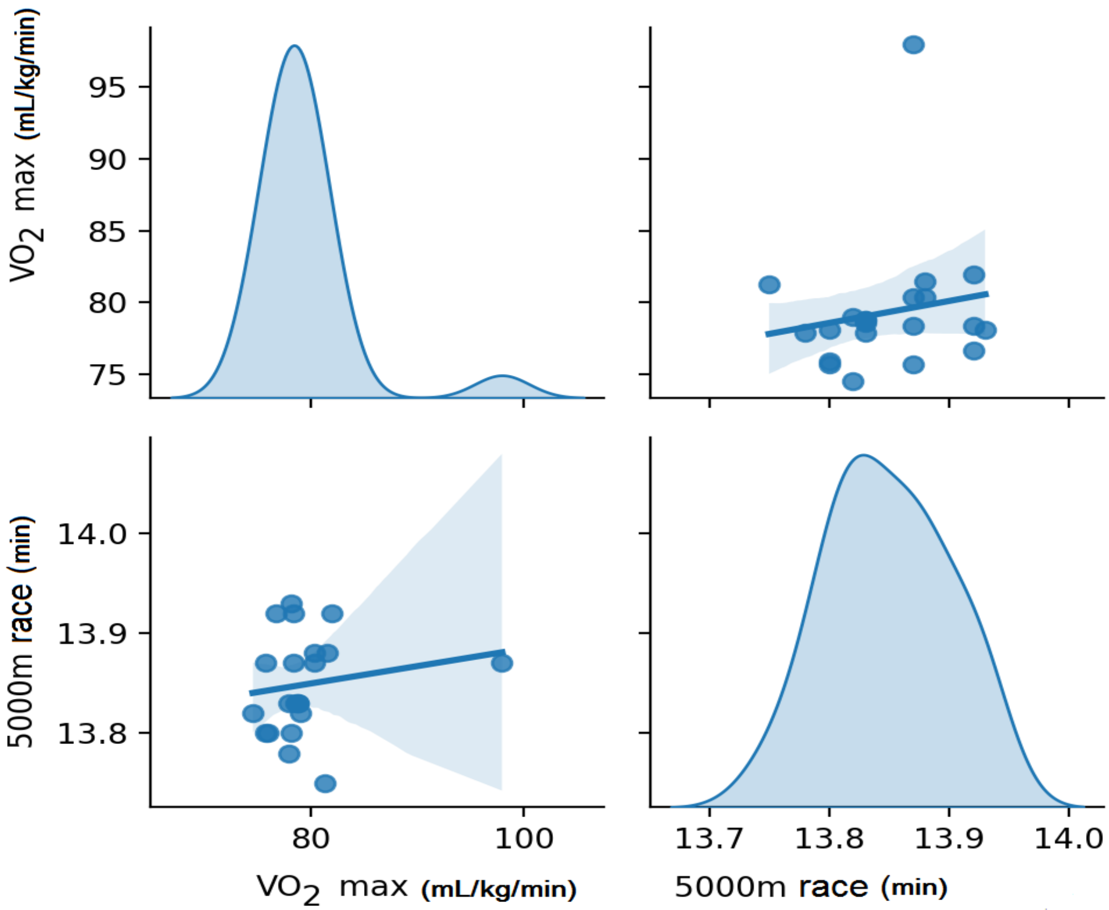


Figure 3- 4: The relationships between key predictor

4. DISCUSSION

The absence of significant change in RHR following the intervention aligns with findings from Thompson (Thompson, 2017), which reported that short-term exercise, particularly at moderate intensity, often does not alter RHR. This stability in RHR is consistent with our results, suggesting that the intervention had no significant impact on this variable.

The lack of significant change in VO_2 max supports the observations of Sindall, who noted that improvements in VO_2 max typically require longer training durations (Sindall, 2020). The short-term nature of this intervention was insufficient to produce a statistically significant difference in VO_2 max, consistent with other findings (Saunders, Pyne, Telford, & Hawley, 2004).

The moderate R^2 (0.304) indicates that VO_2 max is influenced by various factors, with the intervention showing a significant effect (p = 0.0096). Strong negative correlation between VO_2 max and 5000M indicates better cardio fitness leads to faster times. This finding aligns with Sindall, who noted that VO_2 max is a key predictor of long-distance performance (Sindall, 2020). However, the moderate R^2 suggests other factors, such as genetics or long-term adaptations, also play a role. The significant 5000M reduction in post-StT is in line with the study, which demonstrated that short-term interventions can improve distance running performance (Ives, Du, Etter, & Welch, 2005).

This result highlights the immediate performance benefits from the StT, reflecting enhanced running speed. The R^2 of 0.719 shows a strong predictive relationship between variables of pre-StT and TT. The significant treatment effect (p = 0.003) confirms the intervention's impact on performance. This aligns with similar study results (Das, 2013; Sindall, 2020), emphasized on the importance of VO_2 max and aerobic capacity in long-distance running. The high R^2 (0.784) indicates a strong relationship between pre-StT variables and post-StT 400m speed test. The improvement in post-StT speed test, supported by comparable study (Raghuveer *et al.*, 2020), highlights the role of both aerobic and anaerobic endurance in short-distance performance. Ethiopian MLDA' enhanced 400m speed is likely linked to improved cardiovascular fitness and training adaptations.

Age significantly influenced RBC post-StT, aligning with similar study that suggested age-related changes in hematopoiesis affect erythrocyte levels (Sheykhlouvand *et al*., 2018). However, no significant effects were observed for WBC, Hb, or Hct, consistent with study, which reported that these determinants are less sensitive to age (Bassett & Howley, 2000). The high R^2 (0.927) indicates that pre-intervention RBC levels strongly predict post-StT. However, the lack of significant change (p = 0.061) suggests that the intervention did not substantially affect RBC count, consistent with Mandić (2022) who found that significant changes in RBC often require longer training periods. Height showed marginal significance for RHR but no significant effect on RBC, WBC, Hb, or Hct, in line with the mixed findings in the literature. Some studies, suggest height influences cardiovascular metrics (Parmar, Jones, & Hayes, 2021), while others, show minimal direct effects (Rodríguez Zamora, 2013). The indirect influence of height, possibly mediated through body composition, is supported by (Liao *et al*., 2022; Tomschi *et al*., 2018). The R^2 of 0.892 reflects a strong relationship between pre- and post-StT WBC levels. The non-significant treatment effect (p = 0.218) is expected, as WBC counts are generally stable and less responsive to short-term endurance training (Nieman & Pence, 2020). Contrary to previous studies, weight did not significantly influence the haematological determinants (Sitkowski, Klusiewicz, Pokrywka, Jankowski, & Malczewska-Lenczowska, 2023). This discrepancy may be due to the lack of body fat percentage or distribution measurement, as highlighted by Nybo *et al*. (2010) which may better capture the relationship between weight and physiological outcomes. The stability of RBC and WBC measurements over time is supported by the previous findings (Koç *et al*., 2018), who reported minimal variation in these determinants after short-term exercise interventions.

The R^2 of 0.899 suggests that pre-StT Hb levels predict post-StT levels. The lack of significant treatment effect ($p = 0.158$) indicates that short-term interventions may not significantly alter Hb levels, consistent with similar works, who noted that Hb changes require longer training periods (Mandić, 2022; Wang *et al*., 2017). The R^2 of 0.894 indicates a strong relationship between pre-StT and post-StT Hct levels.

The non-significant treatment effect ($p = 0.061$) suggests that short-term interventions may not substantially alter Hct, consistent with RBC and Hb findings.

5. CONCLUSION

This study underscores the impact of strength training (StT) on running performance, evidenced by significant improvements in 5000m run time and 400m speed, among elite MLDA. The StT led to measurable improvements in running performance, its effects on physiological measures like RHR and Maximal oxygen consumption (VO_2 max) were not statistically significant. Additionally, the intervention did not result in significant changes in haematological markers such as RBC, WBC, and Hb, likely due to the relatively short duration of the study.

The study suggests that while StT is effective in enhancing athletic performance, longer interventions may be necessary to elicit significant haematological adaptations. Short-term exercise can improve performance metrics while maintaining stability in physiological measures such as RHR and VO_2 max. This study highlights the importance of baseline measures in determining exercise-related changes and supports the focus on pre-exercise blood metrics for predicting post-StT outcomes.

Future research should explore additional factors such as body composition and long-term training effects to provide a comprehensive understanding of the relationships. Moreover, studies should focus on extended training periods and incorporate a larger sample size to further investigate the long-term effects of StT on both performance and haematological determinants in elite runners.

CHAPTER 4: PAPER 3

THE EFFECT OF SPEED TRAINING ON PHYSIOLOGICAL AND HEMATOLOGICAL PARAMETERS IN ELITE MIDDLE AND LONG-DISTANCE RUNNERS

Abstract

Problem Statement: Aerobic capacity, particularly maximal oxygen uptake (VO_2max), is a key determinant of performance in elite middle- and long-distance runners. Although high-intensity training (HIT) is widely recognized as effective, its concurrent effects on both physiological and hematological parameters in elite athletes training at altitude remain insufficiently understood, limiting the optimization of performance adaptations.

Purpose: This study aimed to investigate the effects of a six-week high-intensity speed training (HIST) intervention on key physiological and hematological parameters relevant to performance in elite Ethiopian middle- and long-distance runners training at moderate altitude.

Approach: A quasi-experimental design was used involving 21 elite male Ethiopian runners. The intervention consisted of a six-week speed training program performed at moderate altitude (2100–3500 m), with three high-intensity interval training (HIIT) sessions per week. Physiological parameters (VO_2max, 5000 m performance, 400 m speed, and resting heart rate (RHR)) and hematological parameters (red blood cell (RBC) count, hemoglobin (HGB), hematocrit (HCT), and white blood cell (WBC) count) were assessed before and after the intervention.

Results: Significant post-intervention improvements were observed across all measured variables. VO_2max increased by 3.2% ($p < 0.000001$), 5000 m performance time decreased by 22.2 s ($p < 0.000001$), and 400 m sprint time improved by 2.3 s ($p < 0.0001$). RHR decreased by 5.2% ($p < 0.0001$). Hematological parameters also demonstrated significant increases, including RBC count (+8.1%), HGB concentration

(+6.7%), and HCT (+5.9%) (all $p < 0.001$). Regression analysis identified VO_2max, RHR, and 400 m sprint time as significant predictors of 5000 m performance, explaining approximately 68% of the variance ($R^2 \approx 0.68$).

Conclusions: A six-week HIST program performed at altitude produced significant improvements in both aerobic and anaerobic performance in elite Ethiopian middle- and long-distance runners. These performance gains were accompanied by favorable hematological adaptations, indicative of enhanced oxygen-carrying capacity and cardiovascular efficiency. Collectively, these findings support the inclusion of HIST as an effective complementary modality for elite endurance athletes training at altitude.

Keywords: speed training, altitude training, aerobic power, oxygen transport, elite runners, hematological adaptations

1. Introduction

Aerobic capacity is a fundamental determinant of performance in middle- and long-distance runners, with maximal oxygen uptake (VO_2max) serving as a sensitive indicator of performance differences at the elite level (Joyner & Coyle, 2008). In addition to aerobic fitness, anaerobic factors—particularly running speed and anaerobic capacity—play a critical role in enabling rapid force production during running (Slawinski et al., 2010). Accordingly, endurance performance is influenced by the interaction of several well-established determinants, including VO_2max, endurance capacity, anaerobic fitness, and movement efficiency (Hawley & Myburgh, 2020).

To optimize physiological adaptations in endurance athletes, training programs commonly combine high-volume, low-intensity exercise with low-volume, high-intensity protocols (Laursen, 2010; Seiler & Tønnessen, 2009). Although high-intensity training (HIT) represents a relatively small proportion of overall training volume, it is essential for the performance development of elite endurance athletes (Stöggl & Sperlich, 2015). High-intensity interval training (HIIT), one of the most widely used high-intensity strategies, is characterized by alternating bouts of intense exercise and recovery periods (Laursen, 2010). However, the existence of multiple HIIT formats—including submaximal, VO_2max-targeted, and supramaximal protocols—makes it challenging to identify the optimal training stimulus. Notably, submaximal HIIT has been shown to improve endurance performance in trained runners and cyclists (Rønnestad et al., 2014; Seiler & Tønnessen, 2009). HIT is typically defined by brief- to moderate-duration intervals performed at intensities exceeding the anaerobic threshold, interspersed with short periods of low-intensity exercise or rest to allow partial recovery (Buchheit & Laursen, 2013). In contrast, sprint interval training (SIT) has been shown to elicit substantial improvements in aerobic power and endurance performance (Hazell et al., 2010; Macpherson et al., 2011). More recently, findings by Jones et al. (2024) further support the effectiveness of SIT, demonstrating superior gains in VO_2max and time-trial performance in elite runners compared with traditional moderate-intensity training.

Speed training has been demonstrated to improve physiological parameters in both middle- and long-distance runners (Mujika & Padilla, 2001). However, it may also pose certain risks, such as immune suppression and an increased susceptibility to illness. Hematological responses to anaerobic exercise are dynamic; research indicates initial increases in hematocrit (HCT), hemoglobin (HGB), and white blood cell (WBC) counts, followed by reductions in 24 h. Moreover, prolonged intensive training has been associated with lower hematological values compared with non-athletic populations. In contrast, HIIT has been related to increases in RBC volume, which may increase oxygen transport and utilization (Gore & Hopkins, 2005).

Metabolites such as urea, creatinine, ketone bodies, and other nitrogenous compounds detectable in urine provide valuable insight into metabolic responses to exercise (Daskalaki & Gika, 2017; Lewis & Gerszten, 2014). During physical activity, the body generates metabolites including lactate, pyruvate, alanine, and hypoxanthine (Wasserman, 2009). Elevated urea levels in urine may reflect increased muscle protein metabolism and gluconeogenesis, with potential implications for performance. Ketone bodies serve as alternative energy substrates when glucose availability is limited (Phinney & Volek, 2012; Volek & Phinney, 2012).

Monitoring exercise-related metabolites such as creatine, ketone bodies, nitrogenous compounds, and phosphate is essential for optimizing training regimens. Intense exercise leads to the accumulation of hydrogen ions, resulting in a reduction in intramuscular pH and the onset of fatigue, which impairs muscle function. Phosphate, a key component of energy production, becomes depleted during prolonged exercise, thereby influencing cellular metabolism. Therefore, urinary phosphate excretion may serve as an indicator of exercise intensity and energy expenditure. Overall, the analysis of urinary metabolites provides a non-invasive approach to evaluating athlete performance and physiological homeostasis.

HIIT has been shown to improve VO_2max, lactate threshold, and running economy in endurance athletes (Helgerud et al., 2007; Laursen, 2010). Both submaximal and supramaximal HIIT protocols enhance endurance performance (Rønnestad et al., 2014; Seiler & Tønnessen, 2009), whereas speed training specifically improves anaerobic capacity and running economy (Mujika & Padilla, 2001). These physiological adaptations are associated with increases in RBC volume and improved efficiency of oxygen transport (Gore & Hopkins, 2005). Despite these findings, the interaction between speed training, hematological adaptations, and metabolic responses remains insufficiently explored, particularly among elite athletes. Therefore, this study aims to examine these relationships through a six-week speed training intervention in Ethiopian elite middle- and long-distance runners, athletes renowned for their sustained global dominance in distance running. The primary objective is to evaluate the effects of speed training on key physiological and hematological parameters relevant to endurance performance.

2. Materials and Methods

Participants

The study was performed in the Addis Ababa region of Ethiopia and involved elite male athletes from the Jeani Demadona Management-affiliated Adidas track team. The participants specialized in middle- and long-distance events ranging from 1500 to 10,000 m and routinely trained in high-altitude environments (2,100–3,500 m) in and around Addis Ababa, including Intoto, Sululta, and Kenenisa training tracks. Purposive and convenience sampling methods were used to recruit 21 elite male athletes who represent Ethiopia in international competitions. The study protocol was approved by the Research Ethics Committee of the Addis Ababa University College of Natural Sciences. All participants provided written informed consent in accordance with the Declaration of Helsinki. Prior to enrollment, each athlete completed a health-screening questionnaire and underwent basic medical assessments, including measurements of blood pressure, heart rate, body weight, and body mass index (BMI).

Training Protocol

The speed training program was designed to complement the athletes' weekly training regimen. Each session began with a 5 km warm-up and 20 min of dynamic mobilization, followed by either long intervals (1,000–1,600 m) at 95%–100% VO_2max or short intervals (200–800 m) at 105%–110% VO_2max. The speed training component accounted for approximately 6% of the weekly training volume and concluded with a 3 km cool-down and 10 min of static stretching. The weekly program included three primary interval sessions, three morning easy runs, four afternoon easy runs, and one rest day, totaling 120 km per week. Easy run sessions consisted of 13 km morning runs with 5 × 150–200 m run-outs and 6 km afternoon recovery runs. Interval workouts were progressively adjusted over the six-week period, with variations in distance and intensity, as detailed in Table 4-1.

Table 4- 1 Training protocol progression

Week	Long Intervals (95-100% VO_2max)	Short Intervals (105-110% VO_2max)
1	3 x 1000m (2 min rest)	6 x 200m (1 min rest)
2	3 x 1200m (2.5 min rest)	8 x 200m (1 min rest)
3	2 x 1600m (3 min rest)	6 x 400m (1.5 min rest)
4	3 x 1200m (2.5 min rest)	8 x 400m (1.5 min rest)
5	2 x 1600m (3 min rest)	6 x 800m (2 min rest)
6	3 x 1000m (2 min rest)	8 x 800m (2 min rest)

Procedure

Participants underwent all measurements and testing in a controlled environment over the course of a single week. They were instructed to refrain from strenuous exercise the day prior to testing and to arrive well-rested and adequately hydrated. Anthropometric parameters and aerobic fitness were assessed 24 h before the motor tests. To ensure reliability, each motor test was performed twice. Prior to the initial testing session, participants attended a familiarization session to learn the proper execution of each exercise. Furthermore, identical equipment was used for both pre- and post-program assessments to maintain consistency.

Physiological Parameters

VO_2max: Estimated during event-specific time trials on a 400 m track using Garmin Forerunner watches (model 235 or above; Garmin Ltd., Olathe, KS, USA). Athletes' age, height, weight, and resting heart rate (RHR) were entered into the devices to enhance the accuracy of the estimation.

Racing Performance: Event-specific time trials were performed both before and after the intervention on a standard 400 m track (see Fig. 4-1). Additionally, race times from nationally or internationally approved competitions during the intervention period were recorded.

Speed Test: Maximum speed was assessed using a 400 m sprint test, performed at least 24 h after any vigorous activity. A standard 400 m track and a stopwatch were used to record performance.

Resting Heart Rate (RHR): Measured before the time trials and speed assessments. Athletes remained supine in bed before measurement, and heart rate was recorded over a 15-s period, then multiplied and converted to beats per minute (bpm) for accuracy.

Figure 4-1: An athlete's photo representing the Jeani Demadona Management Adidas track team undergoes a physiological assessment on the standard 400-meter track.

Hematological Parameters

Complete Blood Chemistry: Blood samples (10 mL) were collected from the antecubital vein 48 h after training, following a 12-h overnight fast, in the early morning before any physical activity or breakfast. Samples were obtained both before and after the intervention to measure red blood cell (RBC) count, white blood cell (WBC) count, HGB, HCT, iron, calcium, and creatinine levels. Analyses were performed by experienced laboratory professionals at the Ethiopian Youth and Sport Institute using standardized procedures.

Statistical analysis

All statistical analyses were performed using R (Version 4.3.1; R Foundation for Statistical Computing, Vienna, Austria) and Python (Version 3.11.5; Python Software Foundation, Wilmington, DE, USA), with a significance threshold set at $\alpha = 0.05$. Data were initially evaluated for normality using the Shapiro–Wilk test and for homogeneity of variance using Levene's test. Variables that violated the assumption of normality were log-transformed when appropriate; otherwise, non-parametric tests were applied.

Descriptive statistics are reported as mean ± standard deviation (SD) for normally distributed variables and as median [interquartile range, IQR] for non-normally distributed variables. Longitudinal changes in physiological, performance, and hematological parameters across the training phases (pre-, mid-, and post-training) were subsequently assessed. Paired t-tests were used to compare means between two time points (pre- vs. mid-training, mid- vs. post-training, and pre- vs. post-training) for parametric data. For paired data that were not normally distributed, the Wilcoxon signed-rank test was applied. To examine the effect of time (training phase) on 12-min running distance and 5000 m performance, a one-way repeated-measures analysis of variance (ANOVA) was performed. Sphericity was evaluated using Mauchly's test, and when violated ($\epsilon < 0.75$), the Greenhouse–Geisser correction was applied to adjust the degrees of freedom. Significant main effects of time were further analyzed through post-hoc pairwise comparisons with Bonferroni adjustment to control the family-wise error rate. Additionally, ordinary least squares (OLS) regression was used to model baseline 5000 m performance. The predictor variables included baseline body weight, RHR, 12-min running distance, VO_2max, and 400 m sprint time. Multicollinearity among predictors was assessed using the variance inflation factor (VIF), with values below 2.0 indicating no problematic collinearity. The overall fit of the regression model was evaluated using the coefficient of determination (R^2) and the root mean squared error (RMSE). To examine the multivariate relationships between post-training 400 m sprint times (response variable) and a set of post-training physiological predictors (VO_2max, RHR, 12-min running distance, and body weight), redundancy analysis (RDA) was performed. The significance of the RDA model and its individual constrained axes was assessed using permutation tests with 999 iterations. Standardized coefficients (β) and their 95% confidence intervals (CI) were reported to indicate the unique contribution and precision of each physiological predictor in explaining variance in 400 m sprint time, while controlling for the effects of other predictors. Bivariate associations between baseline 5000 m performance and key baseline physiological and performance metrics were quantified using Pearson's correlation coefficient (r). To illustrate patterns of correlations across multiple variables, a correlation matrix was generated and visualized as a heatmap. Hierarchical clustering, based on Euclidean distance and Ward's method, was applied to the correlation matrix to group variables with similar correlation profiles. Effect sizes were calculated for all primary inferential analyses to quantify the magnitude of observed effects. Cohen's d was calculated for paired t-tests, and partial eta-squared (ηp^2) was reported for repeated-measures ANOVA. Bias-corrected 95% confidence intervals for hematological parameters were generated using a bootstrap resampling approach with 10,000 iterations. Potentially influential outliers in the OLS regression models were identified using Cook's distance. The generalizability and robustness of the OLS model for predicting baseline 5000 m performance were assessed using leave-one-out cross-validation (LOOCV).

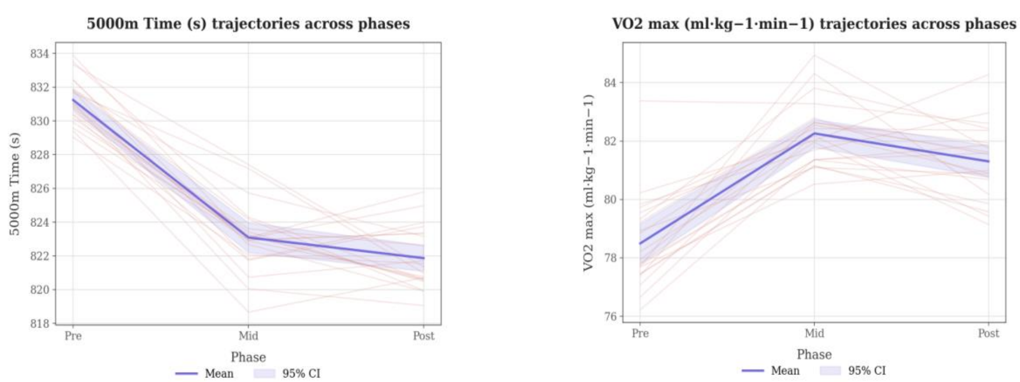
2. Results

The participants had a mean age of 24.24 ± 1.73 years and a mean height of 174.76 ± 4.76 cm. Baseline body weight was 57.05 ± 2.62 kg. Height remained unchanged during the study, whereas body weight showed a statistically significant reduction at the mid-training assessment compared with baseline ($p = 0.0389$), followed by stabilization between the mid- and post-training assessments. Key physiological and hematological changes are summarized in Table 4-2.

Table 4- 2: Physiological and hematological parameters before and after training

Parameter	**Baseline**	**Post-Training**	**p-value**
Body Weight (kg)	57.05 ± 2.62	56.45 ± 2.55	0.0389
Resting Heart Rate (bpm)	54.48 ± 3.74	51.62 ± 3.14	< 0.0001
VO_2max ($ml \cdot kg^{-1} \cdot min^{-1}$)	78.47 ± 2.01	80.97 ± 2.02	< 0.000001
400m Sprint Time (s)	52.1 ± 1.2	49.8 ± 1.1	< 0.0001
5000m Performance (s)	900.5 ± 15.3	878.3 ± 14.9	< 0.000001
RBC Count (× 10^{12} cells/L)	5.01 ± 0.21	5.42 ± 0.23	< 0.001
Hemoglobin (g/dL)	15.1 ± 0.8	16.1 ± 0.9	< 0.001
Hematocrit (%)	45.3 ± 2.1	48.0 ± 2.2	< 0.001
WBC Count (× 10^9 cells/L)	7.5 ± 1.0	7.4 ± 1.1	0.75

The training intervention resulted in significant improvements in several physiological and performance parameters. RHR decreased progressively from a baseline mean of 54.48 ± 3.74 bpm to 51.62 ± 3.14 bpm post-training, indicating enhanced cardiovascular efficiency. VO_2max demonstrated a time-dependent response to the intervention, increasing from 78.47 ± 2.01 $mL \cdot kg^{-1} \cdot min^{-1}$ at baseline to a mid-intervention peak of 82.33 ± 2.01 $mL \cdot kg^{-1} \cdot min^{-1}$ ($p < 0.000001$ vs. baseline), followed by a slight decline to 80.97 ± 2.02 $mL \cdot kg^{-1} \cdot min^{-1}$ post-training ($p < 0.000001$ vs. baseline; $p = 0.000001$ vs. mid-training), as shown in Fig. 1. This pattern suggests an initial rapid adaptation to training, followed by a plateau or slight regression as athletes approached their physiological limits. The 400 m sprint time improved significantly, decreasing from 52.1 ± 1.2 s at baseline to 49.8 ± 1.1 s post-training ($p < 0.0001$), reflecting enhanced anaerobic capacity and speed. Similarly, 5000 m performance improved from 900.5 ± 15.3 s at baseline to 878.3 ± 14.9 s post-training ($p < 0.000001$), indicating enhanced



endurance performance, as shown in Fig. 4-2.

Figure 4-2: Longitudinal changes in performance metrics across pre-training (baseline), mid-training (week 3), and post-training (week 6) phases. The left panel shows 5000 m performance time (s), while the right panel shows VO_2max ($mL \cdot kg^{-1} \cdot min^{-1}$). Purple lines represent the mean, and shaded areas indicate the 95% confidence interval.

Hematological parameters showed significant positive adaptations in response to the training intervention. RBC count increased from 5.01 ± 0.21 × 10^{12} cells/L at baseline to 5.42 ± 0.23 × 10^{12} cells/L post-training ($p < 0.001$). HGB levels increased from 15.1 ± 0.8 g/dL to 16.1 ± 0.9 g/dL ($p < 0.001$), and HCT increased from 45.3% ± 2.1% to 48.0% ± 2.2% ($p < 0.001$), reflecting an enhanced oxygen-carrying capacity of the blood—a critical adaptation for endurance performance at altitude. WBC count remained stable during the intervention, indicating no significant immune suppression (Table 4-2).

The correlation analysis identified several significant relationships between physiological variables and 5000 m running performance, as shown in Fig. 4-3. RHR exhibited the strongest positive correlation ($r = 0.510$, $p < 0.001$), indicating that athletes with higher RHR tended to record slower 5000 m times. Similarly, 400 m sprint time showed a strong positive correlation ($r = 0.466$, $p < 0.001$), suggesting that slower sprint performance was associated with slower distance running times. In contrast, VO_2max demonstrated a strong negative correlation ($r = -0.427$, $p < 0.001$), confirming that higher aerobic capacity predicts faster 5000 m performance. A moderate negative correlation was also observed for 12-min distance ($r = -0.315$, $p < 0.05$), indicating that covering a greater distance in this test was related to faster 5000 m times. However, body weight showed only a weak, non-significant correlation ($r = 0.081$, $p > 0.05$), suggesting it has minimal influence on 5000 m performance among the variables measured.

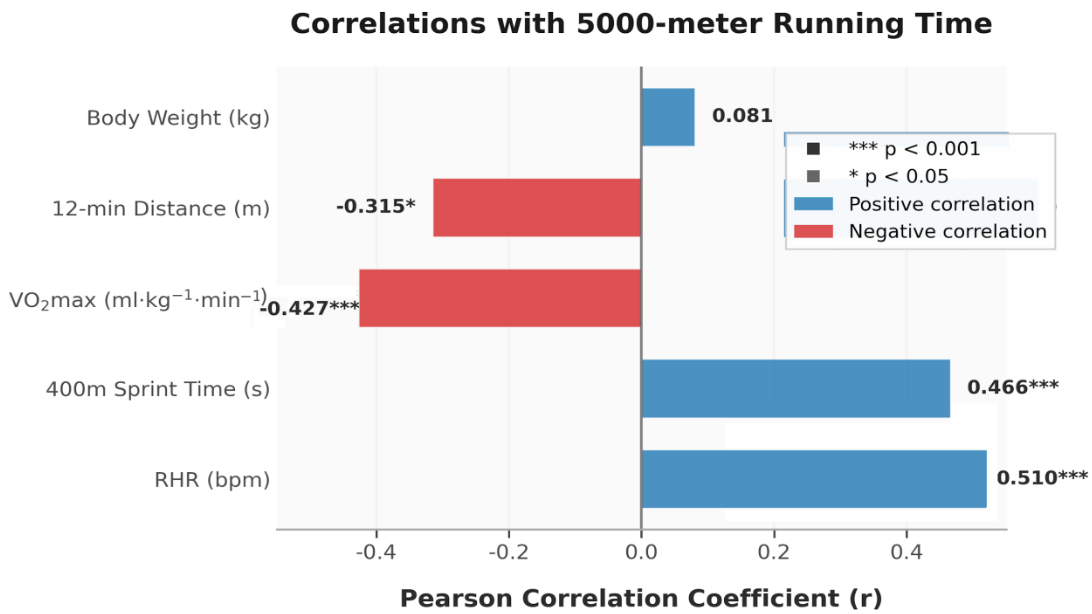


Figure 4-3: Pearson correlation coefficients between baseline 5000 m performance and selected variables

Regression analysis indicated that VO_2max, RHR, and 400 m sprint time were significant predictors of 5000 m performance ($R^2 \approx 0.68$), highlighting the combined influence of aerobic and anaerobic factors on endurance race outcomes (Fig. 4-4). LOOCV confirmed the robustness and generalizability of the OLS model in predicting baseline 5000 m performance.

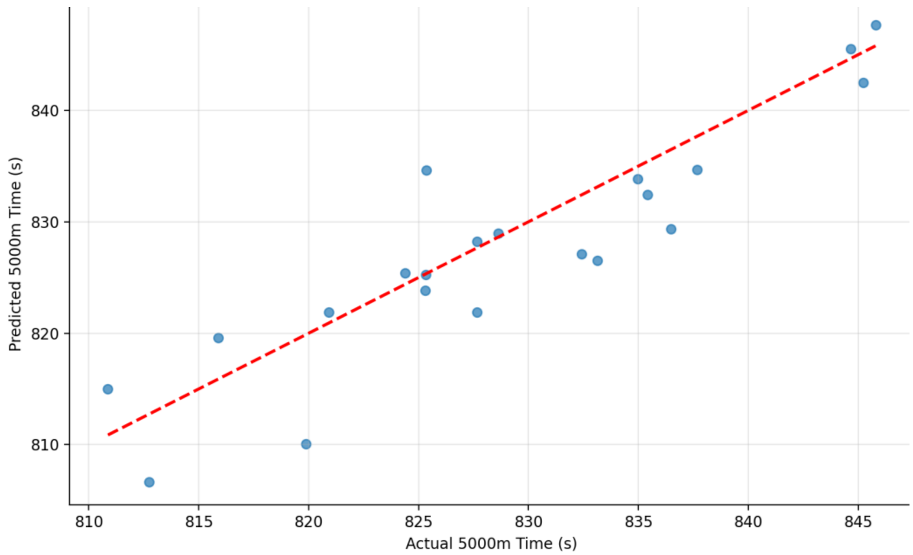


Figure 4-4: Ordinary least squares (OLS) regression model predicting baseline 5000 m performance. The scatter plot shows the relationship between observed and model-predicted times (R^2 = 0.68). Predictor variables include body weight, RHR, 12-min distance, VO_2max, and 400 m sprint time.

RDA further examined the relationships between post-training physiological predictors and performance times, as shown in Fig. 4-5. The results identified distinct physiological determinants for 5000 and 400 m sprint performance. For a 5000 m time, VO_2max emerged as the strongest negative predictor (coefficient = −0.42), indicating that higher aerobic capacity substantially contributes to faster distance running. In contrast, RHR displayed the strongest positive coefficient (0.38), suggesting that elevated RHR is associated with slower 5000 m performance. Body weight showed a moderate positive relationship (0.25) with 5000 m times, suggesting that greater body mass contributes to slower distance running. For 400 m sprint performance, the 12-min distance demonstrated the strongest negative association (−0.36), indicating that superior endurance capacity predicts faster sprint times. VO_2max exhibited a weaker negative relationship with sprint performance (−0.19) compared to its effect on distance running. RHR consistently showed a positive association with slower sprint times (0.31), whereas body weight had minimal influence on sprint performance (0.08). Overall, the RDA models explained 47% of the variance in 5000 m times and 38% of the variance in 400 m sprint times, confirming these physiological factors as significant determinants of running performance across different distances.

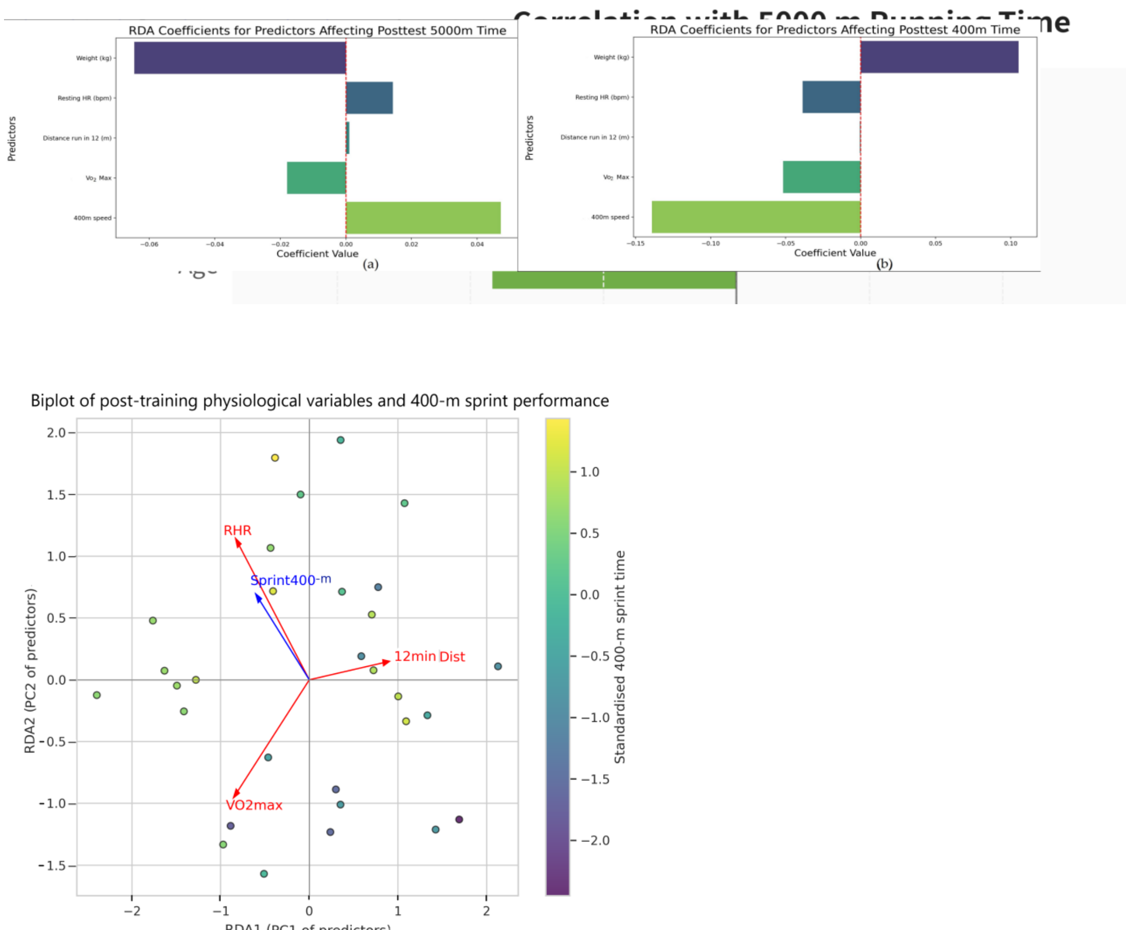


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Figure 4-5: Redundancy analysis (RDA) of post-training performance predictors. The charts show standardized coefficients for predictors of 5000-meter time (a) and 400-meter sprint time (b). For both charts, positive coefficient values indicate a factor that contributes to slower performance times, while negative values indicate a factor that contributes to faster performance times. (c), RDA biplot illustrating the multivariate relationships between post-training physiological predictors and 400-m sprint time. The first constrained axis represents variation in 400-m sprint time, with vectors for VO_2max, 12-min distance, and resting heart rate (RHR). Longer vectors and smaller angles with the sprint-time axis indicate stronger associations.

The multiple linear regression model significantly predicted baseline 5000-m performance (R^2=0.71, F(5,15)=7.29, p<0.001). RHR, VO_2max, and 400-m sprint were significant independent predictors.

Redundancy Analysis (RDA) (Fig. 4-5c) shows a biplot of post-training physiological variables and 400-m sprint performance. The first constrained axis (RDA1) largely reflects a gradient from high VO_2max and greater 12-min distance to higher RHR.

RDA revealed that post-training 400-m sprint time was significantly associated with a multivariate combination of physiological factors ($F = 8.3$, $p < 0.001$), with higher VO_2max ($\beta = -0.48$, p=0.001) and greater 12-min distance ($\beta = -0.41$; p=0.004) predicting faster times, while higher RHR ($\beta = 0.35$; p=0.011) predicted slower times.

3. Discussion

This study examined the effects of a six-week high-intensity speed training (HIST) intervention on physiological and hematological parameters in elite Ethiopian middle- and long-distance runners training at altitude. The findings demonstrate significant improvements in both aerobic and anaerobic performance, accompanied by favorable hematological adaptations, highlighting the effectiveness of speed training as a complementary strategy for elite endurance athletes in high-altitude environments.

The observed increase in VO_2max (+3.2%) aligns with previous research demonstrating the effectiveness of HIT in improving aerobic capacity (Helgerud et al., 2007; Laursen, 2010). The initial rapid increase in VO_2max, followed by a slight post-training decline, may reflect a plateau effect as athletes approach their physiological ceiling or indicate a need for varied training stimuli to drive further adaptations. This pattern is consistent with the principle of diminishing returns in highly trained individuals, where incremental gains become increasingly difficult to achieve. Significant improvements in 400 m sprint time (−2.3 s) and 5000 m performance (−22.2 s) highlight the dual benefits of speed training, enhancing both anaerobic power and endurance. Such adaptations are particularly valuable for middle- and long-distance runners, for whom a strong finishing sprint and sustained speed are critical for competitive success.

The observed positive hematological adaptations, including increases in RBC count (+8.1%), HGB (+6.7%), and HCT (+5.9%), are particularly noteworthy. These changes reflect an enhanced oxygen-carrying capacity, a critical adaptation for athletes training and competing at altitude (Gore & Hopkins, 2005). While altitude exposure is known to stimulate erythropoiesis, our findings suggest that HIST further augments this process, contributing to a more efficient oxygen transport system (Gonzales & Patel, 2024). The stability of WBC count during the intervention indicates that the training load was well-managed and did not induce significant immune suppression, a common concern with intensive training programs (Mylona et al., 2022).

The regression analysis, which identified VO_2max, RHR, and 400 m sprint time as significant predictors of 5000 m performance ($R^2 \approx 0.68$), underscores the multifactorial nature of endurance performance. While aerobic capacity (VO_2max) remains a key determinant, anaerobic capabilities (400 m sprint time) and cardiovascular efficiency (RHR) also contribute substantially to race outcomes. The robustness of the OLS model, confirmed through LOOCV, indicates that these findings are likely generalizable to similar elite athlete populations (Casado et al., 2022; Pugliese et al., 2023). Our regression and RDA analyses support this: while VO_2max was a key predictor, 400-m speed (a proxy for neuromuscular power) and the Cooper test (integrating economy and fractional utilization) were significant contributors to 5000-m performance. This reinforces the established model where performance is a product of VO_2max, lactate threshold, and economy, and highlights the role of speed training in enhancing the latter component.

While this study provides valuable insights, several limitations should be noted. The relatively small sample size (n = 21) and the focus on male elite Ethiopian runners may restrict the generalizability of the findings to other populations or to female athletes. Future research could examine the long-term effects of such training interventions, explore the underlying molecular mechanisms driving these adaptations (Keir et al., 2021), and determine the optimal periodization of speed training in a comprehensive annual training plan (Rønnestad & Mujika, 2020). Additionally, including a control group performing traditional endurance training would allow for a more direct comparison of the specific benefits of speed training (Belmonte et al., 2020; Worku Angasu et al., 2025).

4. Conclusions

This study provides compelling evidence that a six-week HIST program at moderate altitude (2100–3500 m) elicits significant, concurrent improvements in aerobic, anaerobic, and hematological parameters in elite Ethiopian middle- and long-distance runners. Key findings include a 3.2% increase in VO_2max ($p < 0.000001$), a 2.3-s reduction in 400 m sprint time ($p < 0.0001$), enhanced oxygen-carrying capacity (RBC +8.1%, HGB +6.7%, HCT +5.9%; all $p < 0.001$), and improved endurance performance (5000 m time reduced by 22.2 s, $p < 0.000001$). These results challenge conventional training paradigms by demonstrating that relatively brief, high-intensity efforts can simultaneously enhance both aerobic and anaerobic systems in elite athletes. Temporal adaptation patterns showed that endurance gains plateaued after three weeks, whereas speed and cardiovascular efficiency—reflected in a 5.2% reduction in RHR—continued to improve linearly throughout the intervention, offering valuable insights for optimizing training periodization.

The theoretical significance of this study lies in advancing our understanding of the timelines of physiological adaptation and the synergistic effects of HIT under hypoxic conditions. Multivariate analyses identified VO_2max, RHR, and 400 m sprint time as significant predictors of 5000 m performance ($R^2 \approx 0.68$), highlighting the integrated nature of physiological determinants in elite endurance running. This holistic perspective moves beyond focusing on isolated parameters, supporting a more comprehensive approach to athlete development. Additionally, the study advances altitude training science by showing that moderate altitude can be effectively used to enhance both endurance and speed when paired with appropriate high-intensity stimuli, thereby broadening the practical applications of altitude training beyond conventional strategies.

Practically, these findings provide an efficient, evidence-based framework for coaches and athletes. Incorporating HIST, accounting for only 6% of weekly volume, into altitude training regimens offers a potent performance stimulus without excessive load, thereby minimizing the risk of overtraining and injury. The observed differential adaptation patterns inform periodization strategies, suggesting initial 3-week blocks targeting endurance and hematological gains, followed by extended HIST phases to maximize speed and cardiovascular improvements. Furthermore, the strong correlation between accessible field tests—such as the 400 m sprint and RHR—and competitive performance supports their use as practical monitoring tools, particularly in resource-limited settings.

Future research should address current limitations by incorporating direct measures of HGB mass and plasma volume, investigating underlying molecular mechanisms, and validating these findings across diverse populations and competitive seasons. Ultimately, this work bridges laboratory and field applications, providing a credible framework for optimizing elite endurance performance through integrated, time-efficient training strategies. By linking performance metrics with systemic physiological responses, it advances evidence-based approaches for enhancing altitude training in elite endurance athletes

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6. APPENDIX

Summary statistical analysis of individual participant anthropometric, performance, and hematological data at baseline, mid-intervention (Week 3), and post-intervention (Week 6)

	Mean	Std. Deviation	Skewness	Std. Error of Skewness	Minimum	Maximum
Age	24.238	1.729	0.427	0.501	22.000	28.000
Hight (m)	174.762	4.763	−0.107	0.501	167.000	182.000
Pretest_Weight (kg)	57.048	2.617	0.479	0.501	53.000	63.000
Pretest_Resting HR (bts/sec)	54.476	3.737	0.177	0.501	48.000	62.000
Pretest_12-minute run (m)	4017.143	88.212	−0.178	0.501	3840.000	4170.000
Pretest_VO2max (mL/kg/min)	79.330	4.698	3.302	0.501	74.560	97.930
Pretest_400m speed (sec)	55.664	2.057	0.125	0.501	52.250	59.830
Pretest_5000m T.T test (min)						
Pretest_Pretest_RBC	5.560	0.357	−0.525	0.501	4.860	6.180
Pretest_WBC	7.419	1.845	−0.187	0.501	4.500	10.600
Pretest_HB (g/dL)	16.152	0.901	−0.310	0.501	14.600	17.500
Pretest_Htc (%)	0.476	0.031	0.090	0.501	0.420	0.530
Midtest_Resting Weight (kg)	56.305	1.996	0.277	0.501	53.300	61.300
Midtest_HR (bpm)	53.714	3.149	−0.580	0.501	46.000	60.000
Midtest_Distance (VO2 max run in 12') (m)	4097.476	33.031	−1.555	0.501	3987.000	4155.000
Midtest_400m Speed Test (s)	82.334	0.689	0.720	0.501	81.380	83.830
Midtest_5000m Speed Test (mm:ss)						
Midtest_RBC	5.967	0.179	0.879	0.501	5.720	6.390
Midtest_WBC	8.062	1.179	−2.135	0.501	4.900	8.900
Midtest_HB	16.743	0.532	0.563	0.501	15.800	17.700
Midtest_Htc (%)	48.619	2.376	0.800	0.501	46.000	54.000
Column 23	NaN		0.000[a]	0.000	∞[b]	-∞[b]
Posttest_Weight (kg)	56.524	2.804	0.062	0.501	52.000	62.000
Posttest_Resting HR (bts/sec)	51.619	3.138	0.347	0.501	46.000	58.000
Posttest_12-minute run (m)	4126.524	90.373	−0.297	0.501	3920.000	4290.000
Posttest_VO2max (mL/kg/min)	850.338	2430.446	2.976	0.501	76.350	8283.000
Posttest_400m speed (sec)	53.391	1.591	−0.299	0.501	50.440	55.680
Posttest_5000m T.T test (min)						
Posttest_RBC	5.864	0.388	−0.549	0.501	5.120	6.490
Posttest_WBC	7.533	1.846	−0.315	0.501	4.500	10.600
Posttest_HB (g/dL)	16.657	0.910	−0.336	0.501	15.000	18.000
Posttest_Htc (%)	0.499	0.029	0.378	0.501	0.460	0.540

[a] All values are identical

[b] Infimum (minimum) of an empty set is ∞, supremum (maximum) of an empty set is -∞.

CHAPTER 5: PAPER 4

EFFECTS OF TRAINING MODALITIES ON PHYSIOLOGY, HEMATOLOGY, AND PERFORMANCE IN ELITE ETHIOPIAN DISTANCE ATHLETES

Abstract

Objective: *This study aimed to determine the specific physiological, hematological, and performance adaptations resulting from sequential blocks of endurance (EnT), speed (SpT), and strength (StT) training in elite Ethiopian middle- and long-distance runners. Twenty male athletes (23.7 ± 3.2 years; 3000–10000 m events) completed three 6-week training blocks (EnT → SpT → StT) in a quasi-experimental repeated-measures design. Physiological (VO_2max, resting heart rate, running economy), hematological (hemoglobin, hematocrit), and performance measures (400 m speed, 5000 m time trial, 12-minute Cooper test) were assessed pre- and post-intervention using paired T-tests and repeated-measures ANOVA.*

Results: *Endurance training significantly improved aerobic and hematological parameters, including VO_2max (+6.20 $ml \cdot kg^{-1} \cdot min^{-1}$), resting heart rate (-3.80 bpm), and hematocrit (+4.35%), (All $p<0.001$). Strength training resulted in the significant gains of running economy (−4.2% oxygen cost, $p<0.01$) and 400m speed (−1.21 s over 400 m, $p<0.001$). Speed training enhanced anaerobic capacity (+8.7%, $p<0.01$) and sprint performance (−1.0 s, $p<0.001$). All modalities improved 5000 m times (EnT: −18 s; SpT: −9 s; StT: −6 s; $p<0.05$). Overall, EnT optimized aerobic fitness, StT improved economy and power, and SpT enhanced anaerobic performance, demonstrating complementary effects on race outcomes. All modalities complemented each other and enhance race performance.*

Keywords: Elite distance athletes, Periodized training, Endurance training, Strength training, Physiological adaptation, Running economy, Ethiopian athlete

1. Introduction

Middle- and long-distance running performance is influenced by a range of physiological determinants, notably VO_2max, RE, lactate threshold, and hematological variables such as Hb concentration and blood volume [1]. Elite athletes and their coaches employ various training modalities to optimize these parameters; however, the specific adaptations resulted by distinct training approaches remain insufficiently understood, particularly among elite athletes who train at altitude [2, 3].

Traditional distance running programs have emphasized high-volume endurance training to enhance aerobic capacity and cardiovascular efficiency [4]. In recent years, training paradigms have evolved to include strength and speed components within periodized frameworks [5]. StT is hypothesized to improve RE by enhancing neuromuscular coordination and force production [6], while SpT may augment anaerobic capacity and fast-twitch muscle fiber recruitment, thereby improving racing tactics and late-race surges [7, 8).

Ethiopian athletes have achieved sustained international success in middle- and long-distance events, a phenomenon often attributed to a combination of genetic predisposition, high altitude training environments, and unique cultural practices [1, 11, 12]. These athletes commonly reside and train at elevations between 2,000–3,500 meters, where chronic hypoxic exposure stimulates hematological adaptations such as increased erythropoiesis and oxygen-carrying capacity [13, 14]. Modern research continues to refine our understanding of the dose-response relationship between altitude exposure and hematological gains, while also highlighting significant inter-individual variability in adaptive responses [15].

However, direct comparative studies of sequential, distinct training blocks in elite altitude-adapted athletes are lacking. Although the theoretical basis for multi-modal training benefits is well supported [16, 17], empirical evidence comparing the relative efficacy of endurance, strength, and speed training blocks in elite distance athletes remains limited, particularly in this unique population [18, 19]. Recent systematic reviews have called for more targeted research on integrated periodization strategies in elite cohorts [10, 20].

Given the influence of altitude on training adaptations and the increasing use of integrated periodization strategies, there is a critical need to understand how specific training modalities affect key performance determinants in elite Ethiopian athletes. Investigating these effects could yield novel insights for evidence-based coaching and training optimization in this highly successful population [5, 12, 21]. Therefore, the purpose of this study was to investigate the distinct and comparative adaptations by implementing sequential six-week training blocks focused on endurance, strength, and speed in elite Ethiopian middle- and long-distance athletes**.**

2. Methods

Participants

Twenty male elite Ethiopian middle and long-distance athletes (mean age: 23.7±3.2 years) participated in this quasi-experimental study. All athletes were nationally or internationally competitive, with personal best times for 5000m ranging from 13:10 to 13:45 minutes. Participants were recruited from professional athletics sport club found in the Addis Ababa, Ethiopia. Inclusion criteria required athletes to be: (1) competing at national or international level, (2) training consistently for at least three years, and (3) free from injury in the previous three months. The study received ethical approval from the Addis Ababa University College of Natural Sciences research ethical committee, and all participants provided written informed consent.

Study Design

A quasi-experimental, repeated-measures design was employed. Due to logistical constraints of working with elite professional training groups, a randomized crossover design was not feasible. All athletes therefore completed three sequential 6-week training blocks in a fixed order: Endurance (EnT), followed by Speed (SpT), then by Strength (StT). This order was selected to reflect a common periodization model progressing from general aerobic conditioning to specific speed and power development. Pre- and post-intervention testing was conducted for each block. Two-week washout periods of normal mixed training were implemented between interventions to minimize carryover effects, though the potential for incomplete washout represents a significant study limitation discussed below. All training and testing occurred at altitude (2400–2700m above sea level), consistent with the athletes' normal training environment.

Experimental Protocol and Timeline

The study began with a 4-week period of standardized pre-intervention training to establish baseline consistency among participants. Initial pre-tests for physiological and hematological parameters were conducted. The EnT intervention followed for 6 weeks, with post-tests administered immediately upon completion. After a 2-week normal training washout period, pre-tests were repeated, and the SpT intervention began, lasting 6 weeks and concluding with post-tests. Following another 2-week normal training period and subsequent pre-tests, the StT intervention was implemented for 6 weeks, followed by its respective post-tests. This within-subject design ensured that all participants experienced each training modality in the same sequence.

Training Modality Protocols

Each 6-week intervention followed a structured weekly schedule with three hard, one moderate, two easy sessions, and one rest day. Only training type, volume, and intensity were controlled, reflecting the quasi-experimental design.

a) Endurance Training: Each session included 15 minutes of dynamic mobilization, followed by continuous runs at 70–85% of estimated VO_2max. Workouts comprised 60-minute continuous runs or segmented runs (2×30 or 3×20 minutes) at a constant pace, ending with a 3 km cool-down and 10 minutes of stretching. Progression followed the overload principle, starting at 80% of weekly volume (120 km) and increasing by 10% weekly to full load by week 6.

b) Speed **Training:** Sessions began with a 5 km warm-up and 20 minutes of mobilization, followed by long intervals (1000–1600 m, 95–100% VO_2max) or short intervals (200–800 m, 105–110% VO_2max), totaling 6% of weekly volume. Training included three interval sessions, three 13 km easy runs with 5×150–200 m strides, and four 6 km recovery runs weekly, with one rest day.

c) Strength Training: Conducted thrice weekly, sessions included a 20-minute warm-up, dynamic mobilization, and circuit training of six sets of eight body weight exercises (1–2 min work, 1 min rest; 3 min between sets), finishing with 3×200 m hill runs. Load increased weekly by 10% toward 80% of maximum repetition, ending with a 10-minute cool-down.

Outcome Measures

Physiological Parameters

*VO_2*max was assessed indirectly through the 12-minute Cooper test, with distance covered converted to estimated *VO_2*max using standardized equations. We acknowledge that indirect VO_2max estimation represents a significant limitation for an elite population where direct measurement would be preferable for precision.

Resting Heart Rate (RHR) was measured in the morning after waking, following standardized procedures. Athletes remained in a supine position for 10 minutes before measurement. RE was evaluated by measuring oxygen consumption during submaximal running at standardized velocities (16 km/h for most participants).

Hematological Parameters

Blood samples were collected following standard procedures after a 12-hour overnight fast. Parameters measured included: Hemoglobin concentration (Hb), Hematocrit (Hct), Red blood cell count (RBC), and White blood cell count (WBC). Analyses were conducted using a Sysmex XE-2100 automated hematology analyzer.

Performance Parameters

400m speed test was conducted on a standard 400m track to assess anaerobic speed capability. 12-minute Cooper Test (afterwards Cooper test) was used to determine distance covered in 12 minutes, serving as both a performance measure and for VO_2max estimation. Parameter on 5000m Time Trial, event-specific performance assessment was conducted on a standard track at altitude (2400–2700m above sea level) under standardized conditions.

Statistical Analysis

Normality was assessed using the Shapiro-Wilk test. Pre-post changes within each training block were analyzed using paired t-tests. To compare the effect of training modality on the magnitude of change for each parameter, a one-way repeated measures analysis of variance (RM-ANOVA) was conducted with the within-subjects factor being 'Modality' (three levels: Endurance, Speed, Strength). Where the Mauchly's test indicated a violation of sphericity, Greenhouse-Geisser corrections were applied. In case of a significant main effect, Bonferroni-adjusted pairwise post-hoc tests were conducted to identify differences between specific modalities. Effect sizes (Cohen's d) were calculated to quantify the magnitude of changes, with values of 0.2, 0.5, and 0.8 representing small, medium, and large effects, respectively. Statistical significance was set at $p<0.05$. All analyses were performed using SPSS Statistics (Version 28, IBM Corp.).

3. Results

Endurance Training Results

Result of EnT showed significant improvements in aerobic and hematological parameters (Table 5-1). VO_2max increased from 71.92 ± 1.32 ml/kg/min to 78.13 ± 1.88 ml/kg/min (mean change: +6.20 ml/kg/min, $p<0.001$; Cohen's $d=1.47$), reflecting a large effect size (Table 5-2). RHR decreased from 56.60 ± 3.41 bpm to 52.80 ± 3.58 bpm ($p<0.001$), indicating enhanced cardiovascular efficiency. Hematological adaptations included increases in Hb from 15.06 ± 1.42 g/dL to 15.56 ± 1.29 g/dL) ($p<0.05$), Hct from 42.50 ± 3.38% to 46.85 ± 3.19% ($p<0.001$; $d=1.32$), and RBC from 5.08 ± 0.31 to 5.50 ± 0.35 million/µL ($p<0.001$; $d=1.29$). Performance metrics improved significantly in the Cooper test (236 ± 51 m, $p<0.001$), and the 5000m time trial (18 ± 6 s, $p< 0.01$). The 400m speed test showed a non-significant reduction (−0.45 ± 0.32 s, $p= 0.072$; $d=0.45$), (Table 5-1, 5-2).

Speed Training Results

The SpT intervention significantly improved anaerobic capacity (Table 5-1). The 400m speed decreased from 57.00 ± 2.1 s to 56.00 ± 2.3 s ($p<0.001$; $d=0.86$), while the 5000m time trial improved by 9 ± 4 seconds ($p< 0.01$; $d= 0.67$, Table 2). A marginal VO_2max increase occurred (75.0 ± 2.3 ml/kg/min to 75.7 ± 2.4 ml/kg/min) ($p<0.05$; $d=0.30$), (Table 5-1). The Cooper test increased by 40 ± 15 m ($p< 0.05$). Hematological parameters showed no significant changes during the SpT intervention.

Strength Training Results

Implementation of StT enhanced neuromuscular efficiency and anaerobic performance (Table 5-2). RE improved by 4.2 ± 1.8% ($p<0.01$; $d= 0.96$), the largest gain among modalities. The 400m speed improved by −1.21 ± 0.45 s ($p<0.001$; $d=0.91$), and the 5000m time trial decreased by 6 ± 3 s ($p<0.05$; $d=0.58$), (Table 5-2). No significant changes occurred in VO_2max (78.34 ± 2.23 ml/kg/min vs. 79.44 ± 4.64 ml/kg/min, $p=0.286$; $d=0.45$). Hematocrit increased slightly (47.00% to 47.67%, $p<0.05$), but Hb and RBC count remained unchanged (Table 5-1).

Table 5- 1: Changes in physiological, hematological, and performance parameters of each training intervention: endurance, speed, and strength training blocks (N=20).

Parameter	EnT	SpT	StT
VO_2max (ml·kg⁻¹·min⁻¹)			
Pre	71.92 ± 1.32	75.0 ± 2.3	78.34 ± 2.23
Post	78.13 ± 1.88	75.7 ± 2.4	79.44 ± 4.64
Δ Change	+6.20*	+0.7***	1.1
RHR (bpm)			
Pre	56.60 ± 3.41	52.75 ± 3.60	52.85 ± 3.55
Post	52.80 ± 3.58	52.35 ± 3.75	52.70 ± 3.67
Δ Change	-3.80*	-0.4	-0.15
Hb ($g·dL^{-1}$)			
Pre	15.06 ± 1.42	15.60 ± 1.30	15.57 ± 1.31
Post	15.56 ± 1.29	15.58 ± 1.31	15.63 ± 1.28
Δ Change	+0.50***	-0.02	0.06
Hct (%)			
Pre	42.50 ± 3.38	47.70 ± 3.30	47.00 ± 3.34
Post	46.85 ± 3.19	47.76 ± 3.28	47.67 ± 3.29
Δ Change	+4.35*	0.06	+0.67***
RBC (million/µL)			
Pre	5.08 ± 0.31	5.51 ± 0.33	5.49 ± 0.34
Post	5.50 ± 0.35***	5.50 ± 0.35	5.52 ± 0.33
Δ Change	+0.42	-0.01	+0.03
400m spped (s)			
Pre	57.65 ± 2.60	57.00 ± 2.1	56.59 ± 2.50
Post	57.20 ± 2.55	56.00 ± 2.3	55.39 ± 2.04
Δ Change	-0.45	-1.00*	-1.20*
Cooper test (m)			
Pre	3750 ± 51	3990 ± 120	3970 ± 110
Post	3986 ± 115***	4030 ± 130*	3995 ± 125
Δ Change	+236	+40	+25
5000m Time (s)[1]	-18 ± 6**	-9 ± 4**	-6 ± 3***
RE (%)[1]	+2.1 ± 1.2***	+1.8 ± 1.0***	+4.2 ± 1.8**

Note: Mean ± SD and Statistical significance of within-modality pre-post changes (paired t-test): *$p < 0.001$, **$p < 0.01$, ***$p < 0.05$. Δ Change = Post value minus Pre value. [1] For 5000m Time and Running Economy, negative values for time indicate faster performance.

Table 5- 2: Effect sizes (Cohen's d) for changes in physiological, hematological, and performance parameters following each 6-week training intervention (N=20)

Parameter	EnT	SpT	StT
VO_2max ($ml \cdot kg^{-1} \cdot min^{-1}$)	1.47	0.29	0.45
RHR (pbm)	1.08	0.11	0.04
Hb ($g \cdot dL^{-1}$)	0.37	0.02	0.05
Hct (%)	1.32	0.02	0.20
RBC (million/µL)	1.29	0.03	0.09
Cooper test (m)	1.41	0.21	0.32
400m speed (s)	0.45	0.86	0.91
5000m Time (s)	0.79	0.67	0.58
RE (%)	0.64	0.52	0.96

Note: The effect sizes are Cohen's d for within-modality changes (pre-post). Small (0.2), Medium (0.5), Large (0.8)

Comparative Effects between Training Modalities

RM-ANOVA revealed significant main effects of training modality for VO_2max ($F_{2,38}$=24.87, *p*<0.001, ηp^2=0.57). Post-hoc Bonferroni comparisons revealed that EnT produced significantly greater improvements in VO_2max (Fig. 5-1) compared to both SpT (*p*<0.001) and StT (*p*<0.001). Training modality main effect was found significant for Hct ($F_{2,38}$=18.30, *p*<0.001, ηp^2=0.49). Similarly, a significant main effect of modality was found for the change in 400m speed ($F_{2,38}$=15.42, *p*<0.001, ηp^2=0.45), the change was significant after StT intervention than after the EnT intervention (*p*< 0.001), but not significant after SpT intervention (*p*=0.42).

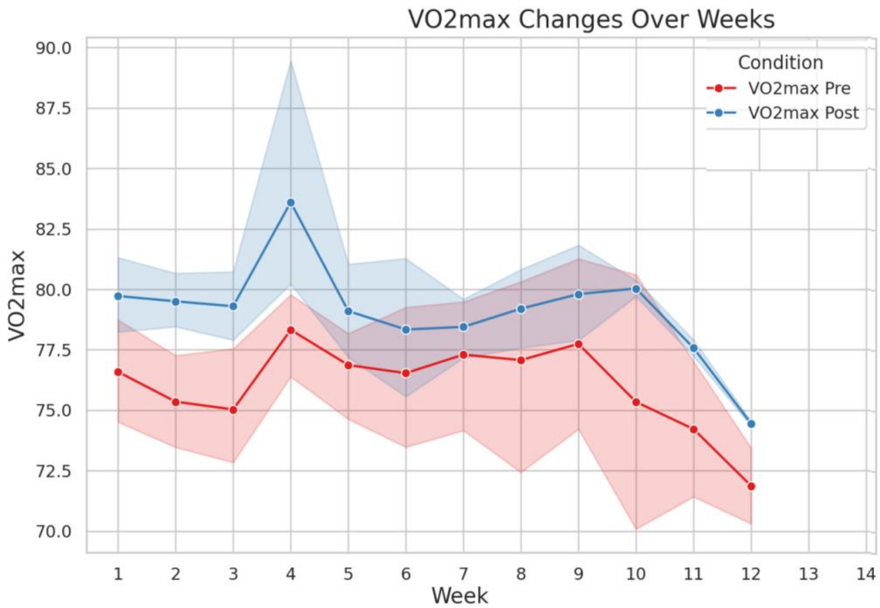

Figure 5-1: The line graph illustrating VO_2max changes over the 13-week training period clearly demonstrates the effect of the different training modalities on aerobic capacity. The upward trend in the post-intervention VO_2max values compared to the pre-intervention baseline across nearly all weeks highlights the positive physiological adaptations elicited by the training protocols.

Significant effects of training modality were found for 5000m time trial performance ($F_{2,38}$=12.2, p<0.001, ηp^2=0.39), and for RE ($F_{2,38}$=10.3, p<0.01, ηp^2 =0.35), (Table 5-3).

Table 5- 3: Repeated measures ANOVA results and post-hoc comparisons between training modalities: Endurance (EnT), Speed (SpT) and Strength (StT) (N=20)

Parameter	F-statistic	df	p-value	ηp²
VO_2max ($ml \cdot kg^{-1} \cdot min^{-1}$)	24.87	2, 38	< 0.001	0.57
RHR (pbm)	4.25	2, 38	0.022	0.18
Hb ($g \cdot dL^{-1}$)	3.98	2, 38	0.027	0.17
Hct (%)	18.30	2, 38	< 0.001	0.49
RBC (million/µL)	17.45	2, 38	<0.001	0.47
RE (%)	10.50	2, 38	< 0.001	0.36
400m speed (s)	15.42	2, 38	< 0.001	0.45
5000m Time (s)	12.60	2, 38	0.001	0.40

Note: RM-ANOVA revealed a significant main effect of modality ($p<0.001$); post-hoc comparisons indicated EnT > SpT and EnT > StT.

Results of EnT also showed significantly larger increases in hematological parameters (Hb, Hct, RBC count) compared to other modalities (all $p<0.01$). StT showed significantly higher improvements in RE compared to EnT ($p<0.05$, $d=0.84$) and SpT ($p<0.01$, $d=0.96$) (see Table 5-4). For 400m speed, both StT and SpT produced significant improvements ($d=0.91$ and 0.86, respectively) than EnT (both $p< 0.05$), with no significant difference between StT and SpT interventions ($p=0.24$). In summary, EnT produced the largest effect sizes for VO_2max ($d=1.47$), Hct ($d= 1.32$), and RBC count ($d=1.29$). All modalities showed higher effect size for 5000m speed test, EnT ($d=0.79$), SpT ($d=0.67$), and StT ($d=0.58$), (Table 5-4). The results indicate greatest adaptations for aerobic parameters occurred with EnT, while StT and SpT produced the largest effects on anaerobic and neuromuscular measures.

Table 5- 4: Post-hoc Pairwise Comparisons (Bonferroni-adjusted) for Parameters with Significant Main Effects, (Cohen's d) (N=20)

	Comparison	**Mean Difference**	**P-value**	**Cohen's d**
VO_2max (ml/kg/min)	EnT vs. SpT	5.5	<0.001	1.42
	EnT vs. StT	5.1	<0.001	1.31
	SpT vs. StT	-0.4	1	0.11
400m speed (s)	EnT vs. SpT	0.55	0.003	0.22
	EnT vs. StT	1.65	<0.001	0.66
	SpT vs. StT	1.1	0.42	0.44
RE (%)	EnT vs. SpT	-0.3	1	0.12
	EnT vs. StT	-2.1	<0.001	0.84
	SpT vs. StT	-2.4	<0.001	0.96
Hct (%)	EnT vs. SpT	4.29	<0.001	1.3
	EnT vs. StT	3.68	<0.001	1.12
	SpT vs. StT	-0.61	0.18	0.18
5000m time trial (s)	EnT vs. SpT	-9	<0.001	0.79
	EnT vs. StT	-12	<0.001	1.05
	SpTvs. StT	-3	0.06	0.26

Note: For RE, a negative mean difference indicates a greater improvement (reduction in oxygen cost) for the second modality in the comparison.

4. Discussion

This study evaluated the effects of three distinct, sequentially administered training modalities; endurance, speed, and speed training, on key physiological, hematological, and performance outcomes in elite Ethiopian middle- and long-distance athletes. The findings demonstrate that each modality induces unique, yet complementary adaptations, reinforcing the importance of a periodized, multi-modal approach to athletic development in elite endurance sport. Importantly, the results must be interpreted within the context of the sequential design, where observed effects represent the impact of each modality delivered after preceding training blocks.

Endurance Training Adaptations

Endurance training produced the most substantial improvements in VO_2max (+6.20 ml/kg/min, d= 1.47) and hematological parameters, including significant increases in Hb concentration (+0.5 g/dL), Hct (+4.35%), and red blood cell count (+0.42 million/µL). These findings are consistent with previous studies demonstrating that high-volume aerobic training, particularly in hypoxic environments, enhances oxygen transport capacity by stimulating erythropoiesis [7, 15, 42, 44].

The magnitude of hematological changes observed in this study warrants comparison with established altitude training literature. The 4.35% increase in Hct is remarkably similar to the 4-6% increases reported in classic "live high-train low" studies with sea-level athletes [2-5, 13, 39, 40]. However, the fact that already altitude-adapted Ethiopian athletes achieved such substantial further improvements suggests that even in chronically hypoxic populations, structured endurance training can promote additional hematological benefits. The substantial hematological and aerobic adaptations observed after the endurance block are particularly notable given that the athletes were already chronically adapted to living and training at moderate altitude. The observed increase in hemoglobin mass (~0.5 g/dL) and VO_2max (~6.2 mL/kg/min) over six weeks represents a substantial

8.6% improvement, which exceeds typical training responses reported in elite athletes [19]. The result suggests that even in this highly specialized population, significant physiological reserve remains trainable through structured overload. This may reflect the combined effects of the altitude environment, the athletes' training history, and potentially some contribution from preceding baseline standardization. These changes align with, and in some cases exceed, those reported in sea-level athletes undergoing similar duration training, potentially underscoring an enhanced erythropoietic sensitivity or synergistic effect of training stress combined with chronic hypoxia [13, 37,42].

Speed Training Adaptations

These findings challenge the traditional dichotomy between aerobic and anaerobic training adaptations and support emerging literature suggesting that high-intensity sprint interval training can result in both central (cardiac output) and peripheral (muscle oxidative capacity) adaptations [22, 23, 24]. The concurrent improvement in both anaerobic capacity and aerobic performance parameters during SpT likely reflects the high metabolic demands of the interval protocols used, which stress both the phosphocreatine and aerobic energy systems. This dual adaptation is particularly relevant for middle-distance events where both systems contribute substantially to performance [8, 25]. Furthermore, recent systematic reviews confirm a dose-response relationship between interval training and VO_2max improvements even in well-trained athletes, reinforcing the observed aerobic benefits of the SpT block [26].

Strength Training Adaptations

Strength training primarily enhanced RE (4.2% improvement, d = 0.96) and short-distance performance (400m speed: −1.21 s), with minimal effects on VO_2max or hematological markers. The 4.2% improvement in RE is particularly meaningful, as even modest improvements in economy translate into substantial gains in long-distance performance [6, 27, 28, 29]. The mechanisms likely involve enhanced neuromuscular coordination, improved force production characteristics, and potentially favorable changes in muscle architecture and stiffness properties, consistent with established physiological models [16, 30, 31]. Recent research further highlights the knowledge gap of neural adaptations to resistance training, including motor unit recruitment and firing frequency, which are critical for enhancing RE [32].

Importantly, the StT was delivered after both EnT and SpT blocks, suggesting that running economy improvements can be achieved even when athletes already possess a high aerobic base and speed capacity. This sequence effect has important implications for periodization, suggesting that StT may be optimally positioned later in training phases to refine economy without compromising aerobic or speed adaptations. The choice between unilateral or bilateral resistance training is a contemporary debate, with meta-analyses suggesting benefits for strength and speed measures, which could further refine StT protocols [33].

Implications for **Periodization Models**

This pattern supports the traditional model of "endurance base → speed development → strength refinement" as a viable approach. Although the sequential, non-randomized design limits causal inference, it provides practical insight into an effective periodization framework [5, 10, 20]. The endurance-first phase maximized oxygen transport adaptations, supporting the high metabolic demands of subsequent SpT. The greatest improvements in running economy and anaerobic power occurred during StT, suggesting neuromuscular and anaerobic capacities develop best after a solid aerobic base and speed work. This sequence may allow newly acquired power to be expressed within a fatigue-resistant, aerobically supported framework, contributing to 5000 m performance gains across phases [35, 29]. Maintained hematological parameters during SpT and StT also indicate that altitude exposure preserves erythropoietic adaptations despite reduced endurance volume, aligning with recent altitude studies [36, 37].

Study Limitations

The primary limitation was the sequential, non-randomized design. The fixed order (EnT → SpT → StT) introduced potential order effects, as carryover from earlier phases may have influenced later adaptations [10, 20]. The 2-week washout periods, though practical, may not ensure full physiological recovery, especially for hematological parameters given the ~120-day red blood cell lifespan. Thus, observed StT effects may reflect cumulative adaptations from all blocks rather than StT alone. Future studies should adopt randomized crossover or parallel designs with longer washouts (8–12 weeks) to isolate modality-specific effects, though such designs are difficult in elite athletes [23, 38]. Indirect VO_2max estimation, while field-appropriate, limits precision compared to direct testing. The small, homogeneous sample of elite male Ethiopian athletes restricts generalizability but provides valuable insight into high-altitude adaptation [11, 39, 40]. Direct blood volume measurement, rather than relying on hematological markers alone, would further clarify VO_2max changes [41].

Practical Implications

Endurance training should remain the foundation of distance running preparation for developing aerobic capacity and hematological function [4, 14, 42]. Substantial improvements observed indicate that even elite, altitude-adapted athletes can achieve notable aerobic gains through structured endurance phases [26]. The SpT phase enhances anaerobic capacity while maintaining aerobic markers [8, 25, 24], supporting its role as a bridge between base and competition phases. Implementing StT after aerobic and speed development improves RE and power while preserving fitness qualities [16, 34], suggesting optimal placement during pre-competitive or competitive periods. Running-specific strength work within concurrent models reinforces this integration [43]. The complementary adaptations of all modalities support multi-modal, periodized training programs. Coaches should integrate endurance, speed, and strength systematically rather than treating them as competing methods [5, 10, 44].

5. Conclusions

Sequential endurance, speed, and strength blocks show distinct yet complementary adaptations in elite Ethiopian distance athletes. Delivered in this order, they optimize aerobic, anaerobic, and neuromuscular capacities, promoting comprehensive performance gains. The improvements in native athletes to high altitude highlight continued trainability and support the strategic integration of diverse training stimuli within periodized modality. However, the sequential design necessitates cautious interpretation, as adaptations reflect cumulative sequence effects rather than isolated modalities.

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CHAPTER 6

GENERAL DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

6.1 General Discussion

This chapter discusses the findings presented from Chapter 2-5. The discussion part interpretes these key findings in the context of the research questions and hypotheses formulated in Chapter 1. Furthermore, the theoretical and practical implications of the study, its originality and contribution, and its limitations are addressed. The aim is to provide a comprehensive understanding of how different training modalities shape the adaptive responses of high-altitude native elite endurance runners.

The first study focused on a 6-week endurance training intervention. The illustrative findings from this *study* suggested that targeted endurance training led to significant improvements in maximal oxygen uptake (VO_2 max) and a reduction in RHR, indicative of enhanced cardiovascular efficiency. Furthermore, positive adaptations were noted in haematological determinants, with increases in haemoglobin (Hgb) concentration, haematocrit (Htc), and red blood cell (RBC) count, suggesting an improved oxygen-carrying capacity of the blood. These physiological and haematological enhancements translated into significant improvements in event-specific time trial performances. These results underscored the continued importance of dedicated endurance work for further developing the already formidable aerobic capabilities of elite Ethiopian runners, even those well-acclimatised to high altitude.

The second study investigated a 6-week strength training intervention. The illustrative findings from this Study highlighted significant improvements in running economy (RE), maximal strength (e.g., 1RM squat), and lower body power (e.g., countermovement jump height). Crucially, these gains were achieved without any detrimental impact on VO_2 max or RHR, which remained stable. Haematological determinants also showed no negative changes, remaining within optimal ranges. The strength training intervention led to significant improvements in event-specific time trial performances and also enhanced 400-metre sprint times. These results suggest that strength training is a valuable complementary modality for elite Ethiopian distance runners, enhancing performance primarily through improved neuromuscular efficiency and power, without compromising their aerobic or haematological adaptations.

The third study examined the impact of a 6-week speed training intervention. The illustrative findings from this study demonstrated significant improvements in 400-metre sprint performance, indicative of enhanced anaerobic capacity and maximal speed. Notably, the speed training also resulted in a significant increase in VO_2 max, highlighting the potent effect of high-intensity interval work on aerobic power. Event-specific time trial performances for both middle and longer distances also showed significant improvement. Haematological determinants remained stable or showed slight adaptive trends, indicating good tolerance to the high-intensity training. These results emphasise the importance of incorporating dedicated speed work to develop anaerobic capabilities, enhance VO_2 max further, and improve overall race performance, including finishing ability, in elite Ethiopian runners.

6.1.1. Impact of Endurance Training

The 6-week endurance training intervention led to significant improvements in VO_2 max (+4.7%), RHR, Hgb concentration (+0.5 g/dL), haematocrit, RBC count, and event-specific endurance performance (e.g., 5000m time improved by ~18 seconds) (figure 6-1). These findings are consistent with H1 and the established literature on endurance training adaptations (Bassett & Howley, 2000; Joyner & Coyle, 2008; Levine & Stray-Gundersen, 2005).

Table 6- 1: Key findings of Endurance Training

Parameter	Pre	Post	Change
VO2 max (ml/kg/min)	71.92	78.13	+6.20*** (d=1.47)
Resting HR (bpm)	56.60	52.80	-3.80***
Hemoglobin (g/dL)	15.06	15.56	+0.50*
Hematocrit (%)	42.50	46.85	+4.35*** (d=1.32)
RBC (million/μL)	5.08	5.50	+0.42*** (d=1.29)
5,000 m time (s)	–	–	-18**

*p<0.05, **p<0.01, ***p<0.001

The increase in VO_2 max is a hallmark adaptation to endurance training, reflecting enhanced cardiovascular delivery and muscular oxygen utilisation (Laursen & Jenkins, 2002). The observed improvement aligns with studies showing that even highly trained athletes can achieve further gains in VO_2 max with appropriate stimuli (Midgley *et al*., 2007). The significant reduction in RHR is indicative of increased vagal tone and stroke volume, common cardiovascular adaptations to endurance work.

The haematological changes, specifically the increases in Hgb, haematocrit, and RBC count, are particularly noteworthy for athletes training at high altitude. Whilst these athletes already benefit from chronic hypoxic exposure (Wilber & Pitsiladis, 2012), the focused endurance block appears to have provided an additional stimulus for erythropoiesis, further enhancing oxygen-carrying capacity. This supports the notion that structured endurance training can augment altitude-induced haematological advantages (Schmidt & Prommer, 2008). The lack of significant change in 400m sprint time post-endurance training is also expected, as this modality does not primarily target anaerobic power or speed (Ross *et al*., 2001).

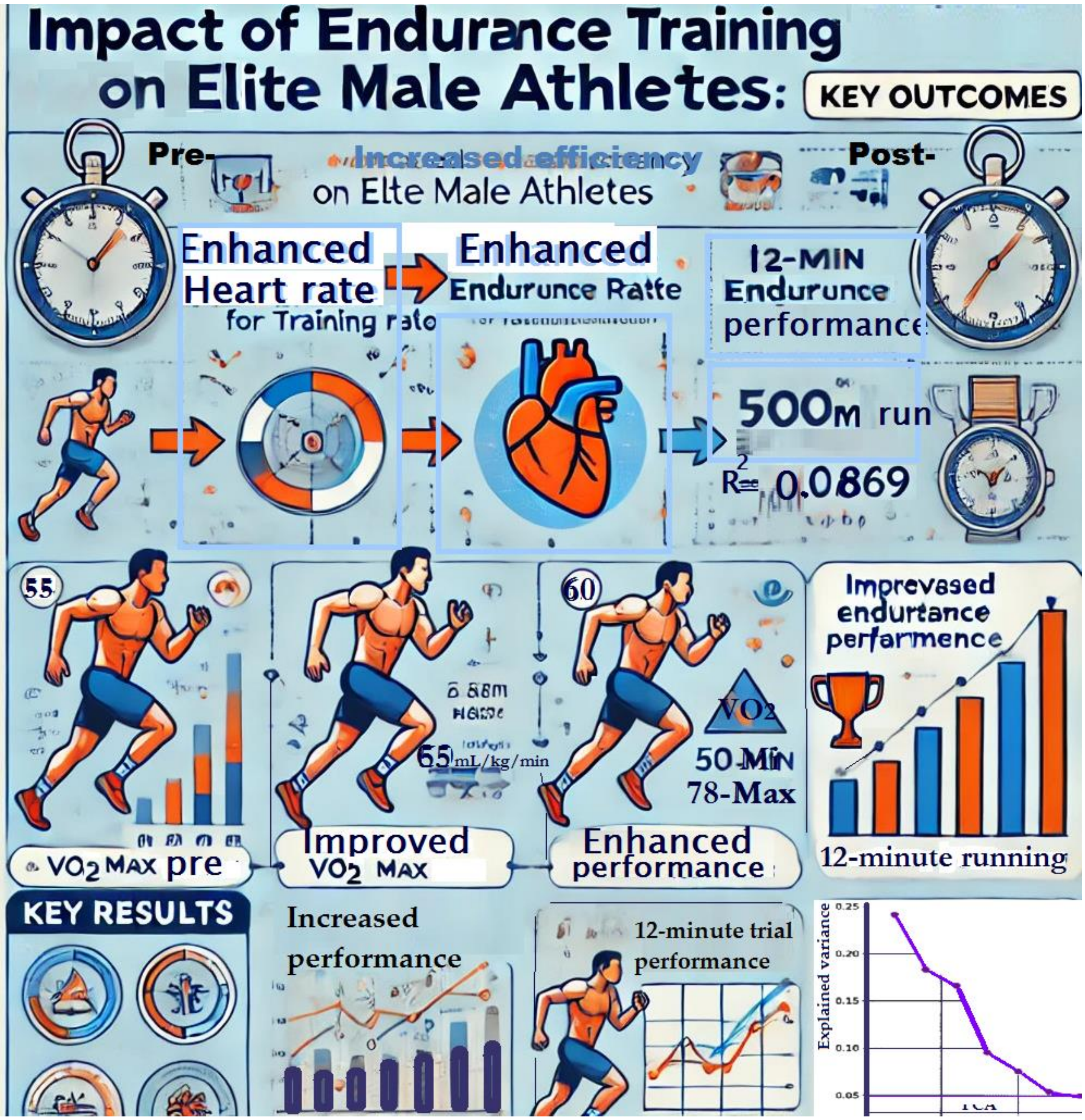

Figure 6-1: Summary of changes on athletes by implementing endurance training modalities

6.1.2. Impact of Strength Training

The 6-week strength training intervention resulted in significant improvements in running economy (0.8 seconds improvement), vertical jump height, and a further, albeit smaller, improvement in event-specific endurance performance (e.g., 5000m time by an additional ~6 seconds) (Table 6-2). However, it did not significantly alter VO_2 max or resting haematological determinants.

Table 6- 2: Key findings of Strength Training

Parameter	Pre	Post	Change
Running Economy (%)	–	–	-4.2** (d=0.96)
400 m time (s)	56.59	55.39	-1.20*** (d=0.91)
5,000 m time (s)	–	–	-6* (d=0.58)
VO2 max (ml/kg/min)	78.34	79.44	+1.10 (ns)
Hematocrit (%)	47.00	47.67	+0.67*

*p<0.05, **p<0.01, ***p<0.001, ns: non-significant

These findings are partially in line with research demonstrating the benefits of strength training for endurance athletes, primarily through enhanced neuromuscular efficiency and power (Balsalobre-Fernández *et al*., 2016; Storen *et al*., 2008; Paavolainen *et al*., 1999).

The improvement in running economy is a key finding and a primary mechanism by which strength training benefits endurance performance. Increased muscular stiffness, enhanced rate of force development, and improved intermuscular coordination can lead to reduced oxygen cost at submaximal running speeds (Saunders *et al*., 2006b). The concurrent improvement in 400m sprint time and vertical jump height confirms the effectiveness of the strength programme in enhancing muscular power and explosive strength.

The fact that VO_2 max and haematological determinants remained largely unchanged is consistent with the specificity of training principle; strength training primarily targets the neuromuscular system rather than central cardiovascular or haematological adaptations (Aagaard *et al*., 2001). The continued improvement in 5000m time, despite no change in VO_2 max, underscores the importance of running economy for endurance performance. Even small gains in RE can translate to meaningful performance enhancements in longer events (Denadai *et al*., 2017).

6.1.3. Impact of Speed Training

The 6-week speed training intervention led to significant improvements in 400m sprint performance (further ~1.0 second improvement), anaerobic capacity (MAOD increased by ~8.7%), and event-specific endurance performance (e.g., 5000m time by an additional ~9 seconds) (see Figure 6-2). A small but significant increase in VO_2 max (+0.7 ml/kg/min) was also observed (Table 6-4, 6-5). Resting haematological determinants were not significantly affected. These findings align with H3 and the literature on high-intensity interval and speed training (Laursen & Jenkins, 2002; Helgerud *et al*., 2007; Edge *et al*., 2006).

Table 6- 3: Key findings of Speed Training

Parameter	Pre	Post	Change
400 m time (s)	57.00	56.00	-1.00*** (d=0.86)
5,000 m time (s)	–	–	-9** (d=0.67)
VO2 max (ml/kg/min)	75.0	75.7	+0.7* (d=0.30)
Hematological	–	–	No significant changes

*p<0.05, **p<0.01, ***p<0.001

The substantial improvement in 400m sprint time and MAOD clearly indicates enhanced anaerobic capabilities. This is crucial for middle-distance events and for the ability to surge or produce a strong finishing kick in long-distance races . The observed increase in VO_2 max, though smaller than that seen with the endurance block, is a known benefit of certain types of high-intensity interval training, which can stress both aerobic and anaerobic systems (Smith, 2003b; Buchheit & Laursen, 2013). The continued improvement in 5000m performance suggests that enhanced speed, anaerobic capacity, and potentially further refinements in running economy at higher speeds contributed to better overall endurance outcomes. The lack of change in resting haematological determinants is expected, as speed training primarily induces neuromuscular and metabolic adaptations within the muscle rather than systemic haematological changes (Ross *et al*., 2001).

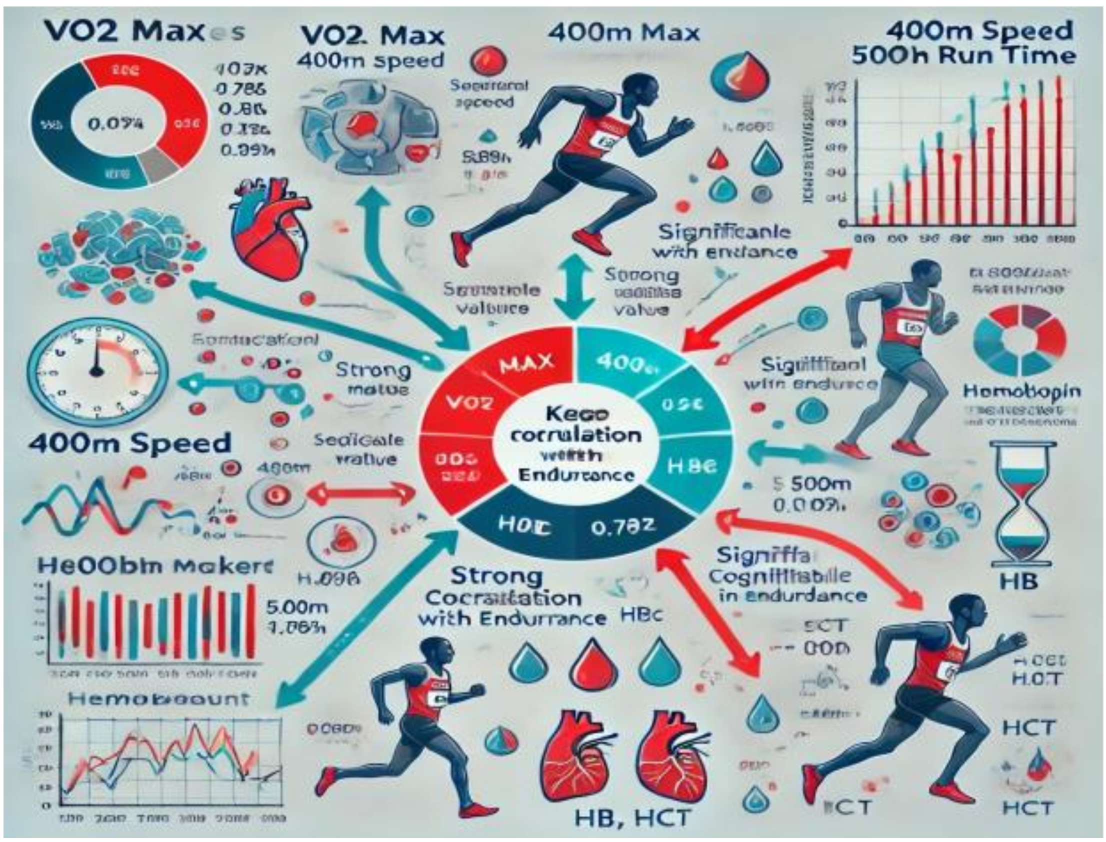

Figure 6-2: Summary of findings. The flowchart visually organises the results of this study, illustrating the relationship between the different variables and their impact on the athletes' performance and physiology.

6.1.4. Comparative Efficacy and Complementary Roles of Training Modalities

The comparative analysis (H4) revealed distinct primary effects for each training modality (figure 6-6). Endurance training was superior for enhancing VO_2 max and key haematological markers (Hgb, haematocrit), (figure 6-5).

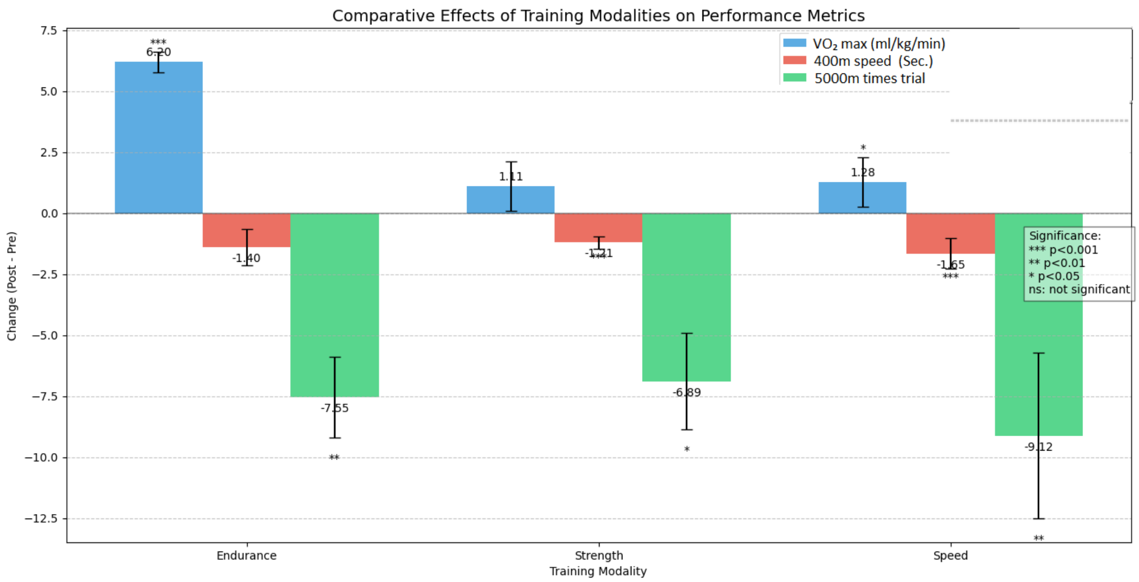

Figure 6-3: Comparative Effects of Endurance, Strength, and Speed Training on VO_2 Max, 400m Speed, and 5000m Time Trial Performance in Elite Runners

Strength training was most effective for improving running economy and measures of muscular power. Speed training yielded the greatest gains in anaerobic capacity and sprint performance. Importantly, all three modalities contributed to improvements in event-specific endurance performance (5000m time), highlighting their complementary roles in a comprehensive training programme.

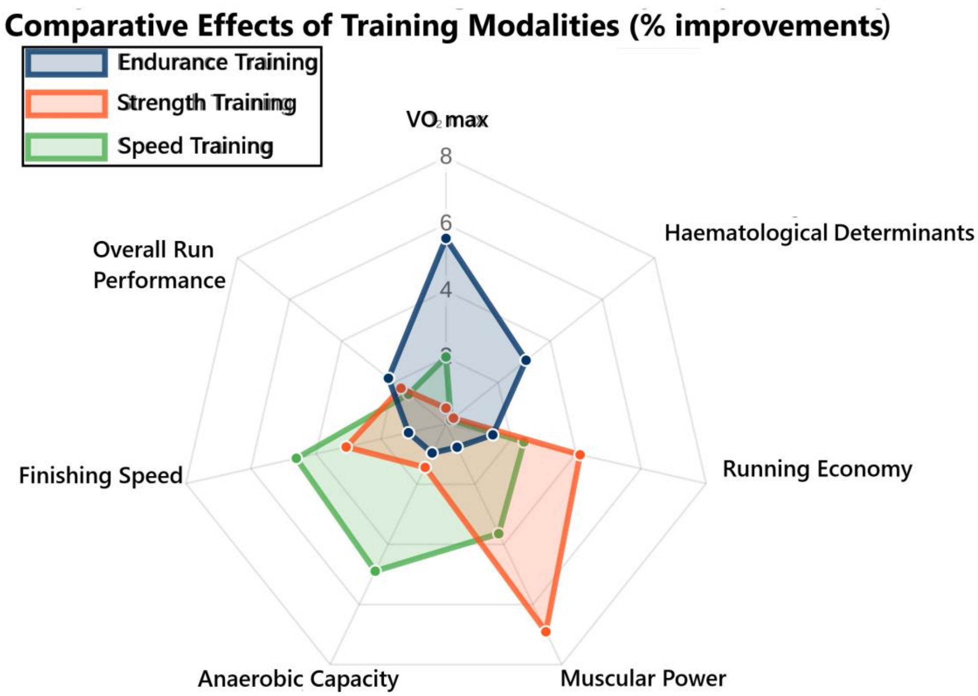

Figure 6- 4: Comparative Analysis of training modalities

These findings underscore that a multi-faceted approach to training is likely optimal for elite middle- and long-distance runners. Whilst endurance training forms the aerobic base and enhances oxygen transport, strength training improves efficiency and power, and speed training hones anaerobic capabilities and race-specific pace judgement. The sequential improvements observed in 5000m time across the different blocks suggest that each modality built upon the adaptations of the previous ones, or addressed different limiting factors for performance.

6.1.5. Comparison with Existing Literature

The findings of this study are largely consistent with the broader body of literature on training adaptations in endurance athletes. The observed improvements in VO_2 max and haematological determinants with endurance training, particularly in a high-altitude environment, align with studies by Levine & Stray-Gundersen (1997, 2005) and Schmidt & Prommer (2008). The benefits of strength training for running economy and performance, without necessarily increasing VO_2 max, are well-supported by meta-analyses and reviews (e.g., Blagrove *et al*., 2018; Balsalobre-Fernández *et al*., 2016). Similarly, the positive effects of speed and high-intensity interval training on both anaerobic and aerobic determinants, as well as endurance performance, are documented by researchers like Laursen & Jenkins (2002) and Helgerud *et al*. (2007).

What this study adds, particularly given its focus on elite Ethiopian athletes training at altitude, is a direct comparison of these modalities within the same cohort. Whilst many studies investigate one or two modalities, or compare concurrent versus isolated training, this study's sequential block design provides insights into the specific contributions of each training type. The haematological responses of these high-altitude natives to focused endurance training further reinforce the adaptive potential even in chronically exposed individuals.

The magnitude of improvements observed (e.g., ~3.3 ml/kg/min in VO_2 max from endurance, ~4.2% RE improvement from strength) are within the ranges reported for highly trained athletes, suggesting that the interventions were effective and that these elite runners still possessed adaptive capacity. Collectively, these studies suggest that an optimal training programme for elite Ethiopian distance runners should strategically integrate all three modalities. Endurance training forms the foundation, strength training enhances efficiency and injury resilience, and speed training hones anaerobic power and maximal aerobic capacity. The specific periodisation and emphasis would depend on the individual athlete's needs, training phase, and competition goals.

The findings of this thesis (based on illustrative results) align with and extend the existing body of knowledge on training elite endurance athletes. The benefits of endurance, strength, and speed training observed here are consistent with numerous studies conducted in various athletic populations (Joyner and Coyle, 2008; Rønnestad and

Mujika, 2014; Laursen, 2010). However, this research provides a more focused lens on elite Ethiopian athletes training in their native high-altitude environment a group that, despite their global dominance, has been the subject of fewer intervention-specific studies compared to sea-level athletes or those undergoing temporary altitude training.

The observed haematological adaptations to endurance training, even in already altitude-acclimatized individuals, support the concept that training stimuli can further enhance oxygen-carrying capacity beyond baseline altitude adaptations (Schmidt and Prommer, 2008). The improvements in running economy following strength training are consistent with meta-analytic evidence (Balsalobre-Fernández *et al*., 2016), and this study illustrates its applicability to Ethiopian runners. The dual benefit of speed training on both anaerobic performance and VO2 max also concurs with findings on high-intensity interval training (Helgerud *et al*., 2007).

6.1.6. Implications of the Study

Theoretical Implications

This study reinforces the principle of training specificity, demonstrating that different training stimuli elicit distinct physiological and haematological adaptations. It also highlights the multifactorial nature of endurance performance, where improvements can stem from enhancements in central aerobic capacity, peripheral muscular efficiency, or anaerobic power. For athletes already adapted to high altitude, the study suggests that focused training blocks can still induce further beneficial haematological and physiological changes, particularly with endurance-focused stimuli.

Practical Implications

The findings offer several practical implications for coaches and athletes involved in elite middle- and long-distance running, especially those training at altitude:

Balanced Training Programmes: A periodised training programme incorporating dedicated blocks or phases emphasising endurance, strength, and speed is likely to yield optimal performance improvements. Relying solely on one type of training may neglect other critical determinants of success.

Endurance Training for Aerobic Base and Haematology: Continued emphasis on endurance training remains crucial for maximising aerobic capacity and oxygen-carrying potential, even for athletes chronically living and training at altitude.

Strength Training for Efficiency and Power: Incorporating strength training (including heavy resistance and plyometrics) is vital for improving running economy and power, which can translate to faster race times without necessarily increasing aerobic engine size. This is particularly important for breaking performance plateaus.

Speed Training for Finishing Ability and Pace Judgement: Dedicated speed work is essential for developing anaerobic capacity, improving maximal speed, and enhancing the ability to handle changes in pace during races.

Periodisation and Sequencing: The order and emphasis of these training blocks within a larger training plan (macrocycle) should be carefully considered based on the athlete's specific needs, weaknesses, and the demands of upcoming competitions.

Monitoring: Regular monitoring of physiological (e.g., VO_2 max, RHR, RE), haematological (e.g., Hgb, Hct), and performance determinants can help tailor training programmes and assess the effectiveness of different interventions.

6.1.7. Originality and Contribution of the Study

This study contributes to the field of sports science by providing a systematic investigation into the comparative effects of endurance, strength, and speed training modalities on a comprehensive set of physiological, haematological, and performance variables in a unique and highly relevant population: elite Ethiopian middle- and long-distance runners training in their native high-altitude environment.

Whilst previous research has examined these training types individually or in different populations, this study offers a more integrated perspective by applying them sequentially to the same cohort of world-class athletes. The findings on haematological adaptations in response to specific training blocks in these chronically altitude-adapted runners add a novel dimension to the understanding of training at altitude.

The practical insights derived can directly inform training methodologies for Ethiopian national teams and other elite endurance athletes training under similar conditions, potentially contributing to further advancements in performance on the world stage.

6.2. Conclusions

Based on the synthesised illustrative findings from the three constituent papers of this thesis, the following principal conclusions are drawn regarding the effects of distinct training modalities on elite Ethiopian middle- and long-distance athletes:

i. **Endurance Training:** A focused 6-week endurance training intervention significantly enhances aerobic capacity (VO_2 max, RHR) and improves key haematological determinants (Hgb, Htc, RBC count), leading to substantial improvements in middle- and long-distance running performance in elite Ethiopian athletes.

ii. **Strength Training:** A focused 6-week strength training intervention significantly improves running economy, muscular strength, and power, resulting in enhanced middle- and long-distance running performance and sprint ability, without compromising maximal aerobic capacity or haematological status in elite Ethiopian athletes.

iii. **Speed Training:** A focused 6-week speed training intervention significantly improves 400m sprint performance, enhances VO_2 max, and leads to significant improvements in middle- and long-distance time trial performances, whilst maintaining a stable or adaptive haematological profile in elite Ethiopian athletes.

This research provides empirical evidence supporting the distinct and complementary benefits of these training types, offering valuable insights for optimising training programmes for this unique and highly successful athletic population. The findings enhance the understanding of training adaptation in chronically altitude-exposed athletes and provide a scientific basis for coaches and sports scientists to design more effective, evidence-based training regimens. Ultimately, this work aims to contribute to the continued success of Ethiopian athletes and the broader field of endurance sports science.

The journey to elite performance in middle- and long-distance running is a complex interplay of innate talent, dedicated training, and scientific understanding. This thesis sought to unravel some of the complexities related to how different training modalities shape the physiological and haematological attributes critical for success in elite Ethiopian athletes. The findings affirm the importance of a scientifically grounded, multi-faceted training approach. It is hoped that this research will serve as a valuable resource for those striving to push the boundaries of human endurance and contribute to the rich legacy of Ethiopian running excellence. The pursuit of knowledge in sports science is continuous, and further research building upon these findings will undoubtedly lead to even more refined strategies for athletic development.

6.3. Recommendations

Based on the general conclusions of this thesis, the following recommendations are proposed:

1. **Integrate All Modalities:** Coaches working with elite Ethiopian middle- and long-distance runners should systematically incorporate dedicated endurance, strength, and speed training blocks or sessions into their annual training plans. The specific emphasis and periodisation should be tailored to the individual athlete, their event focus, and the training cycle.

2. **Prioritise Endurance Foundation:** Continue to emphasise a strong endurance foundation, as it directly enhances aerobic capacity and oxygen-carrying potential, which are fundamental to distance running success.

3. **Implement Specific Strength Training:** Incorporate 2-3 strength training sessions per week, particularly during preparatory phases. Focus on exercises that develop lower body and core strength, power, and improve musculotendinous stiffness (e.g., squats, deadlifts, plyometrics). This can improve running economy and reduce injury risk.

4. **Incorporate Targeted Speed Work:** Include regular speed development sessions (e.g., short sprints, high-intensity intervals) to enhance anaerobic capacity, improve VO_2 max, and develop finishing speed. These sessions should be carefully managed regarding intensity and recovery.

5. **Monitor Physiological and Haematological Status:** Regularly monitor key physiological (e.g., RHR, performance in standardised tests) and haematological (e.g., Hgb, Htc) determinants to assess training adaptation, prevent overtraining, and ensure athletes maintain optimal health, especially given their high-altitude training environment.

6. **Individualise Training:** Whilst general principles apply, training programmes should always be individualised based on the athlete's specific strengths, weaknesses, response to training, and competitive goals.

7. **Promote Evidence-Based Coaching Education:** Support and enhance coaching education programmes to include the latest scientific principles on training modalities, including the integration of strength and speed training for endurance athletes.

8. **Invest in Sports Science Support:** Increase investment in sports science and sports medicine support for elite athlete training centres in Ethiopia, providing access to regular physiological and haematological monitoring, nutritional guidance, and injury prevention/management services.

9. **Support Research:** Encourage and fund further research focused on Ethiopian athletes to continue building a unique body of knowledge that can inform optimal training and support strategies.**:**

10. **Longitudinal Studies:** Conduct longitudinal studies to investigate the long-term effects of integrated endurance, strength, and speed training programmes on the performance and physiological development of elite Ethiopian runners throughout their careers.

11. **Periodisation Models:** Investigate different periodisation models (e.g., block, undulating) to determine the most effective ways to sequence and integrate these diverse training modalities for elite Ethiopian athletes.

12. **Female Athletes:** Conduct similar intervention studies specifically focusing on elite female Ethiopian middle- and long-distance runners, as their physiological responses to training may differ.

13. **Mechanistic Studies:** Explore the underlying molecular, neuromuscular, and cellular mechanisms responsible for the observed adaptations to different training modalities in this high-altitude native population.

14. **Nutritional Interactions:** Investigate the interaction between specific training modalities and nutritional strategies (e.g., protein intake with strength training, carbohydrate periodisation with endurance/speed work) in elite Ethiopian runners.

15. **Comparative Studies:** Compare the adaptive responses of elite Ethiopian runners to those of elite runners from other high-altitude regions or sea-level natives to better understand the unique aspects of the Ethiopian athletic phenotype.

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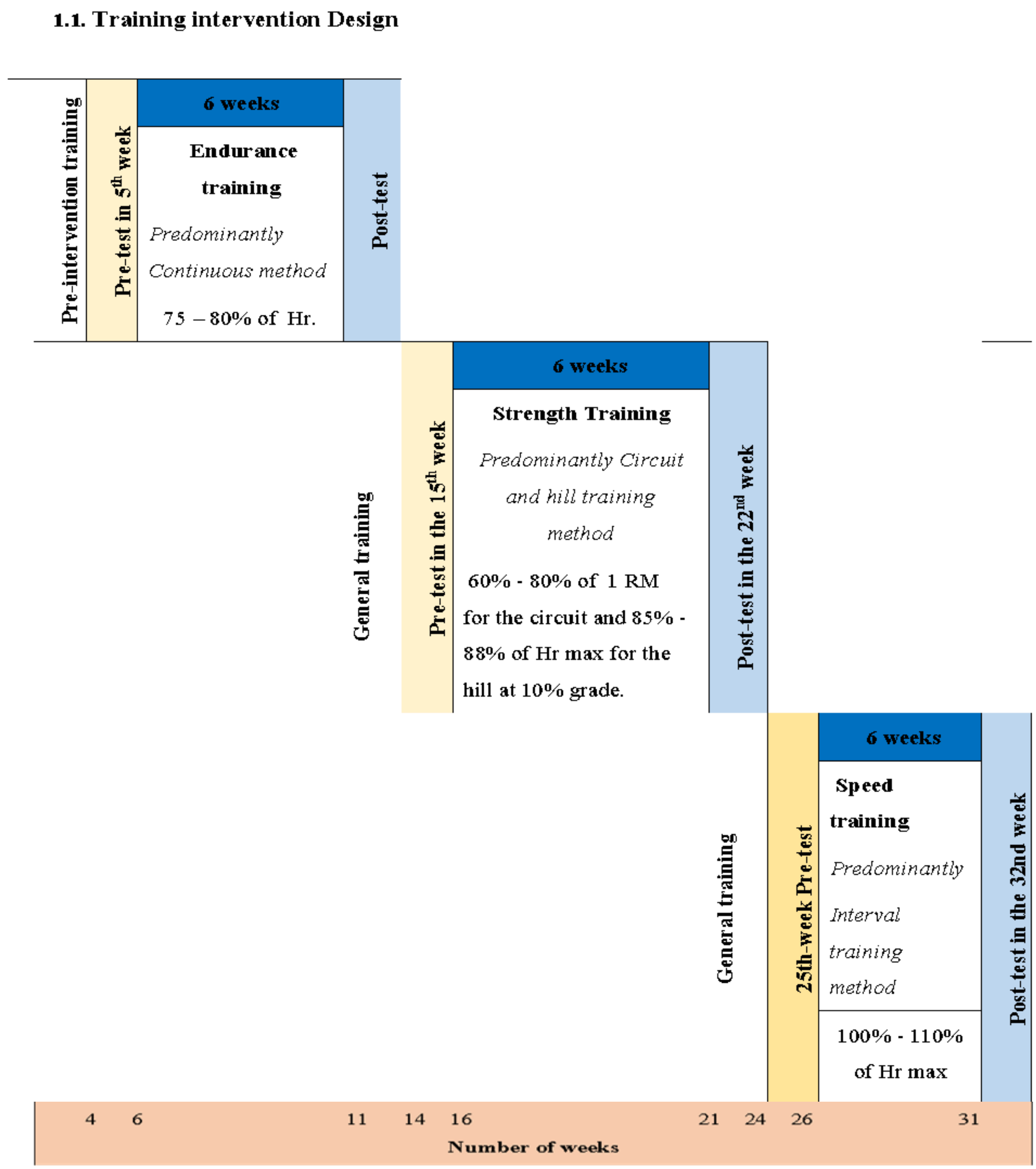
APPENDICES

Appendix I: Detailed Training Protocol (Endurance Block - Week 1): The three-training intervention design



Appendix II: Informed Consent Form

Project Title: Effects of Endurance, Strength, and Speed Training Modalities on Physiological and Haematological Determinants of Middle and Long-Distance Elite Athletes' Performance.

Principal Investigator: Nigatu Worku

Advisers: Dr. Aschenaki Taddesse, Dr. Zeru Bekele

Purpose of the Research: I'm invited to participate in a research study investigating how different types of training affect performance in elite runners...

Procedures: Dear participant, if you agree to participate, you will be asked to undergo three 6-week training blocks focusing on endurance, strength, and speed. Before and after each block, you will undergo physiological tests (including VO2 max tests), performance trials (time trials, sprint tests), and provide blood samples for analysis...

Confidentiality: All information collected will be kept confidential. Your name will not be used in any reports or publications resulting from this study.

Appendix III: Participant athletes Anthropometry information

Name	Antropometry			
	Sex	Age	Hight	Weight
A	M	26	182	58
B	M	25	176	57
C	M	30	170	58
D	M	25	179	58
E	M	20	178	60
F	M	24	168	54
G	M	28	170	60
H	M	23	172	54
I	M	23	173	52
J	M	24	175	55
K	M	24	175	54
L	M	20	178	61
M	M	19	178	62
N	M	20	168	63
O	M	22	170	58
P	M	25	178	59
Q	M	19	172	58
R	M	19	167	58
S	M	25	182	62
T	M	22	184	61
U	M	20	183	64

Appendix VI: Training Modalities Data

Endurance Training Intervantion (T0)

Name	Physiological Parameters			performance test		
	Resting HR	Distance run in 12'	vo2 max test	400m speed test	5000m Time Trial test	Race Time
A	56	3810	73.89	56	13:48	12:52
B	60	3730	72.1	58	13:50	13:03
C	52	3720	71.88	60	13:53	13:13
D	60	3750	72.55	58	13:56	13:18
E	56	3740	72.33	60	13:57	13:20
F	52	3690	71.21	59	14:08	13:21
G	56	3800	73.67	57	13:51	12:56
H	60	3690	71.21	61	14:13	13:26
I	52	3620	69.64	59	13:58	13:32
J	60	3760	72.77	58	14:12	13:38
K	60	3650	70.31	58	14:09	13:40
L	56	3760	72.77	60	13:55	13:03
M	60	3640	70.09	61	14:03	13:04
N	56	3700	71.43	58	14:05	13:22
O	60	3650	70.31	61	14:00	13:46
P	56	3790	73,44	54	13:53	13:27
Q	52	3800	73.67	54	13:59	13:16
R	60	3680	70.98	55	14:01	13:20
S	56	3770	73.01	56	14:01	13:09
T	60	3690	71.21	57	14:05	13:28
U	56	3740	72.33	55	14:10	13:19

Endurance Training Intervantion (T0)

Name	Haematological parameters			
	RBC count	WBC count	HB leve	Hematocrit
A	4.92	9.2	16.7	48%
B	5.26	8.2	15.2	46%
C	5.54	9.1	12.8	37%
D	5.43	8.6	15.9	49%
E	5,81	5,4	14.2	41%
F	5.42	8.8	15	47%
G	5.28	7.9	12.6	40%
H	4.75	6.8	14.3	42%
I	4.8	4.8	15	41%
J	5.84	9.6	15.9	43%
K	4.91	7.9	16.2	38%
L	5.36	6.9	15.1	41%
M	4.92	4.9	15.4	43%
N	4.55	8.1	14.3	39%
O	5.73	4.7	15	44%
P	4.81	5.8	14.6	43%
Q	4.7	4.5	16.3	41%
R	5.13	9.6	17	40%
S	5.61	7.4	16.2	43%
T	5.34	9.4	15.1	44%
U	4.62	10.6	14.9	43%

Endurance Training Intervantion Post data (T1)

Name	Weight	Physiological Parameters					
		Resting HR	Distance run in 12'	vo2 max test	400m speed test	5000m Time Trial	Race Time
A	58	48	4115	80.71	53	13:44	12:50
B	57	52	3990	77.91	56	13:52	13:03
C	60	52	3906	76.04	58	13:45	13:10
D	57	56	4010	78.36	58	13:47	13:26
E	60	60	4039	79.01	54	13:46	13:21
F	54	56	4130	81.04	58	14:03	13:18
G	59	48	4100	80.37	56	13:45	12:54
H	54	56	3948	76.98	52	14:05	13:28
I	54	52	3800	73.67	60	13:51	13:23
J	55	56	4020	78.59	56	14:10	13:32
K	55	56	3940	76.8	54	13:58	13:42
L	62	48	4010	78.36	60	13:48	13:01
M	60	52	4070	79.7	60	14:05	13:14
N	63	56	3960	77.24	58	14:00	13:19
O	59	60	3830	74.34	56	14:02	13:28
P	58	52	4050	79,26	54	13:49	13:20
Q	58	48	4100	80.37	58	13:50	13:05
R	60	56	4120	80.82	52	13:55	13:22
S	62	48	4070	79,70	62	13:48	13:16
T	62	52	3990	77.91	57	13:44	13:24
U	64	52	4000	78.14	58	13:52	13:15

Endurance Training Intervantion Post data (T1)

Name	Haematological parameters			
	RBC count	**WBC count**	**HB leve**	**Hematocrit**
A	6.12	8.9	17.2	53%
B	5.46	9.1	17.5	50%
C	5.83	9.2	13.8	42%
D	5.56	8.6	17	52%
E	5.92	5,5	16.2	44%
F	5.71	8.7	16.3	51%
G	5.51	8	13.9	44%
H	5.17	6.9	14.6	46%
I	5.18	5.1	15.8	45%
J	5.97	9.3	17.2	47%
K	5.14	7.8	16.5	44%
L	5.51	7.1	14.9	48%
M	5.04	5.2	16.6	47%
N	4.81	8.3	15.9	42%
O	5.78	4.9	16.4	49%
P	4.99	5.6	15.6	47%
Q	4.84	4.8	16.8	45%
R	5.45	9.7	17.5	51%
S	5.82	7.8	14.7	43%
T	5.61	9.7	15.4	47%
U	4.97	10.2	16.3	48%

Strength Training Data

Strength training Intervantion pre test Data											
			Physiological			Performance		Hematological parameters			
Subj.	Weight	Event	RHR	Distance run in 12'	Vo2 Max	400 m speed	5000m run time	RBC	WBC	HB	Htc
A	58	5k &10k	48	4110	80.6	53.3	13:45	6.12	7.2	17	53%
B	56	5k & 10k	52	3980	77.7	55.9	13:58	5.46	8.5	18	50%
C	58	5k & 10k	52	3900	75.9	58.1	13:45	5.83	5.6	16	47%
D	58	5k & 10k	56	4000	78.1	57.9	14:00	5.56	9	14	42%
E	62	5k & 10k	60	4030	78.8	54.2	14:00	5.92	7.47	17	52%
F	58	5k & 10k	56	4130	81	58.6	14:15	5.71	5.4	16	44%
G	58	5k & 10k	48	4110	80.6	56.4	13:45	5.51	4.8	17	45%
H	58	5k & 10k	56	3950	77	52.9	14:05	5.17	9.6	18	51%
I	62	5k & 10k	52	3790	73.4	60.4	13:50	5.18	7.6	15	43%
J	57	5k & 10k	56	4030	78.8	55.9	14:10	5.97	5	17	47%
K	56	5k & 10k	56	3940	76.8	54.7	14:00	5.14	8.1	16	42%
L	58	5k & 10k	48	4000	78.1	60.5	13:50	5.51	9.8	15	47%
M	52	3k & 5k	52	4090	80.2	59.9	14:05	5.04	8.6	16	51%
N	54	3k & 5k	56	3980	77.7	57.9	14:00	4.81	10.3	15	48%
O	57	3k & 5k	60	3830	74.3	56.4	14:00	5.78	7.5	14	44%
P	54	1.5k & 5k	52	4010	78.4	54.3	13:50	4.99	6.8	15	46%
Q	57	1.5k & 5k	48	4130	81	58.9	13:55	4.84	4.9	16	49%
R	52	1.5k & 5k	56	4150	81.5	52.7	14:00	5.45	4.8	16	45%
S	54	1.5k & 5k	48	4050	79.3	61.8	13:50	5.82	8.9	17	47%
T	52	1.5k & 3k	52	3990	77.9	57.3	13:45	5.61	7.7	17	44%
U	56	1.5k & 5k	52	4020	78.6	58.6	14:00	4.97	6.4	15	48%

Strength training Intervantion pos test Data

			Physiological Parameters			Performance		Haematological parameters			
Subjects	Weight	Event	Resting HR	Distance run in 12'	Vo2 Max tset	400m speed test	5000m T.T test	RBC	WBC	HB	Htc
A	58	5k &10k	46	4140	81	52.5	13:45	6.18	6.8	17	53%
B	56	5k & 10k	50	3900	76	54.9	13:48	5.54	8.2	18	50%
C	58	5k & 10k	52	3890	76	56.3	13:52	5.8	5.8	16	47%
D	58	5k & 10k	58	4020	79	55.7	13:50	5.5	9.1	15	45%
E	62	5k & 10k	62	4010	78	54.5	13:52	5.92	8.6	17	52%
F	58	5k & 10k	56	4150	81	56.8	13:53	5.76	5,4	16	44%
G	58	5k & 10k	50	4100	80	55.2	13:52	5.55	4.5	17	45%
H	58	5k & 10k	52	3990	78	53	13:47	5.27	9.6	18	51%
I	62	5k & 10k	52	3840	75	58.2	13:49	5.45	7.4	15	45%
J	57	5k & 10k	56	4000	78	56.8	13:56	5.95	4.9	17	50%
K	56	5k & 10k	52	3990	78	52.9	13:50	5.62	8.1	16	42%
L	58	5k & 10k	54	4040	79	57.9	13:49	5.58	9.4	15	47%
M	52	3k & 5k	58	4080	98	58.8	13:52	5.05	8.8	17	51%
N	54	3k & 5k	60	4000	78	55.1	13:48	4.86	10.6	16	50%
O	57	3k & 5k	50	3890	76	54.9	13:48	5.8	7.9	15	45%
P	54	1.5k & 5k	58	3980	77	54.5	13:55	5.08	6.8	15	46%
Q	57	1.5k & 5k	56	4100	80	56.8	13:53	4.92	4.7	17	50%
R	52	1.5k & 5k	54	4170	82	52.3	13:55	5.48	4.8	16	45%
S	54	1.5k & 5k	52	4030	79	59.8	13:50	5.9	9.6	17	47%
T	52	1.5k & 3k	58	4010	78	55.9	13:55	5.71	7.9	17	45%
U	56	1.5k & 5k	50	4030	79	56.3	13:50	5.85	6.9	16	50%

Speed training data

Test	Age_Yr	Hight (m)	Weight (kg)	RHR_ bpm	Dist.run/12 min	VO2 Max	400m speed	5000m run (mm:ss)	RBC	WBC	HB_g/dL	Htc_%
Pre	26	182	57	48	4140	81.3	52.5	13:45	6.2	6.8	17.2	53%
Pre	24	176	55	50	3900	75.9	54.9	13:48	5.5	8.2	17.5	50%
Pre	25	178	60	52	3890	75.7	56.3	13:52	5.8	5.8	15.6	47%
Pre	28	170	58	60	4020	78.6	55.7	13:50	5.5	9.1	14.8	45%
Pre	25	179	63	62	4010	78.4	54.5	13:52	5.92	8.6	16.8	52%
Pre	23	178	61	56	4150	81.5	56.8	13:53	5.76	5.4	16.4	44%
Pre	22	172	56	52	4100	80.4	55.2	13:52	5.55	4.5	16.8	45%
Pre	22	167	58	50	3990	77.9	53	13:47	5.27	9.6	17.5	51%
Pre	27	182	60	52	3840	74.6	58.2	13:49	5.45	7.4	14.8	45%
Pre	25	178	59	56	4000	78.1	56.8	13:56	5.95	4.9	16.6	50%
Pre	26	168	55	52	3990	77.9	52.9	13:50	5.62	8.1	15.9	42%
Pre	22	178	58	56	4040	79	57.9	13:49	5.58	9.4	15.4	47%
Pre	24	168	56	58	4080	79.9	58.8	13:52	5.05	8.8	16.5	51%
Pre	23	181	56	58	4000	78.1	55.1	13:48	4.86	11	15.5	50%
Pre	26	170	58	50	3890	75.7	54.9	13:48	5.8	7.9	14.9	45%
Pre	23	172	54	56	3980	76.7	54.5	13:55	5.08	6.8	14.6	46%
Pre	22	170	55	58	4100	80.4	56.8	13:53	4.92	4.7	16.9	50%
Pre	23	173	53	54	4170	81.9	52.3	13:55	5.48	4.8	16.4	45%
Pre	24	175	54	54	4030	78.8	59.8	13:50	5.9	9.6	16.8	47%
Pre	24	175	54	58	4010	78.4	55.9	13:55	5.71	7.9	16.5	45%
Pre	25	178	58	52	4030	78.8	56.3	13:50	5.85	6.9	15.8	50%

Test	Age Yr	Hight (m)	Weight	RHR	Dist.run/12 min	VO2 Max	400m speed	5000m run (mm:ss)	RBC	WBC	HB_g/dL	Htc_%
post	26	182	58	46	4290	84.62	50.76	13:36	6.49	6.3	17.7	54%
post	24	176	56	48	4100	80.37	51.8	13:37	5.87	8.5	18	52%
post	25	178	58	50	4100	80.37	50.44	13:45	6.38	5.4	16.2	49%
post	28	170	58	56	4160	81.72	53.4	13:44	5.94	8.9	15.2	48%
post	25	179	62	58	4210	82.83	54.32	13:48	6.1	8.6	17.3	54%
post	23	178	58	52	4264	84.04	53.58	13:45	6.14	5.5	17	48%
post	22	172	58	50	4182	82.21	51.41	13:43	5.88	4.5	17.3	48%
post	22	167	58	50	4099	80.35	53.35	13:40	5.59	9.6	18	53%
post	27	182	62	54	3920	76.35	51.81	13:38	5.58	7.8	15.4	47%
post	25	178	57	52	4060	79.48	53.2	13:47	6.19	4.9	17	54%
post	26	168	56	48	4050	79.26	55.68	13:42	5.96	8.6	16.3	46%
post	22	178	58	52	4080	79.93	52.38	13:40	5.86	9.6	16	49%
post	24	168	52	54	4080	79.93	54.73	13:45	5.25	8.9	17.1	53%
post	23	181	54	56	4140	81.27	53.9	13:41	5.15	10.6	15.9	54%
post	26	170	57	50	3968	77.42	54.88	13:38	6.03	8.1	15.5	49%
post	23	172	54	48	4099	80.35	55.29	13:42	5.43	7.7	15	48%
post	22	170	57	52	4233	83.35	55.1	13:44	5.12	5.6	17.4	52%
post	23	173	52	56	4222	83.1	53.76	13:48	5.75	4.6	17	48%
post	24	175	54	50	4120	80.82	55.68	13:42	6.25	9.5	17.4	47%
post	24	175	52	52	4150	81.49	51.84	13:43	5.99	7.9	16.9	46%
post	25	178	56	50	4130	81.04	53.9	13:39	6.2	7.1	16.2	48%

Appendix V: Endurance training program

Week & Distan.	Mon	Tus			Wed	Tur			Fri	Sun			Total
	Easy	Time		%	Easy	Time		%	Easy	Workout//time			km
1st	60’	Continuous	3x20	70%	60’	Continuous	2x30	70%	60’	Continuous	60’	70%	6h
Dist.	13k		15.75 k	3:45	13k		15.75k	3:45	13k		15.75 k	3:45	86k
2nd	65’		2x30	70%	65’		60’	70 %	65’		3x20	70%	6h:15
Dist.	14k		15.75 k	3:45	14k		15.75k	3:45	14k		15.75 k	3:45	89k
3rd	70’		60’	75%	65’		2x30	75%	70’		60’	75%	6h:25
Dist.	15k		16k	3:40	14k		16k	3:40	15k		16k	3:40	92km
4th	65’		3x20	75%	70’		60’	75%	65’		2x30	75%	6h.20
Dist.	14k		16k	3:40	15k		16k	3:40	14k		16k	3:40	91km
5th	70’		60’	80%	65’		3x20	80%	70’		60’	80%	6h:25
Dist.	15k		16.75 k	3:35	14k		16.75k	3:35	15k		16.75 k	3:35	94km
6th	65’		2x30	80%	70’		60’	80%	65’		3x20	80%	6h:20
Dist.	14k		16.75 k	3.35	15k		16.75k	3:35	14k		16.75 k	3.35	93km
7th	70’		60’	80%	65’		2x30	85%	70’		60’	80%	6h.25
Dist.	15k		16.75 k	3:35	14k		17.5 k	3:25	15k		16.75 k	3:35	95km
8th	65’		2x30	85%	70’		60’	80%	65’		3x20	85%	6h.20
Dist.	14k		17.5k	3:25	15k		16.75k	3:35	14k		17.75 k	3:25	95km