©Journal of Sports Science and Medicine (2026) **25**, 950-959
http://www.jssm.org DOI: https://doi.org/10.52082/jssm.2026.950

Review article

Effects of Exercise Type and Dose on Cardiorespiratory Fitness in Children and Adolescents: A Systematic Review and Bayesian Multilevel Network Meta-Analysis

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Abstract
Cardiorespiratory fitness (CRF), commonly assessed using maximal oxygen uptake (VO_2max), is an important health marker in children and adolescents. We compared the effects of different exercise types and examined dose-response associations with CRF. PubMed, Embase, the Cochrane Library, and Web of Science were searched from inception to June 2026 for randomized controlled trials involving participants younger than 18 years. All analyses were conducted after the final search. Interventions were classified as high-intensity interval training (HIIT), sprint interval training (SIT), high-intensity aerobic exercise (HAE), moderate-intensity aerobic exercise (MAE), combined exercise (CE), or resistance exercise (RE). We performed an arm-based Bayesian multilevel random-effects network meta-analysis and Bayesian meta-regression. Fifty-two trials involving 4, 308 participants were included. Compared with the control group, HIIT had the largest estimated improvement in CRF (mean difference [MD] = 2.50, 95% credible interval [CrI]: 1.46 to 3.51), followed by SIT (MD = 2.05, 95% CrI: 0.85 to 3.22), CE (MD = 1.95, 95% CrI: 0.87 to 2.98), and HAE (MD = 1.25, 95% CrI: 0.09 to 2.41). The intervals for MAE and RE included the null value. Dose-response analyses showed the highest posterior mean effects around 1,100 METy-min/week, 40 min/session, and a METy-based intensity of approximately 8.5 METy, although the weekly-dose estimate remained imprecise. Exercise interventions were associated with improved CRF in children and adolescents, with HIIT and SIT ranking most favorably. Study-level analyses suggested favorable patterns around 1,100 METy-min/week, 40 min/session, and 8.5 METy, although these should not be considered precise optimal prescriptions.

Key words: Pediatric population, Youth, Physical training, VO_2max, Dose-response relationship.

Introduction

Cardiorespiratory fitness (CRF) reflects the integrated capacity of the circulatory and respiratory systems and skeletal muscles to take up, transport, and utilize oxygen during sustained physical activity (Raghuveer et al., 2020). It is a marker of cardiometabolic risk and an indicator of overall health status. Maximal oxygen uptake (VO_2max) is a commonly used measure of CRF and reflects aerobic exercise capacity (Harber et al., 2024). Higher CRF is associated with lower incidence and mortality from a range of chronic diseases (Kodama et al., 2009).

Childhood and adolescence are important developmental periods for cardiopulmonary function, metabolic systems, and physical performance. Higher CRF during these stages is associated with better physical functioning, cardiovascular health, mental health, and academic performance (García-Hermoso et al., 2020). CRF is therefore an important biological and public health indicator of current and longer-term health in children and adolescents (Ekelund et al., 2007). Improving CRF during childhood and adolescence may therefore contribute to the early prevention of cardiovascular risk and support long-term cardiovascular health.

Exercise is an important modifiable strategy for improving CRF in children and adolescents (Demchenko et al., 2025). However, several evidence gaps remain. Most previous syntheses have used traditional pairwise meta-analysis and have been restricted to school settings (Pozuelo-Carrascosa et al., 2018), single exercise modalities (Solera-Martínez et al., 2021), or specific populations (Steiman De Visser et al., 2024). These studies support beneficial effects of exercise but do not permit simultaneous comparisons across multiple exercise types. The World Health Organization (WHO) has also noted insufficient evidence to establish dose-response relationships between physical activity and health outcomes in children and adolescents aged 5-17 years (Chaput et al., 2020). Evidence integrating exercise dose to identify potentially favourable ranges for improving CRF remains limited. Moreover, developmental differences in CRF adaptation limit direct extrapolation from adults to younger populations. Meta-analytic evidence covering the broader population of children and adolescents, with VO_2max as the primary outcome, is also limited. Clinicians and educators therefore lack quantitative guidance on which exercise modalities and doses may improve CRF in these populations.

We used an arm-based Bayesian multilevel network meta-analysis to compare the relative effects of exercise modalities on CRF in children and adolescents while accounting for the hierarchical data structure and correlations among arms in multi-arm trials. We also applied Bayesian multilevel meta-regression to examine associations between exercise dose characteristics and changes in VO_2max. By integrating direct and indirect evidence and evaluating dose-related patterns, the study was intended to inform school-based physical activity interventions, youth health promotion, and exercise program design.

Methods

Protocol and registration
This study was conducted and reported in accordance with

Received: 27 July 2026 / Accepted: 13 October 2026 / Published (online): 01 December 2026

the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension statement for network meta-analyses (PRISMA-NMA) (Hutton et al., 2015) and the Cochrane Handbook for Systematic Reviews of Interventions (Higgins et al., 2024). The study protocol was registered in PROSPERO (registration number: CRD420261299173).

Eligibility criteria

We included studies that met the following Population, Intervention, Comparator, Outcome and Study design (PICOS) criteria.

Population. Eligible participants were children and adolescents younger than 18 years, including those with normal weight, overweight, or obesity.

Interventions. Any form of exercise intervention was eligible. Interventions were classified into six categories, as defined in Table 1. They could be delivered in laboratories, gyms, or outdoor settings, or integrated into school curricula or existing physical education program.

Comparators. Comparators included both direct comparisons between different exercise types and comparisons between exercise intervention groups and control groups. Control groups received non-exercise interventions, such as daily activities, health education, or sham treatment, or received no intervention.

Outcomes. The primary outcome was VO_2max. Measurement methods were categorized as either direct or indirect and included graded exercise tests, 20-m shuttle run tests, and submaximal exercise tests.

Study design. We included randomized controlled trials (RCTs), including individually randomized and cluster-randomized parallel-group trials. No minimum adherence or compliance threshold was prespecified for study eligibility.

Exclusion criteria

Studies were excluded according to the following criteria: (1) studies combining exercise interventions with other components (e.g., nutritional intervention and breathing exercises), such that the independent effect of exercise could not be determined; (2) studies that did not provide detailed information on exercise intensity; (3) studies lacking mean and standard deviation data, or for which such data could not be converted into the required format; and (4) non-RCTs, observational studies, and reviews.

Search strategy and study selection

We conducted a systematic search of four electronic databases: PubMed, Embase, the Cochrane Library (CENTRAL) and Web of Science. The literature search covered the period from database inception to June 2026, with no restrictions on language or publication region. The search strategy combined Medical Subject Headings (MeSH) and free-text terms constructed around four core concepts: children or adolescents, cardiorespiratory fitness, exercise interventions, and RCTs. The detailed search strategy is provided in Supplementary Material 1 (*https://www.jssm.org/SM/Man9527-2026SupplMaterials.pdf*). We also manually screened the reference lists of relevant systematic reviews and meta-analyses to identify additional eligible studies. Study selection was performed independently by two reviewers. Initial screening was based on titles and abstracts, followed by full-text review for final eligibility. Disagreements were resolved through discussion and consensus or, when necessary, consultation with a third reviewer. The selection process was documented and presented using a PRISMA flow diagram.

Data extraction and coding

Data extraction focused on several key domains. First, we collected general study information, including study identifiers, country, and funding source. Second, we extracted baseline participant characteristics, including age, sex ratio, body mass index (BMI), and weight. Third, we collected detailed intervention characteristics, including exercise type, supervision, intensity, session duration, frequency, and total intervention duration. When reported, we also extracted intensity-monitoring methods, adherence/compliance, control-group activities, baseline training status, and health status. Fourth, we extracted the mean, standard deviation (SD), and sample size (N) for all VO_2max outcomes before and after the intervention. To standardize exercise exposure across heterogeneous intervention protocols, exercise dose was recalculated using age-specific youth metabolic equivalent (METy) values from the Youth Compendium of Physical Activities (Butte et al., 2018). Each intervention was matched to the closest available activity code according to the reported exercise

Table 1. Definitions of exercise interventions.

Type of exercise	Abbreviation	Definition
High-intensity aerobic exercise	HAE	Intensity: > 65% VO_{2max} or > 75% HR_{max}; any aerobic exercise mode, such as walking, running, cycling, and swimming (Medicine, 2013).
Moderate-intensity aerobic exercise	MAE	Intensity: 45-65% VO_{2max} or 65-75% HR_{max}, any mode of aerobic only (e.g., walking, running, cycling and swimming) (Medicine, 2013)
High-intensity interval training	HIIT	Repetitive relatively short-interval training, performed at intensity ≥ 90% VO_{2max} or ≥ 90% HR_{max}, usually performed at below maximum intensity (Gibala and Little, 2020).
Sprint interval training	SIT	Repetitive short-interval exercise, requires "all-out" efforts at maximal work rates (Atakan et al., 2022).
Combined exercise	CE	Integrated modality of exercise that combines aerobic and resistance exercise (Mann et al., 2014).
Resistance exercise	RE	Refers to repeated voluntary muscle movements against external resistance with the primary purpose of improving muscle strength, power, or local muscle endurance (Lloyd et al., 2014).

HAE, high-intensity aerobic exercise; MAE, moderate intensity aerobic exercise; HIIT, high intensity interval training; SIT, sprint interval training; CE, combined exercise; RE, resistance exercise; VO_{2max}, maximal oxygen uptake; HR_{max}, maximal heart rate.

mode, protocol characteristics, and participant age group. Weekly exercise dose was calculated as METy × session duration × weekly exercise frequency and expressed as METy-min/week.

Risk of bias and certainty of evidence

Quality assessment was conducted at two levels. First, two reviewers independently evaluated the methodological quality of each included study using the Cochrane Risk of Bias 2 tool (RoB 2) (Higgins et al., 2011). Subsequently, we used the Confidence in Network Meta-Analysis (CINeMA) framework to rate the overall confidence in the main network meta-analysis results. This assessment considered within-study bias, reporting bias, indirectness, imprecision, heterogeneity, and incoherence in the evidence network (Nikolakopoulou et al., 2020). The confidence of each network estimate was graded as high, moderate, low, or very low.

Measures of treatment effect

The effect size was expressed as mean difference (MD), quantifying the change in VO_2max from baseline to the end of the intervention in each treatment group. We extracted the mean, SD, and sample size for each group at both pre-intervention and post-intervention time points. We first calculated the mean change within each group and then estimated the SD of the change score using the pre- and post-intervention SD. For this estimation, we assumed a correlation coefficient of 0.5 between pre- and post-intervention measurements, consistent with previous VO_2max studies (van Baak et al., 2021). For studies that did not report the required SD, SDs were derived from reported standard error (SE), 95% confidence interval (CI), or other available statistical information (Higgins et al., 2024).

Statistical analysis

Main effects analysis

The primary analysis used an arm-based Bayesian multilevel random-effects model because the extracted outcomes consisted of arm-level pre-post changes and several included trials contained multiple intervention arms. This framework retained arm-level information while accounting for the hierarchical dependence of arm-level observations within studies. Specifically, we performed a three-level Bayesian network meta-analysis (NMA) with random intercepts at the study and arm-within-study levels. To address multiple outcomes or follow-up time points reported for the same intervention arm, effect sizes within each arm were aggregated into a single composite estimate before the NMA. Priors for fixed effects were specified as Normal (0, 1), and variance components were assigned weakly informative Cauchy (0, 1) priors (Gelman, 2006). To ensure model stability and convergence, we ran eight Markov chains for 6,000 iterations each and discarded the first 3,000 iterations as warm-up (Carpenter et al., 2017). We reported posterior means and 95% credible intervals (CrI) for each intervention relative to the control group. To quantify the strength of evidence, Bayes factors (BFs) were calculated at two levels (Gronau et al., 2020; Wagenmakers et al., 2010). First, we used the Savage-Dickey density ratio to evaluate the evidence for the effect of each exercise intervention relative to a null effect. Second, we compared a full model including all exercise terms with an intercept-only null model and calculated BFs to evaluate the overall effectiveness of exercise interventions.

Network consistency was assessed in two steps. First, the transitivity assumption was evaluated qualitatively by comparing the distribution of key effect modifiers across comparisons. Second, a global inconsistency test was performed to assess overall network consistency (Higgins et al., 2012), supplemented by local evaluation with the node-splitting method (Dias et al., 2010). Furthermore, surface under the cumulative ranking curve (SUCRA) values were calculated to rank the interventions (Salanti et al., 2011). All analyses were conducted in R using packages such as brms, metafor and netmeta. Effect-size preparation and related data handling were performed using the metafor package. The primary arm-based Bayesian multilevel network meta-analysis and Bayesian meta-regression models were fitted in brms. The netmeta package was used for supplementary frequentist network procedures, including network visualization, design-by-treatment inconsistency assessment, node-splitting analyses, and treatment ranking summaries. Accordingly, the primary relative effect estimates were derived from the Bayesian models, whereas netmeta was used as a complementary diagnostic and descriptive tool.

Meta-regression

Separate Bayesian multilevel meta-regression models were used to examine six study-level moderators: weekly exercise dose, session duration, METy-based exercise intensity, mean BMI, mean body weight, and the proportion of female participants. For each moderator, linear and nonlinear models using thin plate regression splines were compared. Model complexity was varied by changing the basis dimension (knots = 3 and knots = 4). Final model selection was based primarily on the leave-one-out cross-validation information criterion (LOOIC) (Wood, 2003), with the Watanabe Akaike information criterion (WAIC) used as a supplementary reference (Vehtari et al., 2017). The model with the lowest value was selected for final inference and interpretation.

Assessment of publication bias

Publication bias and small-study effects were assessed using two complementary funnel plot approaches. First, significance funnel plots were generated using the Publication Bias package (Mathur and VanderWeele, 2020). Studies were classified as “affirmative” or “non-affirmative” according to whether the result reached statistical significance in the preferred effect direction. We also calculated a worst-case corrected pooled effect based solely on the non-affirmative studies to evaluate the sensitivity of the findings to potential publication bias. Second, power-enhanced sunset funnel plots were constructed for each intervention type using the metaviz package. This approach helps distinguish whether non-significant findings are more likely attributable to inadequate statistical power or to selective reporting (Kossmeier et al., 2020).

Results

Study selection and characteristics

The initial search yielded 12,422 records. After removal of duplicates, 7,709 records were screened by title and abstract, of which 183 articles were assessed in full text. Among these, 131 studies were excluded for not meeting the eligibility criteria, leaving 52 studies for inclusion in the network meta-analysis. The detailed PRISMA flow diagram is shown in Figure 1. A total of 4,308 participants were included in the analysis, with 2,655 assigned to exercise intervention groups and 1,653 to control groups. Across studies, mean age ranged from 7.9 to 17.9 years, and mean BMI ranged from 16.6 to 37.8 kg/m2. In terms of intervention type, HIIT was the most frequently investigated modality (26/145 arms), whereas RE was the least studied (4/145 arms). Detailed characteristics of all included studies are presented in Supplementary Material 2 (*https://www.jssm.org/SM/Man9527-2026SupplMaterials.pdf*).

Risk of bias and quality assessment

Overall, the included studies were generally problematic. Specifically, 5 studies (9.6%) were rated as high risk of bias, 44 (84.6%) as some concerns, and 3 studies (5.8%) as low risk (Supplementary Material 3 and 4, *https://www.jssm.org/SM/Man9527-2026SupplMaterials.pdf*). Sensitivity analyses showed broadly similar pooled effects across low-risk and some-concerns strata, whereas high-risk estimates were less precise (Supplementary Material 5, *https://www.jssm.org/SM/Man9527-2026SupplMaterials.pdf*). According to the CINeMA assessment, for most exercise types (HIIT, SIT, CE, HAE, and MAE), the overall confidence in the evidence for improving VO_2max compared with control group was rated as low, whereas RE was rated as very low. These judgments were driven primarily by concerns regarding within-study bias and reporting bias across all comparisons (Supplementary Material 6, *https://www.jssm.org/SM/Man9527-2026SupplMaterials.pdf*).

Network meta-analysis

At the global level, the overall inconsistency test based on the design-by-treatment interaction model indicated significant differences across study designs ($Q = 142.77$, $df = 22$, $P < 0.0001$), and network heterogeneity was substantial ($\tau^2 = 1.84$, $I^2 = 77.3\%$). However, node-splitting analyses under the SIDE random-effects model showed that, across the 17 clinically most relevant comparisons, direct and indirect estimates were broadly consistent in both direction and magnitude, with no evidence of meaningful local inconsistency ($P > 0.05$) (Supplementary Material 7, *https://www.jssm.org/SM/Man9527-2026SupplMaterials.pdf*). These local analyses did not resolve the global inconsistency or substantial heterogeneity. Qualitative assessment also identified differences in BMI, age, and measurement protocols across intervention groups. These differences were considered clinically explainable and were reflected by downgrading indirectness for affected comparisons in the final certainty assessment.

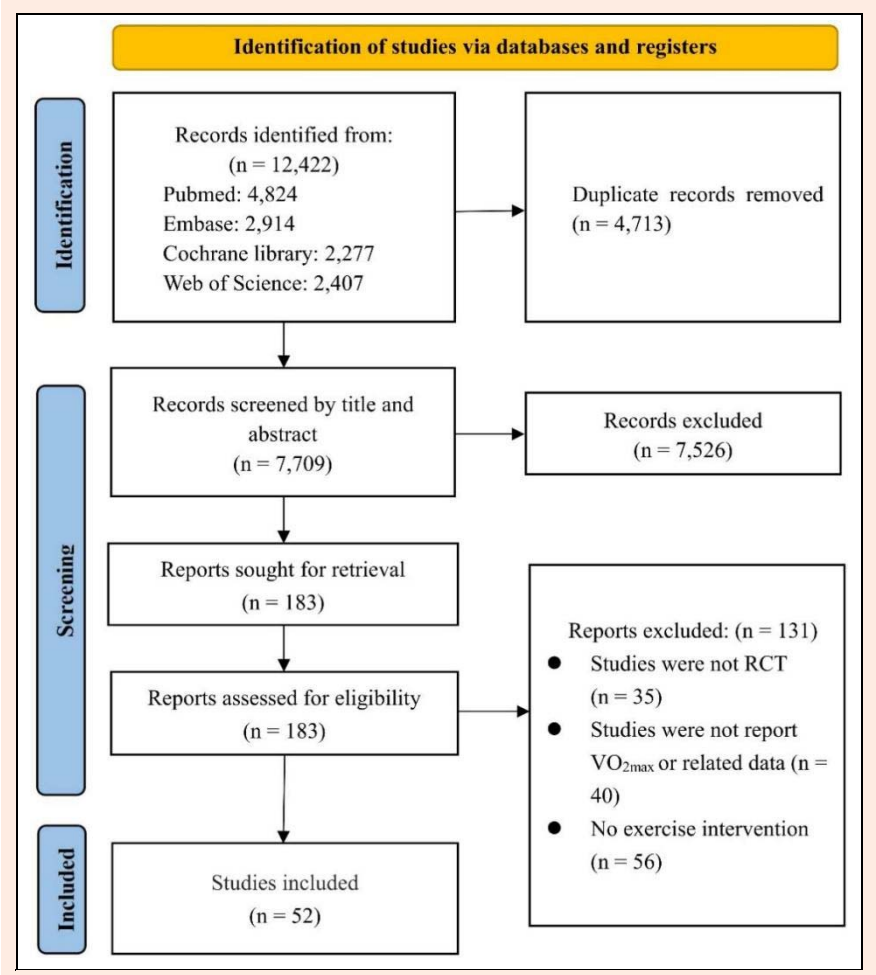

Figure 1. PRISMA flow chart.

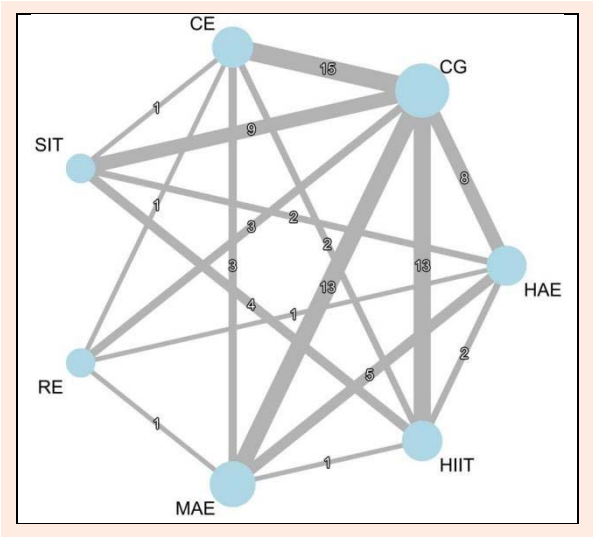

Figure 2. Network geometry of the comparisons among exercise interventions and the control group for VO_2max.

Our network meta-analysis compared the effects of six exercise modalities and a control group, with the control group serving as the most highly connected node in the network (Figure 2). Relative to the control group, HIIT (SUCRA: 93%; MD = 2.50; 95% CrI: 1.46 to 3.51) and SIT (SUCRA: 83%; MD = 2.05; 95% CrI: 0.85 to 3.22) were the most effective interventions for improving VO_2max, followed by CE (SUCRA: 68%; MD = 1.95; 95% CrI: 0.87 to 2.98) and HAE (SUCRA: 48%; MD = 1.25; 95% CrI: 0.09 to 2.41). In contrast, MAE (SUCRA: 32%; MD = 0.92; 95% CrI: -0.18 to 2.01) and RE (SUCRA: 20%; MD = 0.20; 95% CrI: -1.41 to 1.83) showed no significant effects (Figure 3).

Moderator analysis

Bayesian meta-regression suggested non-linear, study-level associations between several moderators and changes in CRF (Figure 4; Supplementary Materials 8-13, *https://www.jssm.org/SM/Man9527-2026SupplMaterials.pdf*). For weekly exercise dose, the posterior mean effect increased with dose and peaked at approximately 1,100 METy-min/week (MD = 0.58; 95% CrI: -0.31 to 1.47), after which the predicted effect gradually declined. However, the credible interval at the peak included the null value, indicating considerable uncertainty regarding a precise favorable weekly dose. For session duration, the highest posterior mean effect was observed at approximately 40 min/session (MD = 0.79; 95% CrI: 0.15 to 1.43). METy-based exercise intensity showed a separate non-linear pattern, with the highest posterior mean effect observed at approximately 8.5 METy (MD = 0.67; 95% CrI: 0.09 to 1.25). Larger predicted improvements tended to occur in studies with higher mean BMI, greater mean body weight, and a higher proportion of male participants. These ecological associations should not be interpreted as causal effects at the individual level.

Publication bias

Funnel plots based on 145 effect sizes indicated that the intervention-stratified, power-enhanced funnel plots did not suggest substantial publication bias. However, statistical power was low for MAE, RE, and CG (Supplementary Material 14, *https://www.jssm.org/SM/Man9527-2026SupplMaterials.pdf*), and these results should therefore be interpreted with caution.

Discussion

Principal findings

This study used an arm-based Bayesian multilevel network meta-analysis, combined with Bayesian meta-regression, to compare the relative effects of different exercise modalities on CRF in children and adolescents and to further examine dose-related associations with CRF improvement. The results showed that HIIT and SIT ranked most favorably, with CE and HAE also demonstrating beneficial trends, whereas MAE and RE did not show stable statistical significance. Dose-response analyses showed that the posterior mean effect for weekly exercise dose peaked at approximately 1,100 METy-min/week, although the corresponding credible interval remained wide and included the null value. The session-duration analysis showed the highest posterior mean effect at approximately 40 min/session, whereas the METy-based intensity analysis showed a separate peak at approximately 8.5 METy. Study-level patterns also suggested larger predicted effects in populations with higher BMI and body weight, whereas the association with sex composition was comparatively modest.

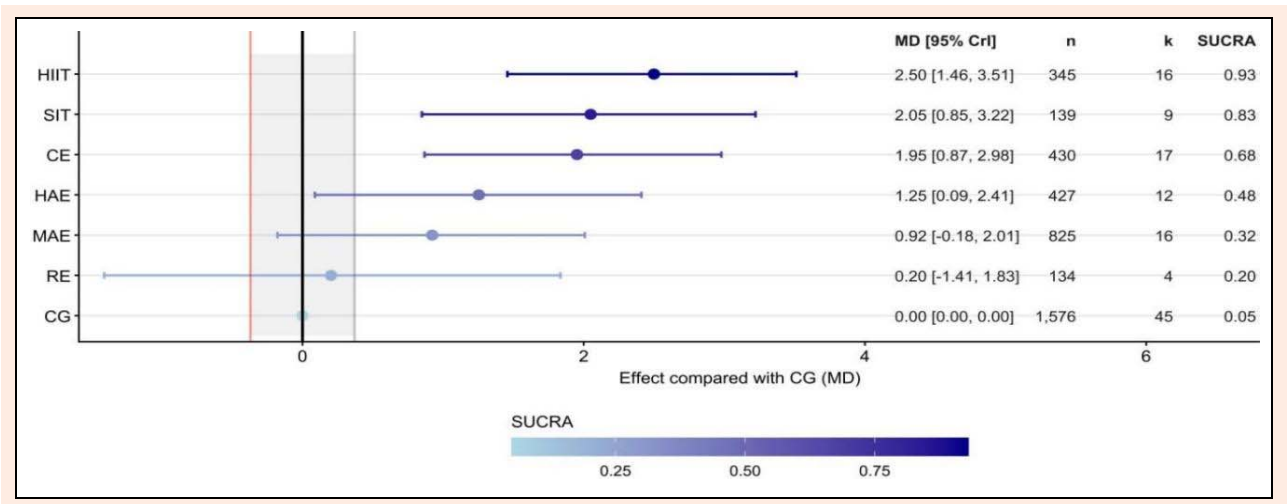

Figure 3. Effects and SUCRA rankings of exercise interventions on VO_2max.

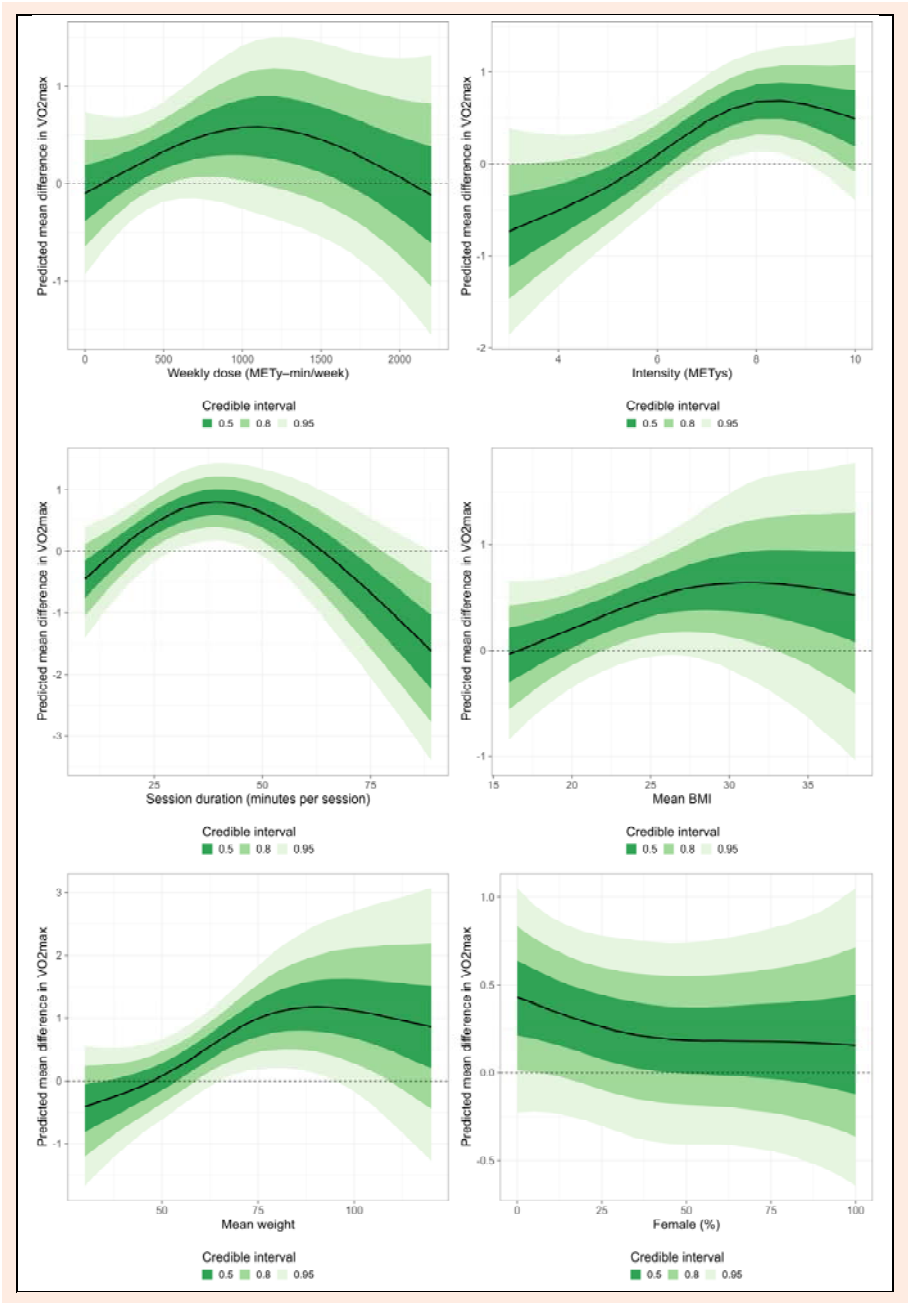

Figure 4. Dose, intensity, and baseline moderators of effects on VO_2max.

Comparison with previous studies

Consistent with previous studies, the present findings further support the positive role of exercise in improving CRF in children and adolescents (Men et al., 2025). In particular, HIIT showed a relatively strong advantage for enhancing CRF, in line with earlier evidence (Solera-Martínez et al., 2021). The underlying mechanisms may involve simultaneous central and peripheral adaptations induced by repeated high-intensity stimuli, including increased stroke volume (Hellsten and Nyberg, 2015), upregulation of PGC-1α expression to enhance muscular oxygen extraction (Mølmen et al., 2025), and improvements in plasma volume and oxygen transport efficiency (Mandić et al., 2022).

CE also demonstrated favorable effects, consistent with previous findings (Li et al., 2024), suggesting that the combination of aerobic exercise and resistance exercise may exert complementary effects on CRF. Aerobic exercise primarily targets the cardiovascular and oxygen transport systems (Martinez et al., 2021), whereas resistance exercise may support aerobic fitness by improving muscle function, movement economy, and local oxygen utilization (Verdijk et al., 2016). It should be noted that although the potential "interference effect" between these two exercise modes has traditionally been discussed (Schumann et al., 2022), this phenomenon may not be evident in children and adolescents; instead, their combination may significantly improve both CRF and muscular strength (Li et al., 2024).

SIT likewise showed beneficial effects, consistent with prior evidence (Zhang et al., 2025). Its physiological basis is partly similar to that of HIIT, but its shorter intervals and higher intensity may induce stronger metabolic

stress and thereby may provide a potent stimulus for mitochondrial and peripheral adaptations (Gibala et al., 2014). However, in children and adolescents, the actual quality of implementation, adherence, and the intensity truly achieved during SIT may vary more substantially, which may partly explain why it appeared effective yet ranked slightly lower than HIIT.

The present study found that HAE significantly improved CRF, whereas MAE did not show stable significant benefits, a pattern consistent with previous meta-analyses in adults (Chen et al., 2025). This finding does not necessarily indicate that MAE is completely ineffective for CRF; rather, it may suggest that, under the training conditions of the included trials, moderate-intensity stimuli were insufficient to consistently exceed the threshold required to elicit meaningful cardiorespiratory adaptations (Gormley et al., 2008). By contrast, HAE is more likely to sustain a higher oxygen uptake during exercise, thereby imposing a stronger stimulus on oxygen transport, oxygen utilization, and cardiorespiratory load (Bassett and Howley, 2000; Gormley et al., 2008). In addition, MAE was rated as low in the CINeMA assessment, and this result should therefore be interpreted cautiously as "insufficient evidence to demonstrate stable benefit" rather than "clear ineffectiveness".

In contrast, RE did not show a significant improvement in CRF. Conventional RE typically consists of repetitive, relatively brief muscle movements against external resistance interspersed with recovery periods with the primary aim of improving muscle function, strength, and hypertrophy (Currier et al., 2026). As a result, expansion of blood volume, maximal stroke volume, and peripheral oxygen acquisition may not result in excessive increases, which may partly explain the absence of a clear improvement in VO_2max (Ozaki et al., 2013). Nonetheless, this does not diminish the broader value of RE for children and adolescents. RE increases muscle mass and alters body composition and is associated with reduced cardiometabolic risk (Lloyd et al., 2014). In addition, the number of RCTs in our results was limited, and the rating of the evidence was "very low", with limited statistical power.

Dose-response and moderator findings

After exercise dose was recalculated using age-specific values from the Youth Compendium of Physical Activities, the posterior mean weekly dose-response curve peaked at approximately 1,100 METy-min/week. However, the corresponding 95% CrI included the null value, indicating that this value should be interpreted as the location of the highest posterior mean rather than as a precisely established optimal weekly dose. The session-duration analysis showed a more favorable predicted effect at approximately 40 min/session. However, this represents an overall study-level association across exercise modalities rather than a modality-specific optimal duration, particularly for HIIT or SIT. METy-based exercise intensity showed a nonlinear association, with higher predicted effects around 7.5-8.5 METy and the highest posterior mean at approximately 8.5 METy. Because METy represents an age-specific estimate of activity energy cost, it should not be interpreted as equivalent to individually achieved relative intensity or as a universal prescription threshold. Higher BMI and body weight were generally associated with larger predicted effects, whereas the association with sex composition was comparatively weak. These moderator findings are based on aggregate study-level data and should not be interpreted as causal individual-level relationships.

Clinical implications and practical guidance

This study provides some practical references for early cardiovascular prevention strategies in children and adolescents. First, within the current evidence framework, HIIT and SIT showed more favorable relative rankings and may therefore be prioritized in school physical education and exercise intervention design, while CE and HAE may also be considered as alternative options. Second, the dose-response findings may inform intervention planning, but weekly dose, session duration, and METy-based intensity should be considered alongside exercise modality rather than as fixed prescription targets. Third, populations with higher BMI and weight, and a higher proportion of boys may have greater potential for improvement, although practical application should still involve progressive adjustment according to individual fitness level, maturational status, adherence, and safety considerations. Overall, the present study supports the use of structured, high-quality exercise programs to enhance CRF in school and community settings, although specific protocols should still be individualized according to contextual conditions and population characteristics.

Limitations

Our study has several limitations. First, substantial heterogeneity and significant global inconsistency were observed across the included studies. These findings may partly reflect differences in participant characteristics, exercise protocols, dose, and VO_2max assessment methods. Although meta-regression was used to explore several potential moderators, these sources of variability could not be fully accounted for, and residual heterogeneity remained. Second, the certainty of evidence for most network comparisons was low or very low, mainly due to risk of bias, imprecision, inconsistency, and network sparsity; therefore, the intervention rankings should be interpreted with caution. Third, the methods used to assess VO_2max were not fully consistent. Although direct gas exchange analysis and indirect field-based tests are correlated, they are not fully interchangeable, which may have introduced additional measurement error. Fourth, the moderator analyses were based on study-level average characteristics and are therefore subject to ecological inference bias, meaning that they cannot directly substitute for individual-level conclusions. Fifth, the number of studies for some exercise modalities was limited, and the quality of reporting on training intensity and dose varied across the original studies, which may have affected the precision of exercise classification and dose estimation.

Conclusion

In conclusion, this study suggests that structured exercise interventions can improve CRF in children and adolescents, although the relative effects differ across exercise modalities. Based on the current evidence, HIIT and SIT

ranked most favorably, with CE and HAE also showing beneficial trends, whereas MAE and RE have not yet demonstrated stable advantages. Study-level analyses indicated higher posterior mean effects around 1,100 METy-min/week, 40 min/session, and 8.5 METy, without establishing precise optimal prescriptions. Given the substantial between-study heterogeneity and the limited certainty of evidence for most comparisons, these findings still require confirmation in high-quality RCTs with more rigorous designs and more standardized reporting.

Acknowledgements

This work was supported by the General Project of the National Social Science Fund of China (Grant No. 25BTY051). Data sets generated during this study are available upon reasonable request. The authors declare that they have no conflicts of interest. All experimental procedures were performed in accordance with the relevant laws and ethical standards of the country in which the study was conducted. The authors declare that no generative AI or AI-assisted technology was used at the time of writing.

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Key points

- HIIT and SIT ranked most favorably for improving VO_2max in children and adolescents.
- Dose-response analyses suggested higher posterior mean effects around 1,100 METy-min/week, 40 min/session, and 8.5 METy.
- Substantial heterogeneity and limited certainty of evidence warrant cautious interpretation of the exercise rankings and dose-response findings.

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