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Physiological and performance adaptations to a 48-week periodized triathlon training program in elite athletes: a longitudinal study

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Abstract

Background and Study Aim Triathlon is a multidisciplinary endurance sport that demands a very high level of physiological and physical capacity. Therefore, the implementation of periodization strategies and the appropriate distribution of training intensity contribute to optimizing performance adaptations in elite athletes. This study aimed to examine longitudinal physiological and performance adaptations to a 48-week polarized periodized training program in elite triathletes, with particular emphasis on the magnitude, consistency, and practical relevance of adaptations.

Material and Methods A longitudinal quasi-experimental research design was used in this study, with repeated measurements taken at three time points: pre-intervention, mid-intervention, and post-intervention. A total of 18 elite Indonesian triathletes (8 men and 10 women) preparing for the 2025 Southeast Asian (SEA) Games participated in this study. A 48-week training program was designed using a polarized training model divided into the general preparation, specific preparation, and competition phases. The variables measured included 1 km swim time, VO_2max, Functional Threshold Power (FTP), and muscular endurance (push-ups and sit-ups). Data analysis was performed using repeated measures ANOVA ($p < 0.05$).

Results The results of the study showed a significant increase in all variables over time ($p < 0.001$). Swimming times improved by 5.61%, while VO_2max and FTP increased by 6.64% and 9.63%, respectively. Muscular endurance capacity showed the greatest improvement, with push-ups increasing by 16.74% and sit-ups by 12.82%. All variables demonstrated a large effect size ($\eta^2 = 0.68–0.73$). All participants showed positive trends; however, interpretation should consider measurement error and the absence of a control group.

Conclusions A 48-week periodized training program using a polarized intensity model is associated with improvements in swimming times, aerobic capacity, FTP, and muscular endurance in elite athletes. These findings provide applied insights for long-term training design in elite endurance athletes.

Keywords: triathlon, elite athletes, periodized training, polarized training, longitudinal study.

Introduction

Triathlon is a competitive discipline that places sustained physiological demands on athletes across multiple energy systems. The preparation of elite triathletes involves the coordination of endurance capacity, muscular function, and sport-specific performance under conditions of prolonged and repeated training exposure. The distribution of training intensity and the organization of training phases are closely associated with the development of aerobic adaptations, fatigue tolerance, and performance stability throughout the competitive season. In elite sport settings, long-term training programs are also influenced by the need to maintain adaptation consistency while minimizing excessive physiological strain and performance decline.

In this context, triathlon is a sport that combines three disciplines: swimming, cycling, and running [1, 2]. As a sport known for its high endurance demands, athletes in this discipline are required to possess exceptional cardiovascular fitness and endurance capacity [3]. To achieve peak performance, elite athletes require a precisely managed training program to stimulate physiological adaptation while preventing overtraining syndrome [4].

In studies on endurance sports coaching, the concepts of periodization and the distribution of training intensity remain topics of discussion and debate [5]. One popular method used in designing endurance training programs is polarized training. This polarized training approach is characterized by a high proportion of high-volume, low-intensity training (Zones 1–2) and a small portion of high-

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intensity training (Zones 4–5) [6, 7]. It has shown superior empirical evidence compared to the threshold training model in improving VO_2max in endurance athletes [8].

Many studies evaluating the effectiveness of a training program tend to use short- to medium-term intervention durations (e.g., 6 to 20 weeks) [9, 10, 11]. Long-term studies examining the development of training characteristics and performance-determining factors in endurance athletes remain limited [12]. Previous evidence has shown that long-term training development is associated with changes in training volume, submaximal performance variables, and selected maximal performance indices in elite endurance athletes [12].

Analysis of research findings has shown that periodized endurance training is associated with physiological and performance adaptations in elite athletes. Researchers emphasize that the distribution of training intensity and the organization of long-term training phases are closely related to aerobic development, endurance performance, and adaptation stability during the competitive season. Authors also highlight that longitudinal monitoring of training characteristics and performance-determining factors provides a broader assessment of athlete development across extended training periods. At the same time, longitudinal studies covering nearly a full macrocycle in elite triathletes, particularly among Southeast Asian athletes participating in national training camps for international multi-event competitions, remain limited. This gap continues to restrict a more comprehensive evaluation of physiological adaptation patterns and inter-individual responsiveness under highly controlled long-term training conditions.

The objective of this study was to evaluate physiological adaptations (particularly VO_2max and FTP) as well as sport-specific performance (swimming time and muscular endurance) following the implementation of a 48-week periodized triathlon training program in elite athletes. It was hypothesized that the 48-week periodized intervention would result in significant improvements in physiological and performance parameters from the pre-intervention to the post-intervention phases.

Materials and Methods

Participants

The participants in this study were elite Indonesian triathlon athletes who were actively preparing for the Southeast Asian (SEA) Games 2025 and enrolled in the national training camp (Pelatnas). A total of 18 athletes voluntarily participated in this study. All athletes had a minimum of 3–5 years of competitive experience at national and international levels, indicating a high level of training adaptation and performance capacity.

Participants were included based on the following criteria: (1) classified as elite-level triathletes, (2) actively involved in the full training program during the study period, (3) free from musculoskeletal injuries or medical conditions that could affect performance, and (4) completed at least 90% of the prescribed training sessions, verified through daily attendance records, coach-supervised training logs, and digital training-monitoring systems used throughout the national training-camp program. Adherence was calculated as the percentage of completed sessions relative to the total number of planned sessions across the intervention period. Athletes who experienced injuries, illness, or incomplete participation during the intervention period were excluded from the final analysis to ensure data consistency and internal validity.

A total of 19 elite triathletes were initially recruited for this study. However, after data-screening procedures, including completeness of repeated measurements and adherence to the intervention protocol (⩾90% training attendance), one participant was excluded because of incomplete data across time points. Therefore, 18 athletes were included in the final analysis.

Given the elite status of the participants, the sample represents a highly specific athletic population, which is appropriate for examining high-performance training adaptations. Such sampling approaches are commonly used in elite sport research, where ecological validity and real-world applicability are prioritized over large sample sizes.

Prior to participation, all athletes were fully informed about the study procedures, risks, and benefits, and provided written informed consent. The study protocol was reviewed and officially approved by the Institutional Review Board of the Sport & Exercise Research Center (SERC), Universitas Negeri Surabaya (Institutional Approval Reference No. 129153/UN38.III.3/TU.00.00/2025). All procedures were conducted in accordance with the ethical standards of the institutional research committee and the 1964 Helsinki Declaration and its later amendments.

Research Design

This study employed a longitudinal quasi-experimental design with repeated measures, aimed at evaluating physiological and performance adaptations following a structured triathlon training program. The absence of a control group reflects the ethical and logistical constraints of working with elite athletes in centralized training programs. Measurements were conducted at three time points: pre-intervention (baseline), mid-intervention, and post-intervention. Such a design allows for the identification of both short-term and long-term adaptations to endurance training interventions [13].

The study was conducted over a 48-week structured training period within a national triathlon training camp setting. All participants underwent a series of standardized physical performance assessments at three time points: pre-intervention (Week 1), mid-intervention (Week 24), and post-intervention (Week 48). Each participant served as their own control through repeated measurements across the training macrocycle. The testing protocol included measurements of aerobic capacity (VO_2max), swimming performance (1 km time trial), cycling performance (functional threshold power/FTP), and muscular endurance (push-up, sit-up).

All assessments were performed under controlled conditions and supervised by certified coaches to ensure consistency and reliability. Participants were instructed to maintain similar nutritional intake and recovery strategies prior to each testing session. The longitudinal design enabled the evaluation of both early-phase and late-phase physiological adaptations to the training intervention, which is essential in endurance-based sports performance analysis [14, 15]. Details of the intervention program are presented in Table 1.

The training intervention was designed based on a periodized endurance training model, incorporating progressive overload, specificity, and recovery principles. The distribution of training intensity followed a polarized training model, characterized by a high proportion of low-intensity training (Zone 1–2) combined with a smaller proportion of high-intensity efforts (Zone 4–5), which has been shown to be effective in improving endurance performance [16, 17].

During Phase 1, the emphasis was placed on building an aerobic base and improving technical efficiency across all disciplines. In Phase 2, training intensity was progressively increased with the inclusion of interval training and sport-specific sessions such as brick workouts, aiming to enhance race-specific physiological adaptations. Finally, Phase 3 focused on tapering strategies and performance optimization, where training volume was reduced while maintaining high intensity to maximize competitive readiness [14, 15].

The intervention program was implemented using a structured endurance-periodization model across the 48-week training period. Weekly training organization generally included aerobic endurance training, threshold-oriented sessions, high-intensity interval training, sport-specific conditioning, resistance training, and recovery-oriented sessions. Training loads were progressively modified throughout the intervention according to periodized training principles to optimize physiological adaptation while minimizing excessive fatigue accumulation.

Training intensity and session content were individually adjusted based on physiological monitoring, perceived fatigue, athlete readiness, recovery status, and coaching evaluations conducted throughout the intervention period. Athletes demonstrating signs of excessive fatigue or inadequate recovery received temporary reductions in training load, whereas athletes

Table 1. Intervention program

Phase	Weeks	Objectives	Weekly Volume (km/week)	Intensity Distribution (%HRmax)	Training Characteristics	Key Training Sessions
Phase 1 (Base Preparation)	1–12	Develop aerobic capacity, technical efficiency, and foundational endurance	Swim: 15–25 km Bike: 200–350 km Run: 40–70 km	Zone 1–2: 70–80% Zone 3: 15–20% Zone 4–5: ~5%	High-volume, low-to-moderate intensity; emphasis on technique and aerobic conditioning	Long ride (80–100 km), steady-state run (10–15 km), swim drills (e.g., 20 × 100 m)
Phase 2 (Specific Preparation)	13–32	Enhance sport-specific performance, increase intensity, and develop race-pace capacity	Swim: 20–30 km Bike: 250–400 km Run: 50–80 km	Zone 1–2: 60–70% Zone 3: 20–25% Zone 4–5: 10–15%	Moderate-to-high volume, high intensity; integration of interval and brick training	Bike time-trial intervals, run intervals (200–400 m), brick sessions (bike–run)
Phase 3 (Competition Phase)	33–48	Optimize performance, tapering, and competition readiness	Swim: 10–20 km Bike: 150–250 km Run: 30–60 km	Zone 1–2: 50–60% Zone 3: 20–25% Zone 4–5: ~20%	Reduced volume with maintained intensity; race simulation and taper strategy	Race-simulation sessions, transition practice, high-intensity short intervals

showing stable adaptation progressed according to the planned training framework. Adherence and training compliance were continuously monitored throughout the intervention using a multi-source tracking approach. Daily training attendance was recorded by coaching staff and cross-verified with athlete training logs and session-monitoring records. Session completion, duration, and prescribed intensity targets were documented after each training session. Weekly adherence rates were reviewed by the coaching and sport-science staff to ensure compliance with the planned macrocycle.

Inter-individual variability in training response was managed using a predefined individualization framework. Training modifications were based on session Rating of Perceived Exertion (sRPE), morning resting heart rate, perceived fatigue, recovery quality, and coach-supervised readiness assessments. Athletes presenting session RPE values >8/10, resting heart-rate elevations >10 bpm above baseline, persistent fatigue exceeding 48 h, or reduced readiness scores received temporary reductions in training volume (15–30%) or modifications to interval intensity and session content. Conversely, athletes demonstrating stable adaptation and recovery progressed according to the planned training structure.

Furthermore, recovery-oriented microcycles were periodically incorporated throughout the intervention to facilitate physiological recovery and support long-term adaptation. The intervention was supervised by the coaching staff, sport scientists, nutritionists, and athlete support personnel to ensure adherence to the planned training structure and recovery protocols. A representative example of weekly training organization during the intervention period is presented in Table 2.

Training progression across the intervention followed predefined progression rules. Training load increased progressively by approximately 5–10% during loading periods over three consecutive weeks and was followed by scheduled recovery microcycles with a 20–30% reduction in volume. High-intensity interval sessions progressed through increases in interval number, duration, and sport-specific complexity. Resistance-training load was modified according to individual performance and fatigue status. During the competition phase, tapering reduced training volume by approximately 40–60% while preserving intensity. To improve reproducibility and provide operational clarity, a representative microcycle structure and progression strategy across the 48-week intervention is presented in Table 3.

To manage inter-individual variability and optimize adaptation, session prescription,

Table 2. Representative example of weekly training organization during the intervention period

Day	Session Type	Intensity	Duration	Main Objective
Monday	Aerobic Endurance	65–75% HRmax	90–120 min	Aerobic base development
Tuesday	Interval Training	90–95% HRmax	45–60 min	VO_2max enhancement
Wednesday	Recovery + Mobility	Low intensity	60–90 min	Recovery optimization
Thursday	Threshold Training	80–88% HRmax	60–90 min	Lactate-threshold improvement
Friday	Resistance Training	50–70% 1RM	60–90 min	Muscular endurance
Saturday	Sport-Specific Endurance	Moderate-to-high	60–120 min	Competition-specific adaptation
Sunday	Active Recovery / Rest	Low intensity	30–45 min	Fatigue reduction

Table 3. Representative microcycle structure and progression strategy across the 48-week intervention

Training Phase	Weekly Frequency	Representative Session Prescription	Progression Strategy	Load Adjustment Criteria
Base Preparation (Weeks 1–12)	Swim 5; Bike 4; Run 4; Resistance 2	Swim: 20 × 100 m at Zone 2 with 20 s rest; Bike: 90 min at 65–75% HRmax; Run: 12 km steady-state	Weekly volume increased by 5–10% for 3 consecutive weeks followed by one reload week (−20–30%)	Session RPE >8/10, resting HR increase >10 bpm, or persistent fatigue >48 h triggered temporary reduction
Specific Preparation (Weeks 13–32)	Swim 5; Bike 5; Run 5; Resistance 2	Bike HIIT: 6 × 4 min at 90–95% HRmax; Run intervals: 10 × 400 m at race pace; Brick: 60 min cycling + 20 min running	Progression through increased interval repetitions and race-specific complexity	Adjustments based on recovery status, perceived exertion, and coach monitoring
Competition Phase (Weeks 33–48)	Swim 4; Bike 4; Run 4; Resistance 1	Race simulation: 1.5 km swim + 40 km bike + 10 km run; HIIT: 8 × 2 min	Volume reduced by 40–60%; intensity maintained; taper applied during the final 2 weeks	Training reduced when readiness scores declined or fatigue markers accumulated

intensity distribution, and progression criteria were dynamically adjusted based on objective and subjective readiness metrics. These included daily resting heart rate fluctuations, session rating of perceived exertion (sRPE), perceived fatigue, and coach-supervised physiological monitoring. Individualization procedures followed a systematic decision-making framework to minimize excessive fatigue and maladaptive responses. Furthermore, the integration of multidisciplinary training (swimming, cycling, and running) alongside transition practice reflected the ecological demands of triathlon competition, ensuring that longitudinal physiological improvements were transferable to real race conditions.

All measurements were conducted using standardized and validated protocols commonly applied in elite endurance athletes to ensure reliability and reproducibility. Aerobic capacity (VO_2max) serves as a physiological determinant of endurance performance, and its systematic evaluation has been established to provide valid indicators of cardiorespiratory fitness in trained populations [18, 19]. In this study, VO_2max was assessed using a graded incremental treadmill test to volitional exhaustion, conducted under standardized laboratory conditions. The test was performed using a motorized treadmill (Woodway, USA), with continuous respiratory gas analysis measured via a calibrated metabolic cart (Cosmed Quark CPET, Italy). The protocol began at a submaximal speed, with incremental increases in speed and/or incline every 1–3 minutes until exhaustion. VO_2max was determined as the highest 30-second averaged oxygen uptake value achieved during the test. This method is widely recognized as a gold standard for assessing aerobic capacity in endurance athletes [18, 20]. Although standardized and validated protocols were used, measurement reliability indices (e.g., CV, ICC, and TE) were not formally assessed in this study. Therefore, interpretation of individual responsiveness should be made with caution.

Swimming performance was evaluated using a 1 km time trial, which is recognized as a reliable indicator of aerobic endurance and technical efficiency in competitive swimmers [21, 22]. The protocol was conducted in a 50-m outdoor swimming pool under standardized environmental conditions, with water temperature maintained at 27–28°C and ambient air temperature ranging between 25–27°C. Prior to testing, athletes completed a standardized 15-min warm-up consisting of low-intensity swimming, dynamic mobility exercises, and progressive pace drills. Athletes started individually at 30-s intervals to minimize pacing interference and drafting effects. Participants were instructed to complete the distance as quickly as possible while maintaining a self-selected pacing strategy consistent across testing sessions. Lap times were recorded by two independent certified coaches using synchronized digital stopwatches, and final performance time was calculated as the mean recorded value. Lane assignment and testing time of day were maintained across pre-, mid-, and post-intervention assessments to minimize environmental and circadian variability.

Cycling performance was assessed using Functional Threshold Power (FTP), representing the highest sustainable power output over prolonged effort and considered a field metric in cycling performance monitoring. Functional Threshold Power (FTP) was assessed using a standardized 20-min cycling time-trial protocol performed on calibrated cycle ergometers (Wahoo KICKR, USA) connected to power-analysis software. Before testing, athletes completed a standardized warm-up consisting of 10 min of low-intensity cycling followed by three 1-min efforts at progressively increasing intensity interspersed with recovery periods. Participants were instructed to maintain the highest sustainable effort throughout the 20-min test. Verbal encouragement was standardized across sessions. Average power output over the 20-min effort was recorded, and FTP was estimated as 95% of mean power output according to established procedures. Equipment calibration was performed before each testing session according to manufacturer guidelines. All FTP tests were conducted at the same time of day and under similar environmental conditions [23, 24].

Muscular endurance was measured using standardized field tests, including push-up (1 minute) and sit-up (2 minutes) assessments. These assessments have demonstrated high validity and reliability in athletic populations and are frequently used to monitor strength-endurance adaptations [25, 26]. Prior to testing, participants completed a standardized dynamic warm-up involving low-intensity mobility and activation exercises. Push-up performance was assessed over a 1-min period, with participants instructed to perform as many correctly executed repetitions as possible while maintaining standardized movement technique and range of motion. Sit-up performance was assessed during a 2-min test period using standardized body positioning with knees flexed at approximately 90°.

All testing protocols followed predefined standard operating procedures regarding warm-up routines, equipment calibration, environmental control, pacing instructions, assessor consistency, and testing sequence. Prior to testing, participants were instructed to avoid strenuous activity for at least 24 hours and to maintain similar nutritional and hydration status to minimize external variability. Such standardization procedures are essential to enhance measurement accuracy in longitudinal performance studies [27].

Participants were instructed to maintain consistent dietary habits throughout the study period. To minimize variability, dietary intake was monitored using periodic 24-hour dietary recall conducted at each testing phase (pre-, mid-, and post-intervention). In addition, participants received standardized nutritional guidelines from team nutritionists, and compliance was regularly supervised by coaching staff during the training camp. Hydration status was also controlled prior to testing sessions, with participants instructed to consume adequate fluids and avoid caffeine or alcohol intake 24 hours before testing.

Statistical Analysis

All statistical analyses were performed using IBM SPSS Statistics (version 23). Descriptive statistics were calculated and presented as mean ± standard deviation (SD). Data normality was assessed using the Shapiro–Wilk test, which is recommended for small to moderate sample sizes in sports science research [28].

To evaluate changes across the three measurement time points (pre-, mid-, and post-intervention), a one-way repeated measures analysis of variance (RM-ANOVA) was conducted. When significant main effects were detected, post-hoc pairwise comparisons with Bonferroni correction were applied to identify specific differences between time points. Effect sizes were calculated using partial eta squared (η^2) to determine the magnitude of training effects and interpreted as small ($\eta^2 \geqslant 0.01$), medium ($\eta^2 \geqslant 0.06$), and large ($\eta^2 \geqslant 0.14$) [29].

An a priori sample size estimation was not performed because participant recruitment was constrained by the fixed number of elite athletes enrolled in the national training camp. However, a post hoc sensitivity analysis was conducted using G*Power (version 3.1; repeated-measures ANOVA, within-factor design; $\alpha = 0.05$; power = 0.80; three measurements; correlation among repeated measures = 0.50). Based on the final analytical sample (n = 18), the study was sufficiently powered to detect moderate-to-large effects ($f \geqslant 0.32$). Therefore, the observed large effects ($\eta^2 = 0.68–0.73$) suggest that the study had adequate statistical sensitivity despite the practical constraints associated with elite athlete recruitment. Additionally, percentage changes (Δ%) were calculated to describe the magnitude of changes across measurement time points.

Results

All variables were tested for normality using the Shapiro–Wilk test, and the results indicated that all data were normally distributed ($p > 0.05$), thus meeting the assumptions for parametric statistical analysis. In addition, the assumption of sphericity was tested using Mauchly's test. All variables met the assumption of sphericity ($p > 0.05$); therefore, no Greenhouse–Geisser correction was required. Participant characteristics, including anthropometric, training, and physiological variables, as well as sex-based comparisons, are presented in Table 4.

As shown in Table 4, no significant differences were observed between male and female athletes in age, training experience, triathlon experience, and resting heart rate ($p > 0.05$), indicating comparable training status. However, significant differences were found in anthropometric variables, with males exhibiting greater height, body mass, and BMI ($p < 0.01$; d = 1.79–2.15). Overall, the relatively small variability across variables suggests a homogeneous sample, supporting the validity of subsequent longitudinal analyses.

As presented in Table 5 and illustrated in Figure 1, all physiological and performance variables demonstrated progressive changes across the intervention period. Swimming performance improved through reduced completion times, whereas VO_2max, FTP, and muscular endurance progressively increased. The largest relative changes were observed in push-up performance (+16.74%) and FTP (+9.63%).

Repeated-measures ANOVA results for all physiological and performance variables are presented in Table 6.

Table 4. Participant characteristics and sex-based comparison (n = 18)

Variable	Total (Mean ± SD)	Male (n = 8)	Female (n = 10)	p-value	Cohen's d
Age (years)	23.11 ± 5.32	24.88 ± 5.62	21.70 ± 4.77	0.182	0.61
Training experience (years)	13.72 ± 4.31	14.88 ± 3.98	12.80 ± 4.46	0.321	0.49
Triathlon experience (years)	4.67 ± 1.94	5.25 ± 1.91	4.20 ± 1.87	0.276	0.55
Height (cm)	165.17 ± 6.79	170.25 ± 4.18	161.20 ± 5.87	0.002	1.79
Body mass (kg)	55.72 ± 6.71	60.88 ± 4.88	51.60 ± 5.41	0.001	1.82
BMI (kg/m^2)	19.94 ± 1.19	21.01 ± 1.02	19.08 ± 0.78	0.001	2.15
Resting HR (bpm)	44.89 ± 2.32	45.25 ± 2.38	44.60 ± 2.30	0.558	0.28

Note. Values are presented as mean ± standard deviation (SD). Differences between male and female athletes were analyzed using an independent samples t-test. Effect sizes were calculated using Cohen's d and interpreted as small (0.2), medium (0.5), and large (0.8). Statistical significance was set at $p < 0.05$.

Table 5. Descriptive statistics and percentage changes across time points (n = 18)

Variable	Pre (Mean ± SD)	Mid (Mean ± SD)	Post (Mean ± SD)	Δ% Pre–Mid	Δ% Mid–Post	Δ% Pre–Post
Swimming (min)	12.43 ± 3.26	12.07 ± 3.11	11.72 ± 3.07	−3.04%	−2.59%	−5.61%
VO_2max ($ml \cdot kg^{-1} \cdot min^{-1}$)	58.21 ± 4.35	60.14 ± 4.12	62.08 ± 3.98	+3.31%	+3.23%	+6.64%
FTP (W)	278.45 ± 32.18	291.63 ± 30.94	305.27 ± 29.88	+4.73%	+4.61%	+9.63%
Push-up (reps)	42.18 ± 6.21	45.76 ± 5.98	49.24 ± 5.73	+8.49%	+7.60%	+16.74%
Sit-up (reps)	68.52 ± 8.47	72.94 ± 8.12	77.31 ± 7.85	+6.45%	+5.99%	+12.82%

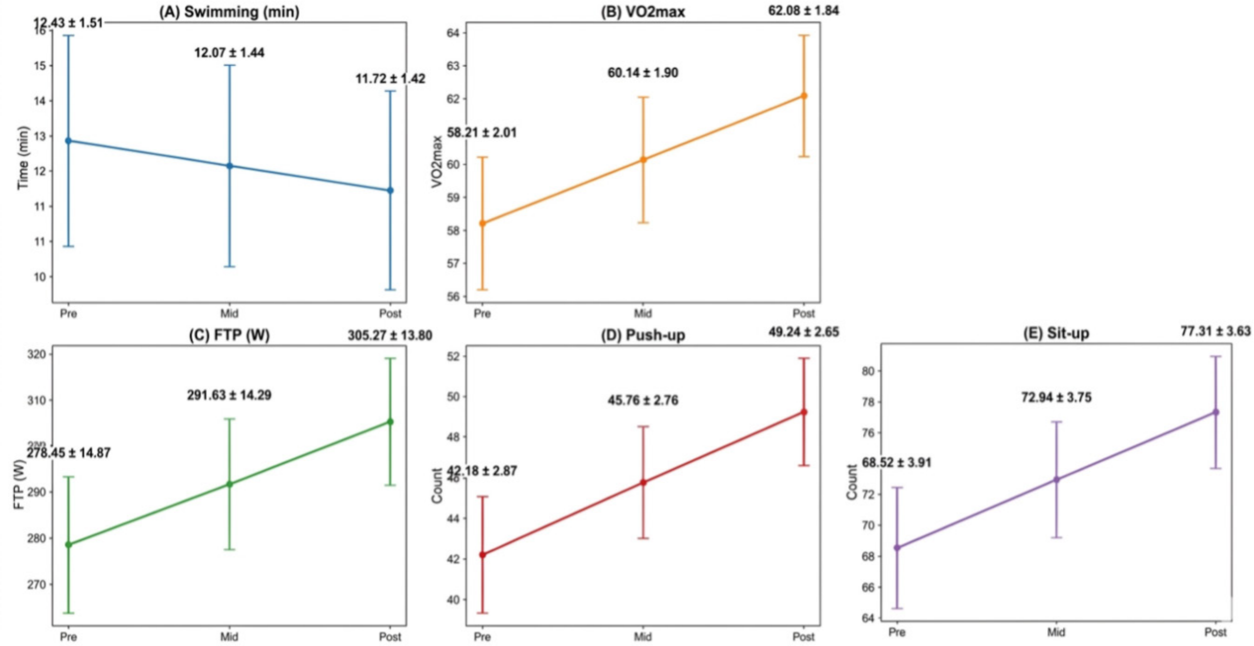

Figure 1. Changes in performance and physiological variables across the training intervention (mean ± 95% confidence interval). Panels represent (A) swimming performance, (B) VO_2max, (C) functional threshold power (FTP), (D) push-up performance, and (E) sit-up performance. Error bars indicate 95% confidence intervals.

Table 6. Repeated measures ANOVA results (n = 18)

Variable	F (2,34)	p-value	η^2 (partial)	Effect magnitude
Swimming	42.87	<0.001	0.73	Large
VO_2max	38.15	<0.001	0.70	Large
FTP	44.02	<0.001	0.73	Large
Push-up	36.44	<0.001	0.69	Large
Sit-up	34.27	<0.001	0.68	Large

As shown in Table 6, the RM-ANOVA revealed significant changes across all variables over time. Swimming performance changed significantly across time ($F(2,34) = 42.87$, $p < 0.001$, $\eta^2 = 0.73$). Significant changes were also observed in VO_2max ($F(2,34) = 38.15$, $p < 0.001$, $\eta^2 = 0.70$). Cycling performance (FTP) also improved significantly ($F(2,34) = 44.02$, $p < 0.001$, $\eta^2 = 0.73$). Similarly, muscular endurance variables showed significant improvements, with increases observed in push-up performance ($F(2,34) = 36.44$, $p < 0.001$, $\eta^2 = 0.69$) and sit-up performance ($F(2,34) = 34.27$, $p < 0.001$, $\eta^2 = 0.68$). All effect sizes were classified as large, indicating substantial practical significance of the training intervention.

From a practical perspective, the observed effect sizes ($\eta^2 = 0.68–0.73$) indicate statistical and practical relevance. In elite endurance athletes, even small improvements (e.g., 2–3%) are considered meaningful; therefore, the magnitude of changes observed in this study (5–16%) represents a significant enhancement in performance capacity.

Post-hoc comparisons with 95% confidence intervals and within-subject effect sizes are presented in Table 7.

As presented in Table 7, post-hoc analyses demonstrated statistically significant pairwise differences across all variables ($p < 0.05$). Importantly, all 95% confidence intervals did not cross zero, indicating consistent directional changes and acceptable precision of estimates across outcomes. Mean differences generally increased from pre–mid to pre–post comparisons. Within-subject effect sizes ranged from large to very large ($d = 0.82–1.67$).

Table 7. Post-Hoc comparisons with 95% CI and within-subject effect sizes (n = 18)

Variable	Comparison	Mean Diff	95% CI	p-value	Cohen's d_rm	Magnitude
Swimming	Pre–Mid	−0.36	[−0.58, −0.14]	0.002	0.88	Large
	Mid–Post	−0.35	[−0.61, −0.09]	0.011	0.82	Large
	Pre–Post	−0.71	[−0.98, −0.44]	<0.001	1.45	Very large
VO$_2$max	Pre–Mid	+1.93	[1.02, 2.84]	0.001	0.95	Large
	Mid–Post	+1.94	[0.88, 3.00]	0.004	0.91	Large
	Pre–Post	+3.87	[2.61, 5.13]	<0.001	1.52	Very large
FTP	Pre–Mid	+13.18	[7.44, 18.92]	<0.001	1.02	Large
	Mid–Post	+13.64	[6.91, 20.37]	0.002	0.98	Large
	Pre–Post	+26.82	[17.05, 36.59]	<0.001	1.67	Very large
Push-up	Pre–Mid	+3.58	[1.92, 5.24]	0.001	0.93	Large
	Mid–Post	+3.48	[1.65, 5.31]	0.002	0.89	Large
	Pre–Post	+7.06	[4.72, 9.40]	<0.001	1.58	Very large
Sit-up	Pre–Mid	+4.42	[2.31, 6.53]	0.001	0.90	Large
	Mid–Post	+4.37	[2.08, 6.66]	0.003	0.87	Large
	Pre–Post	+8.79	[5.84, 11.74]	<0.001	1.49	Very large

Table 8. Individual response analysis (n = 18)

Variable	Participants Showing Improvement (%)	Mean Δ% ± SD	Min–Max
Swimming	18 (100%)	−5.61 ± 1.10%	−7.27 to −3.38
VO$_2$max	18 (100%)	+6.64 ± 1.25%	+4.10 to +8.72
FTP	18 (100%)	+9.63 ± 1.48%	+6.90 to +12.40
Push-up	18 (100%)	+16.74 ± 2.35%	+12.10 to +20.80
Sit-up	18 (100%)	+12.82 ± 1.96%	+9.30 to +16.10

The relationship between percentage changes in VO$_2$max and FTP is illustrated in Figure 2.

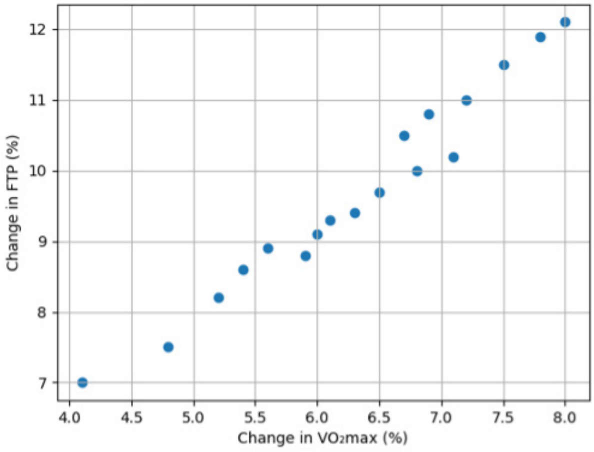

Figure 2. Scatter plot illustrating the relationship between percentage changes in VO$_2$max and Functional Threshold Power (FTP). Each point represents an individual athlete.

As illustrated in Figure 2, correlation analysis demonstrated a strong positive association between percentage changes in VO$_2$max and FTP ($r = 0.72$, $p < 0.01$). The positive linear trend indicates that greater improvements in aerobic capacity are associated with larger gains in cycling performance, highlighting the integrated nature of endurance adaptations. The observed association supports the concept of integrated endurance adaptation, where central cardiovascular improvements are translated into sport-specific functional output. This finding further supports the role of polarized training in enhancing physiological capacity and performance-related outcomes.

Individual response analysis is presented in Table 8. As presented in Table 8, improvement was primarily defined according to relative percentage changes between pre- and post-intervention values. All participants demonstrated directional improvements across all measured variables. Relative percentage changes ranged from +6.64% to +16.74% across physiological and performance variables. Table 8 also presents the distribution of individual responses and variability ranges across the intervention period.

Discussion

The objective of this study was to evaluate physiological adaptations and sport-specific performance following the implementation of a 48-week periodized triathlon training program in elite athletes. The results demonstrated significant improvements across all measured variables throughout the intervention period. Swimming performance improved through reduced completion times, whereas VO_2max, FTP, and muscular endurance showed progressive increases from pre- to post-intervention assessments. In addition, all effect sizes were classified as large, and all participants demonstrated positive directional adaptations across the measured physiological and performance outcomes.

The findings of this study demonstrate significant improvements across all physiological and performance variables following the 48-week training program. This study was conducted in an elite training camp setting, reflecting high-performance practice conditions. Therefore, the observed adaptations are likely representative of competitive environments rather than controlled laboratory conditions. Although no control group was included, the repeated-measures design allowed each athlete to serve as their own control, which is a common approach in elite sport research where experimental manipulation is limited.

A 6.64% increase in VO_2max and a 9.63% increase in FTP were observed in this study, despite the high baseline fitness level of the elite athletes. These findings align with the study [16], which reported that a polarized training model with targeted high-intensity training in Zones 4–5 can stimulate mitochondrial biogenesis and increase lactate threshold. The integration of high-intensity interval training during Phases 2 and 3 in this study was associated with continued physiological adaptation [30], as reflected by the large effect sizes for VO_2max ($d = 1.52$) and FTP ($d = 1.67$). According to the study [31], polarized training involves spending approximately 80% of training time at low-to-moderate intensity and 20% at high intensity, which may reduce the risk of overtraining associated with prolonged moderate-intensity effort. Another study [32] reported that polarized training increased VO_2peak and endurance performance to a greater extent than threshold training. Several physiological mechanisms have been proposed to explain endurance adaptations associated with polarized training, including mitochondrial biogenesis, enhanced oxidative enzyme activity, and peripheral vascular adaptations [4, 33]. However, these mechanisms were not directly assessed in the present study and therefore should be interpreted as theoretical explanations derived from previous literature rather than direct evidence from the current data. These findings suggest that the use of a polarized training model may contribute to improvements in VO_2max and FTP [34].

Although the present findings generally support previous evidence favoring polarized training models [16, 32], contrasting findings have also been reported. Rivera-Köfler et al. (2025) suggested that threshold-based and alternative training-intensity distribution models may produce comparable physiological adaptations depending on athlete characteristics, training history, and intervention context [33]. Similarly, training effectiveness may vary according to competitive level and baseline physiological status [5]. Therefore, the superiority of polarized training should not be interpreted as universal but rather as potentially context-dependent, particularly in elite athletes exposed to highly structured environments.

The strong relationship observed between VO_2max and FTP improvements highlights the integrated nature of endurance adaptations, where central cardiovascular improvements are translated into enhanced sport-specific performance. This supports the concept that polarized training targets both aerobic capacity and functional performance outputs simultaneously [35]. However, some studies suggest threshold training may yield comparable adaptations, indicating that training context and athlete level may moderate effectiveness [33]. Furthermore, the relatively low inter-individual variability observed in this study suggests that well-structured and tightly controlled training programs may reduce the likelihood of divergent adaptation responses in elite populations. However, it should be acknowledged that the magnitude and consistency of these adaptations may be partially influenced by the highly controlled training environment, including standardized nutrition, recovery, and supervision. Therefore, these findings should be interpreted with caution when applied to less structured or more heterogeneous athletic populations.

An important aspect of the present findings is that the longitudinal design allowed observation of adaptation trajectories across an almost complete annual macrocycle, rather than relying solely on isolated pre–post comparisons commonly used in shorter interventions [12]. Previous endurance-training studies have frequently employed intervention periods ranging from approximately 6–20 weeks, which may not fully capture the progressive and cumulative nature of physiological adaptation [9–11]. The present findings suggest that endurance adaptations in elite athletes may continue accumulating during prolonged training exposure, with relatively stable inter-individual responsiveness under highly standardized conditions [15, 36]. Collectively, these observations indicate that adaptation patterns in elite endurance athletes may be dynamic and sustained across a long-term training cycle [12, 36].

The results of this study also showed that the time required to complete the 1 km swim was significantly reduced by 5.61%. This improvement in swimming performance may reflect increases in aerobic endurance and technical efficiency associated with technical drills performed during Phase 1 (basic preparation) [37, 38]. Meanwhile, the greatest percentage increases were observed in the muscular-endurance variables, both in the push-up test (+16.74%) and the sit-up test (+12.82%). Improved muscular endurance is a factor associated with endurance-sport performance [39]. Neuromuscular conditioning through combined sessions (brick training) and multi-faceted exercises reflects the ecological demands of triathlon competition [34].

One observation of this longitudinal investigation was the consistent directional improvement pattern observed across athletes. Nevertheless, interpretation of apparent universal responsiveness should be approached cautiously because formal reliability metrics such as SWC, TE, and CV were unavailable. Contemporary methodological frameworks suggest that responder classifications based solely on raw percentage changes may overestimate true responsiveness [40, 41]. Therefore, the present findings should not be interpreted as evidence of absolute physiological uniformity, but rather as an indication that meaningful adaptations occurred under highly controlled training conditions.

From a broader perspective, these findings contribute to evidence-based training practices and sports-science knowledge, supporting athlete health and performance optimization (SDG 3: Good Health and Well-being) as well as the development of quality education and applied research in sport science (SDG 4: Quality Education).

Limitations of the Study

Although this study provides longitudinal insights into the adaptation of elite triathletes within a full macrocycle, several limitations should be acknowledged. The absence of a parallel control group limits the ability to draw causal inferences regarding the effectiveness of the training intervention. This constraint was inherent to the study context, as all participants were elite athletes engaged in a centralized national training program, making the inclusion of a non-training or alternative-training control group impractical and ethically challenging. While each participant served as their own control through repeated measurements, the observed improvements may still be partially influenced by natural training progression, seasonal variation, or competition-preparation effects.

The relatively small sample size (n = 18), although representative of elite-level populations, limits the statistical power for more detailed subgroup analyses, such as sex-based differences in physiological adaptation. This study focused primarily on performance outcomes and selected physiological variables, without incorporating internal-load biomarkers such as hormonal responses, blood lactate dynamics, or heart-rate variability (HRV). The inclusion of such measures would provide deeper mechanistic insights into the interaction between training stress and recovery processes.

The absence of formal reliability metrics (e.g., CV, ICC, and SWC) limits the precision in distinguishing true physiological adaptations from measurement variability. This limitation is particularly relevant when interpreting individual responses, as the lack of established thresholds for meaningful change may lead to overestimation of responsiveness. Dietary intake was monitored using self-reported methods, which may introduce reporting bias and limit the accuracy of nutritional control throughout the intervention. Therefore, the potential contribution of nutritional factors to the observed performance improvements cannot be fully isolated.

The absence of non-responders observed in this study should be interpreted with caution. This finding may reflect limitations in the sensitivity of the measurement approach or the criteria used to define meaningful change, rather than true universal responsiveness among participants. Despite these limitations, one strength of this study is the highly controlled training environment, including standardized training load, nutrition, and recovery protocols, which minimizes external variability often present in field-based studies. Future studies should incorporate control groups, mechanistic biomarkers, and multi-center designs.

Conclusions

Based on the present 48-week longitudinal observations, a periodized training program using a polarized training approach was associated with improvements in swimming performance, aerobic capacity, FTP, and muscular endurance in elite triathletes. While the repeated-measures design allowed monitoring of adaptation trajectories across a complete training macrocycle, the absence of a control group and study-specific reliability metrics limits causal interpretation and precision of individual responsiveness. Therefore, these findings should be interpreted as evidence of meaningful adaptations occurring under highly controlled training conditions rather than definitive proof of intervention superiority.

From a practical perspective, the present findings may assist coaches in organizing training across specific phases of an annual macrocycle. The observed improvements in VO_2max and FTP appeared to coincide with increased integration of interval and race-specific sessions during the specific preparation phase, whereas improvements in muscular endurance may reflect cumulative adaptations from repeated resistance and brick-training exposure. During competition preparation, maintenance of intensity with reduced volume may contribute to preserving physiological adaptations while minimizing fatigue accumulation. Therefore, phase-specific manipulation of training volume and intensity may be an important consideration for endurance coaches working with elite athletes.

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Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

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Conflict of Interest

The authors declare no conflict of interest.

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