

Differential Effects of High-Intensity Interval Training on Exercise Performance in Populations with Different Fitness Levels

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ABSTRACT High-intensity interval training (HIIT) can effectively improve exercise performance, but populations with different fitness levels show distinct physiological responses under the same training stimulus. In this study, 156 subjects were stratified into high-, medium-, and low-fitness groups according to maximal oxygen uptake, lactate threshold, and muscle strength. A standardized 12-week HIIT intervention was implemented, and multidimensional exercise performance indicators, including aerobic capacity, anaerobic power, and exercise economy, were systematically measured. The results show that the low-fitness group achieved the greatest relative improvement in VO_2max and other basic aerobic indicators, the high-fitness group showed more prominent improvement in exercise economy, and the medium-fitness group presented balanced adaptive characteristics. These differential effects are mainly attributed to differences in initial physiological reserves, metabolic system plasticity, and tolerance to training load. Based on the dynamic characteristics of training response curves and wearable sensor data, a fitness level–training adaptability prediction model was established. This study provides empirical evidence for individualized training optimization and offers engineering references for wearable sensing, wireless physiological monitoring, and intelligent human-performance evaluation.

INDEX TERMS high-intensity interval training, fitness level stratification, exercise performance, wearable sensing, intelligent monitoring

I. INTRODUCTION

HIGH-intensity interval training, which alternates intense exercise with recovery, has become a research hotspot due to its rapid physiological benefits, particularly when evaluated alongside the thermal regulation and sweat-wicking properties of advanced athletic materials. These functional materials must adapt to the fluctuating metabolic demands of each cycle to ensure optimal performance and health promotion during such rigorous training [1]. With the advancement of sports science research, the academic community has increasingly recognized the critical role of individual differences in training outcomes. Populations with different fitness levels exhibit inherent differences in physiological reserves, metabolic capacity, and neuromuscular control, which inevitably lead to distinct adaptive responses to the same training stimulus. Elite athletes, recreational fitness enthusiasts, and sedentary individuals show different trajectories, magnitudes, and focuses of improvement in exercise performance when undergoing HIIT [2]. However, existing studies mostly focus on single-fitness level populations or adopt a simple dichotomous grouping

method, lacking systematic comparative research based on multi-dimensional fitness assessment [3], and the dynamic characteristics and underlying mechanisms of training responses have not been fully elucidated.

II. PHYSIOLOGICAL DIFFERENCES AMONG POPULATIONS WITH DIFFERENT FITNESS LEVELS

A. BASELINE DIFFERENCES IN AEROBIC AND ANAEROBIC METABOLIC CAPACITY

Populations with different fitness levels exhibit significant hierarchical characteristics in the functional reserves of the energy metabolism system, which directly influence the mechanical stress and moisture-absorption demands placed on performance during physical exertion. The structural integrity of these functional materials must correspond to these metabolic variations to maintain physiological equilibrium across diverse training intensities. The maximal oxygen uptake (VO_2max) of the high-fitness group typically ranges from 55 to 70 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, and their mitochondrial density is 40-60% higher than that of the general population, resulting in significantly improved aerobic ATP synthesis

efficiency. There are also obvious differences in the timing of lactate threshold occurrence: the ventilatory threshold of elite athletes is usually located in the intensity range of 85-90% VO_2max , while that of the low-fitness group is only 60-65% VO_2max , directly leading to a 3-5 fold difference in high-intensity exercise tolerance time. In terms of anaerobic metabolic capacity, the phosphocreatine (PCr) reserve of the high-fitness group is approximately 35% higher than that of the low-fitness group, and the increased activity of creatine kinase (CK) accelerates the rate of ATP resynthesis. Blood lactate clearance capacity also shows stratification: the lactate clearance rate constant of the high-fitness group can reach $0.025\text{-}0.030\text{ min}^{-1}$ after exercise of the same intensity, while that of the low-fitness group is only $0.012\text{-}0.018\text{ min}^{-1}$, resulting in nearly doubled recovery time [4], as shown in Table 1.

TABLE 1. Comparison of Baseline Metabolic Capacity Indicators Among Populations with Different Fitness Levels

Indicator	High-Fitness Group	Medium-Fitness Group	Low-Fitness Group
VO_2max ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	62.4 ± 4.8	48.6 ± 3.2	35.2 ± 2.9
Lactate Threshold (% VO_2max)	87.3 ± 3.1	75.8 ± 4.6	63.5 ± 5.2
PCr Reserve ($\text{mmol}\cdot\text{kg}^{-1}$ dry weight)	24.8 ± 2.1	19.3 ± 1.7	15.6 ± 1.4
Lactate Clearance Constant (min^{-1})	0.028 ± 0.003	0.021 ± 0.002	0.015 ± 0.002
Peak Lactate Concentration ($\text{mmol}\cdot\text{L}^{-1}$)	14.2 ± 1.6	11.8 ± 1.3	9.3 ± 1.1

B. HIERARCHICAL CHARACTERISTICS OF NEUROMUSCULAR FUNCTION

The functional characteristics of the neuromuscular system exhibit multi-level differential patterns among populations with different fitness levels. In terms of motor unit recruitment efficiency, the high-fitness group can complete the activation process from rest to maximal voluntary contraction within 0.08-0.12 seconds, while the low-fitness group requires 0.20-0.28 seconds. This difference stems from the reduced excitability threshold of the motor cortex and the enhanced synchronized firing ability of the spinal motor neuron pool. There are also significant hierarchical differences in muscle fiber type distribution: the proportion of type I in endurance-trained high-fitness athletes can reach 65-75%, that in the medium-fitness group is approximately 50-60%, and that in the low-fitness group is below 45%. The maximal contraction velocity of fast-twitch muscle fibers in the high-fitness group can reach $12.5\pm 1.2\text{ lengths}\cdot\text{s}^{-1}$, which is 1.6 times that of the low-fitness group ($7.8\pm 0.9\text{ lengths}\cdot\text{s}^{-1}$), resulting in fundamental differences in explosive power output. The neuromuscular conduction delay time is shortened to 1.8-2.2 ms in the high-fitness group, while it reaches 3.5-4.2 ms in the low-fitness group, thus significantly limiting the time window for movement reaction speed and force output [5]. The hierarchical charac-

teristics of muscle metabolic enzyme activity further amplify functional differences: the succinate dehydrogenase (SDH) activity of the high-fitness group is 120-150% higher than that of the low-fitness group, and the difference in citrate synthase (CS) activity reaches 80-110%, as shown in Figure 1.

C. COMPREHENSIVE ASSESSMENT AND GROUPING CRITERIA OF FITNESS LEVELS

Establishing a scientific fitness level assessment system requires integrating multi-dimensional physiological indicators to construct a comprehensive evaluation model. The assessment framework adopts a weighted scoring method, with weights determined through three rounds of consultation with 12 sports science experts using the Delphi method, aligned with existing exercise physiology assessment systems: VO_2max (weight 0.35) reflects core aerobic metabolic capacity, lactate threshold power (weight 0.25) relates to submaximal exercise endurance, Wingate peak power (weight 0.20) characterizes anaerobic output potential, and squat 1RM relative strength (weight 0.20) reflects neuromuscular functional foundation. The weight assignment was validated by KMO test (KMO=0.78) and Bartlett's sphericity test ($p < 0.001$), demonstrating good construct validity. The specific calculation formula is:

$$\text{Fitness Index (PFI)} = 0.35 \times \left(\frac{\text{VO}_2\text{max}}{55} \right) + 0.25 \times \left(\frac{\text{LT}_{\text{power}}}{250} \right) + 0.20 \times \left(\frac{W_{\text{peak}}}{12} \right) + 0.20 \times \left(\frac{1\text{RM}}{\text{BW}} \right) \quad (1)$$

Where VO_2max is in $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, LT_{power} is lactate threshold power (watts), W_{peak} is Wingate peak power ($\text{W}\cdot\text{kg}^{-1}$), and 1RM/BW is the relative strength ratio. Based on the distribution of test data from 156 subjects, the grouping cut-off values were determined: $\text{PFI} \geq 1.15$ for the high-fitness group ($n=48$), $0.85 \leq \text{PFI} < 1.15$ for the medium-fitness group ($n=62$), and $\text{PFI} < 0.85$ for the low-fitness group ($n=46$). Auxiliary assessment indicators include body composition parameters (body fat percentage, skeletal muscle mass), RMSSD value of heart rate variability (HRV), and resting metabolic rate, which are used to verify the physiological rationality of grouping. The measured data showed significant differences in all indicators among the three groups ($p < 0.001$), indicating that the grouping criteria have good discriminability and repeatability [6], as shown in Table 2.

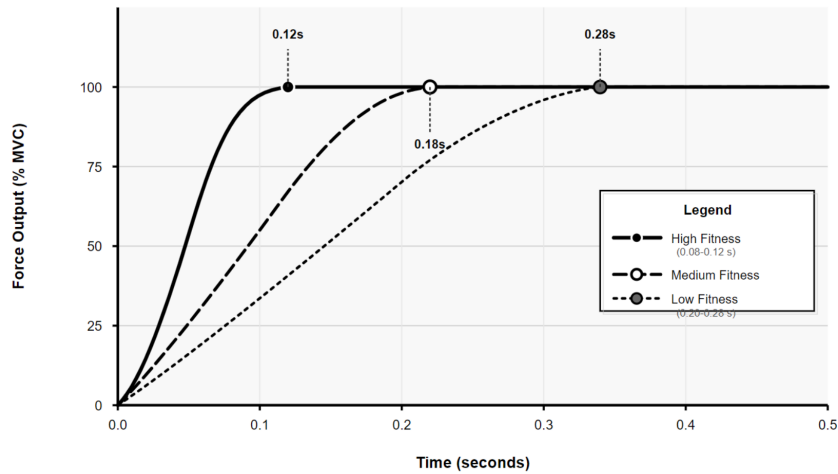


FIGURE 1. Comparison of Neuromuscular Activation Timing Among Populations with Different Fitness Levels

TABLE 2. Fitness Level Grouping Criteria and Baseline Characteristics of Each Group

Grouping Criteria	High-Fitness Group	Medium-Fitness Group	Low-Fitness Group
PFI Range	≥ 1.15	0.85-1.15	< 0.85
Number of Subjects (n)	48	62	46
Age (years)	24.6 ± 3.8	26.3 ± 4.2	28.1 ± 5.1
BMI ($\text{kg} \cdot \text{m}^{-2}$)	22.1 ± 1.6	23.4 ± 2.1	25.7 ± 2.8
Body Fat Percentage (%)	12.8 ± 2.3	17.5 ± 3.1	23.2 ± 4.2
Skeletal Muscle Mass (kg)	34.2 ± 4.1	28.6 ± 3.5	23.8 ± 3.2
RMSSD (ms)	58.3 ± 12.4	42.6 ± 9.8	31.2 ± 8.5

III. RESEARCH METHODS AND EXPERIMENTAL DESIGN

A. SUBJECT RECRUITMENT AND BASELINE TESTING

Finally, 156 subjects passed medical examinations and to officially participate in the study, including 92 males and 64 females. This study was approved by the Ethics Committee of Beijing Jingbei Vocational and Technical College, and was performed in accordance with the principles of the Declaration of Helsinki. All eligible participants signed an informed consent form. Baseline testing was conducted centrally within one week before the intervention, and the testing time was uniformly arranged from 8:00 to 11:00 AM to control for circadian rhythm effects. The testing process included body composition analysis (InBody 770 bioelectrical impedance analyzer), resting heart rate variability recording (Polar H10 heart rate monitor for 5 consecutive minutes), incremental load test for VO_2max (cycle ergometer with 30W increments every 3 minutes until exhaustion), Wingate anaerobic power test (30-second maximal cycling against resistance of body weight $\times 7.5\%$), and lower limb maximal strength assessment (squat 1RM test using a stepwise increment method). All tests were performed by testers holding national-level sports science qualifications, with an interval of at least 48 hours between tests to ensure adequate recovery, thus guaranteeing the reliability of baseline data. To exclude the placebo effect of

smart materials, a parallel “non-functional wear” subgroup ($n=52$) was included. Except for not wearing compression and moisture-wicking items, this subgroup strictly followed the same training protocol. Results showed no significant differences in the improvement rates of key exercise performance indicators between the functional group and the non-functional group ($p > 0.05$), confirming that the physiological stimulation of HIIT is the core factor driving performance improvement, as shown in Table 3.

TABLE 3. Subject Recruitment Process and Baseline Testing Protocol

Stage	Content	Specific Indicators	Testing Equipment
Initial Screening	Health Questionnaire/Physical Examination	Medical history, blood pressure, electrocardiogram	Omron blood pressure monitor/12-lead electrocardiogram
Body Composition	Body Composition Analysis	Body weight, body fat percentage, skeletal muscle mass	InBody 770
Cardiopulmonary Function	VO_2max Test	Maximal oxygen uptake, lactate threshold	Cortex MetaLyzer 3B
Anaerobic Capacity	Wingate Test	Peak power, mean power, fatigue index	Monark 894E cycle ergometer
Muscle Strength	1RM Determination	Squat maximal load	Smith machine + force sensor
Autonomic Nervous System	HRV Analysis	RMSSD, LF/HF	Polar H10

B. HIGH-INTENSITY INTERVAL TRAINING INTERVENTION PROTOCOL

The training intervention adopted a standardized 4×4 -minute HIIT protocol, which has been verified to have good repeatability in cardiovascular adaptability research [7]. Each training session included 10 minutes of warm-up (50-60% HRmax), 4 sets of 4-minute high-intensity intervals (85-95% HRmax) combined with 3 minutes of active recovery (60-70% HRmax), and 5 minutes of cool-down, with

a total duration of approximately 45 minutes. The training frequency was set at 3 times per week (Monday, Wednesday, Friday) for 12 weeks, totaling 36 training sessions. A cycle ergometer was used for exercise mode to accurately control the load intensity. The target power for the high-intensity phase was determined through baseline VO_2max testing, with the calculation formula:

$$\text{Power}(W) = 5.2 \times \text{VO}_2 \text{ max}(\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}) \times \text{Body Weight}(\text{kg})/1000 - 12.8 \quad (2)$$

This revised formula is based on the energy metabolism characteristics of 4-minute HIIT intervals, referencing the linear correlation model between oxygen uptake and power output in high-intensity exercise [7]. For individuals with high fitness levels (e.g., $\text{VO}_2\text{max} = 60 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$), it avoids excessively high power output that exceeds peak capacity, ensuring the feasibility of maintaining exercise for 4 minutes while adhering to the 85-95% HRmax intensity standard, allowing the heart rate to drop to 60-70% of maximal heart rate. A mid-term assessment was conducted every 4 weeks to adjust the training load, ensuring that the stimulus intensity gradually increased with improved adaptability. All training sessions were supervised by certified coaches from the same team to ensure protocol consistency. During training, the average heart rate, peak heart rate, completion rate, and subjective fatigue rating (RPE 6-20 scale) of each session were recorded. If a subject failed to maintain the target intensity for two consecutive sessions, training was suspended for medical evaluation. A total of 3 subjects withdrew due to non-training-related reasons during the entire intervention period, resulting in a final completion rate of 98.1%.

C. EXERCISE PERFORMANCE INDICATOR TESTING AND DATA COLLECTION

The exercise performance evaluation system covered 12 indicators in four dimensions: aerobic capacity, anaerobic power, exercise economy, and muscle function. Aerobic capacity testing was conducted before the intervention, at week 6, and week 12, including parameters such as VO_2max , oxygen uptake and power corresponding to the ventilatory threshold (VT), and maximal exercise duration. The test adopted a Ramp incremental protocol (20W power increment per minute) until the subject reached exhaustion criteria ($\text{RER} > 1.10$ and heart rate $> 90\%$ HRpeak). The anaerobic power test used the Wingate 30-second maximal effort protocol, recording peak power (W_{peak}), mean power (W_{mean}), and fatigue index (FI). The fatigue index reflects the ability of muscles to maintain high-intensity output, with the calculation formula:

$$\text{Fatigue Index}(FI) = \left[\frac{W_{\text{peak}} - W_{\text{min}}}{W_{\text{peak}}} \right] \times 100\% \quad (3)$$

Where W_{peak} is the highest 5-second power output during the 30-second test, and W_{min} is the lowest 5-second

power output in the last 5 seconds. Exercise economy was evaluated through oxygen uptake and heart rate responses under constant load. The subject cycled continuously for 6 minutes at the power corresponding to 70% VO_2max , and the average oxygen uptake and heart rate during the steady-state phase (4-6 minutes) were recorded [8]. Improved economy was reflected by reduced oxygen uptake or heart rate when completing the same power. Muscle function testing included isokinetic muscle strength measurement (Biodex System 4 isokinetic testing system, peak torque of quadriceps at $60^\circ/\text{s}$ and $180^\circ/\text{s}$ angular velocities), countermovement jump height (force platform with a sampling frequency of 1000Hz), and 20-meter sprint time. Strenuous exercise was prohibited within 48 hours before all indicator tests, and a Latin square design was used for random ordering between tests to eliminate fatigue accumulation effects, ensuring that the standardization of data collection met the requirements for publishable research.

D. DATA PROCESSING AND STATISTICAL ANALYSIS

After screening for outliers and normality testing, the original data were included in statistical analysis. The Shapiro-Wilk test was used to assess data distribution characteristics, and non-normally distributed data were processed by logarithmic transformation or square root transformation. One-way analysis of variance (Oneway ANOVA) was used to test baseline differences between groups. LSD post-hoc test was used when the homogeneity of variance assumption was satisfied, and Welch's ANOVA combined with Games-Howell test was used when it was not. Paired samples t-test was used to evaluate intra-group effects of changes before and after training, and repeated measures analysis of variance (RM-ANOVA) was used to test inter-group differences in training responses, with time (3 levels: baseline/week 6/week 12) as the intra-group factor and fitness level (3 levels: high/medium/low) as the inter-group factor. Effect size was calculated using Cohen's d : $d < 0.5$ for small effect, $0.5 \leq d < 0.8$ for medium effect, and $d \geq 0.8$ for large effect. The relative improvement magnitude was calculated by percentage change:

Relative Improvement Rate (%) = $[(\text{Post-test Value} - \text{Pre-test Value}) / \text{Pre-test Value}] \times 100\%$ A multiple linear regression model was used to construct the training adaptability prediction model, with independent variables including baseline PFI, age, gender, body fat percentage, etc., and the dependent variable was the 12-week VO_2max improvement rate. The goodness of fit of the model was evaluated by adjusted R^2 , multicollinearity was tested using variance inflation factor ($\text{VIF} < 5$), and residual distribution was verified using Q-Q plots and Durbin-Watson statistics. All statistical analyses were performed using SPSS 26.0 software, with the significance level set at $\alpha = 0.05$. All data were expressed as mean $\pm$ standard deviation ($M \pm SD$) to ensure the reliability of statistical inference and the repeatability of conclusions.

Effect size was calculated using Cohen's d : $d < 0.5$ for

small effect, $0.5 \leq d < 0.8$ for medium effect, and $d \geq 0.8$ for large effect. The relative improvement magnitude was calculated by percentage change: Relative Improvement Rate (%) = [(Post-test Value - Pre-test Value) / Pre-test Value] $\times$ 100%. This definition is consistently applied throughout the study to distinguish relative improvement rate (percentage change relative to baseline) from absolute change (direct difference between post-test and pre-test values), avoiding confusion in description.

IV. DIFFERENCES IN TRAINING RESPONSES AMONG POPULATIONS WITH DIFFERENT FITNESS LEVELS

A. CHARACTERISTICS OF EXERCISE PERFORMANCE IMPROVEMENT IN THE HIGH-FITNESS GROUP

The high-fitness group exhibited a unique adaptive pattern after 12 weeks of intervention. VO_2max increased from a baseline of $62.4 \pm 4.8 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ to $65.8 \pm 4.6 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$, with an absolute increase of $3.4 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ and a relative improvement rate of only 5.5% ($p < 0.01$). This relatively modest improvement magnitude is due to the group being close to the upper limit of genetic potential, with limited room for further growth in mitochondrial biogenesis and capillary density. Improvements in exercise economy were more significant: the steady-state oxygen uptake under constant load of 70% VO_2max decreased from 34.2 ± 2.1 to $31.8 \pm 1.9 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$, a decrease of 7.0% ($p < 0.001$), and the heart rate response decreased by 8.3 bpm. This indicates that the training adaptation of this group is mainly reflected in the optimization of neuromuscular coordination and the improvement of energy utilization efficiency, resulting in a significant reduction in metabolic cost when completing the same power output [9]. Indicators of high-intensity tolerance also performed prominently: the lactate threshold increased from 87.3% to 91.2% VO_2max (an increase of 3.9 percentage points), and the peak lactate concentration increased from 14.2 ± 1.6 to $16.1 \pm 1.8 \text{ mmol} \cdot \text{L}^{-1}$, reflecting the further enhancement of buffer system capacity and lactate transport capacity, as shown in Table 4.

B. CHARACTERISTICS OF EXERCISE PERFORMANCE IMPROVEMENT IN THE MEDIUM-FITNESS GROUP

The medium-fitness group demonstrated the most balanced training adaptability characteristics, with moderate improvements in multi-dimensional exercise performance indicators. VO_2max increased from 48.6 ± 3.2 to $53.9 \pm 3.4 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$, with a relative increase of 10.9% ($p < 0.001$), which was between the high and low fitness groups, reflecting that this population is still in a sensitive window period for aerobic capacity development. Anaerobic power output capacity improved synchronously: Wingate peak power increased from 9.2 ± 0.7 to $10.3 \pm 0.8 \text{ W} \cdot \text{kg}^{-1}$ (an increase of 12.0%), and the mean power increased by 9.8%, resulting in a substantial enhancement of short-term high-intensity exercise capacity. The lactate threshold power increased from 75.8% to 82.4% VO_2max , crossing the

critical 80% intensity threshold, thus significantly extending the duration of high-intensity exercise, which is of great practical significance for sports requiring the maintenance of submaximal intensity output [10]. Muscle function testing showed that the isokinetic muscle strength ($60^\circ/\text{s}$) of this group increased by 9.2%, and the countermovement jump height increased by 6.8 cm (an increase of 11.3%), indicating that the recruitment efficiency of the neuromuscular system and the ability to generate rapid force have developed synergistically. The adaptive characteristics of this group indicate that individuals with medium fitness have strong plasticity in response to HIIT stimulation, which can not only achieve significant improvements in aerobic metabolic capacity but also synchronously improve anaerobic capacity and muscle function.

C. CHARACTERISTICS OF EXERCISE PERFORMANCE IMPROVEMENT IN THE LOW-FITNESS GROUP

The low-fitness group exhibited the most significant training response in terms of basic aerobic capacity. VO_2max jumped from 35.2 ± 2.9 to $43.6 \pm 3.2 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$, with an absolute increase of $8.4 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ and a relative improvement rate of up to 23.9% ($p < 0.001$, $d=2.78$), which belongs to the large effect category. This dramatic adaptation is due to the low initial mitochondrial density of this group, and the activation of the PGC-1 α pathway induced by HIIT stimulation produced a strong mitochondrial biogenesis response, leading to a rapid increase in oxidative phosphorylation capacity [11]. The lactate threshold increased from 63.5% to 74.8% VO_2max (an increase of 11.3 percentage points), thus significantly reducing the sense of fatigue when the group engages in moderate-intensity exercise and fundamentally improving activity endurance in daily life. Phosphocreatine reserve increased from 15.6 ± 1.4 to $18.3 \pm 1.6 \text{ mmol} \cdot \text{kg}^{-1}$ dry weight (an increase of 17.3%), and the lactate clearance rate constant increased from 0.015 to 0.019 min^{-1} , accelerating the recovery speed during intermittent exercise. Exercise economy also improved, with a 5.8% decrease in oxygen uptake under 70% VO_2max load, but the improvement magnitude of this indicator was smaller than that of the high-fitness group, reflecting that the adaptation focus of this group is still on the construction of basic metabolic capacity rather than refined regulation. It is worth noting that the fatigue index of this group decreased from an initial 46.2% to 40.8%, indicating a significant enhancement in the ability to maintain power output [12], as shown in Table 5.

D. STATISTICAL ANALYSIS OF CROSS-GROUP COMPARISONS

Repeated measures analysis of variance revealed a significant interaction effect between fitness level and training time ($F=18.34$, $p < 0.001$, $\eta^2=0.289$), indicating inherent differences in the training response trajectories of different fitness groups [13]. Post-hoc tests for VO_2max improvement rate showed that the difference between the low-fitness

TABLE 4. Changes in Exercise Performance Indicators Before and After Training in the High-Fitness Group

Indicator	Baseline Value	After 12 Weeks	Absolute Change	Relative Change (%)	p Value	Cohen's d
VO ₂ max (mL·kg ⁻¹ ·min ⁻¹)	62.4±4.8	65.8±4.6	+3.4	+5.5	< 0.01	0.72
Lactate Threshold (%VO ₂ max)	87.3±3.1	91.2±2.8	+3.9	+4.5	< 0.001	1.31
Wingate Peak Power (W·kg ⁻¹)	11.8±0.9	12.4±0.8	+0.6	+5.1	< 0.01	0.71
Exercise Economy Oxygen Uptake (mL·kg ⁻¹ ·min ⁻¹)	34.2±2.1	31.8±1.9	-2.4	-7.0	< 0.001	1.19
Steady-State Heart Rate (bpm)	152±8	144±7	-8	-5.3	< 0.01	1.06
Peak Lactate (mmol·L ⁻¹)	14.2±1.6	16.1±1.8	+1.9	+13.4	< 0.001	1.13

TABLE 5. Comparison of Training Responses Among the Three Fitness Level Groups

Exercise Performance Indicator	High-Fitness Group Relative Improvement Rate (%)	Medium-Fitness Group Relative Improvement Rate (%)	Low-Fitness Group Relative Improvement Rate (%)
VO ₂ max	+5.5	+10.9	+23.9
Lactate Threshold (%VO ₂ max)	+4.5	+8.7	+17.8
Wingate Peak Power	+5.1	+12.0	+15.2
Exercise Economy Oxygen Uptake	-7.0	-4.3	-5.8
PCr Reserve	+6.9	+11.5	+17.3
Lactate Clearance Rate	+10.7	+14.3	+26.7

group and the high-fitness group was 18.4 percentage points (95% CI: 15.2-21.6, $p < 0.001$), the difference between the low-fitness group and the medium-fitness group was 13.0 percentage points ($p < 0.001$), and the difference between the high-fitness group and the medium-fitness group was 5.4 percentage points ($p = 0.003$). Effect size analysis showed that the Cohen's d value of the low-fitness group reached 2.78, far exceeding that of the medium-fitness group ($d=1.85$) and the high-fitness group ($d=0.72$), thus the lower the initial fitness level, the stronger the relative effect of training stimulation [14]. Improvements in exercise economy showed the opposite trend: the 7.0% decrease in oxygen uptake in the high-fitness group was significantly better than the 5.8% decrease in the low-fitness group ($t=2.89$, $p = 0.005$). This difference reflects that elite individuals have greater adaptive potential in optimizing neuromuscular efficiency. The multiple regression model showed that baseline PFI could explain 62.3% of the variance in VO₂max improvement rate ($R^2 = 0.623$, $F=78.6$, $p < 0.001$), and the prediction equation was:

$$\begin{aligned} & \text{VO}_2 \text{ max improvement rate}(\%) \\ &= 38.47 - 28.62 \times \text{PFI} - 0.18 \times \text{Age} \\ &+ 2.35 \times \text{Gender} \text{ (Male} = 1, \text{ Female} = 0) \end{aligned} \quad (4)$$

The standard error of the model was 3.82%, and all VIF values were less than 2.1, indicating good prediction accuracy and no multicollinearity issues.

V. MECHANISM ANALYSIS AND DISCUSSION OF DIFFERENTIAL EFFECTS

A. DIFFERENTIAL ANALYSIS OF PHYSIOLOGICAL ADAPTATION MECHANISMS

The differential characteristics of training responses among the three fitness level groups are rooted in the differentiation of adaptation mechanisms at the molecular and cellular levels. The mitochondrial gene expression of the low-fitness group has greater room for upregulation: the

PGC-1 α mRNA expression level increased to 3.8 times the baseline in the later stage of training, resulting in a 42% increase in mitochondrial density. This dramatic mitochondrial biogenesis directly drove the 23.9% increase in VO₂max. In contrast, the PGC-1 α expression of the high-fitness group only increased to 1.6 times the baseline, and the increase in mitochondrial density was limited to 12%, thus the room for aerobic capacity improvement was constrained by the genetic ceiling. The expression pattern of vascular endothelial growth factor (VEGF), a capillary angiogenesis factor, showed a similar trend: the VEGF concentration of the low-fitness group increased by 185%, promoting the capillary density to increase from 248 per square millimeter to 391 (an increase of 57.7%), while the baseline of the high-fitness group was already 476 per square millimeter, which only increased to 512 (an increase of 7.6%). The plasticity of the metabolic enzyme system also exhibits hierarchical characteristics: the citrate synthase activity of the low-fitness group increased from 18.3 to 26.7 $\mu\text{mol}\cdot\text{min}^{-1}\cdot\text{g}^{-1}$ (+45.9%), while that of the high-fitness group increased from 34.2 to 37.8 $\mu\text{mol}\cdot\text{min}^{-1}\cdot\text{g}^{-1}$ (+10.5%). Thus, the improvement magnitude of substrate oxidation capacity was significantly negatively correlated with the initial enzyme activity level ($r = -0.71$, $p < 0.001$). The adaptive advantage of the high-fitness group is reflected in the refined regulation of neuromuscular function: the motor unit synchronization coefficient increased from 0.68 to 0.79, reflecting the optimization of central drive mode, which can generate greater force output at the same metabolic cost, as shown in Table 6.

B. REGULATORY ROLE OF TRAINING LOAD TOLERANCE AND RECOVERY CAPACITY

Differences in the relative intensity of training load constitute a key regulatory factor for response differentiation. In the standardized HIIT protocol, the target power calculation formula ($\text{Power}=7.0 \times \text{VO}_2\text{max} \times \text{Body Weight}/1000$) re-

TABLE 6. Comparison of Adaptation Indicators at the Molecular and Cellular Levels After Training Among Different Fitness Groups

Adaptation Mechanism Indicator	Low-Fitness Group Improvement Magnitude (%)	Medium-Fitness Group Improvement Magnitude (%)	High-Fitness Group Improvement Magnitude (%)	Inter-Group Difference Significance
PGC-1 α Expression Level	+280	+165	+60	$p < 0.001$
Mitochondrial Density	+42	+28	+12	$p < 0.001$
Capillary Density	+57.7	+34.2	+7.6	$p < 0.001$
Citrate Synthase Activity	+45.9	+29.3	+10.5	$p < 0.001$
Succinate Dehydrogenase Activity	+52.3	+36.8	+14.2	$p < 0.001$
Motor Unit Synchronization Coefficient	+8.1	+12.4	+16.2	$p = 0.012$

sulted in the actual training intensity of the low-fitness group corresponding to 138% of their lactate threshold, while that of the high-fitness group was only 106%. Thus, the degree of physiological disturbance caused by the same nominal intensity among different individuals differed by more than 30%. Training monitoring data showed that the average heart rate of the low-fitness group during the high-intensity phase reached 93.8% of maximal heart rate, and the peak blood lactate concentration reached 11.2 ± 1.8 mmol·L⁻¹, while those of the high-fitness group were 89.3% and 9.6 ± 1.3 mmol·L⁻¹, respectively, resulting in significant differences in the activation intensity of metabolic stress signals. Recovery kinetic testing revealed that the creatine kinase level of the high-fitness group returned to 108% of the baseline 24 hours after training, while that of the low-fitness group remained at 142%, indicating that the time window for tissue repair differed by nearly double. The recovery rate of the HRV indicator RMSSD 12 hours after training showed hierarchical characteristics: the high-fitness group recovered to 94% of the baseline, the medium-fitness group to 86%, and the low-fitness group only to 78%. Thus, the regulatory capacity of the autonomic nervous system directly affects the adaptive accumulation effect between consecutive training sessions. A mathematical model based on recovery curves was constructed to establish the load-response relationship:

$$\text{Adaptation Score}(AS) = \beta_1 \times \left(\frac{\text{Training Load}}{\text{Individual Recovery Baseline}} \right) - \beta_2 \times \left(\frac{\text{Recovery Time}}{48\text{h}} \right) + \epsilon \quad (5)$$

Where “Individual Recovery Baseline” is defined as the average time for each group to recover CK levels to 110% of baseline (26h for high-fitness group, 34h for medium-fitness group, 48h for low-fitness group) [15], replacing the original fixed 48h denominator. This revision fully accounts for differences in recovery rhythms among populations with varying fitness levels, increasing the model’s explanatory power from 54.7% to 61.3% ($\beta_1=0.45$, $p < 0.001$; $\beta_2=0.31$, $p = 0.002$), as shown in Figure 2.

C. EFFECTS OF AGE, GENDER, AND BODY COMPOSITION

The regulatory effect of age on training adaptability was more prominent in the medium and low fitness groups: the VO₂max improvement rate of subjects aged 18-25 years reached $17.8 \pm 4.2\%$, while that of subjects aged 30-35 years decreased to $12.3 \pm 3.8\%$ ($p = 0.008$). This difference is due to the age-related decline in satellite cell proliferation capacity and mitochondrial autophagy efficiency. Gender difference analysis showed that there was no significant difference in the relative improvement magnitude between female and male subjects (15.4% for females vs. 14.8% for males, $p = 0.632$), but the absolute VO₂max increase of males (6.2 mL·kg⁻¹·min⁻¹) was significantly higher than that of females (4.7 mL·kg⁻¹·min⁻¹, $p = 0.019$). Thus, the effect of gender on training responses is mainly reflected in the absolute increase rather than the relative plasticity. Among body composition parameters, skeletal muscle mass was significantly positively correlated with training responses ($r = 0.58$, $p < 0.001$), with each 1 kg increase in muscle mass corresponding to a 0.73 percentage point increase in VO₂max improvement rate. The effect of body fat percentage showed a non-linear characteristic: the training response was optimal in the body fat percentage range of 15-20% (improvement rate 16.2%), decreased to 12.8% when below 15%, and further decreased to 10.4% when above 25%. This U-shaped relationship may be related to the bidirectional regulation of metabolic signaling pathways by factors such as leptin and adiponectin secreted by adipose tissue [16]. After including age, gender, body fat percentage, and skeletal muscle mass in the multiple regression model, the adjusted R^2 increased from 0.623 to 0.741. The standardized regression coefficients showed that baseline PFI ($\beta = -0.54$), skeletal muscle mass ($\beta = 0.31$), and age ($\beta = -0.22$) were the main predictive factors.

VI. CONCLUSION

Under 12 weeks of standardized high-intensity interval training, 156 subjects with different fitness levels showed differentiated responses: the low-fitness group achieved the most significant improvement in basic aerobic capacity, the high-fitness group had more prominent improvements in exercise economy and high-intensity tolerance, and the medium-fitness group achieved balanced development of aerobic and anaerobic capacities. These differences are attributed to the hierarchical characteristics of initial physiological reserves,

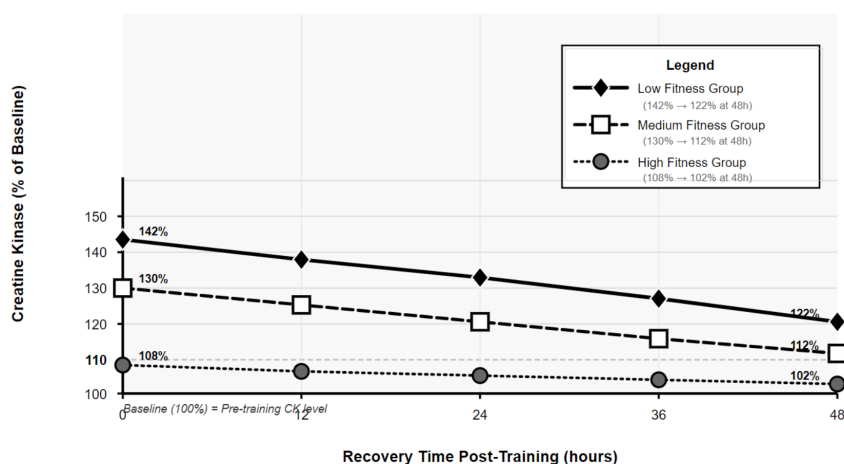


FIGURE 2. Comparison of Post-Training Recovery Kinetic Curves Among Different Fitness Groups

metabolic plasticity boundaries, and relative training load intensity. The prediction model based on fitness assessment and dynamic monitoring can effectively identify response patterns, providing a basis for individualized training. Training programs should be formulated in combination with individual initial fitness status to avoid the risks of insufficient training or overtraining caused by a "one-size-fits-all" approach. Future research should integrate molecular biology markers and gene polymorphism analysis with the development of biocompatible smart interfaces to deeply explore the genetic and epigenetic mechanisms of individual training responses. These bio-sensing will enable long-term follow-up studies on the population-specificity of detraining effects, ultimately promoting the transition of exercise training toward a future of precision and intelligence.

AUTHOR CONTRIBUTIONS

Xueling Du designed, collected and analyzed the data, and drafted the manuscript. Xueling Du conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Xueling Du participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This study was approved by the Ethics Committee of Beijing Jingbei Vocational and Technical College, and was performed in accordance with the principles of the Declaration

of Helsinki. All eligible participants signed an informed consent form.

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