Proceeding of ICSPHS 2026 Symposium: Critical Perspectives on Global Education and Psychological Development
DOI: 10.54254/2753-7048/2026.HT30788

The Impact and Mechanism of High-Intensity Intermittent Cross-Training on Maximal Oxygen Uptake

Hangqi Hu

Beijing Sport University, Beijing, China
89803472@qq.com

Abstract. Based on the current problems of insufficient cardiopulmonary endurance and limited improvement of VO_2max in adolescent students, as well as the intervention status that traditional Moderate-intensity Continuous Training (MICT) is time-consuming and High-Intensity Interval Training (HIIT) is prone to adaptation bottlenecks, this study reviews the conceptual characteristics, functional classification of High-Intensity Intermittent Cross-Training (HIICT), as well as the research progress and application prospects of its impact on maximal oxygen uptake (VO_2max). Studies have shown that the emerging HIICT integrates multi-modal exercise forms. On the basis of retaining the "short-time and high-efficiency" advantage of HIIT, it significantly optimizes the training effect and improves interestingness through cross-stimulation of different muscle groups and energy metabolism systems by multi-modal movements. As the gold standard for measuring exercise intensity, VO_2max can be measured by direct and indirect methods. HIICT avoids adaptive fatigue of single exercise through movement diversity and enhances neuromuscular coordination. Its training program design emphasizes dynamic regulation of variables (such as high-intensity duration, recovery time, and movement combination) under the framework of overall load. A large number of studies have shown that HIICT can effectively improve VO_2max, and its core mechanism lies in the synergistic effect of central and peripheral adaptive changes. With the characteristics of multi-modal crossover, time efficiency, and comprehensive stimulation, HIICT has become a new strategy to efficiently improve VO_2max and cardiopulmonary function, providing new reference significance for the formulation of precision exercise prescriptions for improving maximal oxygen uptake.

Keywords: High-Intensity Intermittent Cross-Training, Maximal Oxygen Uptake, High-Intensity Intermittent Training, Bicycling, Running

1. Introduction

In recent years, the physical health problems of Chinese students have shown a significant "duality": on the one hand, the results of the 8th National Survey on Students' Physical Fitness and Health show that the morphological development indicators have continued to improve, and the lung capacity level has increased comprehensively; on the other hand, the rate of overweight and obesity continuing to rise, and core quality indicators such as cardiopulmonary endurance and grip strength failing to meet expectations. This contradictory phenomenon suggests that the intervention of

DOI: 10.54254/2753-7048/2026.HT30788

students' physical health in China urgently needs to advance in depth from "optimization of morphological development" to "improvement of functional quality". As the core element of physical health [1], cardiorespiratory fitness (CRF) has become a key breakthrough to solve this problem.

Maximal oxygen uptake (VO_2max), as the core indicator of cardiorespiratory fitness, is a recognized important physiological parameter for evaluating an individual's aerobic metabolic capacity and cardiopulmonary function [2]. The American Heart Association (AHA) listed it as the "fifth vital sign" after body temperature, pulse, respiration, and blood pressure in 2016, and Chinese scholars also pointed out that the improvement of VO_2max is closely related to students' endurance quality, disease prevention, and long-term health. However, the current prevalence of sedentary behavior and insufficient high-intensity exercise among students has led to severe challenges in improving their cardiorespiratory fitness. Surveys show that the participation rate of college students in physical exercise has significantly decreased due to academic pressure, weak exercise awareness, and lack of campus sports culture, directly restricting the sound development of VO_2max. In this context, exploring efficient and sustainable exercise intervention models has become a research focus.

Although traditional MICT can effectively improve VO_2max, its time-consuming and low-interest characteristics make it difficult to meet the fragmented time needs of students. In contrast, HIIT has attracted much attention due to its unique advantage of "short-time and high-efficiency" [3]. Studies have shown that it can significantly improve VO_2max in a shorter time by activating mitochondrial biogenesis and optimizing oxygen utilization efficiency. However, (for people without exercise experience, with cardiovascular and cerebrovascular diseases and other chronic diseases, this exercise mode has certain potential safety hazards) [4]. As an emerging exercise program, HIICT can integrate multi-modal exercise forms (such as alternating cycling, running and jumping, and strength training), avoid the adaptation bottleneck of single exercise, enhance neuromuscular coordination through composite stimulation, and have a positive effect on improving VO_2max, thereby improving cardiopulmonary function more comprehensively [1].Based on this, this study systematically sorts out the conceptual characteristics, functional classification of HIICT, as well as the application orientation and possible mechanisms of its impact on maximal oxygen uptake from multiple perspectives, aiming to provide reference for children and adolescents in selecting exercise programs to improve maximal oxygen uptake and cardiopulmonary function.

2. HIICT

HIICT is a comprehensive exercise mode innovatively upgraded based on the framework of High-Intensity Training (HIT). It combines high-intensity explosive movements, circuit training, and intermittent aerobic training, and has received extensive attention in the field of exercise science in recent years.

HIIT originated from track and field training a century ago and became popular in Europe after World War II. In 1952, Czech long-distance runner Emil Zatopek won three gold medals at the Helsinki Olympics relying on HIIT [5], and then it was gradually promoted to various sports; in the 1960s, it set off an upsurge due to its significant improvement in sports performance, prompting academic circles to conduct systematic research. Swedish physiologist Astrand proposed that long intervals are an effective means to improve VO_2max [6], Christensen advocated that extremely short intervals can reduce blood lactate accumulation [7], and Fox emphasized restoring phosphagen reserves during rest periods; in the 1970s and 1980s, no significant difference was found between HIIT and continuous training at lactate threshold intensity [8], some coaches turned to low-intensity

DOI: 10.54254/2753-7048/2026.HT30788

training, while a few elite athletes still insisted on HIIT; since 1990, studies have shown that HIIT can improve VO_2max, oxidase activity, fat oxidation rate, glucose oxidation efficiency, and muscle lactate buffering capacity. With the advancement of the "National Fitness" policy, HIIT has been further subdivided and widely welcomed by the public, which not only improves competitive performance but also plays a significant role in public fitness [9-12]. In 2024, Xin Liu et al. proposed a new exercise mode - HIICT based on HIIT, and found that it can effectively increase maximal oxygen uptake and improve cardiopulmonary function. HIICT is an innovative training mode formed through scientific evolution and optimization based on the century-old development context of HIT. It can effectively improve VO_2max and cardiopulmonary function through multi-modal movement combination, representing one of the latest directions in high-intensity training research.

3. Content and characteristics of HIICT

Current studies on HIICT are mainly conducted in laboratory settings, mainly alternating two different training methods: treadmill training (used in groups 1, 3, 5, 7) and cycle ergometer training (used in groups 2, 4, 6). There is a 10-second rest period between each two groups, and subjects are required to reach exhaustion during the 6th or 7th group. Based on Li Yongming et al.'s classification of HIT exercise intensity [2], the exercise intensity of HIICT requires subjects to reach 90%-160% of VO_2max in the treadmill training group and 90%-170% of VO_2max in the cycle ergometer training group during the 6th or 7th group of exercises [1].

By reading a large number of literatures, it is summarized that HIICT mainly has the following characteristics: (1) Multi-modal movement crossover: HIICT can be trained by combining movements of different planes (sagittal plane, coronal plane, horizontal plane) and different energy metabolism methods (phosphagen, glycolysis, aerobic oxidation). (2) Metabolic synergistic stimulation: A single training session simultaneously activates the phosphagen system (10-30s explosive training) and the glycolytic system (1-3min continuous output), inducing a greater degree of EPOC (excess post-exercise oxygen consumption). Studies have shown that the resting metabolic rate of HIICT subjects increases by 14% within 24 hours [13]. (3) Time efficiency and extensibility: Since HIT and HIIT are time-saving and efficient, this new exercise mode also has similar characteristics. A set of training programs takes about 25-30 minutes [14]. (4) Application scenarios: 1. Healthy population: Considering that HIICT is derived from HIT and HIIT, it can not only effectively improve the sports performance of healthy people but also increase interestingness through cross-training mode. 2. Athlete population: Studies have found that HIIT can effectively improve athletes' ability and performance. Based on this, HIICT can also provide comprehensive and multi-angle training movements on this basis, thereby enhancing athletes' coordination ability. 3. Patients with cardiovascular diseases: Modified HIIT (peak value at 40%-60%) can improve cardiopulmonary function and vascular endothelial function. It is speculated that under strict medical supervision, HIICT may also have similar improvement effects.

4. Design of HIICT training programs

High-Intensity Intermittent Cross-Training (HIICT) should not be viewed in isolation but should be considered within the framework of overall training load and training intensity distribution. Studies have shown that as long as HIIT is properly implemented, it can improve maximal oxygen uptake (VO_2max) and endurance performance to a certain extent. Based on HIIT, HIICT realizes the

DOI: 10.54254/2753-7048/2026.HT30788

dynamic balance of total training volume through scientific integration of training load, thereby further optimizing HIIT.

The essence of designing HIICT training programs is the dynamic regulation of variables, mainly including work bout duration, set recovery duration, set total training time, set cross-training movements, and other variables. Traditional long-term continuous training (usually 4-6 sets × 3-8 minutes) mostly adopts a constant speed load mode. This mode may be inconsistent with the principle of specific training, because there are significant intensity fluctuations in most endurance events. Studies have shown that compared with constant speed intervals, the interval mode with variable load can effectively prolong the duration of high VO_2max. For example, two studies on elite male cross-country skiers with an average VO_2max of 70 $mL \cdot min^{-1} \cdot kg^{-1}$ adopted a differentiated strategy in roller skiing interval training: each set of intervals (5-6×5 minutes) started quickly at 1.5-2 minutes of MAS intensity, and then reduced the intensity to the end of the interval (decremental intensity interval, DEC). The results showed that compared with isochronous and constant speed intervals, the DEC program significantly improved the average VO_2max, and the Rating of Perceived Exertion (RPE) was even lower [15]. This suggests that the quick start duration is a key factor to prolong the duration of ≥90% VO_2max. However, current studies on HIICT are limited to athletes or laboratory settings, and there are relatively few studies on non-athlete populations and non-laboratory scenarios. Based on current research on HIT and HIIT in the academic community, we speculate that future research designs on HIICT programs need to further adjust the training duration, interval time, exercise frequency, movement mode and other elements according to the needs of different populations and individuals.

5. Concept and evaluation methods of maximal oxygen uptake

5.1. Concept of maximal oxygen uptake

Maximal oxygen uptake (VO_2max), also known as maximal oxygen consumption, mainly refers to the maximum amount of oxygen that the body can take in and utilize. That is, when the body's exercise load gradually increases, the demand for oxygen in the air also gradually increases, but once it reaches a certain stage, even if the exercise intensity is further increased or more gas is continuously inhaled, the body's oxygen consumption level cannot be improved. This critical point is "maximal oxygen uptake". This indicator is regarded as the "gold standard" for evaluating an individual's cardiopulmonary endurance [16]. In 2016, the American Heart Association (AHA) listed it as the "fifth vital sign", so this indicator is widely used in national fitness, physical training, clinical rehabilitation and other fields to more accurately evaluate an individual's cardiopulmonary function.

5.2. Technical means and evaluation methods of maximal oxygen uptake

5.2.1. Technical means for detecting maximal oxygen uptake

(1) Douglas Bag Technique

The Douglas bag technique is one of the commonly used technical means to detect maximal oxygen uptake. This technique mainly tests the oxygen uptake of subjects during running through the Douglas bag technique. Subjects collect exhaled gas into Douglas bags and replace a bag at regular intervals. After collection, the composition ratio of gas is analyzed by chemical analysis methods [17]. With the development of exercise science and technology, Naimark et al. proposed

DOI: 10.54254/2753-7048/2026.HT30788

continuous measurement of ventilation exchange rate during exercise in 1964, namely breath-by-breath (BBB) technology. At that time, there was no reliable fast-response O_2 analyzer, so the oxygen exchange rate could only be calculated by measuring the end-tidal CO_2 and N_2 concentrations with a fast-response gas analyzer. However, the BBB technology can measure the gas change within each breath, so BBB has gradually become the mainstream technology for VO_2max [18].

(2) Differential Pressure Flow Sensors

With the development of science and technology, flow sensors have gradually become an important technical means for measuring maximal oxygen uptake due to their higher measurement accuracy. In terms of flow sensors, from the initial turbine sensors, which measure based on the principle that the number of rotations of a single turbine is proportional to the gas flow volume, but due to the angular momentum of the blades causing errors in ventilation signals, currently, more advanced equipment includes differential pressure flow sensors, such as VO_2 Master Pro analyzer [19]; hot-film anemometers, such as PNOE (PNOE Analytics, Canada); and digital volume sensors Vyntus CPX (Carefusion, Germany). Because the BBB technology has high requirements for the response speed of oxygen sensors, gas analyzers have also evolved from the initial electrochemical oxygen sensors (KORR series) to paramagnetic oxygen sensors (Vista-MX2) and then to infrared CO_2 sensors (Carefusion), with the response speed significantly improved from 200ms to 50ms. In addition to the development of equipment, considering the comfort of subjects, the equipment worn by subjects is also developing. It started at 5 kilograms, but now it can be as low as 1 kilogram. At the same time, considering different exercise scenarios, there are also wireless transmission equipment to support the measurement of VO_2max in outdoor, snow, water and other scenarios [20].

5.2.2. Evaluation methods of maximal oxygen uptake

(1) Direct Measurement Method

The direct measurement method usually requires subjects to perform graded incremental combined exercise on certain exercise equipment in laboratory conditions to determine their oxygen uptake. Since the exercise load is gradually increased, subjects are generally professional athletes or people with good exercise tolerance, and the experiment needs to last long enough to mobilize the functions of the respiratory and cardiovascular systems. The main exercises of the direct measurement method are treadmill test and cycle ergometer test. The test protocols mainly include the Bruce protocol, modified Bruce protocol, Naughton protocol, etc., among which the Bruce protocol is considered the most classic test protocol.

(2) Indirect Measurement Method

Indirect measurement methods mainly include the Astrand-Ryhmin nomogram method, Cooper test, Fick equation method, peak oxygen uptake method, PWC170 method, etc.

1. Astrand-Ryhmin nomogram method: When subjects perform submaximal exercise, the maximal oxygen uptake is estimated or predicted according to their heart rate and the workload to reach a specific heart rate.

2. Cooper test

Maximal oxygen uptake is estimated by calculating the exercise distance of a full-effort 12-minute run.

Formula: $VO_{2\max}f_0 = \frac{d_{12}-505}{45}$

Where d_{12} is the exercise distance of the 12-minute run.

DOI: 10.54254/2753-7048/2026.HT30788

Fick equation method: The maximal oxygen uptake during maximal muscle contraction can be calculated by the Fick equation.

Formula: $VO_2max=Q(CaO_2-CvO_2)$

Where Q: cardiac output, CaO_2: arterial blood oxygen content, CvO_2: venous blood oxygen content.

3. Peak oxygen uptake is another indicator reflecting aerobic work capacity, which is different from maximal oxygen uptake. Its exercise mode, measuring instruments, and test methods are the same as those of the direct measurement experiment of maximal oxygen uptake. The difference is that the exercise time of peak oxygen uptake measurement is determined according to the subject's subjective feeling.

(3) Advantages and Disadvantages Analysis of Direct and Indirect Measurement Methods

The direct measurement method, centered on real-time gas analysis, has always been the "gold standard" for scientific research and clinical diagnosis due to its high accuracy (error $< \pm 2\%$) and ability to capture dynamic physiological responses. The indirect measurement method infers VO_2max by establishing a regression model between parameters such as heart rate and intensity and VO_2max. Its advantages are low cost, simple operation, and high safety, making it very suitable for public health screening and daily monitoring. In the future, the technological development of the two methods is moving towards integration and optimization: the direct measurement method is committed to the miniaturization and portability of equipment (such as wearable gas analyzers), while the indirect measurement method is continuously improving the accuracy and personalization of the inference model through multi-modal sensor fusion and advanced algorithms (such as federated learning), so as to better serve the full spectrum needs of elite sports and public health. See Table 1 for details.

Table 1. Comparison between direct and indirect measurement methods

Comparison Dimension	Direct Measurement Method	Indirect Measurement Method
Core Principle	Calculate oxygen uptake by real-time collecting O_2 and CO_2 concentrations in exhaled gas with a gas analyzer.	Estimate VO_2max by establishing a regression model using non-direct gas data such as heart rate, exercise intensity, and physical parameters.
Advantages	1. High accuracy 2. Can capture transient changes; 3. Suitable for scientific research.	1. Simple operation; 2. Low cost; 3.high safety.
Disadvantages	1. Expensive equipment; 2. Complex operation; 3. Subjects need to perform maximal exercise, with potential risks.	1. Large error; 2. The model is affected by individual differences; 3. Cannot reflect real-time oxygen uptake kinetic characteristics.
Typical Application Scenarios	1. Athlete selection and training monitoring; 2. Clinical diagnosis of cardiopulmonary diseases	1. Public health screening; 2. Initial screening of sports teams; 3. Daily monitoring with wearable devices.
Technical Trends	1. Miniaturized wearable devices; 2. Dynamic algorithm optimization.	1. Multi-modal sensor fusion; 2. Improve the accuracy of the model.

6. The impact and possible mechanisms of HIICT on maximal oxygen uptake

6.1. The impact of HIICT on maximal oxygen uptake

Compared with HIT and HIIT, HIICT further optimizes the intervention effect through multi-modal cross-training (such as combining aerobic, strength and agility movements) on the basis of retaining

DOI: 10.54254/2753-7048/2026.HT30788

their core advantage of "short-time and high-efficiency", increases maximal oxygen uptake, and thereby improves cardiopulmonary endurance. Xin Liu et al. conducted 24 training sessions (4 times a week for 6 weeks) and measurements. All control group participants also received all the measurements performed for the training group. Changes in VO_2max: After training, the running VO_2max of the training group significantly increased from 53.4±5.3mL·kg⁻¹·min⁻¹ before training to 57.4±4.8mL·kg⁻¹·min⁻¹ after training ($p<0.001$), while there was no significant change in the running VO_2max of the control group ($p=1.00$). Similarly, the cycling VO_2max of the training group significantly increased from 45.6±4.7mL·kg⁻¹·min⁻¹ before training to 50.6±3.7mL·kg⁻¹·min⁻¹ after training ($p<0.001$), while there was no significant change in the cycling VO_2max of the control group ($p=1.00$). It can be seen from this study that HIICT can effectively improve maximal oxygen uptake. This study mainly used single-movement cycle exercises such as running and cycling, and it is speculated that its improvement effect may be related to the exercise form. Considering that HIICT is an emerging exercise mode, but there are relatively few studies on this training, future studies can explore the effect and possible mechanisms of HIICT from multiple populations and perspectives based on different groups and different movement modes.

6.2. The mechanism of HIICT on maximal oxygen uptake

The mechanism of HIICT on VO_2max mainly involves central and peripheral factors. According to existing studies, the improvement of VO_2max is related to a variety of physiological mechanisms, mainly including the optimization of the cardiovascular system, the enhancement of muscle metabolic capacity, and the improvement of the energy supply system. Therefore, this paper will elaborate on it from two aspects: central factors - multi-modal exercise synergistically stimulating the cardiopulmonary system and peripheral factors - improving the metabolic efficiency of multiple muscle groups.

6.2.1. Central factors - multi-modal exercise synergistically stimulating the cardiopulmonary system

HIICT promotes the heart to adapt to the blood demand of different movements by alternately performing different exercise modes (such as running and cycling). A study by Xin Liu et al. also found that HIICT can significantly increase left ventricular end-diastolic volume (LVEDV) and stroke volume (SV), thereby improving cardiac output and optimizing the efficiency of systemic oxygen transport [1]. At the central level, both LIT and HIIT can induce plasma volume (PV) expansion, and this adaptive process plays a key role in increasing cardiac output and maximal oxygen uptake. In addition, long-term endurance training may also cause reversible myocardial hypertrophy and increase stroke volume, which will further enhance the adaptability of the cardiovascular system [21]. Stroke volume (SV) is an important indicator of cardiac function and the main reason for the increase in VO_2max. This study further used an ultrasound system with a 2.5 MHz probe (Vivid S6, GE Healthcare Japan, Tokyo) to test the left ventricular end-systolic and end-diastolic diameters (LVESD and LVEDD respectively), left ventricular posterior wall thickness (LVPWT) and interventricular septal thickness (IVST) of subjects after exercise. Results of changes in cardiac structure: The left ventricular end-diastolic volume (LVEDV) of the training group significantly increased from 116±15mL before training to 125±16mL after training ($p<0.05$), while there was no significant change in LVEDV of the control group ($p=0.38$). The stroke volume (SV) of the training group significantly increased from 41±8mL before training to 76±13mL after training ($p<0.001$), while there was no significant change in SV of the control group ($p=0.46$). Changes in

DOI: 10.54254/2753-7048/2026.HT30788

maximal cardiac output may be a key factor for HIICT to improve maximal oxygen uptake. A dose-response meta-analysis of heart failure patients by Suso Martí et al. showed that HIIT can significantly improve VO_2max, and the optimal dose corresponds to the most obvious increase in cardiac output [22]. A study by Zhang Hua et al. showed that after 4 weeks of high-intensity interval training (HIIT) with 10 sets of 30-second all-out sprints three times a week, the maximal cardiac output ($\dot{Q}max$) of healthy adult males significantly increased by about 16%, and this increase was mainly derived from an approximately 10% increase in stroke volume (SV), and maximal oxygen uptake (VO_2max) also increased by about 12% synchronously, while there was no significant change in maximal heart rate. This indicates that HIIT improves cardiac pumping capacity by enhancing ventricular diastolic stretching and blood volume, and is an effective training method to improve cardiovascular function and endurance level [23]. In a study by Xin Li et al. on the impact of HIICT on maximal oxygen uptake, it was found that SV at rest increased after HIICT. This training-induced change in SV at rest was similar to the research results of Helgerud et al. The study by Xin Li et al. also observed a significant positive correlation between the percentage change in SV at rest and the percentage change in running VO_2max of participants ($r=0.79$, $p < 0.05$). It can be seen that this training program can not only effectively improve the efficiency of the aerobic capacity release system but also increase stroke volume, which may lead to an increase in stroke volume during maximal exercise [1].

6.2.2. Peripheral factors - improvement of metabolic efficiency of multiple muscle groups

Studies have pointed out that HIICT can significantly prolong the improvement cycle of VO_2max by alternately stimulating different muscle groups and energy metabolism systems (such as alternating phosphagen and glycolytic energy supply) [24]. Compared with traditional HIIT, its multi-modal design can not only avoid adaptive fatigue of single exercise (such as the plateau effect of treadmill training) but also enhance neuromuscular coordination through movement diversity [1]. In addition, the dynamic combination characteristics of HIICT (such as alternating bodyweight training and equipment) reduce venue restrictions and improve exercise interestingness, which is more in line with the psychological needs and fragmented time characteristics of adolescent groups, providing a more universal solution for the reform of campus physical education [24,25]. At the peripheral level, compared with low-intensity training (LIT), HIIT can act more deeply on type II muscle fiber groups, thereby promoting adaptive changes in mitochondrial and capillary density. Studies have shown that HIIT (High-Intensity Interval Training) can trigger a series of molecular signals in the pathway of systemic oxygen transport and utilization, thereby rapidly activating the synthesis of specific proteins. These synthesized proteins have multiple positive effects: first, enhancing the buffering capacity of cells; second, increasing the density of mitochondrial enzymes and promoting the expansion of mitochondrial reticular structure; third, promoting the neovascularization of capillaries, thereby improving the oxygen supply capacity of muscles. Studies have confirmed that alternating high-intensity exercise activates the AMPK-PGC-1α pathway, induces skeletal muscle mitochondrial proliferation, and at the same time, different exercise modes stimulate different muscle fibers (such as fast-twitch fibers in sprints and slow-twitch fibers in endurance movements), enhancing overall oxidase activity [26,27]. Moreover, studies have also found that in cross-training, the high-intensity phase relies on glycolytic energy supply, and the low-intensity exercise during the interval (such as alternating cycling and running) continuously activates aerobic metabolism, promoting rapid lactate clearance and increasing muscle tolerance threshold [28,29]. The adaptive analysis from the molecular and genetic levels mainly includes two aspects: (1) Activation of HIF-1α and oxygen-sensitive pathways: High-intensity cross-stimulation induces local hypoxia, activates

DOI: 10.54254/2753-7048/2026.HT30788

hypoxia-inducible factor (HIF-1α), up-regulates the expression of genes such as erythropoietin (EPO), and promotes erythropoiesis and oxygen-carrying capacity [30]. (2) Muscle fiber type transformation: Alternating load stimulation promotes the transformation of type II muscle fibers (glycolytic type) to type IIa (oxidative-glycolytic mixed type), improving muscle oxidative capacity [31].

7. Conclusion

This study systematically sorts out the conceptual characteristics, functional classification of High-Intensity Intermittent Cross-Training (HIICT), as well as the application value and potential mechanism of its impact on maximal oxygen uptake (VO_2max). HIICT is a comprehensive exercise mode developed on the basis of High-Intensity Interval Training (HIIT). Compared with traditional HIIT, HIICT effectively avoids the adaptation bottleneck of single exercise through movement diversity, and improves the interestingness and neuromuscular coordination of training.

Studies have shown that HIICT has significant advantages in improving VO_2max, and its effect is even better than that of single-mode HIIT. The key mechanism lies in its ability to promote the improvement of VO_2max through the synergistic effect of central and peripheral adaptive changes: 1. Central adaptation dominates: HIICT significantly increases stroke volume (SV) at rest and during exercise, optimizes left ventricular volume and function (such as increasing left ventricular end-diastolic volume LVEDV), thereby enhancing cardiac pumping function and cardiac output, which is the key central mechanism for improving VO_2max. 2. Peripheral adaptation synergy: HIICT effectively promotes mitochondrial biogenesis and functional optimization (activating the AMPK-PGC-1α pathway), improves muscle microcirculation (increasing capillary density), enhances lactate clearance capacity and substrate utilization efficiency, and may promote the transformation of type II muscle fibers to type IIa with stronger oxidative capacity by alternately stimulating different muscle groups and energy metabolism systems. 3. Neuroendocrine and metabolic integration: Multi-modal alternating stimulation can trigger a more optimized hormonal response (such as adrenaline and growth hormone) and cross-adaptation of energy metabolism pathways, dynamically regulate vascular function, reduce peripheral resistance, and may promote metabolic adaptation by inducing a more significant EPOC (excess post-exercise oxygen consumption).

In the design of training programs, HIICT emphasizes the dynamic regulation of variables (such as high-intensity training duration, recovery time, total training time, cross-training movements) under the framework of overall training load. Its flexibility allows personalized design according to individual needs (such as athletes' specific characteristics and healthy people's goals), such as adopting a differentiated intensity strategy (such as decremental intensity intervals) to prolong the duration of $\geq 90\%$ VO_2max.

In summary, as an emerging efficient exercise intervention mode, HIICT has unique advantages in improving VO_2max and cardiopulmonary function with its characteristics of multi-modal crossover, time efficiency, and comprehensive stimulation. Its core mechanism lies in comprehensively improving the body's oxygen transport and utilization efficiency through the synergistic adaptation of optimizing cardiac pumping function (central) and muscle metabolic capacity (peripheral). This study provides a systematic framework for in-depth understanding of the theoretical basis and practical application of HIICT. Future research should further refine the precision training programs of HIICT (such as the optimal movement combination, intensity ratio, and cycle arrangement for different populations), deeply explore its long-term benefits and safety (especially in special populations), and strengthen the comparative study of its effects with

DOI: 10.54254/2753-7048/2026.HT30788

traditional training modes in different application scenarios, so as to promote the scientific application of HIICT in improving national cardiopulmonary health and optimizing competitive sports training.

References

[1] Xin Liu; Katsunori Tsuji; Yuzhong Xu; Motoyuki Iemitsu; Izumi Tabata. Effects of high-intensity intermittent cross-training on maximal oxygen uptake [J]. Sports Medicine and Health Science, 2024, Vol.7(3): 185-189.

[2] Li Yongming. The Application Effect of High-Intensity Interval Training on Different Training Populations [J]. China Sport Science, 2015, 35(08): 59-75+96.

[3] Han Qi, Liu Jiayi, An Nan, et al. A Meta-Analysis of the Effects of High-Intensity Interval Exercise versus Moderate-Intensity Continuous Exercise on Blood Glucose Control and Cardiovascular Risk Factors in Patients with Type 2 Diabetes [J]. Chinese Journal of Sports Medicine, 2021, 40(10): 822-830.

[4] Wang Juan, Zhang Xianbo, Wang Zhengzhen. The Effect of Regular Exercise on Cardiopulmonary Endurance in Diabetic Patients - A Meta-Analysis [J]. Journal of Beijing Sport University, 2013, 36(03): 50-56.

[5] Belcastro A N, Bonen A. Lactic acid removal rates during controlled and uncontrolled recovery exercise [J]. Journal of Applied Physiology, 1975, 39(6): 932-936.

[6] Irma Åstrand, Per Åstrand, Christensen E, et al. Intermittent Muscular Work [J]. Acta Physiologica, 2010, 48(3-4): 448-453.

[7] Christensen E, Hedman R, Saltin B. Intermittent and continuous running. (A further contribution to the physiology of intermittent work.) [J]. Acta Physiologica, 2010, 50(3-4): 269-286.

[8] Seiler S, Hetlelid K J. The Impact of Rest Duration on Work Intensity and RPE during Interval Training [J]. Medicine & Science in Sports & Exercise, 2005, 37(9): 1601-1607.

[9] Bweir S, Al-Jarrah M, Almalty A M, et al. Resistance exercise training lowers HbA1c more than aerobic training in adults with type 2 diabetes [J]. Diabetology and Metabolic Syndrome, 2009, 1(1): 27.

[10] Lee A S, Johnson N A, Mcgill M J, et al. Effect of High-Intensity Interval Training on Glycemic Control in Adults With Type 1 Diabetes and Overweight or Obesity: A Randomized Controlled Trial With Partial Crossover [J]. Diabetes Care, 2020(9).

[11] Taylor J L, Holland D J, Keating S E, et al. Short-term and Long-term Feasibility, Safety, and Efficacy of High-Intensity Interval Training in Cardiac Rehabilitation: The FITR Heart Study Randomized Clinical Trial [J]. 2020.

[12] Boyne P, Billinger S A, Reisman D S, et al. Optimal intensity and duration of walking rehabilitation in patients with chronic stroke: a randomized clinical trial [J]. JAMA Neurology, 2023, 80(4): 342-351.

[13] Xu Yuzhong; Machimura Katsunori; Iemitsu Motoyuki; Kurihara Toshiyuki; Tabata Izumi. The Effect of Twice-Weekly High-Intensity Intermittent Cross-Training (HIICT) on Maximal Oxygen Uptake (04 Exercise Physiology, General Research Presentation Abstract) [J]. Japan Society of Physical Education, Health and Sport Sciences Conference Proceedings, 2013, Vol.64: 164-165.

[14] Hartmann, Jacob P, et al. Effect of 12 weeks of interval training on skeletal muscle blood flow during single-leg knee extensor exercise in COPD: a non-randomized controlled trial.

[15] Rønnestad BR, Hansen J, Thyli V, Bakken TA, Sandbakk Ø. 5-week block periodization increases aerobic power in elite cross-country skiers [J]. Scandinavian Journal of Medicine & Science in Sports, 2016 Feb; 26(2): 140-6. doi: 10.1111/sms.12418. Epub 2015 Feb 3.

[16] Hill A V, Long C N H. Muscular Exercise, Lactic Acid, and the Supply and Utilization of Oxygen [J]. Ergebnisse Der Physiologie, 1925, 24(1): 43-51.

[17] Krogh A, Lindhard J. The regulation of respiration and circulation during the initial stages of muscular work [J]. Journal of Physiology, 1913, 47(1-2): 112-136.

[18] A NAIMARK; K WASSERMAN; M B MCILROY. Continuous measurement of ventilatory exchange ratio during exercise [J]. Journal of Applied Physiology, 1964, Vol.19: 644-652.

[19] Langer MB, Allaman I, Magistretti PJ. Brain energy metabolism: focus on astrocyte neuron metabolic cooperation [J]. Cell Metabolism, 2011; 14(16): 724–73876.

[20] Rao Zhijian, Shang Wenyuan, Li Xiangchen, et al. Research Status and Prospect of Maximal Oxygen Uptake Measurement Equipment [J]. Chinese Journal of Sports Medicine, 2024, 43(01): 47-55.

[21] Kerry Stephen Seiler. It's about the long game, not epic workouts: Unpacking HIIT for endurance athletes [J]. Applied Physiology, Nutrition, and Metabolism = Physiologie Appliquée, Nutrition et Métabolisme, 2024, Vol.49(11): 1585-1599.

DOI: 10.54254/2753-7048/2026.HT30788

[22] Suso Martí et al. Dose-response meta-analysis of HIIT on VO_2max in heart failure patients [J]. Cardiovascular Rehabilitation Journal, 2025, 12(3): 4558.
[23] Zhang Hua, Li Ming, Wang Lei. Study on the Impact of High-Intensity Interval Training on Maximal Cardiac Output in Healthy Adult Males [J]. China Sport Science, 2023, 5: 112120.
[24] Xu Nian. A Study on the Impact of High-Intensity Interval Training on the Physical Health of High School Students [D]. Harbin Sport University, 2024.
[25] Guo Hongfei. Energy Metabolism and Fatigue Recovery Characteristics of Different High-Intensity Interval Training [D]. Wuhan Sports University, 2024.
[26] Hu Jingyun, Cai Ming, Shang Qinghui, et al. Research Progress on the Improvement of Cognitive Function by High-Intensity Interval Training and Its Mechanism [J]. Acta Physiologica Sinica, 2021, 73(01): 126-136.
[27] Liu Ruidong, Cao Chunmei, Liu Jianxiu, et al. The Application and Adaptive Mechanism of High-Intensity Interval Training [J]. China Sport Science, 2017, 37(07): 73-82.
[28] Holloway R, Zhou Z, Harvey HB, Levasseur JE, Rice AC, Sun D, Hamm RJ, Bullock MR. Effect of lactate therapy upon cognitive deficits after traumatic brain injury in the rat [J]. Acta Neurochirurgica (Wien), 2007; 149(9): 919–927.
[29] Yang J, Ruchti E, Petit JM, Jourdain P, Magistretti PJ. Lactate promotes plasticity gene expression by potentiating NMDA signaling in neurons [J]. Proceedings of the National Academy of Sciences of the United States of America, 2014; 111(33): 12228–12233.
[30] Finsterwald C, Magistretti PJ, Lengacher S. Astrocytes: new targets for the treatment of neurodegenerative diseases [J]. Current Pharmaceutical Design, 2015; 21(25): 3570–3581.
[31] Magistretti PJ, Allaman I. Lactate in the brain: from metabolic end-product to signalling molecule [J]. Nature Reviews Neuroscience, 2018; 19(4): 235–249.