

Review article

Comparative Effectiveness of Aerobic Exercise versus Resistance Training on Cardiometabolic Health in Patients with Diabetes: A Systematic Review and Meta-Analysis of Randomized Controlled Trials

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Abstract

To evaluate the effects of aerobic exercise (AE) versus resistance training (RT) on cardiometabolic health-related outcomes in patients with type 2 diabetes mellitus and concurrent obesity (diabetes). Systematic review and meta-analysis of randomized controlled trials (RCTs). PubMed, Web of Science, Scopus, ScienceDirect, Cochrane Library, and Google Scholar databases were searched from inception up to April 2026. RCTs comparing AE and RT for a minimum duration of two weeks. Participants were adults with diabetes. A total of 23 RCTs qualified, involving 1,184 patients (58/42 women/men ratio; age range: 30 - 70 years; body mass index: 32.1 ± 6.6 kg/m²). AE appears to be more efficacious than RT in reducing fasting blood glucose (mean differences (MD) = -0.89 mmol/L, 95% CI: -1.62 to -0.16; I² = 0%) and increasing cardiorespiratory fitness (MD = 1.78 mL/kg/min, 95% CI: 0.38 to 3.18; I² = 66%). However, AE led to a greater increase in body fat (MD = 0.34%, 95% CI: 0.10 to 0.57; I² = 1%) and less fat-free mass retention (MD = -0.86 kg, 95% CI: -1.46 to -0.26; I² = 37%) compared with RT. For selected cardiometabolic health-related outcomes, including anthropometrics, blood lipids, and hemodynamics, no statistically significant between-group difference was detected. The overall certainty of the evidence across outcomes ranged from high to very low, with most being moderate. In adults with diabetes, AE appears to pro-

vide greater benefits for FBG and CRF, whereas RT appears more favorable for preserving FFM and improving BF. For the majority of cardiometabolic outcomes, the two modalities exhibit analogous effects. The present findings support a goal-directed and complementary approach to exercise prescription, as opposed to a one-modality-fits-all model, for the improvement of cardiometabolic health in patients with diabetes.

Key words: Exercise, type 2 diabetes, obesity, body composition, glucose metabolism, lipid metabolism, blood pressure, cardiorespiratory fitness.

Introduction

In 2021, cardiovascular disease and type 2 diabetes mellitus (T2DM), including T2DM-related kidney disease, accounted for more than 20 million deaths globally (World Health, 2026, Li et al., 2025, World Health, 2024; 2025). These conditions share cardiometabolic abnormalities, including central adiposity, hypertension, dyslipidemia, impaired fasting glucose, and insulin resistance, historically grouped under metabolic syndrome (Peterseim et al., 2024, Pigeot and Ahrens, 2025). More recently, the American

Heart Association (AHA) introduced cardiovascular-kidney-metabolic (CKM) syndrome to capture the interconnected metabolic, cardiovascular, and renal pathways driving morbidity (Ndumele et al., 2023a, Ndumele et al., 2023b). Unlike fragmented disease-specific care models, network medicine offers a systems-oriented approach targeting shared mechanisms across obesity, diabetes, hypertension, cardiovascular disease, and kidney dysfunction (Pati et al., 2025, Wang et al., 2025, Ndumele et al., 2023b, Gregg et al., 2024)(Sonawane et al., 2022, Theodorakis and Nikolaou, 2025, Wang et al., 2023).

Within network medicine, the complexity of cardiometabolic diseases resolves into mechanism-defined subphenotypes that capture high-leverage risk modules amenable to scalable lifestyle interventions (Piche et al., 2020, Lee et al., 2021, Coral et al., 2023, Rutters et al., 2024, Shrestha et al., 2025). One such module, diabetes, links insulin resistance, impaired glycemic control, ectopic and visceral fat deposition, adipose-tissue inflammation, and chronic low-grade systemic inflammation as shared mechanisms among patients with concurrent obesity and T2DM (Ortega et al., 2020, Allocca et al., 2025, Gorgojo-Martinez, 2025, Sindhwani et al., 2025, Ruze et al., 2023). Diabetes carries disproportionate cardiometabolic risk because excess adiposity and chronic hyperglycemia jointly worsen endothelial dysfunction, oxidative stress, atherogenic dyslipidemia, and adverse cardiac remodeling, while progressively reducing functional reserve and exercise tolerance (Wong and Sattar, 2023, Chakraborty et al., 2023, Zhong et al., 2025). This phenotype maps conceptually onto early CKM stages; accordingly, the CKM staging system functions throughout this synthesis as a translational interpretive framework rather than as a trial enrollment criterion, recognizing that the system was formalized after most of the available randomized evidence was generated (Sindhwani et al., 2025, Wong and Sattar, 2023, Handelsman et al., 2023, Ndumele et al., 2023a, Ndumele et al., 2023b, Rutters et al., 2024, Forte et al., 2023).

Lifestyle medicine has been proposed as the foundation of such prevention and treatment because its pillars (i.e., healthy nutrition, adequate sleep, stress management, risk behavior modification, social connection, and physical activity/exercise) can favorably modify diabetes's overlapping pathways (Berisha et al., 2025, Pikula et al., 2024). Within this paradigm, structured exercise functions as a pleiotropic, multi-system acting "polypill" that elicits coordinated adaptations and improves glycemic control, resting blood pressure, adiposity, lipoprotein profile, endothelial function, and cardiorespiratory fitness (CRF) (Ashcroft et al., 2024, Zhou et al., 2024, Fiuza-Luces et al., 2013, Sanchis-Gomar et al., 2015, Jakicic et al., 2024, Papadakis et al., 2022). Aerobic exercise (AE) preferentially enhances CRF, mitochondrial oxidative capacity, and vascular function (American Diabetes Association Professional Practice, 2025, Paluch et al., 2024, Papadakis, 2025b, Papadakis, 2025a, Papadakis, 2026b), whereas resistance training (RT) maintains or increases skeletal muscle mass, strength, and insulin sensitivity, while combating the sarcopenia and muscle-quality declines that frequently accompany obesity and T2DM (Al-Mhanna et al., 2025a, Al-Mhanna et al., 2024b, Al-Mhanna et al., 2025b, Al-Mhanna

et al., 2025c, Al-Mhanna et al., 2025d, Al-Mhanna et al., 2025e). Despite guideline endorsement of both modalities (American Diabetes Association Professional Practice, 2025, Paluch et al., 2024, Amare et al., 2025, Savikj and Zierath, 2020), clinicians still face the practical question of which to emphasize when adherence, tolerability, injury risk, and real-world access barriers constrain prescription (Herold et al., 2020, Kim and Kwon, 2024, Martinez-Vizcaino et al., 2022, McAvoy et al., 2025, Neto et al., 2023, Rutters et al., 2024, Mousavi Zadeh et al., 2025, Papadakis, 2025c).

Existing meta-analyses have largely compared each modality with non-exercise or usual care (Al-Mhanna et al., 2025a, Al-Mhanna et al., 2024b, Al-Mhanna et al., 2025b, Amare et al., 2025, Mannucci et al., 2021, Al-Mhanna et al., 2025c), or rely on data that no longer reflect contemporary pharmacotherapy and clinical practice (Yang et al., 2014, Schwingshackl et al., 2014, Pan et al., 2018). The comparative effectiveness of AE versus RT in adults with diabetes therefore remains uncertain. The novelty of the present systematic review and meta-analysis is the application of an explicit diabetes criterion together with an updated literature base, restricted to randomized controlled trials (RCTs) that directly compare AE with RT in adults with concurrent T2DM and excess adiposity. Synthesizing comparisons across anthropometric, body composition, glycemic, lipid, and hemodynamic outcomes aims to sharpen clinical decision-making and inform scalable, high-yield lifestyle medicine exercise interventions targeting diabetes (Ma et al., 2024, Al-Mhanna et al., 2025b, Kobayashi et al., 2023, Mannucci et al., 2021, Al-Mhanna et al., 2025c).

Methods

Registration

This study adhered to the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement (Page et al., 2021) and the Cochrane Handbook for Systematic Reviews of Interventions (Chandler et al., 2019). The methodology or protocol was registered with the Open Science Framework registry <https://osf.io/rh9w2>. Because our research did not involve individual patient data, but rather previously published studies, institutional bioethics committee approval was not required.

Literature search strategy

A comprehensive electronic search was performed to identify previously published reports from multiple databases, including PubMed, Web of Science, Scopus, ScienceDirect, Cochrane Library, and Google Scholar. Search strategies conducted by four authors (S.B.A.M., A.I., S.M.N., and A.B), incorporated controlled vocabulary (e.g., MeSH and Emtree terms) and free-text keywords related to T2DM, obesity, aerobic exercise, resistance training, and randomized controlled trials. The complete database-specific search syntax is presented in Table S1 (see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>). The search strategy followed the PICOS framework: (P) Population: individuals with concurrent obesity and T2DM; (I)

Intervention: AE; (C) Comparator: RT; (O) Outcomes - primary: lipid metabolism [high-density lipoprotein cholesterol (HDL-C), low-density lipoprotein cholesterol (LDL-C), total cholesterol (TC), and triglycerides (TG)]; glucose metabolism [fasting blood glucose (FBG), glycated hemoglobin (HbA1c), fasting insulin (FI), and homeostatic model assessment for insulin resistance (HOMA-IR)]; and cardiovascular function, including resting systolic blood pressure (SBP), diastolic blood pressure (DBP), and CRF ($\text{VO}_2\text{max}/\text{VO}_{2\text{peak}}$); and body mass index (BMI); secondary: anthropometrics [body weight (BW), waist circumference (WC), hip circumference (HC), and waist-to-hip ratio (WHR)]; body composition [body fat (BF) and fat-free mass (FFM)], and resting heart rate (RHR). Only RCTs were included in the review. Furthermore, the reference lists of selected studies and relevant systematic reviews were examined to identify additional published investigations that met the inclusion criteria.

Eligibility criteria

The inclusion criteria were as follows: (i) participants diagnosed with T2DM ($\text{FBG} \geq 126 \text{ mg/dL}$) and concurrent obesity. Because obesity definitions differed across international trials, broader adiposity criteria were accepted to maximize external validity while preserving clinical relevance. Specifically, two different methods were used to define obesity: a) a BMI of 30 kg/m^2 or more (World Health Organization, 2000) and b) abdominal obesity, defined as a BMI $\geq 25 \text{ kg/m}^2$, but with high WC for men, $\geq 102 \text{ cm}$ (Black) or $\geq 94 \text{ cm}$ (White/Asians) and for women, $\geq 88 \text{ cm}$ (Black) or $\geq 80 \text{ cm}$ (White/Asians) (Cerhan et al., 2014); (ii) individuals aged 18 years or older; (iii) studies implementing AE and RT as the specific interventions; (iv) research that assessed at least one primary outcome of interest in human participants, with secondary outcomes included if relevant to cardiometabolic health; (v) full-text reports published in peer-reviewed journals up until April

2026; (vi) no language restrictions; and (vii) inclusion of only RCTs. Studies were excluded if they: (i) focused on acute exercise interventions (single bouts or 1-week interventions), or (ii) reviews, case reports, or published studies that lacked clear and complete data.

Study selection

A linear evaluation process was conducted by five researchers (S.B.A.M., A.I., S.M.N., Y.L., and M.S.M.S.) to assess eligibility. The process was initiated with an initial screening of titles and abstracts, followed by a comprehensive review of full texts when necessary. Reports that satisfied the initial criteria were then subjected to a rigorous evaluation process, with the results being compared against a set of predefined inclusion criteria. Discrepancies and ambiguities were addressed through an independent review by a sixth author (A.B.), who applied the same methodology. The software EndNote 2025.2 (Clarivate Analytics, Philadelphia, PA, USA) was employed for the organization and management of the search results.

Data extraction

The data collection and extraction process was performed independently by ten authors (S.B.A.M., A.I., S.M.N., Y.L., M.S.M.S., N.H.A., B.B.S., M.Y., and A.B.) following a thorough review of the full-text articles. A total of 23 RCTs were included, providing comprehensive datasets that included information such as the lead author, publication year, demographic details, gender distribution, sample size, exercise intervention characteristics (frequency, intensity, duration, and type), study duration, and predefined outcomes. All outcome data included in the quantitative synthesis were extracted directly from reported numerical values in the text, tables, or supplementary materials; no data were extracted from graphical figures. The details that were extracted were systematically organized and summarized in Table 1.

Table 1. Characteristics of the included studies according to population, intervention, comparator, and outcomes.

Study	C	P	N (AE/RT)	Weeks	Age (yrs)	BMI (kg/m^2)	Intervention (AE)	Comparator (RT)	Primary outcomes	Dropout (%) (AE/RT)
Ranasinghe et al., 2021	Sri Lanka	Adults with diabetes	28 / 28	12	~50	NR	60 - 75% HRmax, walking/cycling/stepper, 60 - 75 min, 2×/wk	50 - 60% 1RM, 7 exercises, 3×8 reps, 2×/wk; supervised	BW, BF, WC, FBG, FI, HbA1c, SBP, DBP	26 / 26
Bacchi et al., 2012	Italy	Adults with diabetes	19 / 19	16	40-70	~29	cycling 60% $\text{VO}_{2\text{max}}$, 60 min, 3×/wk	70 - 80% 1RM, 9 exercises, 3×/wk; supervised	BMI, WC, FBG, HbA1c, HDL, LDL, TC, TG, SBP, DBP, CRF	5 / 5
Cauza et al., 2005	Austria	Adults with diabetes	17 / 22	16	~58-60	~31-34	~60 - 80% $\text{VO}_{2\text{peak}}$, 3×/wk	~70 - 80% 1RM, 3×/wk	BW, BF, FFM, FBG, FI, HbA1c, HDL, LDL, TC, TG, SBP, DBP, CRF	14 / 13
Church et al., 2010	USA	Adults with diabetes	72 / 73	36	NR	~35	12 kcal/kg/wk, 50 - 80% $\text{VO}_{2\text{max}}$, 3×/wk	7 machine exercises, progressive, 3×/wk	BMI, HbA1c	4 / 7
Jorge et al., 2011	Brazil	Adults with diabetes	12 / 12	12	~54	~29-32	cycling at lactate threshold, 60 min, 3×/wk	60 - 80% 1RM, 8 exercises, circuit, 3×/wk	BMI, WHR, FBG, HbA1c, HOMA-IR, HDL, TC, TG, CRF	0 / 0

Table 1. Continue ...

Study	C	P	N (AE/RT)	Weeks	Age (yrs)	BMI (kg/m ²)	Intervention (AE)	Comparator (RT)	Primary outcomes	Dropout (%) (AE/RT)
Kadoglou et al., 2013	Greece	Adults with diabetes	21 / 23	24	AE 58 ± 5 RT 56 ± 5	AE 32 ± 3 RT 33 ± 3	60 - 75% HRmax, 60 min, 4×/wk	60 - 80% 1RM, supervised	BF, WHR, FBG, FI, HOMA-IR, HbA1c, HDL, LDL, TC, TG, SBP, DBP, CRF	16 / 8
Ku et al., 2010	South Korea	Adults with diabetes	15 / 13	12	NR	NR	walking 60 min, 3.6 - 5.2 METs, 5×/wk	elastic band, 40 - 50% max, 5×/wk	BW, BMI, WHR, FBG, HbA1c	0 / 0
Moe et al., 2011	Norway	Adults with diabetes	13 / 13	12	~56 - 58	~29 - 31	75 - 85% VO2peak, 3×/wk	~60% 1RM, 3×/wk	BMI, FBG, HbA1c, HC, WC, WHR, SBP, DBP, CRF	0 / 0
Ng et al., 2010	Singapore	Adults with diabetes	30 / 30	8	58 ± 7	28 ± 5	similar volume aerobic exercise; 8 wk	progressive resistance training of similar volume; 8 wk	BW, BF, BMI, FBG, HbA1c, WC, WHR, SBP, DBP	20 / 17
Shenoy et al., 2009	India	Adults with diabetes	10 / 10	16	NR	~26 - 27	moderate intensity, 3×/wk	60→100% 1RM progressive, 2×/wk	BMI, FBG, HbA1c, SBP, DBP	0 / 0
Sigal et al., 2007	Canada	Adults with diabetes	60 / 64	22	NR	~34 - 36	treadmill/ cycling, 60 - 75% HRmax, 3×/wk	8 - 9RM progressive, 3×/wk	BW, BF, FFM, BMI, WC, HbA1c, HDL, LDL, TC, TG, SBP, DBP	0 / 0
Yavari et al., 2012	Iran	Adults with diabetes	15 / 15	52	51 ± 9	NR	60→75% HRmax, 20→60 min, 3×/wk	60→80% 1RM, 10 exercises, 3×8 - 10 reps, 3×/wk	BW, BF, FBG, HbA1c, HDL, LDL, TC, TG, SBP, DBP, RHR, CRF	25 / 25
Kobayashi et al., 2023	Japan	Adults with diabetes	63 / 61	36	~60	NR	moderate-to- vigorous target HR zone, 3×/wk	8 - 12RM progressive, 3×/wk	BF, FFM, FBG, HbA1c	28 / 27
Duan and Lu, 2024	China	Adults with diabetes	12 / 12	12	40 - 45	≥ 30	60 - 75% HRR, 4×/wk	60 - 80% 1RM, 3×/wk	FBG, FI, HOMA- IR, HbA1c, HDL, LDL, TC, TG, CRF	0 / 0
Shahzadi et al., 2025	Pakistan	Adults with diabetes	20 / 20	12	~50 - 55	NR	~60 - 70% HRmax, 3×/wk	~60 - 70% 1RM, 3×/wk	HbA1c, CRF	9 / 4
Piralaity et al., 2025	Thailand	Adults with diabetes	11 / 11	12	~50 - 55	NR	~60 - 70% HRR, 3×/wk	~60 - 70% 1RM, 3×/wk	BMI	15 / 15
Kwon et al., 2011	South Korea	Adults with diabetes	13 / 12	12	57 ± 7	27 ± 2.3	walking 60 min, 3.6 - 6.0 METs, 5 ×/wk	bands, 3×10-15, progressive, 3×/wk	BW, FBG, HbA1c, HDL, LDL, TC, TG, SBP, DBP, CRF	0 / 0
Sukala et al., 2012	New Zealand	Adults with diabetes	9 / 9	16	49 ± 5	44 ± 10	supervised, 3×/wk, 16 wk	supervised, 3×/wk, 16 wk	BW, BF, BMI, WC, FBG, FI, HbA1c, HDL, LDL, TC, TG, SBP, DBP	31 / 31

Table 1. Continue ...

Study	C	P	N (AE/RT)	Weeks	Age (yrs)	BMI (kg/m ²)	Intervention (AE)	Comparator (RT)	Primary outcomes	Dropout (%) (AE/RT)
Elsayed et al., 2024	Egypt	Adults with diabetes	20 / 20	12	~mid-50s	≥ 25	~60 - 70% HRmax, 3×/wk	~60 - 70% 1RM, 3×/wk	FI, TC	0 / 0
Arora et al., 2009	India	Adults with diabetes	10 / 9	8	NR	NR	walking 30 min, 3×/wk	60→100% 1RM, 7 exercises, 3×10, 2×/wk	BMI, HbA1c, HDL, TC, TG, SBP, DBP, RHR	0 / 10
Oliveira et al., 2012	Brazil	Adults with diabetes	11 / 10	12	AT 52 ± 9 RT 54 ± 9	AT 29 ± 2 RT 31 ± 4	cycling at lactate threshold, progressed to 50 min, 3×/wk	circuit 7 exercises, 4×8 - 12 to failure, 3×/wk	BW, BF, WC, WHR, FBG, HbA1c, HDL, LDL, TC, TG, SBP, DBP, CRF	0 / 0
Swift et al., 2012	USA	Adults with diabetes	50 / 58	~36	AE 56 ± 8 RT 59 ± 8	AE 34 ± 6 RT 34 ± 5	12 kcal/kg/wk (HART-D)	3×/wk, 2-3 sets, 10 - 12 reps, progressive	BF, FFM, FBG, HbA1c, WC, CRF	8 / 5
Reid et al., 2010	Canada	Adults with diabetes	51 / 58	22	39-70	AE 34 ± 6 RT 33 ± 6	treadmill/cycling to 45 min at 75% HRmax, 3×/wk	8 machine exercises, 2-3 sets, ~8RM, 3×/wk	BMI, RHR	0 / 0

C: country, P: Population, AE: Aerobic exercise, RT: Resistance training, BMI: Body mass index, BW: Body weight, BF: Body fat, WC: Waist circumference, WHR: Waist-to-hip ratio, FBG: Fasting blood glucose, FI: Fasting insulin, HbA1c: Glycated hemoglobin, HOMA-IR: Homeostatic model assessment of insulin resistance, HDL=High-density lipoprotein cholesterol, LDL: Low-density lipoprotein cholesterol, TC: Total cholesterol, TG: Triglycerides, SBP: Systolic blood pressure, DBP: Diastolic blood pressure, CRF: Cardiorespiratory fitness.

Risk of bias assessment

The risk of bias in each study was evaluated independently by four authors (S.B.A.M., N.H.A., B.B.S., and A.B.) in accordance with the guidelines provided in the Cochrane Handbook for Systematic Reviews of Interventions (Chandler et al., 2019). The assessment addressed the following domains: Pertinent sources of bias were identified: (i) random sequence generation, (ii) allocation concealment, (iii) blinding of participants and study personnel, (iv) blinding of outcome assessors, (v) completeness of outcome data, (vi) selective reporting of outcomes, and (vii) other potential sources of bias, as outlined in the Cochrane Handbook (Figure S1, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>). In accordance with the above-referenced criteria, the studies were categorized into one of three risk levels: low, some concerns (moderate), or high. This categorization was determined based on the number and severity of biases identified. Because participant and personnel blinding is rarely feasible in exercise-training trials, risk was judged by whether lack of blinding could affect outcomes. Objective outcomes were rated low risk, and insufficient reporting as unclear risk. Assessor blinding and selective reporting were assessed separately, with registrations or protocols checked when available.

Data analysis

The meta-analyses were conducted using the Review Manager Web version 9.1 (Cochrane Collaboration). The synthesis of continuous outcomes was conducted utilizing the random-effects model, and the results were expressed as mean differences (MDs) with 95% confidence intervals (CIs). The MD was employed because most of the included studies generally measured each pooled outcome on a common scale or one that was clinically comparable (Higgins et al., 2011, Batrakoulis et al., 2022). Pooled effect

estimates were calculated using post-intervention mean values and corresponding standard deviations (SDs) from the intervention and control groups.

When studies reported continuous outcomes as mean ± standard error (SE) instead of mean ± SD, SD values were calculated using the formula $SD = SE \times \sqrt{n}$, where n represents the sample size. For studies reporting 95% confidence intervals (CI), SDs were estimated according to the recommendations of the Cochrane Handbook for Systematic Reviews of Interventions using the formula $SD = \sqrt{n} \times [(upper\ CI - lower\ CI)/3.92]$. The calculated SD values were subsequently used in the meta-analysis.

Statistical heterogeneity was categorized as low when I^2 was < 40%, moderate when I^2 was 40% to < 60%, substantial when I^2 was 60% to < 75%, and considerable when I^2 was ≥ 75% (Higgins and Green, 2008). The estimation of effect sizes was conducted through the utilization of MD, accompanied by 95% CIs. Statistical significance was determined by a two-sided p -value < 0.05.

Grading quality of evidence

The quality of evidence for both primary and secondary outcomes was independently evaluated by three authors (S.B.A.M., A.I., and A.B.) using the GRADE approach (Batrakoulis et al., 2022), available at <https://www.grade-pro.org> (Atkins et al., 2004). The assessment incorporated various factors, including the risk of bias, inconsistency, indirectness, imprecision, and publication bias. The evidence was then classified into one of the following quality categories: very low, low, moderate, or high. In instances of disagreement or uncertainty, a third author (N.O.) was consulted to resolve the issue. The quality of the evidence may be enhanced by the presence of criteria such as a substantial effect size, dose-response relationships, or the

absence of plausible confounders that could either diminish the observed effect or suggest a false positive. Conversely, downgrading was possible due to risk of bias, inconsistent results, indirect evidence, imprecision, or publication bias (Table 2). Publication bias was assessed using funnel plot inspection, Egger's regression test, and Begg's rank correlation test. Egger's and Begg's tests were used to evaluate potential publication bias and small-study effects, with results interpreted cautiously when fewer than ten studies were included (Begg and Mazumdar, 1994, Egger et al., 1997).

Subgroup analysis

Subgroup analyses were conducted for primary outcomes when sufficient subgroup-specific data were available to permit comparison between categories. The analyses were conducted using two predefined subgroup variables: (i) intervention duration (≤ 12 weeks versus > 12 weeks) and (ii) comorbidity reporting status (reported versus not reported). Subgroup analyses were applied to the primary outcomes for which subgroup data were available, namely BMI, HDL-C, LDL-C, TC, TG, FBG, FI, HOMA-IR, HbA1c, SBP, DBP, and CRF. The interpretation of the tests for subgroup differences was undertaken with caution when considered exploratory in nature. All subgroup analyses were considered exploratory and interpreted cautiously because of limited statistical power.

Sensitivity analysis

Sensitivity analyses were conducted using a leave-one-out approach, whereby each study was sequentially excluded

and the meta-analysis was repeated to assess the robustness of selected pooled estimates. The objective of these analyses was to determine whether the direction, magnitude, or statistical significance of the pooled effect underwent substantial modification after the exclusion of influential studies or the utilization of the available reduced study set. Sensitivity analyses were particularly relevant for outcomes such as HbA1c and HDL-C, to assist in the interpretation of heterogeneity and estimate stability.

Results

Literature search and selection

A total of 25, 107 studies were initially retrieved from the specified databases, including PubMed, Scopus, Web of Science, Cochrane Library, ScienceDirect, and Google Scholar (Figure 1). Subsequent to the removal of 5, 141 duplicates, the total number of studies decreased to 19, 966, which were then subjected to further assessment. After a thorough review of titles and abstracts based on predefined inclusion and exclusion criteria, 19, 927 studies were excluded. The remaining 34 reports were then subjected to a thorough review, resulting in the exclusion of 11 of these studies for specific reasons (Table S2, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>). The remaining 23 studies were included in this systemic review and meta-analysis, with data extracted from 1, 184 patients [582 in AE and 602 in RT; 58/42 women/men ratio; age range, 39 - 70 years; mean (SD) BMI, 32.1 (6.6) kg/m²] who met the eligibility criteria.

Table 2. Summary of findings using GRADE quality assessment.

Outcome	No of studies	Study design	Risk of bias	Inconsistency	Indirectness	Imprecision	AE	RT	Effect	Certainty
BMI (kg/m²)	15	RCT	serious	not serious	not serious	not serious	336	346	MD 0.42 lower (95% CI 0.93 lower to 0.09 higher)	⊕⊕⊕⊕ Moderate ^a
FBG (mmol/L)	16	RCT	serious	not serious	not serious	not serious	332	342	MD 0.89 lower (95% CI 1.62 lower to 0.16 lower)	⊕⊕⊕⊕ Moderate ^a
HbA1c (%)	20	RCT	serious	serious	not serious	not serious	494	508	MD 0.09 lower (95% CI 0.27 lower to 0.09 higher)	⊕⊕⊕⊕ Low ^{ab}
FI (mIU/L)	6	RCT	serious	serious	not serious	serious	107	114	MD 0.35 lower (95% CI 1.67 lower to 0.98 higher)	⊕⊕⊕⊕ Very low ^{abd}
HOMA-IR	3	RCT	serious	very serious	not serious	serious	45	47	MD 0.58 lower (95% CI 1.87 lower to 0.71 higher)	⊕⊕⊕⊕ Very low ^{acd}
HDL-C (mg/dL)	10	RCT	serious	very serious	not serious	not serious	187	195	MD 2.35 higher (95% CI 0.06 lower to 4.76 higher)	⊕⊕⊕⊕ Very low ^{ac}
LDL-C (mg/dL)	9	RCT	serious	not serious	not serious	not serious	177	186	MD 0.12 higher (95% CI 0.28 lower to 0.51 higher)	⊕⊕⊕⊕ Moderate ^a
TG (mg/dL)	11	RCT	serious	not serious	not serious	not serious	199	207	MD 0.77 lower (95% CI 2.47 lower to 0.93 higher)	⊕⊕⊕⊕ Moderate ^a
TC (mg/dL)	12	RCT	serious	not serious	not serious	not serious	219	227	MD 0.12 lower (95% CI -0.34 lower to 0.59 higher)	⊕⊕⊕⊕ Moderate ^a
DBP (mmHg)	13	RCT	serious	not serious	not serious	not serious	250	259	MD 2.04 higher (95% CI 0.46 lower to 4.55 higher)	⊕⊕⊕⊕ Moderate ^a
SBP (mmHg)	13	RCT	serious	not serious	not serious	not serious	250	259	MD 0.02 lower (95% CI 1.57 lower to 1.52 higher)	⊕⊕⊕⊕ Moderate ^a
RHR (bpm)	3	RCT	serious	not serious	not serious	serious	76	82	MD 1.87 higher (95% CI 4.53 lower to 8.26 higher)	⊕⊕⊕⊕ Low ^{ad}
CRF (mL/kg/min)	11	RCT	serious	serious	not serious	not serious	203	216	MD 1.78 higher (95% CI 0.38 higher to 3.18 higher)	⊕⊕⊕⊕ Low ^{ab}

^a Downgraded one level for risk of bias, ^b Downgraded one level for serious inconsistency, ^c Downgraded two levels for very serious inconsistency, ^d Downgraded one level for serious imprecision. AE: Aerobic exercise, RT: Resistance training, BMI: Body mass index, FBG: Fasting blood glucose, HbA1c: Glycated hemoglobin, FI: Fasting insulin, HOMA-IR: Homeostatic model assessment of insulin resistance, HDL-C: High-density lipoprotein cholesterol, LDL-C: Low-density lipoprotein cholesterol, TG: Triglycerides, TC: Total cholesterol, DBP: Diastolic blood pressure, SBP: Systolic blood pressure, RHR: Resting heart rate, CRF: Cardiorespiratory fitness.

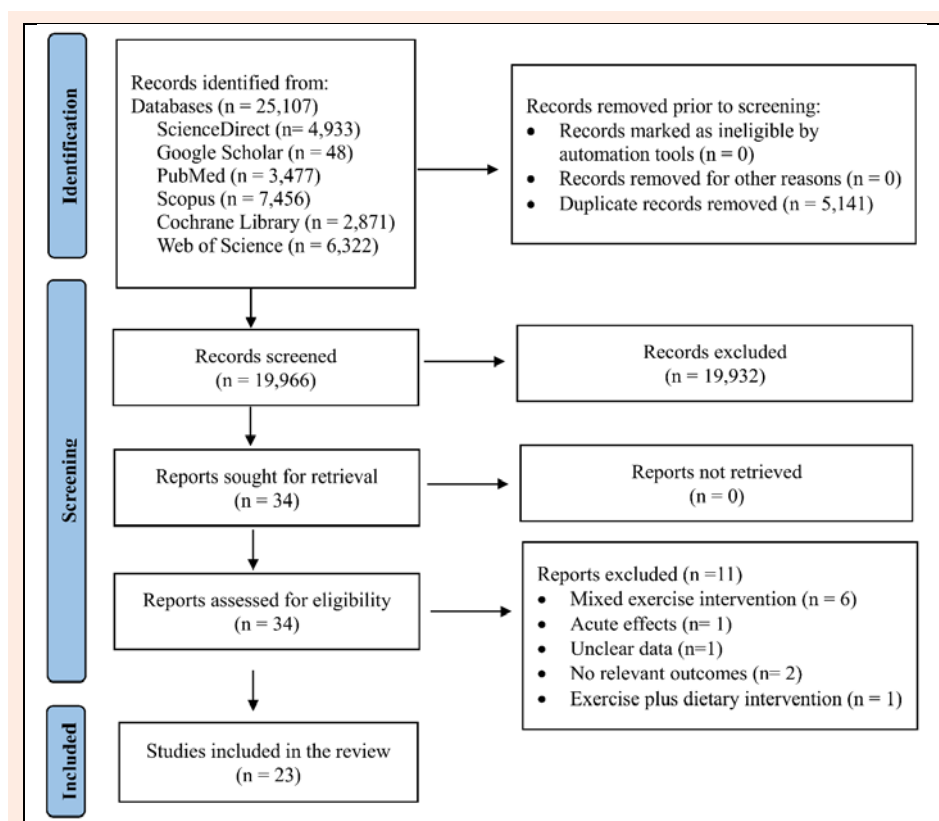


Figure 1. Preferred reporting items for systematic reviews and meta-analyses flow diagram. RCT: randomized controlled trial.

Literature characteristics

Table 1 summarizes the characteristics of the included studies. The reports were published between 2005 and 2025, with 18 studies (78%) published between 2005 and 2014 and another 5 studies (22%) published between 2015 and 2025. Trials ($n = 23$) were conducted in 18 countries: Asia ($n = 11$), Europe ($n = 4$), North America ($n = 4$), South America ($n = 2$), Oceania ($n = 1$), and Africa ($n = 1$). Twelve studies involved short-term exercise interventions with a duration of 8 - 12 weeks. In contrast, 11 studies focused on long-term exercise interventions with a duration of 16 - 52 weeks. The mean attendance rate was 91%, with a range of 69% to 100% across all AE and RT intervention groups. The most frequently reported AE protocol was a 12-week walking or stationary cycle ergometer routine, conducted three times a week (60 minutes/session) at 70%-75% of maximum heart rate, requiring a weekly time commitment of 180 minutes. The most frequently reported RT protocol was a supervised 12-week whole-body routine, required a weekly time commitment of 135 min, conducted three times a week (45 min per session), encompassing three sets per exercise/major muscle group, 8 - 12 repetitions per set at 60%-70% of 1-RM (non-failure), and a 60-s rest interval.

Risk of bias assessment

The risk of bias across included studies was assessed using the Cochrane Risk of Bias 1 tool across the seven standard domains. Overall several studies had unclear risk in randomization-related domains, particularly random sequence generation and allocation concealment, whereas outcome completeness and selective reporting were generally better

documented. Most studies were judged as low or unclear risk for blinding of participants and personnel, reflecting the practical difficulty of blinding exercise interventions. Outcome-assessor blinding was more frequently rated as low risk, particularly for objective cardiometabolic outcomes. Selective reporting was commonly judged as unclear when trial registration or protocols were unavailable. The domain-level summary and study-level judgments are presented in Figure 2 and Figure S1 (see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>).

Summary of Quality Assessment (GRADE)

The overall certainty of the evidence across outcomes ranged from high to very low. Specifically, of the 16 outcomes assessed, 2 were rated as high certainty, 9 as moderate certainty, 4 as low certainty, and 1 as very low certainty. The certainty of evidence was downgraded primarily due to concerns regarding risk of bias, inconsistency, and imprecision, resulting in no outcomes being rated as high-certainty evidence (Table 2). The risk of bias was predominantly associated with methodological limitations identified in multiple included studies, while inconsistency reflected substantial heterogeneity in effect estimates across studies. The imprecision observed was predominantly attributed to the limited sample sizes and the substantial confidence intervals, which led to a reduction in the confidence placed in the estimated effects. The evidence supporting most outcomes was of moderate certainty, suggesting that the true effect is likely close to the estimated effect. However, the findings may be influenced by future well-designed studies that could refine these estimates and potentially increase confidence in the results.

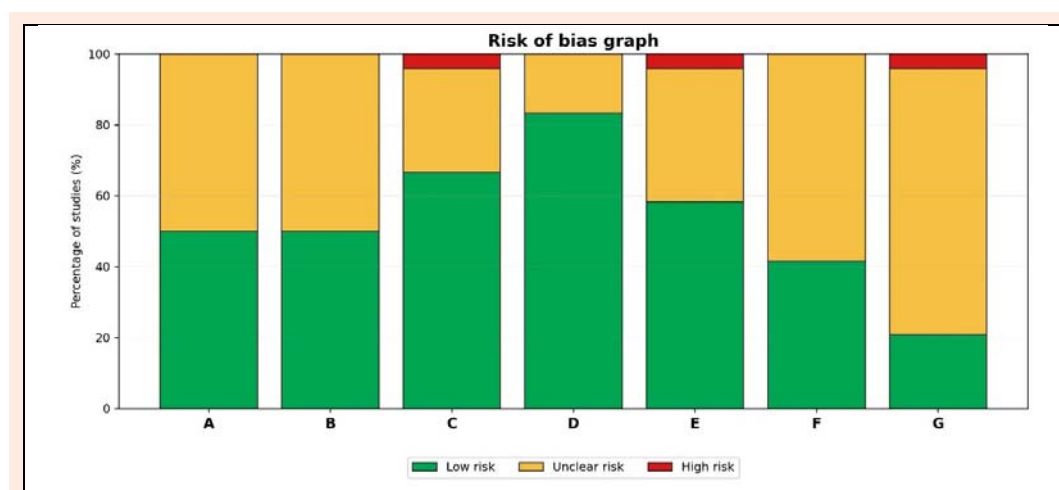


Figure 2. Summary of the risk of bias assessment.

Outcomes

Anthropometrics

Detailed effect sizes, confidence intervals, and study-specific estimates for all outcomes are presented in Table S3 (see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>) and the corresponding forest plots.

For BW, 9 trials comprising 390 participants were included (Cauza et al., 2005, Ku et al., 2010, Kwon et al., 2011, Ng et al., 2010, de Oliveira et al., 2012, Ranasinghe et al., 2021, Sigal et al., 2007, Sukala et al., 2012, Yavari et al., 2012). For BMI, 15 trials comprising 682 participants were included (Arora et al., 2009, Bacchi et al., 2012, Cauza et al., 2005, Church et al., 2010, Jorge et al., 2011, Kadoglou et al., 2013, Ku et al., 2010, Moe et al., 2011, Piralaiy et al., 2025, Ng et al., 2010, Ranasinghe et al., 2021, Shenoy et al., 2009, Sukala et al., 2012, Sigal et al., 2007, Yavari et al., 2012). No statistically significant difference was observed between AE and RT for BW (Figure S2a; MD = -1.55 kg, 95% CI: -4.84 to 1.75; I² = 38%, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>) or BMI (Figure S2b; MD = -0.42 kg/m², 95% CI: -0.93 to

0.09; I² = 14%, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>). Graphic overview of the results was given in Figure 3.

For WC, 8 trials involving 440 participants were included (Bacchi et al., 2012, Moe et al., 2011, Ng et al., 2010, de Oliveira et al., 2012, Ranasinghe et al., 2021, Sigal et al., 2007, Sukala et al., 2012, Swift et al., 2012). HC was assessed in 1 trial involving 26 participants (Moe et al., 2011). For WHR, 6 trials involving 192 participants were included (Jorge et al., 2011, Kadoglou et al., 2013, Ku et al., 2010, Moe et al., 2011, Ng et al., 2010, de Oliveira et al., 2012). Meta-analysis showed no statistically significant difference between AE and RT for WC (Figure S2c; MD = 0.02 cm, 95% CI: -0.01 to 0.05; I² = 49%, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>), HC (MD = 0.75 cm, 95% CI: -4.19 to 5.69), or WHR (Figure S2d; MD = 0.50, 95% CI: -0.87 to 1.87; I² = 0%). Subgroup analyses for BMI according to intervention duration and comorbidity reporting showed no significant subgroup differences (Figure S3a, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>).

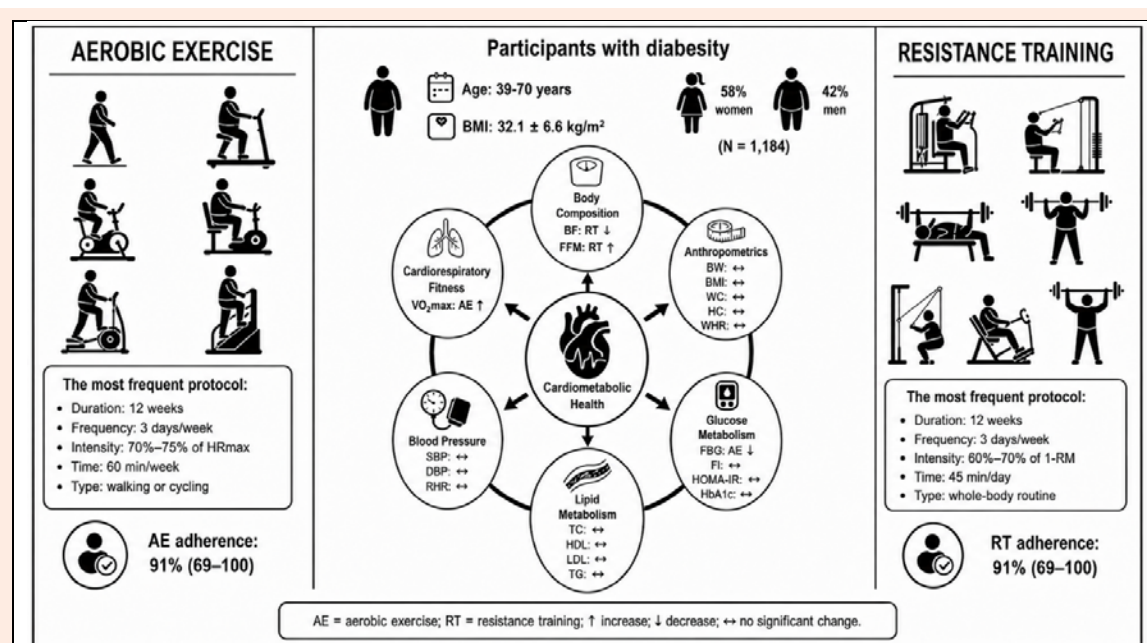


Figure 3. Graphic overview of the results.

Body composition

For BF, 10 trials involving 613 participants were included (Cauza et al., 2005, Kadoglou et al., 2013, Kobayashi et al., 2023, Ng et al., 2010, de Oliveira et al., 2012, Ranasinghe et al., 2021, Sigal et al., 2007, Sukala et al., 2012, Swift et al., 2012, Yavari et al., 2012). For FFM, 4 trials involving 395 participants were included (Cauza et al., 2005, Kobayashi et al., 2023, Sigal et al., 2007, Swift et al., 2012). Meta-analysis showed that AE was associated with significantly less favorable body composition outcomes than RT, with higher BF (Figure S2e; MD = 0.34%, 95% CI: 0.10 to 0.57; I² = 1%, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>) and lower FFM (Figure S2f; MD = -0.86 kg, 95% CI: -1.46 to -0.26; I² = 37%, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>).

Glucose metabolism

For FBG, 16 trials involving 674 participants were included (Bacchi et al., 2012, Cauza et al., 2005, Jorge et al., 2011, Duan and Lu, 2024, Kadoglou et al., 2013, Kobayashi et al., 2023, Ku et al., 2010, Kwon et al., 2011, Moe et al., 2011, Ng et al., 2010, de Oliveira et al., 2012, Ranasinghe et al., 2021, Shenoy et al., 2009, Sukala et al., 2012, Swift et al., 2012, Yavari et al., 2012). For HbA1c, 20 trials involving 1002 participants were included (Arora et al., 2009, Bacchi et al., 2012, Cauza et al., 2005, Church et al., 2010, Duan and Lu, 2024, Jorge et al., 2011, Kadoglou et al., 2013, Kobayashi et al., 2023, Ku et al., 2010, Kwon et al., 2011, Moe et al., 2011, Ng et al., 2010, de Oliveira et al., 2012, Ranasinghe et al., 2021, Shenoy et al., 2009, Sigal et al., 2007, Sukala et al., 2012, Swift et al., 2012, Yavari et al., 2012, Shahzadi et al., 2025). FI was assessed in 6 trials involving 221 participants (Cauza et al., 2005, Duan and Lu, 2024, Kadoglou et al., 2013, Ranasinghe et al., 2021, Sukala et al., 2012, Elsayed et al., 2024), while HOMA-IR was assessed in 3 trials involving 92 participants (Duan and Lu, 2024, Jorge et al., 2011, Kadoglou et al., 2013). Meta-analysis showed that AE was associated with a significantly greater reduction in FBG than RT (Figure S2 g; MD = -0.89 mmol/L, 95% CI: -1.62 to -0.16; I² = 0%, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>). In contrast, no significant between-group differences were observed for HbA1c (Figure S2h; MD = -0.09%, 95% CI: -0.27 to 0.09; I² = 64%, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>), FI (Figure S2i; MD = -0.35 mIU/L, 95% CI: -1.67 to 0.98; I² = 72%), or HOMA-IR (Figure S2j; MD = -0.58, 95% CI: -1.87 to 0.71; I² = 94%, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>). Subgroup analyses for FBG, FI, HOMA-IR, and HbA1c were performed according to intervention duration and comorbidity reporting, showing no significant subgroup differences (Figures S3b, S3c, S3h, and S3k, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>). This finding was consistent across a sensitivity analysis for HbA1c.

Lipid metabolism

For HDL-C, 10 trials involving 382 participants were included (Arora et al., 2009, Bacchi et al., 2012, Cauza et al., 2005, Jorge et al., 2011, Kadoglou et al., 2013, Kwon et al., 2011, de Oliveira et al., 2012, Sigal et al., 2007, Sukala et

al., 2012, Yavari et al., 2012). For LDL-C, 9 trials involving 363 participants were included (Bacchi et al., 2012, Cauza et al., 2005, Duan and Lu, 2024, Kadoglou et al., 2013, Kwon et al., 2011, de Oliveira et al., 2012, Sigal et al., 2007, Sukala et al., 2012, Yavari et al., 2012). TC was assessed in 12 trials involving 446 participants (Arora et al., 2009, Bacchi et al., 2012, Cauza et al., 2005, Duan and Lu, 2024, Elsayed et al., 2024, Jorge et al., 2011, Kadoglou et al., 2013, Kwon et al., 2011, de Oliveira et al., 2012, Sigal et al., 2007, Sukala et al., 2012, Yavari et al., 2012), while TG were assessed in 11 trials involving 406 participants (Arora et al., 2009, Bacchi et al., 2012, Cauza et al., 2005, Duan and Lu, 2024, Jorge et al., 2011, Kadoglou et al., 2013, Kwon et al., 2011, de Oliveira et al., 2012, Sigal et al., 2007, Sukala et al., 2012, Yavari et al., 2012). Meta-analysis showed no statistically significant difference between AE and RT for HDL-C (Figure S2k; MD = 2.35 mg/dL, 95% CI: -0.06 to 4.76; I² = 98%, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>), LDL-C (Figure S2l; MD = 0.12 mg/dL, 95% CI: -0.28 to 0.51; I² = 0%, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>), TC (Figure S2m; MD = 0.12 mg/dL, 95% CI: -0.34 to 0.59; I² = 0%, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>), or TG (Figure S2n; MD = -0.77 mg/dL, 95% CI: -2.47 to 0.93; I² = 17%, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>). Subgroup analyses were conducted according to two distinct parameters: intervention duration and comorbidity reporting. These analyses revealed that there were no statistically significant differences observed in any of the lipid metabolism indicators (Figures S3d, S3e, S3f, and S3g, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>). For HDL-C, however, subgroup analysis by intervention duration showed a statistically significant subgroup difference ($p = 0.02$). In studies ≤ 12 weeks, AE was associated with higher HDL-C than RT (MD = 6.00 mg/dL, 95% CI: 1.08 to 10.92), whereas no statistically significant difference was observed in studies > 12 weeks (Figure S3e, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>). This finding was consistent across a sensitivity analysis.

Resting blood pressure

For resting DBP and SBP, 13 trials involving 509 participants were included (Arora et al., 2009, Bacchi et al., 2012, Cauza et al., 2005, Kadoglou et al., 2013, Kwon et al., 2011, Moe et al., 2011, Ng et al., 2010, de Oliveira et al., 2012, Ranasinghe et al., 2021, Shenoy et al., 2009, Sigal et al., 2007, Sukala et al., 2012, Yavari et al., 2012). Meta-analysis showed no statistically significant difference between AE and RT for DBP (Figure S2o; MD = -0.02 mmHg, 95% CI: -1.57 to 1.52; I² = 0%, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>) or SBP (Figure S2p; MD = 2.04 mmHg, 95% CI: -0.46 to 4.55; I² = 0%, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>). For RHR, three trials involving 158 participants were included (Arora et al., 2009, Yavari et al., 2012, Reid et al., 2010). Meta-analysis showed no significant difference between AE and RT for RHR (Figure S2r, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>). Subgroup analyses for DBP and SBP showed no statisti-

cally significant subgroup differences according to duration or comorbidity reporting (Figures S3i and S3j, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>). The limited number of available comparisons precluded pooled subgroup analyses for RHR.

Cardiorespiratory fitness

For CRF, 11 trials involving 419 participants were included (Bacchi et al., 2012, Cauza et al., 2005, Duan and Lu, 2024, Jorge et al., 2011, Kadoglou et al., 2013, Kwon et al., 2011, Moe et al., 2011, de Oliveira et al., 2012, Shahzadi et al., 2025, Swift et al., 2012, Yavari et al., 2012). AE was associated with a significantly greater improvement in CRF than RT (Figure S2s; MD = 1.78 mL/kg/min, 95% CI: 0.38 to 3.18; I² = 66%, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>). Subgroup analyses showed statistically significant differences according to duration in studies ≤ 12 weeks (Figure S3l; MD = 3.39 mg/dL, 95% CI: 1.90 to 4.89; I² = 0%, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>) favoring AE. Furthermore, subgroup analyses revealed no statistically significant differences according to comorbidity reporting status.

Publication bias

Publication bias and small-study effects were assessed for the 10 outcomes for which sufficient data were available, namely BF, BMI, SBP, DBP, FBG, FI, HbA1c, HDL-C, TC, and CRF (Figure S4, see at <https://www.jssm.org/SM/Man9414-2026SupplMaterials.pdf>). Visual inspection of funnel plots showed no consistent evidence of marked asymmetry across outcomes. Formal small-study-effect testing using Egger's regression test and Begg's rank correlation test also did not detect statistically significant evidence of publication bias for BF (Egger *p* = .616; Begg *p* = .601), BMI (Egger *p* = .638; Begg *p* = .093), DBP (Egger *p* = .133; Begg *p* = .111), FBG (Egger *p* = .902; Begg *p* = .095), HDL-C (Egger *p* = .139; Begg *p* = .719), HbA1c (Egger *p* = .101; Begg *p* = .417), SBP (Egger *p* = .859; Begg *p* = .759), TC (Egger *p* = .961; Begg *p* = .737), or CRF (Egger *p* = .578; Begg *p* = .165). For FI, neither Egger's test (*p* = .628) nor Begg's test (*p* = 1.000) suggested statistically significant small-study effects; however, this finding should be interpreted with caution, because only six studies comprised this analysis. Overall, no statistically significant evidence of publication bias was detected for the assessed outcomes, although the power of these tests was limited for outcomes with smaller numbers of studies.

Discussion

Summary of findings

To our knowledge, this systematic review and meta-analysis is among the few quantitative syntheses directly comparing AE and RT in adults with diabetes. AE was superior to RT for FBG and CRF, whereas RT was superior for BF and FFM; no significant differences were found for BW, BMI, WC, HC, FI, HbA1c, HOMA-IR, lipid markers, SBP, or DBP. Viewed through the CKM syndrome framework, applied here as a translational lens because the in-

cluded trials predated the 2023 AHA advisory, these findings suggest broadly comparable cardiometabolic effects with modality-specific advantages (Ndumele et al., 2023a, Ndumele et al., 2023b, Ndumele et al., 2023a, Ndumele et al., 2023b, Ortega et al., 2020, Allocca et al., 2025, Gorgojo-Martinez, 2025, Sindhwani et al., 2025, Ruze et al., 2023). This interpretation aligns with the network medicine (Sonawane et al., 2022, Theodorakis and Nikolaou, 2025, Wang et al., 2023) and supports current diabetes exercise guidelines positioning AE and RT as complementary, rather than competing, strategies (American Diabetes Association Professional Practice, 2025, Colberg et al., 2016, Kanaley et al., 2022, Paluch et al., 2024, Savikj and Zierath, 2020, Amare et al., 2025).

Body composition

RT showed more favorable effects than AE on BF and FFM, a result consistent with prior evidence that RT preserves and accrues lean tissue while improving adiposity-related outcomes (Paluch et al., 2024, Al-Mhanna et al., 2025b, Cheng et al., 2024, Sun et al., 2025, Lopez et al., 2022). Heterogeneity was low to moderate (BF I² = 1%; FFM I² = 37%), pointing to program-design factors (load, volume, supervision) rather than modality differences as the residual source of variability. Clinically, FFM preservation matters in diabetes because skeletal muscle accounts for the majority of insulin-stimulated glucose disposal (Richter et al., 2025), and the progressive sarcopenia that frequently accompanies obesity and T2DM undermines glycemic regulation and functional reserve (Cheng et al., 2024, Sun et al., 2025, Lopez-Pedrosa et al., 2024, Whytock and Goodpaster, 2025). RT may be preferable when preservation or enhancement of lean mass is a primary therapeutic objective. In light with the above, RT is likely to be prioritized when the dominant treatment target is the mitigation of sarcopenic obesity in diabetes care (Batakoulis et al., 2022, Khalafi et al., 2025, Sorace et al., 2024).

Glucose metabolism

AE was superior for FBG (MD = -0.89 mmol/L, I² = 0%), whereas HbA1c did not differ between modalities. This dissociation is plausible because FBG reflects shorter-term hepatic glucose output, whereas HbA1c integrates longer-term average glycemia and is more strongly influenced by trial duration, prescribed medications, baseline glycemic control (Richter et al., 2025). The null HbA1c finding and the modest FBG advantage are broadly consistent with prior comparative meta-analytic work in T2DM (Mannucci et al., 2021, Yang et al., 2014). Heterogeneity for fasting insulin (I² = 72%) and HOMA-IR (I² = 94%) constrains mechanistic interpretation. For prescription, AE retains a central role for day-to-day fasting glycemia, consistent with current guidelines (American Diabetes Association Professional Practice, 2025, Kanaley et al., 2022, Savikj and Zierath, 2020), while RT remains complementary, particularly when insulin sensitivity gains via FFM preservation are a priority (Khalafi et al., 2026c, Khalafi et al., 2026b, Allocca et al., 2025, Piche et al., 2020, Stocks and Zierath, 2022).

Lipid metabolism

AE and RT produced broadly comparable lipid effects, with no statistically significant between-group differences for HDL-C, LDL-C, TC, or TG. The HDL-C pooled estimate, however, was undermined by considerable heterogeneity ($I^2 = 98\%$); a subgroup signal favoring AE for shorter interventions should be regarded as hypothesis-generating, given the non-significant primary estimate and the low GRADE certainty. Heterogeneity is plausibly driven by background diet, baseline lipid profile, and concomitant lipid-lowering medications, which were inconsistently reported across the included trials. For prescription, both modalities can be deployed as effective non-pharmacological strategies for lipid-related cardiometabolic risk (Al-Mhanna et al., 2025a, Cauza et al., 2005, Colberg et al., 2016, Kanaley et al., 2022, Kobayashi et al., 2023, Lopez et al., 2022, Al-Mhanna et al., 2024a, Binmahfoz et al., 2025, Brun et al., 2022, Chen et al., 2025, Franczyk et al., 2023, Fritzen et al., 2020, Latino et al., 2021, Lundsgaard et al., 2018, Mengistu et al., 2025, Muscella et al., 2020, Pourmontaseri et al., 2024, Smart et al., 2025, Tremblay et al., 2024), and combined programming may yield additive benefit when lipid management is a clinical priority (Batrakoulis et al., 2022, Chen et al., 2025, Martinez-Vizcaino et al., 2022, Smart et al., 2025). Given the extreme heterogeneity observed for HDL-C, the pooled estimate should be interpreted cautiously, and may reflect clinically meaningful differences in intervention intensity, medication use, and baseline dyslipidemia across trials.

Blood pressure

Resting blood pressure showed no between-group difference for either SBP or DBP (Papadakis, 2024), consistent with the comparable net effects observed when AE and RT are compared head-to-head (Paluch et al., 2024, American Diabetes Association Professional Practice, 2025, Savikj and Zierath, 2020). Variability across these estimates likely reflects inconsistent baseline blood-pressure reporting, antihypertensive medication use, and dose differences across trials. The absence of a between-group difference should not be interpreted as exercise being ineffective for blood-pressure modification; both modalities are beneficial, and combined programming over time remains the most defensible long-term strategy (American Diabetes Association Professional Practice, 2025, Colberg et al., 2016, Ceriello and Colagiuri, 2025). This complementary view is consistent with recent evidence that combined AE and RT improves glycemic control and other cardiometabolic outcomes in adults with diabetes (Al-Mhanna et al., 2025a, Al-Mhanna et al., 2024b, Al-Mhanna et al., 2025d, Al-Mhanna et al., 2025e), and with the AHA's CKM syndrome advisory, which positions intensive lifestyle modification, including structured exercise, as the foundation of early-stage interventional management (Ndumele et al., 2023a, Ndumele et al., 2023b, Ndumele et al., 2023a, Ndumele et al., 2023b, Rutters et al., 2024, Papadakis, 2026a, Papadakis, 2025b, Papadakis, 2025a, Papadakis, 2026b, Papadakis, 2026a, Papadakis, 2025b, Papadakis, 2025a, Papadakis, 2026b).

Cardiorespiratory fitness

AE produced a small but consistent CRF advantage (MD

1.78 mL/kg/min, $I^2 = 66\%$), as physiologically expected given AE's more direct stimulus for the central and peripheral adaptations underlying oxygen utilization (Fiuza-Luces et al., 2013, Sanchis-Gomar et al., 2015, Jakicic et al., 2024, Al-Mhanna et al., 2025c). The substantial heterogeneity indicates that the magnitude of CRF benefit depends on program design, intensity, volume, supervision, and participant characteristics rather than on modality alone (Al-Mhanna et al., 2025c, Al-Mhanna et al., 2025e, American Diabetes Association Professional Practice, 2025, Kanaley et al., 2022). CRF improvement is a primary therapeutic target in early-stage CKM management (stages 0 - 2), where supervised multimodal exercise reliably evokes improvements in CRF and endothelial function (Papadakis, 2026b, Papadakis, 2026a, Papadakis, 2025b, Papadakis, 2026a, Papadakis, 2025b). Because reduced CRF is independently associated with worse cardiometabolic prognosis in T2DM (Al-Mhanna et al., 2025c, Jakicic et al., 2024), AE may be considered a priority when functional or aerobic capacity is the dominant therapeutic goal (Al-Mhanna et al., 2025a, Al-Mhanna et al., 2025c, Al-Mhanna et al., 2025d, Al-Mhanna et al., 2025e).

Interpretation of subgroup and sensitivity findings

Most subgroup analyses showed no significant differences by intervention duration, comorbidity reporting, or baseline BMI, suggesting that the main comparative findings were relatively stable across examined strata. However, subgroup analyses in meta-analyses are often underpowered and should be interpreted cautiously (Higgins JPT et al., 2024). The only notable exception was HDL-C by intervention duration, where shorter interventions appeared to favor AE. Nevertheless, because the primary HDL-C analysis was non-significant and highly heterogeneous ($I^2 = 98\%$), this finding should be considered uncertain. Although sensitivity analysis favored AE (MD = 3.93, 95% CI: 0.99 to 6.86; $I^2 = 34\%$), it does not supersede the prespecified primary estimate. For HbA1c, the null effect remained unchanged after leave-one-out analysis (MD = -0.01, 95% CI: -0.16 to 0.13; $I^2 = 25\%$), supporting the robustness of the main finding.

Clinical applicability and exercise prescription

The present findings have direct implications for exercise prescription in adults with diabetes. Contemporary guidelines from the American Diabetes Association, American College of Sports Medicine, and international diabetes organizations consistently recommends regular moderate-to-vigorous physical activity, including both aerobic and RT, as part of the standard management of T2DM (American Diabetes Association Professional Practice, 2025, Kanaley et al., 2022, Ceriello and Colagiuri, 2025, Paluch et al., 2024, Amare et al., 2025, Savikj and Zierath, 2020). Within the CKM syndrome framework (Ndumele et al., 2023a, Ndumele et al., 2023b), exercise modality may be tailored to the dominant treatment target and CKM stage. Papadakis (Papadakis, 2026a) similarly proposed a stage-informed, mechanistic approach in which supervised multimodal exercise provides synergistic, rather than competing, adaptations. When fasting glycemia or CRF is the main priority, particularly in early-stage CKM, AE may be

preferred (Ndumele et al., 2023a, Rutters et al., 2024, Papadakis, 2025b, Papadakis, 2025a, Papadakis, 2026b, Papadakis, 2026aPapadakis, 2026a). Conversely, when improving body composition and preserving or increasing lean body mass are central, especially in emerging sarcopenic obesity, RT may be more appropriate (Paluch et al., 2024, Al-Mhanna et al., 2025b, Cheng et al., 2024, Sun et al., 2025). However, because most outcomes showed no clear between-group differences, AE and RT should not be viewed as mutually exclusive. Rather, both modalities should be combined or sequenced according to patient needs, feasibility, adherence potential, and therapeutic goals. This approach is particularly relevant in diabetes, where management requires simultaneous improvement in glycemic control, adiposity, muscle mass, physical function, and long-term CV risk (Ndumele et al., 2023a, Ndumele et al., 2023bNdumele et al., 2023a, Ndumele et al., 2023b, Rutters et al., 2024, Papadakis, 2026b, Papadakis, 2025b, Papadakis, 2026aPapadakis, 2026a). Within lifestyle medicine, exercise may function as a pleiotropic “polypill” producing coordinated multisystem adaptations (Berisha et al., 2025, Pikula et al., 2024, Papadakis, 2025a, Papadakis, 2026b, Papadakis, 2025c, Papadakis, 2026a, Fiuza-Luces et al., 2013, Sanchis-Gomar et al., 2015, Jakicic et al., 2024). Therefore, integrating modality-specific evidence into individualized, goal-directed programs may support scalable lifestyle interventions for diabetes (Rutters et al., 2024, Papadakis, 2026b, Papadakis, 2025b, Papadakis, 2026a, Papadakis, 2025c).

Strengths and limitations

This review has several strengths. It included only RCTs, used direct AE versus RT comparisons rather than indirect network estimates, and examined clinically relevant cardiometabolic outcomes in adults specifically defined by co-existing T2DM and obesity. It also incorporated subgroup and sensitivity analyses, publication-bias assessment, and GRADE certainty evaluation, supporting a more nuanced interpretation. The findings were clinically coherent, with AE favoring fasting glycemia and CRF, and RT favoring body composition.

Several limitations should be acknowledged. The included trials varied in duration, exercise dose, supervision, participant characteristics, comorbidity burden, and methods, contributing to heterogeneity. Some outcomes were supported by few studies, limiting precision and the reliability of subgroup or publication-bias analyses. Blinding limitations, unclear randomization reporting, and substantial heterogeneity for HDL-C, fasting insulin, and HOMA-IR further reduced certainty. Resting heart rate could not be pooled, and meta-regression was not appropriate because of limited comparisons and inconsistent dose reporting. Medication and dietary co-interventions were inconsistently reported, limiting isolation of exercise-specific effects, particularly in the context of contemporary T2DM pharmacotherapy. Moreover, most eligible RCTs were published between 2005 and 2014, before current diabetes management approaches. Finally, because CKM staging was formalized only in 2023, its application here is translational and interpretive rather than empirical (Ndumele et al., 2023a, Ndumele et al., 2023bNdumele et

al., 2023a, Ndumele et al., 2023b, Papadakis, 2026a; 2026b).

Implications for future research

The most beneficial subsequent action would be a dose-stratified individual-participant data meta-analysis or a sufficiently powered factorial AE $\times$ RT trial within contemporary T2DM care. Future trials in adults with diabetes should use larger samples, clearer randomization reporting, standardized exercise dosing, longer follow-up, and more consistent reporting of medication use, diet, adherence, adverse events, and baseline phenotype. Given current uncertainty for lipid and insulin-resistance outcomes, studies should be powered to detect clinically meaningful changes in these variables, as well as inflammation, adipokines, visceral adipose tissue, and liver enzymes. Aligning trial designs with the AHA CKM staging framework and stage-informed exercise prescription models would enable stage-specific analyses and support more precise recommendations (Ndumele et al., 2023a, Ndumele et al., 2023bNdumele et al., 2023a, Ndumele et al., 2023b, Rutters et al., 2024, Papadakis, 2025b, Papadakis, 2026b, Papadakis, 2026a, Khalafi et al., 2026aPapadakis, 2026a, Khalafi et al., 2026a). Further work should also determine whether specific subphenotypes, including greater obesity severity, low fitness, or sarcopenic risk, benefit more from AE, RT, or combined/sequential prescriptions (Ma et al., 2024, Mannucci et al., 2021, Mousavi Zadeh et al., 2025, Papadakis, 2025c, Papadakis, 2025a, Al-Mhanna et al., 2025a, Al-Mhanna et al., 2024b, Al-Mhanna et al., 2025d, Al-Mhanna et al., 2025e, Amare et al., 2025).

Conclusion

In adults with diabetes, AE appears to provide greater benefits for FBG and CRF, whereas RT appears more favorable for preserving FFM and improving BF. For most cardiometabolic outcomes, no statistically significant between-group difference was detected. When interpreted within the lifestyle medicine paradigm, these complementary findings support a goal-directed and individualized approach to exercise prescription rather than a one-modality-fits-all model. Clinicians managing diabetes should select individualized exercise prescription based on the dominant therapeutic objective at each stage of disease management and the patient-specific clinical characteristics.

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Key points

- Aerobic exercise appears more effective than resistance training for improving fasting blood glucose in adults with diabetes.
- Aerobic exercise also produces greater improvements in cardiorespiratory fitness compared with resistance training.
- Resistance training appears superior for body composition, leading to better fat-free mass preservation and less body fat gain than aerobic exercise.
- Aerobic exercise and resistance training show broadly no statistically significant between-group difference on anthropometric indices, blood lipids, and hemodynamic outcomes.
- These findings support a goal-directed, complementary exercise prescription strategy rather than a one-modality-fits-all approach for cardiometabolic health in patients with diabetes.

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