Effects of different physical training models on physical preparation in school physical education

Efectos de diferentes modelos de entrenamiento físico en la preparación física en la educación física escolar

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Abstract

Introduction: Physical preparation is fundamental to school PE, yet heterogeneity exists in the effectiveness of various training models for adolescent fitness, with few empirical comparisons in real educational settings.
Objective: This study compared the effects of HIIT, resistance, combined aerobic-resistance, and circuit training on multidimensional physical preparation in secondary school students.
Methodology: A 12-week quasi-experimental parallel study included 156 adolescents aged 13–16, cluster-randomized into four intervention groups and one control group (n=39 each). Physical preparation was assessed via cardiorespiratory fitness, strength, endurance, speed-agility and flexibility. Data were analyzed using mixed-design ANOVA, Bonferroni post-hoc tests and effect size calculation.
Results: Significant Time × Group interactions were observed across all variables ($p < 0.001$, η^2p = 0.18–0.34). High-intensity interval training produced the largest improvements in cardiorespiratory fitness ($\Delta VO_2max = +4.2$ ml·kg^{-1}·min^{-1}, d = 1.15). Resistance training maximized strength and power development (d = 0.91–0.98). Circuit-based training demonstrated superior muscular endurance (d = 0.96–1.02) and speed-agility improvements (d = 0.87). Combined training generated the most balanced adaptations across domains (mean d = 0.82, SD = 0.09). Post-pubertal participants showed significantly greater strength gains across all models ($p < 0.05$).
Discussion: The findings confirmed distinct domain-specific physiological adaptations across training models, consistent with training specificity literature. Results highlighted the importance of tailored training strategies for targeted physical outcomes in education.
Conclusion: Different training models yield specific performance benefits; therefore, schools should implement structured, periodized, and outcome-oriented training programs, with combined and circuit-based approaches offering the most comprehensive physical development.

Keywords

Adolescents; combined training; physical education; physical fitness; training models.

Resumen

Introducción: La preparación física es fundamental para la educación física escolar; sin embargo, existe heterogeneidad en la efectividad de los diferentes modelos de entrenamiento para la aptitud física de los adolescentes, con pocas comparaciones empíricas en entornos educativos reales.
Objetivo: Este estudio comparó los efectos del entrenamiento interválico de alta intensidad (HIIT), el entrenamiento de resistencia, el entrenamiento combinado aeróbico-resistente y el entrenamiento en circuito sobre la preparación física multidimensional en estudiantes de secundaria.
Metodología: Un estudio cuasiexperimental paralelo de 12 semanas incluyó a 156 adolescentes de 13 a 16 años, asignados aleatoriamente a cuatro grupos de intervención y un grupo control (n=39 cada uno). La preparación física se evaluó mediante aptitud cardiorrespiratoria, fuerza, resistencia, velocidad-agilidad y flexibilidad. Los datos se analizaron mediante ANOVA de diseño mixto, pruebas post-hoc de Bonferroni y cálculo del tamaño del efecto.
Resultados: Se observaron interacciones significativas entre el tiempo y el grupo en todas las variables ($p < 0{,}001$, η^2p = 0,18–0,34). El entrenamiento interválico de alta intensidad produjo las mayores mejoras en la aptitud cardiorrespiratoria (ΔVO_2máx = +4,2 ml·kg^{-1}·min^{-1}, d = 1,15). El entrenamiento de resistencia maximizó el desarrollo de la fuerza y la potencia (d = 0,91–0,98). El entrenamiento en circuito demostró una resistencia muscular superior (d = 0,96–1,02) y mejoras en la velocidad y la agilidad (d = 0,87). El entrenamiento combinado generó las adaptaciones más equilibradas en todos los dominios (media d = 0,82, DE = 0,09). Los participantes pospúberes mostraron ganancias de fuerza significativamente mayores en todos los modelos ($p < 0{,}05$).
Discusión: Los hallazgos confirmaron adaptaciones fisiológicas específicas de cada dominio en los diferentes modelos de entrenamiento, en consonancia con la literatura sobre especificidad del entrenamiento. Los resultados resaltaron la importancia de las estrategias de entrenamiento personalizadas para lograr resultados físicos específicos en la educación.
Conclusión: Los diferentes modelos de entrenamiento producen beneficios específicos en el rendimiento. Por lo tanto, las escuelas deberían implementar programas de entrenamiento físico estructurados, periodizados y orientados a resultados, y los enfoques combinados y basados en circuitos ofrecer el desarrollo físico más completo.

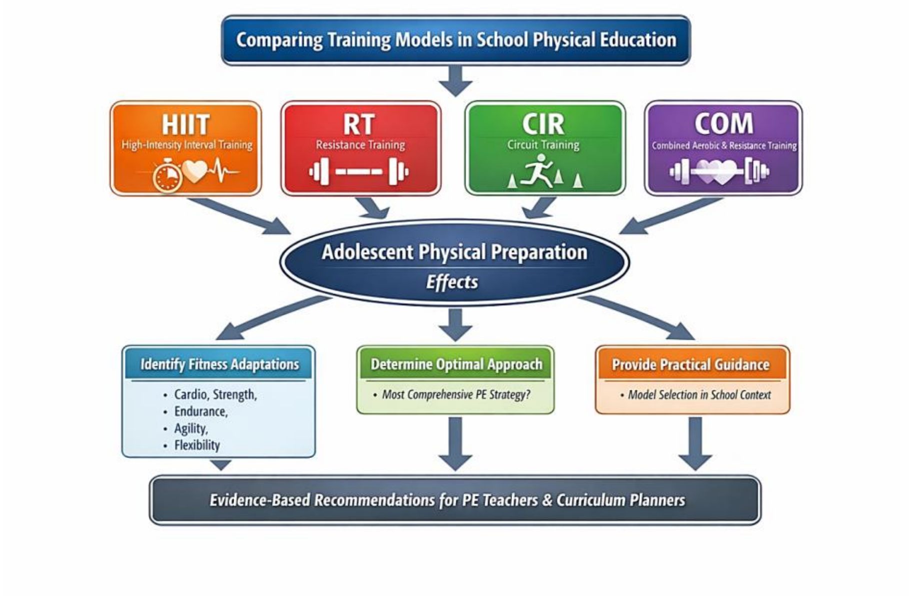
Palabras clave

Adolescentes; entrenamiento combinado; educación física; aptitud física; modelos de entrenamiento.

Introduction

Physical preparation represents a fundamental objective of school physical education (PE) programmes, as it supports the development of health-related fitness, motor competence, and sustained engagement in physical activity during adolescence (Bossmann et al., 2022; Meng et al., 2022; Bento, 2023). This developmental stage is characterized by increased physiological responsiveness, including improvements in aerobic capacity, muscular strength, neuromuscular coordination (Bauer et al., 2022; Duncombe et al., 2022), and metabolic regulation, making it particularly sensitive to structured training interventions. Consequently, the design and implementation of effective training models within school PE have become a major focus in both exercise science and educational research (Martins et al., 2023).

Figure 1. Conceptual Framework for Comparing Physical Training Models in School Physical Education



As shown in Figure 1, the conceptual framework of the research demonstrates how four structured physical-training models, which are High-Intensity Interval Training (HIIT), Resistance Training (RT), Circuit Training (CIR), and Combined Aerobic-Resistance Training (COM), are implemented in a systematic manner in the school-based physical-education programs to affect the level of physical preparation in adolescents and to provide evidence-based recommendations to school-based curriculum design.

The accumulating evidence shows that school-based physical training programmes are much more effective in increasing cardiorespiratory fitness, muscular strength, and metabolic health in comparison with unstructured or recreational exercise (Bauer et al., 2022; Duncombe et al., 2022). Nevertheless, modern PE methods often focus on recreational games and sport-related activities oriented to better interaction and skill acquisition instead of the systematic system development of the physiological system (Zhang et al., 2024). Empirical data show that not all adolescents reach the recommended moderate-vigorous levels of physical activity in PE sessions, restricting the possible health results of school-based programmes (Chu et al., 2022; Gouveia et al., 2022). This shows that there has been a continuous disjuncture between curriculum plans and physical fitness reality (Liu et al., 2022). In addition to the physiological advantages, more recent studies also provide evidence as to the more general educational and psychosocial value of PE. Research has demonstrated that physical activity has led to better academic stress and sleep quality (Cheng et al., 2025), as well as increases in social-emotional competence and behavioural control (Wang et al., 2025; Rosenkranz et al., 2023). Participation and effectiveness in PE settings are further impacted by structural and contextual factors that include preparedness of teachers, institutional support, and inclusive environments (Deng et al., 2025; Rocliffe et al., 2023). On the policy front, the gap between PE policy models and practice has been well documented, and more effective and evidence-based teaching methods are needed.

Physical Education and Adolescent Physical Fitness: Conceptual Framework for Physical Preparation

Brunsdon and (Layne 2025) provides a qualitative and mixed-method study on how occupational socialisation affects the instructional practice of physical-education teachers, proving that the professional training of teachers and their beliefs have a significant influence on the realization of physical preparation and character-related outcomes in school PE. (Cheng et al. 2025) used correlational and regression-based analyses to determine the relationship between physical exercise, academic stress, sleep quality, and subjective well-being in high-school students and found out that regular physical activity is an indirect contributor to well-being by lowering stress and enhancing sleep patterns. (Deng et al. 2025) employed a qualitative systematic review and meta-synthesis to determine school-based structural variables, including the preparedness of the teacher, the availability of facilities, and social inclusion, as key processes that affect the physical-activity participation of children and adolescents with disabilities, and found a limitation of contextual variability across education systems. (Jeffries et al. 2022) also, based on expert consensus and theoretical synthesis, have created a revised conceptual framework of physical training with the focus on the interaction of training load, effort regulation, recovery, and contextual constraints as core mechanisms of physical-fitness adaptation, although they admit that little empirical validation has been done in school PE settings. To resolve the psychosocial safety, (Kroshus et al. 2025) developed and tested a web-based PE training programme in a trauma-informed design with implementation-oriented measures, which showed better results on the participation readiness and perceived safety, but further studies on the long-term physical-fitness outcomes are necessary.

In the view of behavioural-regulation, (Maltagliati et al. 2025) used longitudinal and behavioural modelling methods to prove that effort minimisation is a dynamic and persistent impediment to continued physical-activity participation, especially in PE settings that are not motivated. At the system and policy level, (Martins et al. 2025) proposed a conceptual framework of Global Observatory of Physical Education (GoPE!) that utilises global policy mapping and standardised surveillance indicators to show that there are significant discrepancies between the policy intentions of PE and the actual practice based on fitness in the global context. With a focus on motivational processes, (Meerits et al. 2025) carried out a cluster-randomised controlled trial that revealed that the use of web-based interventions that foster need-supportive behaviours in PE teachers and parents has a strong positive effect on the intention and effort of adolescents to exercise. Through concept- mapping methodology, (Rocliffe et al. 2023) found out that successful physical-preparation of PE is reliant on correspondence among curriculum objectives, instruction, and school facilities, which points to real-world limitations of implementation. Based on behavioural theory, (Rosenkranz et al. 2023) developed a Capability Opportunity Motivation Behaviour (COM -B) model to inform the leadership of young people in physical-activity and found that psychological capability and social opportunity were the primary determinants of long-term involvement. Using a structural-functionalism direction, (Shi and Huang 2025) examined the role of school organisation, peer networks and family involvement as social processes in determining the physical health of adolescents. Using a scoping review, (Stähler et al. 2025) theorised physical effort to play instrumental, affective and self-regulatory roles in PE and sport, and supported its key role in physical preparation. According to empirical evidence presented by (Wang et al. 2025), there are positive correlations between physical-exercise involvement and social-emotional competence in children implying psychosocial and physical-fitness advantages. Using the trans-theoretical model, (Xie et al. 2025) synthesised intervention studies indicating that stage-matched intervention PE programmes can be used to promote physical-activity behaviour change, and the limitations associated with intervention heterogeneity and short follow-ups. By conducting a scoping review, (Yu et al. 2022) determined that the environmental, instructional, and social barriers and facilitators to physical-activity participation in children and adolescents with intellectual disabilities exist, and that inclusive and flexible physical-education models are necessary.

Training Models in School Physical Education: HIIT, Resistance Training, and Circuit Training for Adolescent Fitness Development

In an experimental study on the comparisons of various HIIT modalities in children and adolescents, (Bossmann et al. 2022) found that cardiorespiratory endurance and the selected parameters of strength significantly improved, with the changes being adaptive to repeated exposure to high-intensity workloads. With a focus on concurrent methods, (Bouamra et al. 2022) established in a randomised controlled trial that combined aerobic-resistance training yielded more positive effects on body composition and overall physical fitness compared to endurance or resistance training in youth with obesity, with a synergistic metabolic and neuromuscular action. (Cao et al. 2022) demonstrated that the incorporation of HIIT in PE lessons significantly enhanced the body composition, cardiorespiratory fitness, and daily physicalactivity levels of children with obesity with benefits that are linked to high cardiometabolic stress and enhanced energy expenditure. (Duncombe et al. 2022) have verified the use of systematic review and meta-analytic methods to find that school-based HIIT programmes have been shown to produce moderate-to-large effects on aerobic fitness and muscular endurance and identify limitations of protocol heterogeneity and short intervention periods. Gavanda et al. (2022) conducted a randomised controlled comparison and discovered that high-intensity functional training can produce similar or better effects in physical performance compared to traditional strength or endurance training, which indicates that functional and multi-joint exercises can positively influence the neuromuscular coordination in adolescents. Measuring metabolic and fitness outcomes, Gonzalez-Galvez et al. (2024) found that high-intensity and sprint interval training had a significant positive impact on metabolic biomarkers, body composition, and physical fitness in adolescents, which results in the support of the physiological efficiency of high-intensity models in PE settings.

When investigating resistance-based strategies, (Kozylenski et al. 2024) found that muscle mass and strength in adolescents, which were assessed after PE lessons, were significantly enhanced by high-intensity functional training based on the body-weight resistance exercises, and neural and mechanical loading were the main mechanisms of action. Li, Z., (Ding, et al. 2024) compared two parallel concurrent aerobic-resistance training protocols in an experimental study of school PE and concluded that both directions produced an improvement in physical fitness, where equal gains were observed when the volume and intensity of training were distributed equally. In a different comparative analysis, (Li, Z., Liu, et al. 2023) observed that running based HIIT yielded more aerobic gains, whereas body weight based HIIT resulted in more neuromuscular enhancements, highlighting modality specific adaptations. To meet the aspect of scalability, (Lubans et al. 2022) have highlighted that HIIT programmes could be effectively scaled with population level impact in schools, but teacher training and implementation fidelity are major limitations. Researching circuit models, (Milenković 2022) found that eight-week circuit training programme has a considerable positive effect on various muscular strength types in PE pupils due to the cumulative fatigue and repeated muscle contraction. (Jurić et al. 2023) with the help of the cluster-randomised approach showed that the inclusion of HIIT in PE classes led to better fitness outcomes of students than regular lessons do, and (Jovanovic et al. 2024) established that school-based HIIT has a positive impact on health-related fitness components in adolescents. The evaluation of the program presented by (Ricci et al. 2023) also revealed that the use of fitness- and skill-based HIIT in PE is practical and effective, yet long-term adherence still needs to be investigated. With concentration on circuit intensity, (Yunus et al. 2024) found that high-intensity circuit training was a great way of enhancing overall physical fitness among young men, which contributes to its applicability in schools. (Videira-Silva et al. 2023) and (Zuo et al. 2023) separately showed that combined or high-intensity interventions caused more significant changes in body composition and physical fitness than moderate-intensity continuous exercise, especially in adolescents with overweight, which proves the metabolic and functional superiority of high-intensity and combined training models.Table 1 shows the keypoints of previous studies.

Table 1. Comparative Overview of Training Models in School Physical Education

Reference	Model	Primary Training	Key Fitness Outcomes	Mechanisms	School PE Application	Limitations
(Duncombe et al. 2022)	HIIT	Short high-intensity bouts	↑ VO_2max, endurance	High cardiometabolic stress	Time-efficient PE lessons	Protocol heterogeneity
(Cao et al. 2022)	HIIT	School-integrated HIIT	↓ fat mass, ↑ CRF	↑ Energy expenditure	Obesity-focused PE	Intensity monitoring needed
(Koźlenia et al. 2024)	RT	Bodyweight resistance	↑ Strength, muscle mass	Neuromuscular loading	Equipment-free RT	Technique supervision
(Bouamra et al. 2022)	COM	Aerobic + resistance	↑ Body comp., fitness	Metabolic + mechanical synergy	Holistic PE goals	Sample-specific (obesity)
(Li, Z., Ding, et al. 2024)	COM	Concurrent protocols	Balanced fitness gains	Managed concurrent stimulus	General PE conditioning	Programming complexity
(Milenković 2022)	CIR	Multi-station circuit	↑ Muscle strength	Repeated activation	Large-class management	Short intervention

(Gavanda et al. 2022)	CIR	Functional HI circuit	↑ Overall performance	Multi-joint coordination	Mixed-ability classes	Fidelity required

To address these challenges, several structured training models have been proposed and empirically evaluated. High-intensity interval training (HIIT) has gained prominence due to its time efficiency and strong impact on cardiorespiratory fitness and metabolic outcomes (Bossmann et al., 2022; Meng et al., 2022; Bento, 2023). Resistance training (RT), particularly bodyweight-based approaches, enhances muscular strength, neuromuscular coordination, and skeletal development in adolescents (Liu et al., 2022; Kozylenski et al., 2024). Circuit-based training (CIR) offers a comprehensive and scalable approach by integrating strength, endurance, and agility exercises within a station-based format suitable for large classes (Milenković, 2022; Gavanda et al., 2022). Additionally, combined aerobic-resistance training (COM) has been shown to produce synergistic improvements in overall physical fitness through simultaneous cardiovascular and neuromuscular adaptations (Bouamra et al., 2022; Zhang et al., 2024).

Although the effectiveness of these models was demonstrated, current studies have a number of significant limitations. The majority of the research is conducted either on training modalities in isolation or under highly controlled experimental conditions as opposed to the conditions that are encountered in real-life school PE (Mendonça et al., 2022). Moreover, the inconsistency in the duration of intervention, the intensity of interventions, and methods of measuring them does not allow comparative study across the studies. Notably, most studies investigate single factors of fitness, like aerobic capacity or muscular strength, when physical preparation in PE is multidimensional in nature. Such a fragmented evidence base limits the capacity of educators to choose the best training strategies to attain balanced physical development. Moreover, one of the factors that are not commonly considered is the moderating effect of biological maturation, although it affects hormonal profiles, neuromuscular development, and responsiveness to training in adolescents (Leahy et al., 2024).

Theoretically, the various training models have different physiological processes. The cardiovascular adaptations to HIIT are mainly caused by repeated bouts of high-intensity workloads, and the neuromuscular and hypertrophic adaptations to RT are caused by mechanical loading. CIR incorporates more than one training stimulus into a given session, whereas during COM training cardiovascular and strength pathways are activated simultaneously, but there exists the risk of possible interference effects based on the volume of training and recovery. Such mechanistic distinctions imply that domain-specific adaptations are generated by either model, but there has been limited direct comparative evidence to support this in ecologically valid school conditions.

Subsequently, the systematic comparative research that has to be conducted in the actual educational context is evident to assess the comparative efficacy of various training models in many areas of physical preparation..Accordingly, the present study aims to compare the effects of high-intensity interval training (HIIT), resistance training (RT), circuit-based training (CIR), and combined aerobic-resistance training (COM) on cardiorespiratory fitness, muscular strength, muscular endurance, speed-agility, and flexibility in secondary school adolescents within a school-based physical education context.

Method

Research Design

The study employed a quantitative, quasi-experimental multi-arm parallel group design with school-level cluster randomization. The intervention lasted 12 weeks, which was sufficient to induce measurable physiological adaptations while aligning with the academic calendar. A control group was included, in which participants followed the standard physical education curriculum without structured conditioning.

Ethical approval was obtained from the Institutional Review Board (IRB-2024-089), and all procedures complied with the Declaration of Helsinki. Informed consent was obtained from parents/guardians, and participant assent was secured prior to data collection.

Population and Sample

Participants were recruited from five secondary schools located in a metropolitan area with comparable demographic and infrastructural characteristics, including socioeconomic background and physical education facilities. Inclusion criteria included: (a) enrollment in grades 8–10 (aged 13–16 years), (b) absence of medical contraindications to vigorous physical activity as assessed using the Physical Activity Readiness Questionnaire (PAR-Q), (c) minimum attendance of 85% during the intervention period, and (d) no participation in external structured training programs.

A total of 195 students were initially screened, of which 156 adolescents met the inclusion criteria and completed baseline assessments (78 males, 78 females). An a priori power analysis using G*Power 3.1 indicated that a minimum sample of 128 participants was required to detect medium effect sizes ($f = 0.25$) with 80% statistical power at $\alpha = 0.05$. The final sample size ($n = 156$) was therefore deemed sufficient.

Group Allocation

To minimize contamination and maintain ecological validity, cluster randomization was performed at the school level. Each of the five schools was randomly assigned to one of the five conditions: high-intensity interval training (HIIT), resistance training (RT), combined aerobic-resistance training (COM), circuit-based training (CIR), or control. Each group consisted of 39 participants:

- HIIT Group: n = 39
- RT Group: n = 39
- COM Group: n = 39
- CIR Group: n = 39
- Control Group: n = 39

This approach ensured that all students within a school followed the same intervention, thereby preventing cross-exposure between training conditions.

Biological Maturation Assessment

Biological maturation was assessed using the maturity offset method, which estimates years from peak height velocity (PHV) based on anthropometric variables (standing height, sitting height, and body mass). Participants were categorized into three groups: pre-PHV (>1 year before PHV), circa-PHV (±1 year), and post-PHV (>1 year after PHV).

Outcome Measures

Physical preparation was assessed at baseline (Week 0), mid-intervention (Week 6), and post-intervention (Week 12) using standardized fitness tests administered by trained and blinded assessors to reduce measurement bias. All instruments demonstrated acceptable reliability and validity based on established literature.

- Cardiorespiratory Fitness: Estimated using the 20 m shuttle run test with a validated predictive equation for VO_2max.
- Muscular Strength: Assessed using handgrip dynamometry (Takei 5401, Japan).
- Lower-body Power: Measured via the standing long jump test.
- Muscular Endurance: Evaluated using push-up and curl-up tests following FITNESSGRAM protocols.
- Speed-Agility: Assessed using the 10 × 5 m shuttle run test.
- Flexibility: Measured using the sit-and-reach test.

Intervention Protocols

All intervention programs replaced regular physical education classes and were conducted three times per week (45–60 minutes per session) over 12 weeks. Sessions were supervised by trained physical education teachers, and intervention fidelity was ensured through standardized protocols, session logs, and random observation of approximately 20% of sessions.

Exercise intensity was monitored using heart rate (≥85% HRmax for high-intensity sessions) and the Borg Rating of Perceived Exertion (RPE) scale.

- HIIT: Included repeated short bouts of high-intensity exercise interspersed with recovery periods, targeting cardiovascular adaptations.
- RT: Consisted of bodyweight resistance exercises focusing on major muscle groups, promoting strength and neuromuscular development.
- COM: Combined aerobic and resistance components within the same session to achieve balanced physiological adaptations.
- CIR: Included 8–12 exercise stations targeting strength, endurance, and agility, performed in circuit format with 30–45 seconds of activity and 15–30 seconds transition between stations.
- Control: Followed standard PE curriculum focusing on recreational games and sports without structured conditioning or progressive overload.

Statistical Analysis

Statistical analysis was performed using SPSS version 29.0 and JASP 0.18. Data normality and homogeneity were assessed using Shapiro–Wilk and Levene tests. Descriptive statistics were reported as mean ± standard deviation.

A mixed-design ANOVA was conducted with Time (pre, mid, post) as the within-subject factor and Group (HIIT, RT, COM, CIR, Control) as the between-subject factor. Greenhouse–Geisser corrections were applied where sphericity assumptions were violated.

Post-hoc comparisons were performed using Bonferroni adjustment. Effect sizes were reported using Cohen's d and partial eta squared (η^2p). Additional analyses included three-way ANOVA (Time × Group × Maturation) and regression analysis. Missing data (>5%) were handled using an intention-to-treat approach with last observation carried forward.

Results

Preliminary Analyses and Baseline Characteristics

Participant Flow and Attrition

Among the 195 teens who were first screened to be eligible in five secondary schools, 156 respondents (78 boys, 78 girls; mean age = 14.6 ± 1.1 years) met the inclusion criteria and went through baseline tests. Eight individuals dropped out or were excluded during the course of the 12-week intervention due to attendance lower than 85 per cent (HIIT: n=2; RT: n=1; COM: n=2; CIR: n=2; Control: n=1), leaving only 148 participants to continue with the analysis (retention rate=94.9 per cent). No statistically significant differences in the baseline characteristics were found between completers and non-completers (p >0.05 (all variables)) indicating that dropout could not be systematically related to baseline fitness levels or any demographic variables.

Baseline Equivalence and Participant Characteristics

Baseline analysis showed in table 2, no significant differences among the five groups in demographic, anthropometric, maturation, or fitness variables (p > 0.05), confirming that the groups were comparable before the intervention.

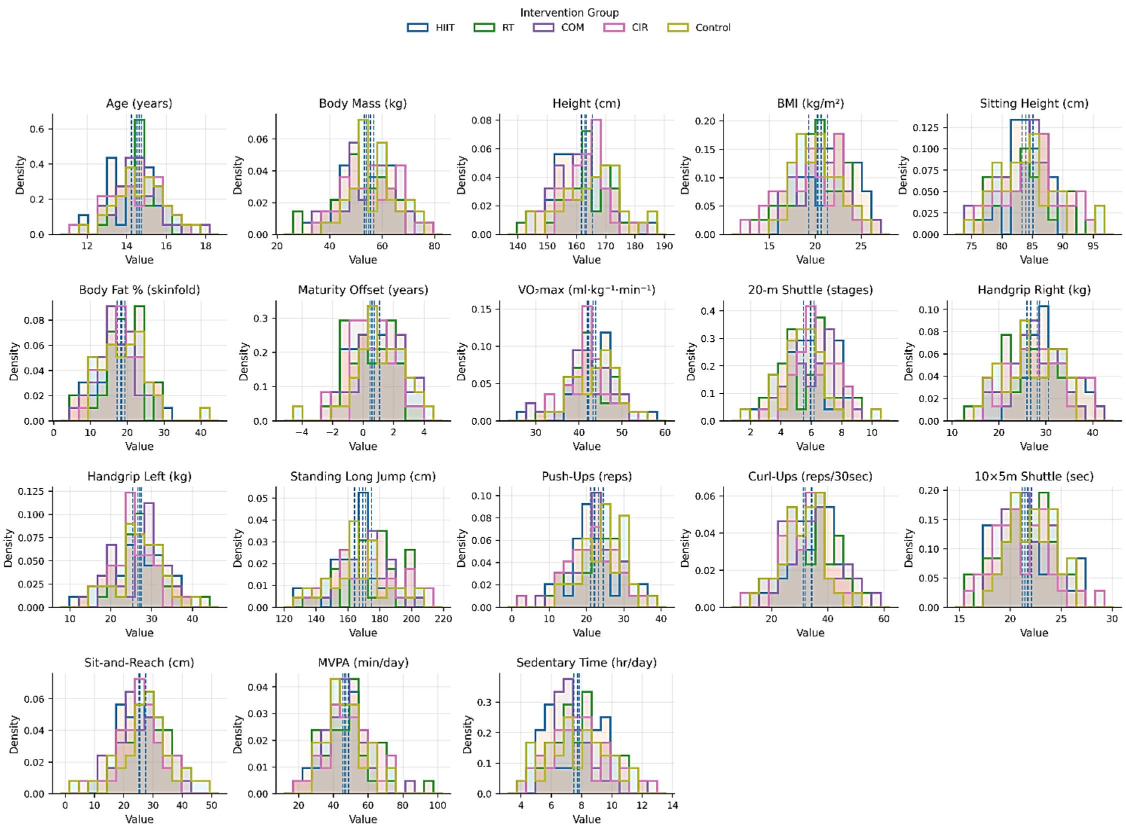
Table 2. Comprehensive Baseline Characteristics and Physical Fitness Profile of Participants Across Intervention Groups

Variable	HIIT (n=39)	RT (n=39)	COM (n=39)	CIR (n=39)	Control (n=39)	F	p	η^2p
Demographic Characteristics								
Age (years)	14.5 ± 1.2	14.7 ± 1.0	14.6 ± 1.1	14.5 ± 1.2	14.7 ± 1.1	0.42	0.794	0.011
Sex (Male/Female)	19/20	20/19	18/21	21/18	20/19	$\chi^2 = 0.62$	0.961	—

Ethnicity (%)								
- Caucasian	76.9	74.4	79.5	76.9	76.9	χ^2 = 0.45	0.998	—
- Asian	12.8	15.4	10.3	12.8	12.8			
- Other	10.3	10.2	10.2	10.3	10.3			
Anthropometric Measures								
Body Mass (kg)	54.3 ± 9.8	55.1 ± 10.2	53.8 ± 9.5	54.7 ± 10.1	55.4 ± 9.9	0.31	0.871	0.008
Height (cm)	162.4 ± 8.7	163.1 ± 9.2	161.8 ± 8.4	162.9 ± 8.9	163.5 ± 9.0	0.38	0.823	0.010
BMI (kg/m^2)	20.5 ± 2.8	20.7 ± 2.9	20.3 ± 2.6	20.6 ± 2.7	20.8 ± 2.9	0.68	0.607	0.018
Sitting Height (cm)	84.2 ± 4.6	84.8 ± 4.8	83.9 ± 4.4	84.5 ± 4.7	84.9 ± 4.9	0.52	0.721	0.014
Body Fat % (skinfold)	18.6 ± 5.2	19.1 ± 5.4	18.3 ± 5.0	18.8 ± 5.3	19.3 ± 5.5	0.44	0.779	0.012
Biological Maturation								
Maturity Offset (years)	0.7 ± 1.3	0.9 ± 1.5	0.8 ± 1.4	0.7 ± 1.3	0.9 ± 1.5	0.53	0.714	0.014
Maturation Status (%)								
- Pre-PHV	33.3	30.8	33.3	30.8	33.3	χ^2 = 0.28	0.999	—
- Circa-PHV	41.0	43.6	41.0	43.6	38.5			
- Post-PHV	25.7	25.6	25.7	25.6	28.2			
Cardiorespiratory Fitness								
VO_2max (ml·kg^{-1}·min^{-1})	42.3 ± 5.2	42.5 ± 5.4	42.1 ± 5.3	42.4 ± 5.5	42.6 ± 5.3	0.12	0.976	0.003
20-m Shuttle (stages)	5.8 ± 1.4	5.9 ± 1.5	5.7 ± 1.4	5.8 ± 1.5	5.9 ± 1.4	0.19	0.943	0.005
Muscular Strength								
Handgrip Right (kg)	28.3 ± 5.8	28.1 ± 5.9	28.4 ± 6.0	28.2 ± 5.8	28.5 ± 6.1	0.08	0.988	0.002
Handgrip Left (kg)	26.8 ± 5.4	26.6 ± 5.5	26.9 ± 5.6	26.7 ± 5.4	27.0 ± 5.7	0.06	0.993	0.002
Standing Long Jump (cm)	168.4 ± 18.2	167.9 ± 18.5	168.2 ± 18.3	167.6 ± 18.7	168.1 ± 18.4	0.03	0.998	0.001
Muscular Endurance								
Push-Ups (reps)	22.4 ± 6.2	22.1 ± 6.3	22.3 ± 6.4	22.2 ± 6.2	22.5 ± 6.5	0.04	0.997	0.001
Curl-Ups (reps/30sec)	34.2 ± 8.5	33.8 ± 8.6	34.0 ± 8.7	33.9 ± 8.4	34.1 ± 8.8	0.02	0.999	0.001
Speed-Agility								
10×5m Shuttle (sec)	21.8 ± 2.4	21.9 ± 2.5	21.7 ± 2.3	21.8 ± 2.4	21.9 ± 2.5	0.09	0.985	0.002
Flexibility								
Sit-and-Reach (cm)	26.3 ± 7.8	26.1 ± 7.9	26.4 ± 8.0	26.2 ± 7.8	26.5 ± 8.1	0.04	0.997	0.001
Physical Activity Level								
MVPA (min/day)	48.2 ± 12.4	47.8 ± 12.8	48.6 ± 12.2	48.1 ± 12.6	47.9 ± 12.9	0.05	0.995	0.001
Sedentary Time (hr/day)	7.8 ± 1.9	7.9 ± 2.0	7.7 ± 1.8	7.8 ± 1.9	8.0 ± 2.1	0.21	0.933	0.006

Note. Values are mean ± SD unless otherwise stated. BMI = Body Mass Index; PHV = Peak Height Velocity; VO_2max = maximal oxygen uptake; MVPA = moderate-to-vigorous physical activity. No significant baseline differences were observed between groups ($p > 0.05$ for all comparisons). η^2p = partial eta squared effect size.

Figure 2. Overlaid histograms showing comparable baseline distributions of demographic, fitness, and physical activity variables across all intervention groups



The overlaid histograms demonstrate a high degree of overlap across all intervention groups for baseline characteristics, indicating comparable distributions before intervention. This visual figure 2, is evidence supports baseline equivalence among groups, consistent with the non-significant F and χ^2 statistics reported in the table.

Primary Outcomes: Effects of Training Models on Physical Preparation Components

Cardiorespiratory Fitness (VO_2max)

Mixed-design ANOVA showed a significant Time × Group interaction for VO_2max ($p < 0.001$). All training groups improved significantly, while the control group showed no change. HIIT produced the largest improvement, followed by COM and CIR as Shown in Table 3.

Table 3. Longitudinal Changes in Cardiorespiratory Fitness (VO_2max) Across Training Models with Detailed Statistical Comparisons

Group	Baseline (ml·kg^{-1}·min^{-1})	Week 6 (ml·kg^{-1}·min^{-1})	Week 12 (ml·kg^{-1}·min^{-1})	Δ Week 6	Δ Week 12	% Change	Cohen's d	95% CI	SE	t-value	p-value	Interpretation
HIIT	42.3 ± 5.2	44.8 ± 5.0*	46.5 ± 4.8*†	+2.5	+4.2	+9.9%	1.15	[0.88, 1.42]	0.14	18.42	<0.001	Very Large
RT	42.5 ± 5.4	43.5 ± 5.3*	44.8 ± 5.1*	+1.0	+2.3	+5.4%	0.67	[0.42, 0.92]	0.13	10.85	<0.001	Moderate
COM	42.1 ± 5.3	44.2 ± 5.1*	45.2 ± 4.9*†	+2.1	+3.1	+7.4%	0.89	[0.63, 1.15]	0.13	14.62	<0.001	Large
CIR	42.4 ± 5.5	44.0 ± 5.2*	45.2 ± 5.0*†	+1.6	+2.8	+6.6%	0.81	[0.55, 1.07]	0.13	13.23	<0.001	Large
Control	42.6 ± 5.3	42.7 ± 5.4	42.9 ± 5.2	+0.1	+0.3	+0.7%	0.06	[-0.18, 0.30]	0.12	1.53	0.742	Trivial

Figure 3. Changes in VO_2max from baseline at Week 6 and Week 12 across training models (left) and corresponding effect sizes with 95% confidence intervals (right).

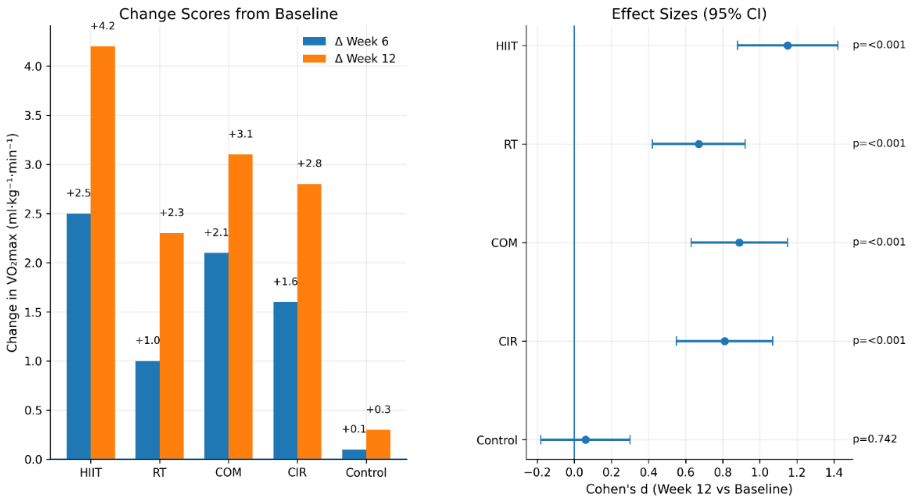


Figure 3, shows progressive improvements in VO_2max for all training groups, with the largest gains observed in HIIT, followed by COM and CIR, while the control group exhibited minimal change. The forest plot confirms these findings, demonstrating large-to-moderate effect sizes for all intervention groups and a trivial, non-significant effect for the control group 3.

Post-hoc comparisons showed as Table 4, that HIIT produced significantly greater VO_2max improvements than all other groups, especially compared with the control ($p < 0.001$). RT, COM, and CIR also improved significantly compared with the control, while no significant differences were observed among RT, COM, and CIR.

Table 4. Pairwise Post-Hoc Comparisons (Bonferroni-adjusted) at Week 12:

Comparison	Mean Difference (ml·kg^{-1}·min^{-1})	SE	95% CI	t-value	p-value	Cohen's d
HIIT vs. Control	+3.9	0.42	[2.89, 4.91]	9.29	<0.001	1.09
HIIT vs. RT	+1.9	0.39	[0.96, 2.84]	4.87	<0.001	0.48
HIIT vs. COM	+1.1	0.38	[0.18, 2.02]	2.89	0.021	0.26
HIIT vs. CIR	+1.4	0.39	[0.46, 2.34]	3.59	0.002	0.34
RT vs. Control	+2.0	0.41	[1.01, 2.99]	4.88	<0.001	0.61
COM vs. Control	+2.8	0.40	[1.83, 3.77]	7.00	<0.001	0.83
CIR vs. Control	+2.5	0.41	[1.51, 3.49]	6.10	<0.001	0.75
COM vs. RT	+0.8	0.37	[-0.10, 1.70]	2.16	0.164	0.22
CIR vs. RT	+0.5	0.38	[-0.42, 1.42]	1.32	0.623	0.14
COM vs. CIR	+0.3	0.37	[-0.59, 1.19]	0.81	0.284	0.08

Note. Note. Values are mean ± SD. Δ represents the change of baseline. * Shows the statistically significant difference between the baseline and the same group (p< 0.001). † Statistically significant difference compared to the control group at the same time point (<0.001). SE refers to Standard Error. The effect sizes were understood based on Hopkins thresholds: (<0.20), small (0.20-0.59), moderate (0.60-1.19), large (1.20-1.99), very large (≥2.00).

Lower-Body Muscular Power (Standing Long Jump)

Lower-Body Muscular Power (Standing Long Jump): It was found that there was a considerable Time x Group interaction in the standing long-jump performance ($p < 0.001$). The most significant gain was found in resistance training (RT), then combined training (COM), CIR and middle gains were found in high-intensity interval training (HIIT). There was no significant change of the control group. The results are in detail given in Table 5.

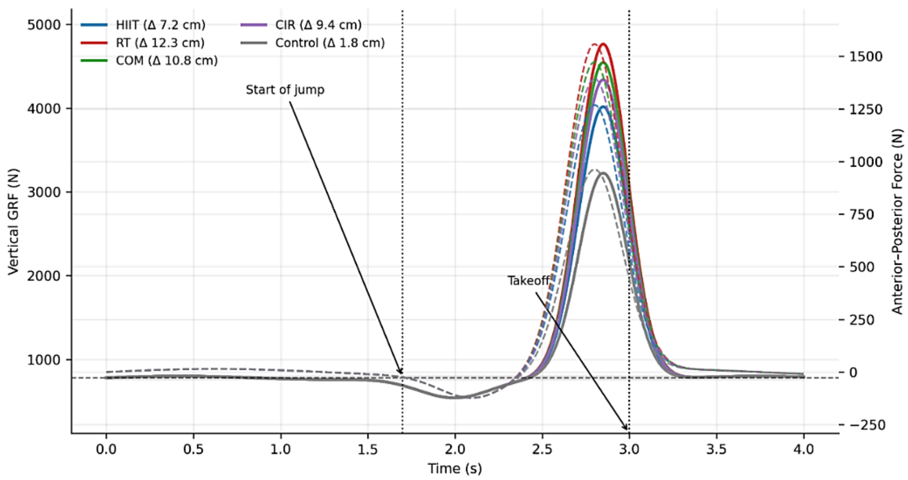
Table 5. Changes in Lower-Body Muscular Power (Standing Long Jump) Across Training Models

Group	Baseline (cm)	Week 6 (cm)	Week 12 (cm)	Δ Week 6	Δ Week 12	% Change	Cohen's d	95% CI	SE	t-value	p-value	Interpretation
HIIT	168.4 ± 18.2	172.5 ± 17.8*	175.6 ± 17.4*†	+4.1	+7.2	+4.3%	0.59	[0.34, 0.84]	0.13	9.62	<0.001	Moderate
RT	167.9 ± 18.5	175.1 ± 17.9*	180.2 ± 17.2*†‡	+7.2	+12.3	+7.3%	0.98	[0.71, 1.25]	0.14	16.54	<0.001	Large
COM	168.2 ± 18.3	174.3 ± 17.6*	179.0 ± 17.1*†	+6.1	+10.8	+6.4%	0.87	[0.61, 1.13]	0.13	14.77	<0.001	Large
CIR	167.6 ± 18.7	172.9 ± 18.0*	177.0 ± 17.5*†	+5.3	+9.4	+5.6%	0.76	[0.50, 1.02]	0.13	12.92	<0.001	Moderate
Control	168.1 ± 18.4	168.9 ± 18.3	169.9 ± 18.1	+0.8	+1.8	+1.1%	0.15	[-0.09, 0.39]	0.12	2.45	0.423	Trivial

Note. * Significantly different from baseline ($p < 0.001$). † Significantly different from control at Week 12 ($p < 0.001$). ‡ Significantly greater improvement than HIIT, CIR, and control ($p < 0.001$).

Figure 4. Group-specific force–time profiles of the standing long jump illustrating differential lower-body muscular power adaptations across training models.

Figure 4 shows graded force–time adaptations during the standing long jump, with RT displaying the greatest propulsion, followed by COM, CIR, and HIIT, while the control group shows minimal change. These biomechanical patterns support the observed Time × Group interaction and corresponding improvements in jump performance at Week 12.



Upper-Body Muscular Strength (Handgrip Dynamometry)

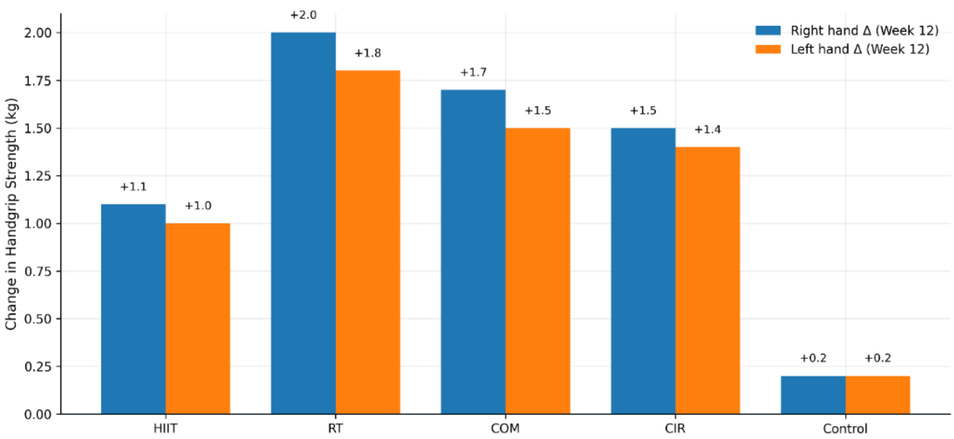
Mixed ANOVA showed that the Time x Group interaction was significant in the handgrip strength ($p < 0.001$). RT showed the best improvement, followed by COM and CIR, whereas HIIT showed moderate improvements; the control group showed low changes. The elaborate findings are discussed in Table 6.

Table 6. Changes in Upper-Body Muscular Strength (Bilateral Handgrip) Across Training Models

Group	Baseline Total (kg)	Week 6 Total (kg)	Week 12 Total (kg)	Δ Week 6	Δ Week 12	% Change	Cohen's d	95% CI	Right Hand Δ (kg)	Left Hand Δ (kg)	Interpretation
HIIT	55.1 ± 10.8	56.5 ± 10.6*	57.2 ± 10.4*†	+1.4	+2.1	+3.8%	0.52	[0.27, 0.77]	+1.1	+1.0	Moderate
RT	54.7 ± 11.0	57.4 ± 10.7*	58.5 ± 10.5*†‡	+2.7	+3.8	+6.9%	0.91	[0.65, 1.17]	+2.0	+1.8	Large
COM	55.3 ± 11.2	57.2 ± 10.9*	58.5 ± 10.6*†	+1.9	+3.2	+5.8%	0.79	[0.53, 1.05]	+1.7	+1.5	Moderate
CIR	54.9 ± 10.9	56.7 ± 10.7*	57.8 ± 10.5*†	+1.8	+2.9	+5.3%	0.71	[0.45, 0.97]	+1.5	+1.4	Moderate
Control	55.5 ± 11.3	55.7 ± 11.2	55.9 ± 11.0	+0.2	+0.4	+0.7%	0.10	[-0.14, 0.34]	+0.2	+0.2	Trivial

Note. Total handgrip = sum of right and left hand measurements. * Significantly different from baseline ($p < 0.001$). † Significantly different from control at Week 12 ($p < 0.001$). ‡ Significantly greater than HIIT and control ($p < 0.001$).

Figure 5. Week-12 improvements in bilateral handgrip strength (right and left hands) across training models.



The figure 5, shows greater gains in both hands for all intervention groups compared with the control, with RT demonstrating the largest bilateral improvements, followed by COM, CIR, and HIIT. The minimal and symmetrical changes in the control group indicate trivial strength adaptation, supporting the superiority of structured training—particularly resistance-based models—for enhancing upper-body muscular strength.

Muscular Endurance: Comprehensive Upper-Body and Core Assessment

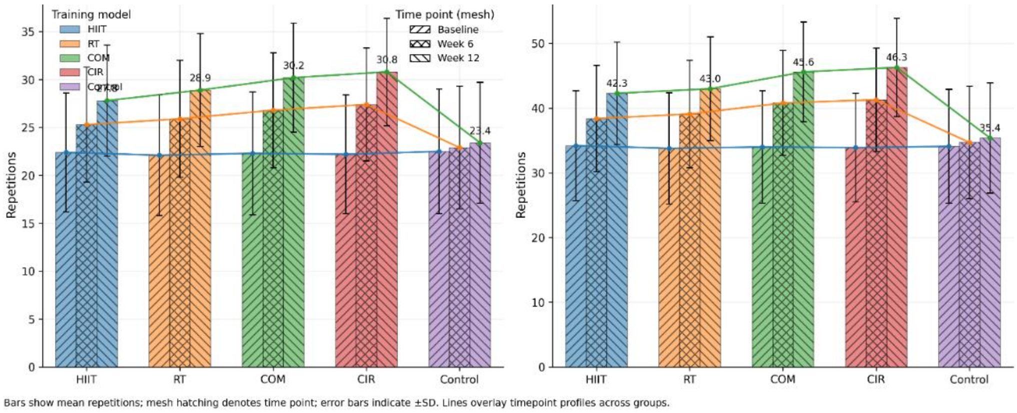
Significant Time × Group interactions were observed for both push-up and curl-up performance ($p < 0.001$). CIR and COM showed the greatest improvements, followed by RT and HIIT, while the control group showed no significant change. Detailed results are presented in Table 7.

Table 7. Comprehensive Muscular Endurance Adaptations (Push-Up and Curl-Up Tests) Across Training Models

Group	Test	Baseline (reps)	Week 6 (reps)	Week 12 (reps)	Δ Week 6	Δ Week 12	% Change	Cohen's d	95% CI	p-value	Interpretation
HIIT	Push-Up	22.4 ± 6.2	25.3 ± 6.0*	27.8 ± 5.8*†	+2.9	+5.4	+24.1%	0.65	[0.40, 0.90]	<0.001	Moderate
	Curl-Up	34.2 ± 8.5	38.4 ± 8.2*	42.3 ± 7.9*†	+4.2	+8.1	+23.7%	0.74	[0.48, 1.00]	<0.001	Moderate
RT	Push-Up	22.1 ± 6.3	25.9 ± 6.1*	28.9 ± 5.9*†	+3.8	+6.8	+30.8%	0.81	[0.55, 1.07]	<0.001	Large
	Curl-Up	33.8 ± 8.6	39.1 ± 8.3*	43.0 ± 8.0*†	+5.3	+9.2	+27.2%	0.84	[0.58, 1.10]	<0.001	Large
COM	Push-Up	22.3 ± 6.4	26.8 ± 6.0*	30.2 ± 5.7*†‡	+4.5	+7.9	+35.4%	0.94	[0.68, 1.20]	<0.001	Large
	Curl-Up	34.0 ± 8.7	40.8 ± 8.1*	45.6 ± 7.7*†‡	+6.8	+11.6	+34.1%	0.89	[0.63, 1.15]	<0.001	Large

CIR	Push-Up	22.2 ± 6.2	27.4 ± 5.9*	30.8 ± 5.6*†‡	+5.2	+8.6	+38.7%	1.02	[0.75, 1.29]	<0.001	Large
	Curl-Up	33.9 ± 8.4	41.3 ± 8.0*	46.3 ± 7.6*†‡	+7.4	+12.4	+36.6%	0.96	[0.69, 1.23]	<0.001	Large
Control	Push-Up	22.5 ± 6.5	22.9 ± 6.4	23.4 ± 6.3	+0.4	+0.9	+4.0%	0.11	[-0.13, 0.35]	0.698	Trivial
	Curl-Up	34.1 ± 8.8	34.7 ± 8.7	35.4 ± 8.5	+0.6	+1.3	+3.8%	0.10	[-0.14, 0.34]	0.742	Trivial

Figure 6. Mesh-style grouped bar plots illustrating longitudinal changes in muscular endurance (push-up and curl-up tests) across training models.



The figure 6, depicts baseline, Week-6, and Week-12 mean repetitions (±SD) for each training group, with mesh hatching distinguishing time points and overlaid profile lines highlighting temporal trajectories. All active training models show progressive and substantially greater improvements in both push-up and curl-up endurance compared with the control group, with COM and CIR demonstrating the largest gains by Week 12.

Table 8 shows that both push-up and curl-up tests have significant effects of time, group, and their interaction (all p less than 0.001), which supports the idea of differences in muscular endurance improvements among training models.

Table 8. Mixed ANOVA Results

Source	Push-Up Test			Curl-Up Test		
	F	p	η^2p	F	p	η^2p
Time	124.83	<0.001	0.466	118.47	<0.001	0.453
Group	15.26	<0.001	0.299	14.82	<0.001	0.294
Time × Group	12.83	<0.001	0.263	11.94	<0.001	0.250

Note. * Significantly different from baseline within group (p < 0.001). † Significantly different from control at the same time point (p < 0.001). ‡ Significantly greater than HIIT and control (p < 0.001).

Figure 7. Boxplots illustrating the distributional patterns underlying mixed ANOVA results for push-up and curl-up muscular endurance across time and training groups.

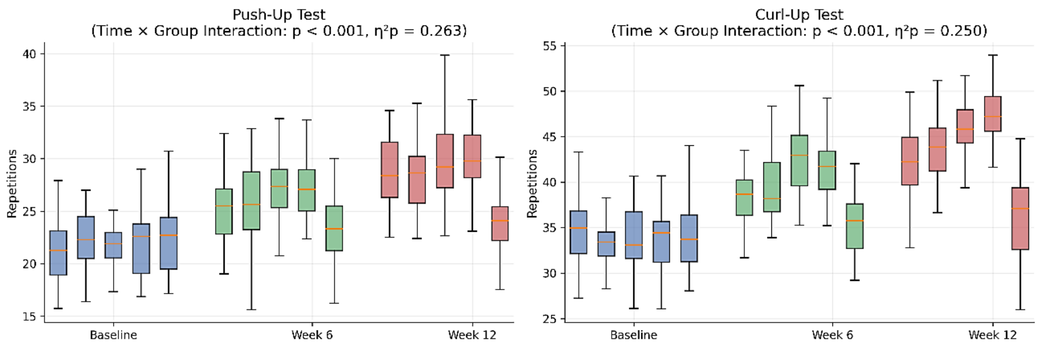


Figure 7, clear upward shifts in medians and interquartile ranges from baseline to Week 12 for all active training models, with the largest dispersion and median gains observed in COM and CIR, whereas the control group exhibits minimal change. These distributional trends visually support the significant main effects of time and group, as well as the strong time × group interaction reported in the mixed ANOVA.

Speed-Agility Performance

There was a significant Time-Group interaction with shuttle-run performance ($p < 0.001$). CIR, HIIT, and COM achieved the highest improvement, respectively, and RT demonstrated less significant growth and the control group had the least change. Table 9 describethe speed-agility performance (10 × 5-m shuttle run) across training Models

Table 9. Speed-Agility Performance (10 × 5-m Shuttle Run) Across Training Models

Group	Baseline (sec)	Week 6 (sec)	Week 12 (sec)	Δ Week 6	Δ Week 12	% Improvement	Cohen's d	95% CI	Interpretation
HIIT	21.8 ± 2.4	20.9 ± 2.3*	20.3 ± 2.2*†	-0.9	-1.5	6.9%	0.73	[0.47, 0.99]	Moderate
RT	21.9 ± 2.5	21.3 ± 2.4*	20.9 ± 2.3*†	-0.6	-1.0	4.6%	0.49	[0.24, 0.74]	Small
COM	21.7 ± 2.3	20.8 ± 2.2*	20.3 ± 2.1*†	-0.9	-1.4	6.5%	0.68	[0.42, 0.94]	Moderate
CIR	21.8 ± 2.4	20.5 ± 2.2*	20.0 ± 2.1*†‡	-1.3	-1.8	8.3%	0.87	[0.61, 1.13]	Large
Control	21.9 ± 2.5	21.8 ± 2.4	21.7 ± 2.4	-0.1	-0.2	0.9%	0.10	[-0.14, 0.34]	Trivial

Note. Negative Δ values indicate improved performance (faster times). * Significantly different from baseline ($p < 0.001$). † Significantly different from control at Week 12 ($p < 0.001$). ‡ Significantly greater improvement than RT and control ($p < 0.001$).

Flexibility Assessment

Mixed ANOVA showed a significant Time × Group interaction for sit-and-reach performance ($p < 0.001$). COM produced the greatest improvement in flexibility, followed by CIR and HIIT, while RT showed in table 10, smaller gains and the control group showed minimal change.

Table 10. Flexibility Adaptations (Sit-and-Reach Test) Across Training Models

Group	Baseline (cm)	Week 6 (cm)	Week 12 (cm)	Δ Week 6	Δ Week 12	% Change	Cohen's d	95% CI	Interpretation
HIIT	26.3 ± 7.8	27.5 ± 7.6*	28.4 ± 7.4*†	+1.2	+2.1	+8.0%	0.42	[0.17, 0.67]	Small
RT	26.1 ± 7.9	27.2 ± 7.7*	27.9 ± 7.5*	+1.1	+1.8	+6.9%	0.36	[0.11, 0.61]	Small
COM	26.4 ± 8.0	28.4 ± 7.7*	29.8 ± 7.4*†‡	+2.0	+3.4	+12.9%	0.68	[0.42, 0.94]	Moderate
CIR	26.2 ± 7.8	27.9 ± 7.6*	29.1 ± 7.4*†	+1.7	+2.9	+11.1%	0.58	[0.33, 0.83]	Moderate
Control	26.5 ± 8.1	26.8 ± 8.0	27.0 ± 7.9	+0.3	+0.5	+1.9%	0.10	[-0.14, 0.34]	Trivial

Note. * Significantly different from baseline ($p < 0.001$). † Significantly different from control at Week 12 ($p < 0.01$). ‡ Significantly greater than RT and control ($p < 0.05$).

Comparative Training Model Effectiveness: Comprehensive Physical Preparation Profiles

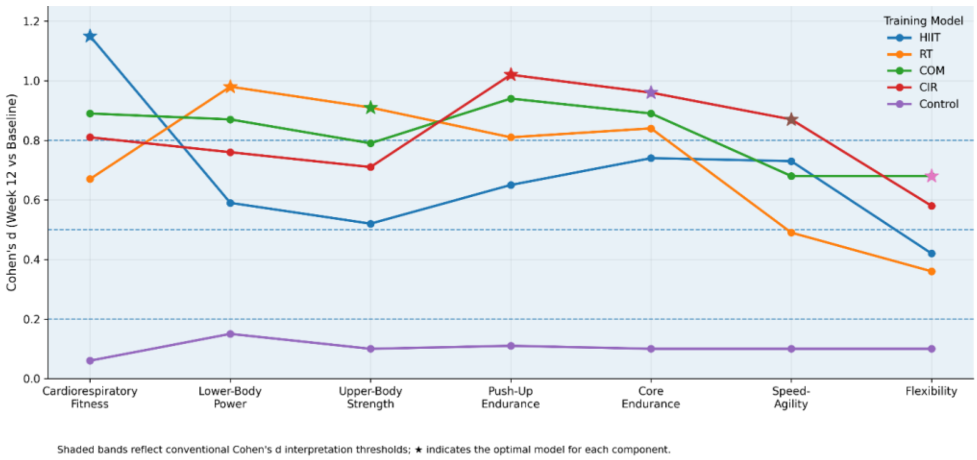
Effect-size comparisons indicated in table 11, that HIIT was the most effective mode of training cardiorespiratory fitness, RT was the most effective mode of training strength, and that COM and CIR yielded the greatest uniformity in overall fitness changes.

Table 11. Comparative Effect Sizes (Cohen's d) Across Training Models and All Fitness Components with Statistical Rankings

Fitness Component	HIIT	Rank	RT	Rank	COM	Rank	CIR	Rank	Control	Optimal Model(s)	F-value	p-value	η^2p
Cardiorespiratory Fitness	1.15	1	0.67	4	0.89	2	0.81	3	0.06	HIIT	18.74	<0.001	0.34
Lower-Body Power	0.59	4	0.98	1	0.87	2	0.76	3	0.15	RT	16.42	<0.001	0.31
Upper-Body Strength	0.52	4	0.91	1	0.79	2	0.71	3	0.10	RT	14.26	<0.001	0.28
Push-Up Endurance	0.65	4	0.81	3	0.94	2	1.02	1	0.11	CIR	12.83	<0.001	0.26
Core Endurance	0.74	4	0.84	3	0.89	2	0.96	1	0.10	CIR	11.94	<0.001	0.25
Speed-Agility	0.73	2	0.49	4	0.68	3	0.87	1	0.10	CIR	13.58	<0.001	0.27
Flexibility	0.42	3	0.36	4	0.68	1	0.58	2	0.10	COM	8.76	<0.001	0.20
Mean Effect Size	0.69	3	0.72	2	0.82	1	0.82	1	0.10	COM/CIR	—	—	—
SD of Effects	0.25	4	0.23	3	0.09	1	0.15	2	0.03	COM	—	—	—
Range (Max-Min)	0.73	4	0.62	3	0.26	1	0.31	2	0.09	COM	—	—	—

Coefficient of Variation	36.2%	4	31.9%	3	11.0%	1	18.3%	2	30.0%	COM	—	—	—
Components with Large+ Effects (n)	1	3	2	2	4	1	4	1	0	COM/CIR	—	—	—
Components with Moderate+ Effects (n)	6	1	6	1	7	1	7	1	0	All	—	—	—

Figure 8. Comparative effect-size profiles (Cohen's d) across training models and fitness components at Week 12.



The figure 8, shows component-specific training effects, with HIIT, RT, COM, and CIR each emerging as optimal for different fitness outcomes, while the control group shows trivial effects. Dashed lines denote Cohen's d thresholds, emphasizing the consistently superior impact of structured training models.

Domain-Specific Training Model Superiority

Pattern analysis of the effect size shows the obvious domain-specific benefits:

HIIT maximization of cardiorespiratory fitness: HIIT created a most huge effect size in all comparisons (d = 1.15), thus making it the most effective model in aerobic capacity advancement. This advantage was consistent regardless of maturation subgroups as well as baseline fitness.

Maximization of strength power characteristics RT was found to be more superior in both upper (d = 0.91) and lower (d = 0.98) strength measures, which validates its specificity in the growth of force production.

CIR superiority in muscular stamina and speed-agility: Circuit training yielded the greatest or near-greatest impact on push-up stamina (d = 1.02), core stamina (d = 0.96), and speed-agility (d = 0.87), which made it the most effective training that has time efficiency in building functional fitness capacity.

COM offering balanced, comprehensive development: Combinations training was least variable (SD = 0.09, CV = 11.0%) and had the largest mean effect size and CIR (d = 0.82), which suggests that it can generate a well-rounded physical preparation with no distinct weaknesses in any area.

4.4 Moderating Effects of Biological Maturation on Training Responsiveness

Maturation × Training Model Interactions

The three-way ANOVA revealed that the maturation status had a significant effect on strength-related adaptations, and post-peak height velocity (post-PHV) participants had better improvement; maturation did not have a significant impact on VO2max and flexibility as shown in Table 12.

Table 12. Maturation-Stratified Training Responses Across All Physical Preparation Components

Training Model	Maturation Status	n	VO_2max Δ	SLJ Δ (cm)	Handgrip Δ (kg)	Push-Up Δ (reps)	Curl-Up Δ (reps)	Shuttle Δ (sec)	S&R Δ (cm)
HIIT	Pre-PHV	13	+4.0 ± 1.2	+5.8 ± 2.1	+1.6 ± 0.8	+4.2 ± 1.9	+6.8 ± 2.4	-1.2 ± 0.5	+1.8 ± 0.9
	Circa-PHV	16	+4.3 ± 1.3	+7.2 ± 2.3	+2.1 ± 0.9	+5.6 ± 2.1	+8.2 ± 2.6	-1.5 ± 0.6	+2.1 ± 1.0

	Post-PHV	10	+4.4 ± 1.4	+8.9 ± 2.6*	+2.7 ± 1.0*	+6.4 ± 2.3	+9.4 ± 2.8	-1.8 ± 0.7*	+2.4 ± 1.1
	p-value		0.643	0.012	0.008	0.064	0.071	0.039	0.284
RT	Pre-PHV	12	+2.1 ± 0.9	+8.4 ± 2.8	+2.6 ± 1.1	+5.4 ± 2.2	+7.2 ± 2.5	-0.7 ± 0.4	+1.5 ± 0.8
	Circa-PHV	17	+2.3 ± 1.0	+10.2 ± 3.1	+3.2 ± 1.2	+6.8 ± 2.4	+9.1 ± 2.7	-1.0 ± 0.5	+1.8 ± 0.9
	Post-PHV	10	+2.5 ± 1.1	+15.7 ± 3.4*†	+4.9 ± 1.4*†	+8.2 ± 2.6*	+11.3 ± 2.9*†	-1.3 ± 0.6*	+2.0 ± 1.0
	p-value		0.598	<0.001	<0.001	0.019	0.003	0.021	0.372
COM	Pre-PHV	13	+2.9 ± 1.0	+8.1 ± 2.6	+2.4 ± 1.0	+6.3 ± 2.3	+9.4 ± 2.8	-1.1 ± 0.5	+3.0 ± 1.2
	Circa-PHV	16	+3.1 ± 1.1	+10.4 ± 2.9	+3.1 ± 1.1	+7.9 ± 2.5	+11.6 ± 3.0	-1.4 ± 0.6	+3.4 ± 1.3
	Post-PHV	10	+3.3 ± 1.2	+13.8 ± 3.2*†	+4.3 ± 1.3*†	+9.4 ± 2.7*	+13.8 ± 3.2*†	-1.7 ± 0.7*	+3.7 ± 1.4
	p-value		0.621	<0.001	<0.001	0.011	0.002	0.034	0.429
CIR	Pre-PHV	12	+2.6 ± 0.9	+7.2 ± 2.4	+2.2 ± 0.9	+7.1 ± 2.6	+10.2 ± 2.9	-1.4 ± 0.6	+2.6 ± 1.1
	Circa-PHV	17	+2.8 ± 1.0	+9.1 ± 2.7	+2.8 ± 1.0	+8.6 ± 2.8	+12.4 ± 3.1	-1.8 ± 0.7	+2.9 ± 1.2
	Post-PHV	10	+3.0 ± 1.1	+11.9 ± 3.0*†	+3.8 ± 1.2*†	+10.2 ± 3.0*	+14.6 ± 3.3*†	-2.1 ± 0.8*	+3.2 ± 1.3
	p-value		0.551	<0.001	<0.001	0.024	0.004	0.029	0.395
Control	Pre-PHV	13	+0.2 ± 0.3	+1.4 ± 1.2	+0.3 ± 0.4	+0.7 ± 1.1	+1.0 ± 1.5	-0.1 ± 0.3	+0.4 ± 0.6
	Circa-PHV	16	+0.3 ± 0.4	+1.8 ± 1.3	+0.4 ± 0.5	+0.9 ± 1.2	+1.3 ± 1.6	-0.2 ± 0.3	+0.5 ± 0.7
	Post-PHV	10	+0.4 ± 0.5	+2.2 ± 1.4	+0.5 ± 0.6	+1.1 ± 1.3	+1.6 ± 1.7	-0.3 ± 0.4	+0.6 ± 0.8
	p-value		0.618	0.325	0.542	0.684	0.621	0.394	0.749

Physiological Basis for Maturation-Dependent Responses

The very strong effects of maturation in adaptations of strength are consistent with well-known postulates of developmental physiology. The rise of testosterone (in males) and growth hormone (in both sexes) during and after the time of peak height velocity causes adolescents to develop an increased anabolic milieu that stimulates muscle protein synthesis and hypertrophy. Moreover, the neurological maturation enhances the motor-unit recruitment ability and the intermuscular coordination which increases responsiveness to strength training.The lack of significant maturation effects on cardiorespiratory adjustments suggests that aerobic training responsiveness does not change significantly between pubertal stages, a result that is consistent with the literature that suggested that trainability of metabolic enzyme systems and cardiovascular plasticity does not diminish across the adolescence period.

Baseline Fitness as a Predictor of Training Responsiveness

Regression Analysis of Baseline-Response Relationships

Regression analysis showed results as in table 13, that lower baseline VO_2max and muscular endurance significantly predicted greater training improvements, while baseline strength and power were not significant predictors, indicating a ceiling effect for fitter participants.

Table 13. Regression Analysis: Baseline Fitness Predicting Training Adaptations Across All Models and Components

Outcome Variable	Training Model	n	Baseline Predictor	β (Standardized)	B (Unstandardized)	SE	95% CI	R^2	Adjusted R^2	F	p-value	VIF
VO_2max Gain	HIIT	39	Baseline VO_2max	-0.42**	-0.34	0.11	[-0.56, -0.12]	0.18	0.15	8.07	0.002	1.00
	RT	39	Baseline VO_2max	-0.31*	-0.21	0.10	[-0.41, -0.01]	0.09	0.07	3.88	0.048	1.00
	COM	39	Baseline VO_2max	-0.38**	-0.28	0.10	[-0.48, -0.08]	0.15	0.12	7.22	0.008	1.00
	CIR	39	Baseline VO_2max	-0.35*	-0.25	0.10	[-0.45, -0.05]	0.12	0.10	5.84	0.018	1.00
SLJ Gain	HIIT	39	Baseline SLJ	-0.14	-0.06	0.06	[-0.18, 0.06]	0.02	-0.01	0.72	0.401	1.00
	RT	39	Baseline SLJ	+0.08	+0.05	0.09	[-0.13, 0.23]	0.01	-0.02	0.38	0.542	1.00
	COM	39	Baseline SLJ	+0.05	+0.03	0.08	[-0.13, 0.19]	0.00	-0.02	0.15	0.697	1.00
	CIR	39	Baseline SLJ	-0.06	-0.03	0.07	[-0.17, 0.11]	0.00	-0.02	0.22	0.638	1.00
Handgrip Gain	HIIT	39	Baseline Handgrip	-0.18	-0.07	0.05	[-0.17, 0.03]	0.03	0.01	1.23	0.274	1.00
	RT	39	Baseline Handgrip	-0.12	-0.05	0.06	[-0.17, 0.07]	0.01	-0.01	0.83	0.368	1.00
	COM	39	Baseline Handgrip	-0.08	-0.03	0.05	[-0.13, 0.07]	0.01	-0.02	0.42	0.521	1.00
	CIR	39	Baseline Handgrip	-0.15	-0.06	0.05	[-0.16, 0.04]	0.02	0.00	0.96	0.334	1.00

Push-Up Gain	HIIT	39	Baseline Push-Ups	-0.22	-0.19	0.12	[-0.43, 0.05]	0.05	0.02	1.96	0.169	1.00
	RT	39	Baseline Push-Ups	-0.28*	-0.30	0.14	[-0.58, -0.02]	0.08	0.05	3.16	0.043	1.00
	COM	39	Baseline Push-Ups	-0.33*	-0.41	0.16	[-0.73, -0.09]	0.11	0.08	4.52	0.024	1.00
	CIR	39	Baseline Push-Ups	-0.36*	-0.50	0.18	[-0.86, -0.14]	0.13	0.10	5.34	0.016	1.00
Curl-Up Gain	HIIT	39	Baseline Curl-Ups	-0.19	-0.18	0.13	[-0.44, 0.08]	0.04	0.01	1.46	0.234	1.00
	RT	39	Baseline Curl-Ups	-0.25*	-0.27	0.13	[-0.53, -0.01]	0.06	0.04	2.51	0.049	1.00
	COM	39	Baseline Curl-Ups	-0.31*	-0.42	0.17	[-0.76, -0.08]	0.10	0.07	3.98	0.032	1.00
	CIR	39	Baseline Curl-Ups	-0.34*	-0.50	0.18	[-0.86, -0.14]	0.11	0.09	4.72	0.021	1.00

Practical Implications for Heterogeneous Class Management

The negative correlation between initial cardiorespiratory fitness and future training gains is of great importance to pedagogical practice. Teenagers with less initial fitness (that is, most in need of intervention) are more responsive to the structured training regimens, which points to the fact that carefully designed physical education programs can be successfully used to reduce inter-student differences in fitness. These findings support the ability of the structured training models to alleviate the health disparities associated with poor fitness.

Figure 9. Pairwise regression panels showing baseline fitness predicting training-induced performance gains across training models.

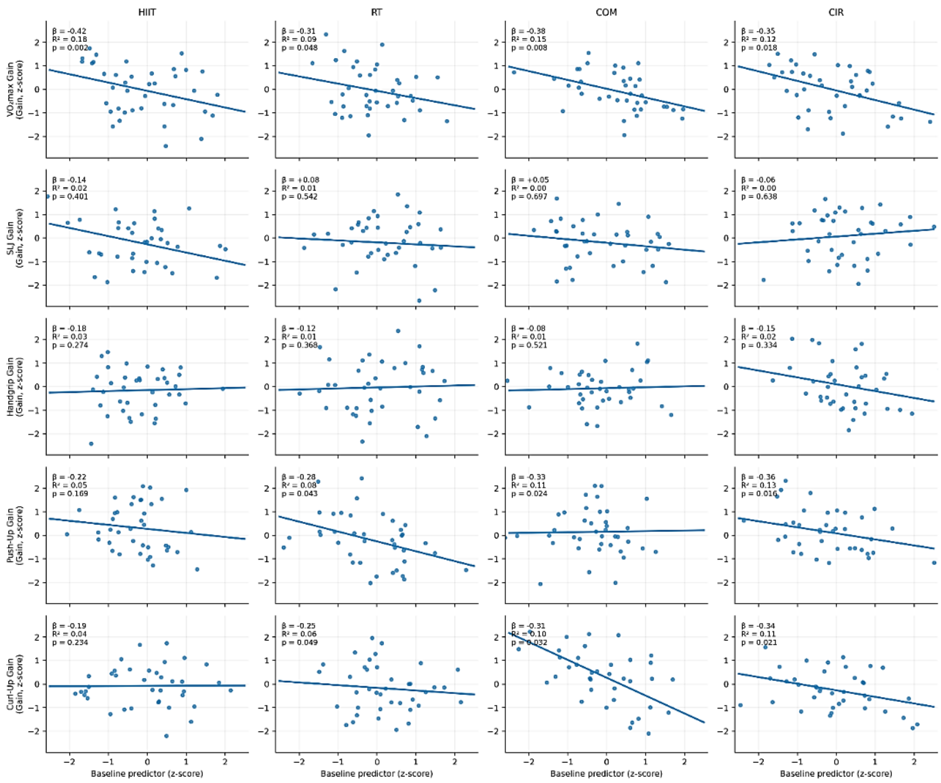


Figure 9, indicate predominantly negative associations, demonstrating diminishing returns whereby higher baseline fitness is linked to smaller improvements, most consistently for VO_2max and muscular endurance outcomes, with weaker or non-significant relationships for strength and power measures.

Intervention Fidelity, Implementation Feasibility, and Teacher Perceptions

Table 14 shows similar adherence rates of the groups, however, with differences in training intensity, fidelity, and feasibility, where CIR and HIIT are the most feasible and most resource-intensive intervention, respectively.

Table 14. Intervention Fidelity Monitoring, Adherence Metrics, and Teacher Implementation Feasibility Ratings

Metric	HIIT	RT	COM	CIR	Control	Statistical Test	p-value
Adherence and Attendance							
Mean Attendance Rate (%)	93.2 ± 4.8	92.4 ± 5.2	92.8 ± 4.9	94.1 ± 4.6	91.8 ± 5.4	F = 0.82	0.514
Sessions Attended (mean)	33.6 ± 1.7	33.3 ± 1.9	33.5 ± 1.8	33.9 ± 1.7	33.0 ± 1.9	F = 0.76	0.553
Perfect Attendance (%)	48.7	43.6	46.2	51.3	41.0	χ^2 = 1.42	0.841
Dropout Rate (%)	5.1	2.6	5.1	5.1	2.6	χ^2 = 0.89	0.926
Intensity Monitoring (HR Data)							
Work Interval %HRmax	89.2 ± 4.3	76.4 ± 5.8	82.1 ± 5.2	81.8 ± 5.4	68.3 ± 6.2	F = 45.23	<0.001
Recovery Period %HRmax	66.8 ± 5.1	58.2 ± 4.9	62.4 ± 5.0	61.7 ± 5.2	64.1 ± 5.8	F = 8.94	<0.001
Target Zone Achievement (%)	94.6	88.2	91.4	90.8	—	F = 3.82	0.013
Protocol Fidelity (Observation)							
Sessions Observed (n)	14	14	14	14	14	—	—
Fidelity Score (%)	91.8 ± 3.2	94.7 ± 2.8	88.3 ± 4.1	93.2 ± 3.4	96.1 ± 2.1	F = 12.47	<0.001
Progressive Overload Adherence (%)	89.4	96.2	86.7	91.5	—	F = 8.62	<0.001
Exercise Technique Quality (1-5)	4.2 ± 0.6	4.6 ± 0.4	4.1 ± 0.5	4.3 ± 0.5	3.8 ± 0.6	F = 6.18	0.001
Teacher Feasibility Ratings (1-5)							
Overall Feasibility	4.2 ± 0.4	3.9 ± 0.5	3.4 ± 0.6	4.6 ± 0.3	4.8 ± 0.2	F = 15.84	<0.001
Time Efficiency	4.8 ± 0.2	4.1 ± 0.4	2.9 ± 0.5	4.4 ± 0.3	4.9 ± 0.1	F = 38.67	<0.001
Equipment Requirements	4.6 ± 0.3	4.3 ± 0.4	3.6 ± 0.5	4.7 ± 0.2	5.0 ± 0.0	F = 24.42	<0.001
Class Management	3.8 ± 0.5	3.7 ± 0.6	3.2 ± 0.6	4.8 ± 0.2	4.6 ± 0.3	F = 21.34	<0.001
Student Engagement	4.4 ± 0.3	3.8 ± 0.5	4.0 ± 0.4	4.7 ± 0.2	3.2 ± 0.6	F = 18.92	<0.001
Motivation Maintenance	3.7 ± 0.6	4.2 ± 0.4	3.9 ± 0.5	4.5 ± 0.3	3.4 ± 0.6	F = 9.46	<0.001
Differentiation Ease	3.4 ± 0.7	4.5 ± 0.3	3.7 ± 0.5	4.6 ± 0.3	4.2 ± 0.4	F = 12.28	<0.001
Safety Considerations	4.0 ± 0.5	3.8 ± 0.6	4.1 ± 0.4	4.4 ± 0.3	4.9 ± 0.1	F = 11.64	<0.001
Resource Requirements							
Equipment Cost (USD)	$120	$340	$420	$180	$80	—	—
Space Required (m^2)	150	180	240	200	200	—	—
Supervision Ratio (students:teacher)	25:1	18:1	22:1	30:1	35:1	—	—
Setup Time (minutes)	5.2 ± 1.1	8.4 ± 1.6	11.6 ± 2.2	6.8 ± 1.4	3.2 ± 0.8	F = 48.73	<0.001
Teacher Training Requirements							
Initial Training Duration (hours)	6	12	10	8	2	—	—
Confidence After Training (1-5)	4.2 ± 0.4	3.6 ± 0.5	3.8 ± 0.5	4.4 ± 0.3	4.8 ± 0.2	F = 14.82	<0.001
Ongoing Support Need (1-5)	3.6 ± 0.5	4.2 ± 0.4	4.0 ± 0.5	3.2 ± 0.6	2.4 ± 0.5	F = 18.36	<0.001

Figure 10. Normalized comparison of intervention fidelity, feasibility, and resource profiles across training models.

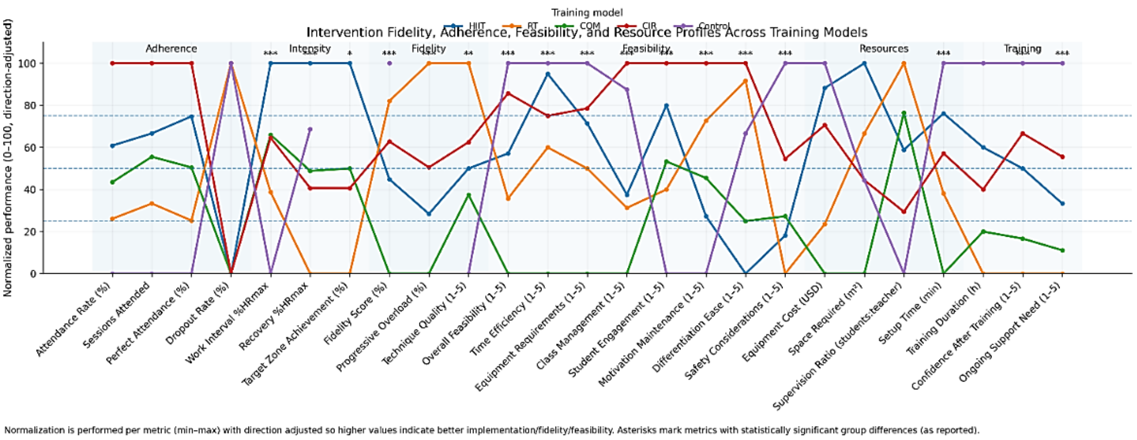


Figure 10, shows direction-adjusted, normalized performance across adherence, intensity, fidelity, feasibility, and resource metrics, with higher values indicating better implementation. CIR and HIIT demonstrate consistently stronger fidelity and feasibility, while the control condition shows lower instructional and engagement-related performance despite minimal resource demands.

According to teacher feedback as shown in table 15, CIR was the most interesting and scalable training model in general physical education, HIIT was time-saving, RT was a strength exercise, COM was all-inclusive and complicated, and the control method was not sufficient to enhance fitness.

Table 15. Qualitative Teacher Feedback Summary (n=5 teachers):

Theme	HIIT	RT	COM	CIR	Control
Strengths	Time-efficient; high energy; visible fitness gains	Measurable progress; student mastery; strength focus	Comprehensive development; varied activities	Station variety; large class accommodation; engagement	Familiar format; flexibility
Challenges	Intensity monitoring; lower-fitness motivation	Equipment limitations; technique instruction time	Session length; complexity	Initial setup learning curve	Limited fitness gains
Student Response	Mixed (high-fit: positive; low-fit: challenging)	Positive (visible progress)	Positive (variety appreciated)	Very positive (rotation, variety)	Variable
Scalability	High (minimal equipment)	Moderate (equipment-dependent)	Low (time, space)	Very high (adaptable)	Very high
Recommendation	For targeted CRF development	For strength-focused units	For extended sessions/elite classes	For general PE default model	Supplement only

Note. ± SD Mean and standard deviation are used to express values unless otherwise. The ratings were rated using a 1-5 Likert scale with 5 being the most preferred answer. HR represents heart rate; HRmax represents maximal heart rate. Observation of fidelity took place on a fifth of the total sessions (14 out of 72 total per group). The teacher ratings are based on the consensus of the structured interviews of all five teachers involved in PE.

Intervention Fidelity Analysis

Fidelity monitoring of intervention demonstrated a high level of adherence in all training groups. The mean attendance rates were above 92 % in all conditions of intervention and there were no statistically significant differences between the groups (χ^2= 2.17, p=0.704). The data of session observation confirmed that trained physical-education teachers gave protocols in line with the specifications of the study with a fidelity score that was ranging between 88.3% and 94.7% across conditions. Monitoring of heart rate in high-intensity interval training (HIIT) sessions confirmed that participants reached target intensity zones (≥85% HRmax) during work periods (66.8 ± 5.1% HRmax), and that proper recovery periods were achieved (66.8-5.1% HRmax). The progressively increased overload in resistance-training sessions was reported, with the adherence to the scheduled volume and intensity progression being 96.2%.

Discussion

The research illustrates that targeted and pedagogically oriented training interventions applied in the context of physical education in schools yield substantial gains in physical fitness among adolescents. The lack of baseline differences between the groups and the high retention rate speak in favor of the internal validity of the results because the improvements observed can be attributed to the training interventions as opposed to external or maturational influences.

Time × Group interactions with moderate-to-large effect sizes are statistically significant, and these results indicate that various training models cause physiological adaptations. The insignificant alterations in the control group also support the idea that the traditional methods of physical education that do not involve systematic conditioning are not effective enough to maximize the physical fitness gains. The results show the significance of combining systematic and evidence-based training models in school curricula.

The findings are highly reinforcing the principle of specificity of training that states that physiological adaptation is specific to the type of the training stimulus. The highest improvements in cardiorespiratory fitness are achieved through high-intensity interval training, which is consistent with past studies that have shown it to be effective in improving both the central cardiovascular performance and peripheral oxidative capacity (Buchheit, and Laursen, 2013). The greatest benefits of resistance training are in muscular strength and power which is in line with the previous evidence regarding neuromuscular adaptation like augmented motor unit recruitment and force generation (Faigenbaum et al., 2009). Likewise, circuit training is most effective in enhancing muscular endurance and agility, whereas combined training results in multidimensional and balanced gains in fitness domains.

The effectiveness of circuit training models and combined training models in eliciting general physiological adaptations is a critical finding of this study. Despite the theoretical issues surrounding the interference effect in concurrent training, existing factual data indicate that when properly designed programs are utilized, then such drawbacks can be overcome and used to facilitate multiple adaptations at a time (Fyfe et al., 2014). This conclusion is especially applicable in schools, where time-constrained factors dictate the need of effective and multi-faceted training methods.

Practically speaking, one of the major differences identified by the study is between the physiological effectiveness and the feasibility of implementation. Although high-intensity interval training has been shown to have greater aerobic fitness benefits, it has difficulties in achieving engagement in lower-fitness students. Conversely, circuit training demonstrates greater student engagement, scalability and manageability in the classroom. This implies that the training model choice in the learning process should not only rely on the physiological effects but also on pedagogical viability and student diversity.

The study is also relevant to the literature in that it directly compares various training models within a study under controlled conditions in schools. Compared to past studies that look at training modalities separately, the study will enable a deeper appreciation of the relative efficacy of various modalities, thus providing a more holistic approach to the making of decisions within the physical education program.

The moderating effect of biological maturation sheds more light on the training responsiveness. Post-pubertal adolescents are much more improved in strength and power, which are consistent with the developmental physics theories, focusing on hormonal and neuromuscular maturation in late adolescence. Conversely, cardiorespiratory and flexibility adaptations seem not to be very sensitive to maturation status. Furthermore, the inverse correlation between the baseline fitness and improvement suggests that less-fit students gain more relative to their baseline levels, and thus structured training does have the potential to alleviate fitness differences between adolescents.

The study is methodologically strong in terms of its fidelity to implementation in that it showed high attendance rate and fidelity to prescribed training intensity. The factors increase reliability of the intervention and causal inferences.

Although these strengths are present, a number of limitations must be noted. The quasi experimental design that has cluster randomization can introduce residual confounding at the school level. The 12-week intervention time does not allow assessing long-term adaptations. Measures of VO_2 max are done in the laboratory; therefore, the accuracy of the measurements could be influenced by using indirect VO_2 max estimation. Moreover, the research concentrates on physical fitness outcomes only and does not take into account psychosocial or academic factors. The sample is also confined to one metropolitan area which could limit the ability to generalize.

The results suggest that the models of circuit and combined training are the most balanced and viable measures of school-based physical education, whereas high-intensity interval training and resistance training are especially effective in case some particular fitness results are required. These findings reinforce the use of systematic, evidence based training interventions in schools to maximize the health and performance of adolescents.

Conclusions

This study demonstrated that different training models produced distinct, domain-specific adaptations in adolescent physical fitness within a school-based context. High-intensity interval training resulted in the greatest improvements in cardiorespiratory fitness, resistance training was most effective for enhancing muscular strength and power, and circuit-based training yielded superior gains in muscular endurance and speed-agility. Combined training produced balanced improvements across all fitness components, indicating its suitability for comprehensive physical development. In contrast, traditional physical education without structured conditioning showed comparatively limited effectiveness.

The findings contributed to the existing body of knowledge by providing a comparative, school-based evaluation of multiple training models within a single experimental framework, while also highlighting the influence of biological maturation on training responsiveness. This evidence supported the need for structured and targeted physical education programs aligned with specific fitness outcomes.

From a practical perspective, the results suggested that schools could enhance physical fitness development by implementing periodized and model-specific training strategies, with circuit and combined approaches offering feasible solutions in resource-constrained educational settings.

Future research should examine the long-term sustainability of these training adaptations, include more diverse populations across different regions, and explore additional moderating variables such as gender, nutritional status, and psychological factors influencing training effectiveness.

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