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REVIEW

Comparative Efficacy of Exercise Type on Visceral Adipose Tissue in Patients With Prediabetes and Type 2 Diabetes Mellitus: A Systematic Review With Pairwise and Network Meta-Analyses

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ABSTRACT

The aim of this systematic review with pairwise and network meta-analyses was to examine the effects of different exercise types on visceral adipose tissue (VAT) in patients with prediabetes and type 2 diabetes mellitus (T2DM). A comprehensive search was conducted in PubMed, Web of Science, and Scopus using four main keywords including "exercise training," "visceral fat," "diabetes," and "randomization" from inception to April 2025. Thirty-three randomized controlled trials or clinical trials with parallel groups were included (1740 patients), in which exercise training was compared with either nonexercise or other types of exercise training. Combined training ($n = 5$) (−0.63 [95% CI −0.95 to −0.30], $p = 0.001$), high-intensity interval training ($n = 11$) (−0.53 [95% CI −0.86 to −0.19], $p = 0.001$), and aerobic training ($n = 24$) (−0.38 [95% CI −0.59 to −0.18], $p = 0.001$), but not resistance training ($n = 8$) (−0.25 [95% CI −0.54 to 0.03], $p = 0.08$) were more effective for reducing VAT as compared with controls. Subgroup analyses based on age, health status, body mass index, or intervention duration confirmed that combined training, high-intensity interval training, aerobic training, but not resistance training, induced advantageous alterations in VAT compared to the control group. The main findings show that the *P*-score–based ranking of interventions reported the highest probability ranking for CT (0.89), followed by HIIT (0.76), AT (0.52), and RT (0.32). These findings provide compelling evidence to support the use of exercise training as a noninvasive and cost-effective nonpharmacological intervention for the reduction of VAT in patients with prediabetes and T2DM.

PROSPERO Registration Number: CRD42024598045.

1 | Introduction

1.1 | Glucose Metabolism and Visceral Fat

Impaired glucose metabolism, frequently associated with excess body weight or adiposity, is a common global public health issue that increases the risk of morbidity and mortality associated with cardiovascular diseases [1]. Consequently, physically inactive individuals with poor glucose control commonly demonstrate metabolic dysregulation and cardiovascular complications, as well as excess visceral adiposity [2, 3]. People with prediabetes and type 2 diabetes mellitus (T2DM) usually exhibit abdominal obesity associated with increased visceral adipose tissue (VAT) located within the abdominal cavity surrounding internal organs, including the liver and intestines [4]. Excessive VAT accumulation fosters harmful diabetes-related health effects resulting in an increased risk of hepatic steatosis, cardiovascular diseases, and metabolic syndrome [5]. Moreover, abnormal VAT leads to chronic low-grade inflammation, elevated oxidative stress, low antioxidant capacity, and compromised immune function [6]. In order to improve metabolic health among people with prediabetes and T2DM, reducing visceral adiposity is therefore considered more effective than other anthropometric parameters in glucose management [7].

1.2 | Role of Exercise in Visceral Fat

In light of these considerations, the prioritization of nonpharmacological interventions, such as physical exercise, has emerged as an important approach for medical practitioners, healthcare professionals, and policymakers striving to address the adverse health consequences and concomitant economic burdens associated with T2DM [8]. Physical exercise can be a noninvasive and cost-effective therapeutic tool for reducing VAT and improving glucose homeostasis in individuals with metabolic health impairments [9–12]. Although regular exercise may not always reduce body weight, extra literature indicates that exercise can decrease visceral adiposity, even in the absence of weight loss [13], and improve hormonal alterations that impact the regulation of glucose levels and fatty acid metabolism among people with poor glucose control [14].

1.3 | Impact of Different Exercise Types on Visceral Fat

Exercise training can have inconsistent effects on VAT among individuals with prediabetes and T2DM [9, 15]. A plethora of studies investigating some of the most popular exercise training modalities in both exercise communities and clinical practice [16] display positive effects on VAT in populations with prediabetes and T2DM. In particular, aerobic training, high-intensity interval training (HIIT) and combined aerobic and resistance training, but not resistance training alone, exhibit favorable changes in VAT [9, 13, 17–29]. However, these beneficial exercise-induced changes are not always clinically significant, and the role of different exercise types in lowering VAT requires further elucidation. Any discrepancies may be attributed to diverse study populations, which may have resulted in varying outcomes [9, 30–33], meaning whether there is an optimal type of exercise for patients with prediabetes and T2DM is unknown.

1.4 | Research Objectives

Although robust evidence supports a vital role for exercise in improving cardiometabolic risk associated with diabetes [34], the comparative efficacy of the most widely used exercise types for reducing VAT among individuals with prediabetes and T2DM remains unclear. The objectives of the present systematic review that uniquely adopted pairwise and network meta-analyses was to investigate the efficacy of different types of exercise for reducing VAT in patients with prediabetes and T2DM and to identify the most effective type of exercise training.

2 | Methods

2.1 | Registration

This systematic review with pairwise and network meta-analyses was conducted according to Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [35] and the Cochrane Handbook for Systematic Reviews of Interventions [36]. The present study was registered at the International Prospective Register of Systematic Reviews (PROSPERO) with registration number: CRD42024598045

2.2 | Literature Search Strategy

A comprehensive search was conducted in PubMed, Web of Science, and Scopus using four main keywords, including "exercise training," "visceral fat," "diabetes," and "randomization" from inception to July 2024. There were restrictions set for the English language and studies of humans, where possible. The full search strategy is summarized in Table S1. In addition, the search was updated through to April 2025. In addition, the reference lists of the included studies, additional relevant meta-analyses [9, 13, 18] and Google Scholar were manually searched to ensure that all relevant studies were included in the meta-analyses. Two authors (M.K. and S.F.) independently performed the database and manual searches.

2.3 | Study Selection and Eligibility Criteria

All retrieved records were imported to EndNote and duplicate articles excluded. Subsequently, the records were screened against the inclusion and exclusion criteria. The screening process was conducted in two stages: 1) title and abstract screening and 2) screening of the full texts of eligible articles. Study selection was completed by two independent authors (S.F. and F.D.) and any disagreements were resolved through discussion with another author (M.K.). Interrater agreement [37] assessed using Cohen's κ statistic was 0.86 before resolving discrepancies. The studies included in the meta-analysis met the following criteria: they must have been written in

the English language. Additionally, the studies must have met the following population, intervention, comparison, outcomes, and study (PICOS) criteria to be included: For population, studies must have involved adults with prediabetes or type 2 diabetes mellitus (T2DM) with mean ages ≥ 18 years, regardless of biological sex. Prediabetes was defined as fasting blood glucose (FBG) between 6.1 and 6.9 mmol/L, two-hour blood glucose (2 h-BG) between 7.8 and 11.1 mmol/L, or glycated hemoglobin (HbA1c) between 5.7 and 6.4% (39–46 mmol/mol). T2DM was defined as FBG ≥ 7.0 mmol/L, or 2 h-BG ≥ 11.1 mmol/L, or HbA1c ≥ 6.5% (48 mmol/mol). HbA1c was prioritized among these glycemic markers for diagnosing prediabetes or T2DM [38–40]. In addition, participants with obesity, metabolic syndrome, or fatty liver diseases were included if they met the prediabetes definition. For intervention, studies were included if they involved any mode of exercise including aerobic training, resistance training, HIIT, or combined aerobic and resistance training and had a duration ≥ 2 weeks. In addition, studies involving other exercise types such as Pilates, yoga, or tai chi were included. In order to facilitate comparison, studies involving nonexercise or usual care control groups and other exercise training groups were included. For outcomes, studies had to measure visceral fat, interabdominal fat, or preperitoneal fat before and after intervention using valid measurement units such as grams/kg, percentages, mm, cm^2, L, or cm^3 [41]. To ensure the methodological quality of the study, randomized controlled trials or clinical trials with parallel groups that had undergone peer review were included when they compared exercise training and nonexercise or other types of exercise. Exclusion criteria were nonoriginal, nonrandomized studies. In addition, studies without more than one group or studies that used the bioelectrical impedance method were excluded because of some concerns about the validity of quantifying VAT, especially in clinical settings [42, 43].

2.4 | Data Extraction

Two authors (S.F. and F.D.) independently extracted the data, and any disagreements were resolved by discussion with another author (M.K.). The following data were extracted: 1) publication characteristics, including first author name and publication year; 2) study design, including randomized controlled or clinical trials; 3) participant characteristics, including sample size, ages, body mass indexes (BMI), and health status; 4) exercise characteristics, including type, intensity, duration of intervention, and protocol; 5) outcome variable (VAT), including measurement methods and reported units.

2.5 | Data Synthesis

In order to perform the requisite analyses, the mean changes and their standard deviations (SDs) were extracted. However, when required, these data were calculated from means and SDs of preintervention and postintervention data using a relevant formula with conservative values of 0.5 for correlations, as recommended in the Cochrane Handbook. In addition, when required, means and SDs were calculated from other data such as standard errors, medians, and interquartile ranges (IQRs), and 95% confidence intervals, or were extracted from figures using Getdata software [44–46]. If studies had more than one intervention arm with different exercise types (such as aerobic and resistance), each one was included as a separate arm, and the sample size of the control group was divided by the number of intervention arms in the pairwise analysis. However, if studies had more than one exercise arm with the same exercise type (such as aerobic training with moderate versus high intensities), these were combined using the relevant formulas recommended by the Cochrane Handbook for Systematic Reviews of Interventions. In addition, studies involving exercise training plus a dietary intervention, versus dietary intervention alone, were included in the analyses if the diet was the same in all intervention arms.

2.6 | Quality Assessment

The overall quality of the included studies was assessed using the Physiotherapy Evidence Database (PEDRO) scale, which contains 11 items [47]. However, two items, including "blinding of all subjects," and "blinding of all therapists who administered the therapy," were excluded from our review because of the impossibility of applying them in exercise interventions. Finally, the quality of the included studies was assessed using the 9 remaining items by two independent authors (S.F. and F.D.), and any disagreements were resolved by discussion with another author (M.K.). The scores ranged from 0 to 9, with higher scores demonstrating higher quality. The quality assessment scores are summarized in supplementary Table 2.

2.7 | Statistical Analysis

The pairwise meta-analysis was conducted using comprehensive meta-analysis software (version 3) to compare the effects of exercise training versus nonexercise control groups. The standardized mean differences (SMDs) were calculated using random effects models, and effect sizes were interpreted using the Cochrane guidelines, with 0.20–0.49, 0.50–0.79, and ≥ 0.80 indicating small, medium, and large effect sizes, respectively [36]. The heterogeneity among included studies was determined using I^2 and Q-statistics, with the I^2 interpreted according to the Cochrane guidelines, with 25%, 50%, and 75% indicating low, moderate, and high heterogeneity, respectively. Publication bias was assessed using the visual interpretation of funnel plots and Egger's tests as a secondary measure, where a p value of < 0.10 indicated possible publication bias [48]. A sensitivity analysis was conducted by removing individual studies to ascertain that the findings were not unduly influenced by a single study. Additionally, several subgroup analyses were performed based on the age of participants (middle-aged: < 60 years, older: ≥ 60 years), health status (prediabetes, T2DM), BMI classification (nonobese: BMI < 30 kg m^2, obese: BMI ≥ 30 kg m^2), and intervention duration (short-term: < 16 weeks, long-term: ≥ 16 weeks). To investigate the direct and indirect effects of exercise modes, the network meta-analysis was conducted with a frequentist framework using the netmeta package in the statistical software R (V.4.4.1). Because the visceral fat reported with different measurement units in the included studies, the standardized mean differences (SMDs) were determined using

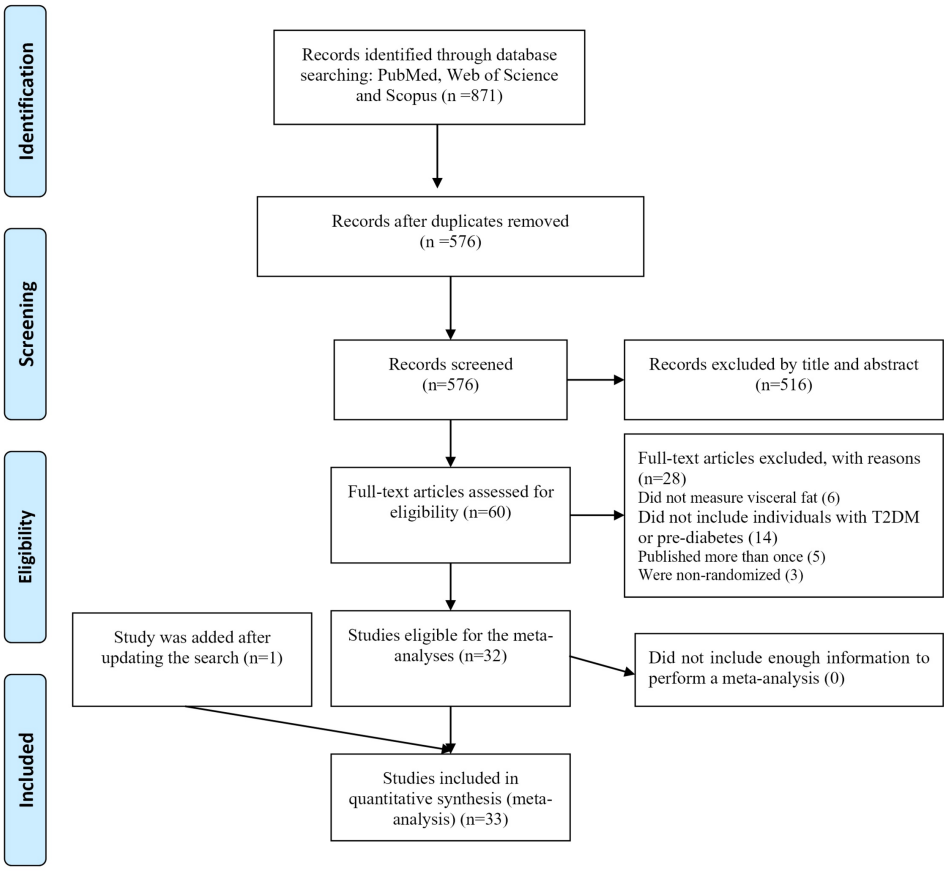


FIGURE 1 | Flow diagram of systematic literature search.

a random effects model to calculate the effect size. Network forest plots and league tables were used to show the relative estimate of mixed (direct and indirect) effect sizes and 95% CIs for all combinations of interventions in the network. *P* score values (ranging from 0 to 1) were used to rank each intervention, with smaller values indicating the better rank. In addition, the transitivity assumption was assessed by a visual inspection of participant characteristics including age, biological sex, and health status; study design characteristics including randomization; and intervention characteristics including intervention duration. The assumption of consistency was assessed using direct and indirect estimates via node-splitting models, and statistical inconsistency was considered present when $p \leq 0.05$ [49, 50]. Heterogeneity was assessed using the I^2 and Q-statistic according to Cochrane guidelines, which describe within-design heterogeneity and between-design inconsistency. Publication bias was assessed using the visual interpretation of funnel plots and confirmed using Egger's tests.

3 | Results

3.1 | Search Strategy

The initial search yielded 871 records, of which 576 remained after removing duplicates. Subsequently, 516 articles were removed based on title and abstract screening, and 60 articles were deemed eligible for the full-text screening. Following the complete screening process, 28 studies were removed because of reasons such as not measuring visceral fat ($n = 6$), not including individuals with T2DM or prediabetes ($n = 14$), published more than once ($n = 5$), and being nonrandomized ($n = 3$) as presented in Figure 1. In addition, 1 study was added after updating the search [51]. Finally, 33 studies met all inclusion criteria and were included in the analyses [52–83]. Among the included studies, six did not have a control group and were not included in the pairwise meta-analysis but were included in the network meta-analysis [53, 54, 65, 70, 74, 76]. All included studies were randomized control or clinical trials with parallel groups. The details of the searches and study selection process are presented in Figure 1, and study characteristics are summarized in Table 1.

3.2 | Participants and Interventions Characteristics and Quality Assessment

Overall, 1740 participants with a mean age ranging from 45 to 70 years and a mean BMI ranging from 25 to 40 kg m^2 were included in the meta-analysis, with 20 studies having participants with T2DM [51–57, 59–62, 67, 68, 70–75, 77, 81] and 12 with prediabetes [58, 63–66, 69, 76, 78–80, 82, 83]. In addition, the participants had other comorbidities such as nonalcoholic fatty liver disease [52, 58, 63, 64], nonalcoholic steatohepatitis [28, 66], metabolic dysfunction–associated [80], and metabolic syndrome [75, 76] before or stage I hypertension [62]. The intervention duration ranged from 2 to 24 weeks, with a weekly frequency of exercise sessions ranging from 2 to 7 sessions per week. Different modes of

TABLE 1 | Characteristics of participants and interventions.

Source, year	Groups	Sample size (male, female)	Participants characteristics	Glycemic marker (s)	Age (years)	BMI (kg/m^2)	Ex program duration, frequency and type	Supervision	Measurement method and unit
Abdelbasset et al., 2020 [52]	HIIT, AEx, C	47 (M, F)	T2D, obese, NAFLD	HbA1c: 6.56 ± 0.50%	HIIT: 54.40 ± 5.80 AEx: 54.90 ± 4.70 C: 55.20 ± 4.30	HIIT: 36.3 ± 4.5 AEx: 36.7 ± 3.4 C: 35.9 ± 5.3	8-wk, 3×/wk., HIIT: 40 min: warmup: 5 min, cycle ergometer: 3 × 4 min at 80%–85% of VO_{2max}, between intervals recovery: 2 min at 50% of VO_{2max}, cooldown: 5 min. AEx: 40–50 min: warmup: 5 min, cycle ergometer: 60–70% of HR_{max}, cooldown: 5 min.	S	MRI – cm^2
Baasch-Skytte et al., 2020 [53]	HIIT, AEx	44 (M)	T2DM	FBG: 161 ± 61.50 mg/dL	HIIT: 61.0 ± 6.2 AEx: 61.2 ± 7.1	HIIT: 30.6 ± 5.4 AEx: 30.7 ± 4.4	10-wk, 3×/wk.; cycling, HIIT: 29 min, warmup: 10 min at low-intensity, 5 intervals of 1 min divided into 30, 20 and 10 s at low ~ 30–100 W, moderate ~ 60–180 W and maximal ≥ 400 W intensity, between intervals recovery: passive 2 min; AEx: 50 min at 60%–75% of HRR.	S	DXA—kg
Bacchi et al., 2012 [54]	AEx, REx	38 (M, F)	T2DM	FBG: 143.5 ± 31.93 mg/dL	AEx: 57.2 ± 5.65 REx: 55.6 ± 5.83	AEx: 29.50 ± 4.69 REx: 29.20 ± 4.47	16-wk, 3×/wk., AEx: cardiovascular training equipment, 60 min at 60%–65% of HRR. REx: weight machines and free weights, 60 min: 3 sets of 70%–80% of 1-RM.	S	MRI – cm^2

(Continues)

TABLE 1 | (Continued)

Source, year	Groups	Sample size (male, female)	Participants characteristics	Glycemic marker (s)	Age (years)	BMI (kg/m^2)	Ex program duration, frequency and type	Supervision	Measurement method and unit
Botton et al., 2018 [55]	REx, C	44 (M, F)	T2DM	FBG: 144.07 ± 41.18 mg/dL	REx: 70.6 ± 6.70 C: 68.6 ± 7.06	REx: 28.20 ± 3.60 C: 28.64 ± 3.26	12-wk, 3×/wk., warmup: treadmill, REx: traditional machines, 15 RMs (avoided failure), 2–3 sets, between sets recovery: 60s, plus functional exercises, 2–3 sets, more than 6 on OMNI scale, between sets recovery: 60s.	S	USG—mm
Boudou et al., 2003 [56]	AEx, C	16 (M)	T2DM	FBG: 160.50 ± 31.14 mg/dL	AEx: 42.90 ± 5.20 C: 47.90 ± 8.35	AEx: 28.30 ± 3.90 C: 30.85 ± 5.20	8-wk, 3×/wk.; continuous exercise: 2×/wk., 45 min at 75% of VO_{2peak} plus intermittent exercise: 1×/wk., 5 × 2 min at 85% of VO_{2peak}, between intervals recovery: 3 min at 50% of VO_{2peak}. C: 1×/wk.; bicycle ergometer: 60 R.P.M. for 20 min at low intensity (30 W).	S	MRI—cm^2
Cassidy et al., 2016 [57]	HIIT, C	23 (M, F)	T2DM	FBG: 124 ± 23.80 mg/dL 2 h-BG: 218 ± 54.90 mg/dL HbA1c: 7 ± 0.78%	HIIT: 61 ± 90 C: 59 ± 90	HIIT: 31 ± 50 C: 32 ± 60	12-wk, 3×/wk.; cycle ergometer, warmup: 5 min at 9–13 RPE, 5 intervals: pedal cadence of more than 80 R.P.M. at RPE of 16–17, between cycle recovery: active 3 min.	Both	MRI—cm^2

(Continues)

TABLE 1 | (Continued)

Source, year	Groups	Sample size (male, female)	Participants characteristics	Glycemic marker (s)	Age (years)	BMI (kg/m^2)	Ex program duration, frequency and type	Supervision	Measurement method and unit
Cheng et al., 2017 [58]	AEx, C	85 (M, F)	PD, NAFLD	FBG: 99.8 ± 11.88 mg/dL 2 h-BG: 144.7 ± 27 mg/dL HbA1c: 6.09 ± 0.44%	AEx: 59.51 ± 3.95 C: 60 ± 3.75	AEx: 26.84 ± 3.25 C: 26.82 ± 2.76	24-wk, 2–3×/wk.; Nordic brisk walking + stretching and other exercises, warmup: 5 min, 30–60 min at 60%–75% VO_{2max}, cooldown: 5 min. Diet: 24–32 w, lunch: 30%–40% of the total daily energy intake: 37%–40% carbohydrate with 9–13 g as fiber, 35%–37% fat (SAFA 10%, MUFA 15%–20%, PUFA 10%) and 25%–27% protein.	S	1H-MRS, − kg
Choi et al., 2012 [59]	AEx, C	75 (F)	T2DM	FBG: 139.29 ± 30.33 mg/dL	AEx: 53.8 ± 7.2 C: 55.0 ± 6.0	26.8 ± 2.4	12-wk, 5×/wk.; walking, 60 min at moderate intensity	Non	CT—cm^2
Cuff et al., 2003 [60]	AEx, CEx, C	28 (F)	T2DM, obese, postmenopausal	HbA1c: 6.70 ± 1.06%	AEx: 59.4 ± 5.7 CEx: 63.4 ± 6.95 C: 60 ± 8.7	AEx: 32.5 ± 4.2 CEx: 33.3 ± 4.74 C: 36.7 ± 6	16-wk, 3×/wk.; CEx: AEx: 75 min of aerobic exercise equipment at 60%–75% HRR plus REx: weight machines: 2 sets of 12 reps with progressive intensity. AEx: structured exercise classes: 75 min plus low-impact low intensity dynamic movement ~ 0.1 kcal.min^{-1}.kg^{-1}	S	CT—cm^2

(Continues)

TABLE 1 | (Continued)

Source, year	Groups	Sample size (male, female)	Participants characteristics	Glycemic marker (s)	Age (years)	BMI (kg/m^2)	Ex program duration, frequency and type	Supervision	Measurement method and unit
Giannopoulou et al., 2005 [61]	AEx, C	22 (F)	T2DM, obese, postmenopausal	FBG: 165 ± 46.44 mg/dL	AEx: 57.4 ± 5.63 C: 58.5 ± 5.63	AEx: 33.7 ± 6.3 C: 34.3 ± 6.3	14-wk, 3–4×/wk.; AEx: walking, 60 min at 65%–70% of VO_{2peak} ~ 1050 to 1250 kJ Diet: high-MUFA fat diet composed of 40% fat (30% MUFA, 5% PUFA, and 5% SAFA), 40% carbohydrates (15% simple and 25% complex carbohydrates), and 20% protein. AEx + diet: AEx days ~1460-kJ deficit from the diet and ~1050-kJ deficit from the AEx. Non—AEx days ~2510 kJ deficit was provided from the diet alone.	S	MRI—cm^2
Gibbs et al., 2012 [62]	CEx, C	112 (M, F)	T2DM pre or Stage I Hypertension	HbA1c: 6.60 ± 1.30%	CEx: 58 ± 5 C: 56 ± 6	CEx: 32.30 ± 5.30 C: 33.50 ± 4.30	24-wk, 3×/wk.—CEx: warmup: 15 min, AEx: 45 min at 60%–90% of HR_{max} plus REx: weight training exercises: 2 sets of 12–15 reps at 50% of 1-RM.	S	MRI – cm^2
Hallsworth et al., 2011 [63]	REx, C	19 (M, F)	PD, NAFLD	FBG: 107.10 ± 38.160 mg/dL HbA1c: 6.26 ± 0.93%	REx: 52 ± 13.3 C: 62 ± 7.4	REx: 32 ± 4.9 C: 32 ± 4.8	8-wk, 3×/wk.; circuit training: 45–60 min, warmup: 10 min, 2–3 circuits with 50%–70% of 1-RM	S	1H-MRS—cm^2

(Continues)

TABLE 1 | (Continued)

Source, year	Groups	Sample size (male, female)	Participants characteristics	Glycemic marker (s)	Age (years)	BMI (kg/m^2)	Ex program duration, frequency and type	Supervision	Measurement method and unit
Hallsworth et al., 2015 [64]	HIIT, C	23 (F)	PD, NAFLD	FBG: 100.63 ± 26.82 mg/dL 2 h-BG: 161.82 ± 70.38 mg/dL HbA1c: 6.60 ± 1.50%	HIIT: 54 ± 10 C: 52 ± 12	HIIT: 31 ± 4 C: 31 ± 5	12-wk, 3×/wk.; cycling, 30–40 min: warmup: 5 min, 5 intervals in 2–3 min and 50s at RPE of 16–17, between intervals recovery: 3 min, cooldown: 3 min.	S	1H-MRS—cm^2
Honkala et al., 2017 [65]	HIIT, AEx	16 (M)	PD	FBG: 131.04 ± 12.96 mg/dL HbA1c: 5.74 ± 0.58%	HIIT: 47 ± 4.59 AEx: 47 ± 4.72	HIIT: 29.8 ± 2.76 AEx: 31.1 ± 4.05	2-wk, 3×/wk.; cycle ergometer, 4–6 × 30s all-out intervals; healthy participants: 7.5% of whole-body weight (kg) and in defective glucose tolerance participants: 10% of lean body mass (kg), between intervals recovery: 4 min. AEx: cycle ergometer, 40–60 min at 60% of VO_{2peak}	S	MRI—kg
Houghton et al., 2017 [66]	CEx, C	24 (N. R)	PD, NASH	FBG: 112.50 ± 29.34 mg/dL	CEx: 54 ± 12 C: 51 ± 16	CEx: 33 ± 5 C: 33 ± 7	12-wk, 3×/wk.; 45–60 min, warmup: 5 min; AEx: cycling: 3 × 2 min at RPE of 16–18, between intervals recovery: 1 min and plus REx: circuit cycles at RPE of 14–16	S	MRI—cm^2

(Continues)

TABLE 1 | (Continued)

Source, year	Groups	Sample size (male, female)	Participants characteristics	Glycemic marker (s)	Age (years)	BMI (kg/m^2)	Ex program duration, frequency and type	Supervision	Measurement method and unit
Lyngbak et al. 2024 [51]	CEx_1, ce_2, C	62 (M, F)	T2DM	FBG: 147.24 ± 35.46 mg/dL HbA1c: 6.72 ± 4.03%	CEx_1: 60.9 ± 7.6 ce_2: 57.3 ± 11.8 C: 55.9 ± 10	CEx_1: 33.2 ± 4.1 ce_2: 33.4 ± 3.5 C: 33.2 ± 3.8	CEx_1 (medium) + diet: 16-wk, 3×/wk., AEx: 2×/wk., 50 min, stationary bikes, 60–100% of HR_{max} + CEx: 1×/wk. AEx: 30 min, stationary bikes + REx: 30–45 min, large muscle groups, upper and lower body exercises, 2–3 sets of 8–12 reps at 0–3 RIR, time/wk. ~ 150–165 min. CEx_2 (high) + diet: 16-wk, 6×/wk., AEx: 4×/wk. same + CEx: 2×/wk., exercise training, time/wk. ~ 300–330 min. Diet: ~25%–30% caloric restriction, CHO: 45%–60% + protein: 15%–20%, fat <35% (< 7% sat. fat), personalized meal plan + 3 dietitian sessions, 3-day food diaries for monitoring.	S	MRI—cm^2
Jung et al., 2012 [67]	AEx C	28 (F)	T2DM	FBG: 138.34 ± 32.66 mg/dL	AEx: 52.6 ± 8.21 C: 55.5 ± 7.6	AEx: 25.7 ± 1.51 C: 27.7 ± 3.4	12-wk, 5×/wk.; 500 kcal/day; AEx1: 5×/wk., 30 min, 5.3 METs, AEx2: 5×/wk., 60 min, 3.5 to 5.2 METs	Non	CT—cm^2

(Continues)

TABLE 1 | (Continued)

Source, year	Groups	Sample size (male, female)	Participants characteristics	Glycemic marker (s)	Age (years)	BMI (kg/m^2)	Ex program duration, frequency and type	Supervision	Measurement method and unit
Karstoft et al., 2013 [68]	HIIT, AEx, C	32 (M, F)	T2DM	FBG: 140.04 ± 15.48 mg/dL	HIIT: 57.5 ± 8.31 AEx: 60.8 ± 7.62 C: 57.1 ± 8.48	HIIT: 29 ± 4.5 AEx: 29.9 ± 5.54 C: 29.7 ± 5.37	16-wk, 5×/wk.; 60 min, walking, HIIT: 3 min of brisk walking above target and 3 min of slow walking below target, target: 70% of the peak energy-expenditure rate AEx: moderate intensity, target: 55% of the peak energy-expenditure rate	Non	MRI—L
Keating et al., 2023 [69]	HIIT, C	12 (M, F)	PD, NASH	FBG: 132.48 ± 26.10 mg/dL	HIIT: 53 ± 12 C: 61 ± 5	HIIT: 39.6 ± 7.1 C: 38.3 ± 6.9	12-wk, 3×/wk.; treadmill running/walking with aerobic exercise equipment, warmup: 5 min at 60% of HR_{max}, 4 × 4-min intervals at 85%–95% of HR_{max}, between intervals recovery: 3 min at 60% of HR_{max}, cooldown: 5 min	S	MRI—cm^2
Koh et al., 2018 [70]	HIIT, AEx	16 (M, F)	T2DM	FBG: 151.20 ± 37.80 mg/dL	HIIT: 56 ± 5 AEx: 58 ± 9	HIIT: 27.6 ± 2.7 AEx: 28.6 ± 2.5	11-wk, 3×/wk.; cycle ergometer; AEx: 4 min at 50% of W_{peak}, HIIT: 20 min, alternating 95% of W_{peak} and 20% of W_{peak} at 1 min each.	S	DXA—kg

(Continues)

TABLE 1 | (Continued)

Source, year	Groups	Sample size (male, female)	Participants characteristics	Glycemic marker (s)	Age (years)	BMI (kg/m^2)	Ex program duration, frequency and type	Supervision	Measurement method and unit
Koo et al., 2010 [71]	AEx, C	64 (F)	T2DMM	FBG: 128.88 ± 29.52 mg/dL	AEx: 55.7 ± 6.97 C: 57 ± 7.88	AEx: 28.98 ± 3.73 C: 27.42 ± 2.01	12-wk, lifestyle intervention, C and AEx: mild hypocaloric diet (30 kcal per kg of ideal bodyweight per day) + brisk walking for 120 min/day ~ 500 kcal/day. Diet and AEx + diet: reduce usual energy intake to 1200 kcal/day + ≥ 150 min/wk. Dietary macronutrient composition: same for groups; carbohydrate: 50%–55% of energy intake, protein: 15%%–20% and fat: 20%–25%.	Non	CT—cm^2
Ku et al., 2010 [72]	AEx, REx, C	44 (F)	T2DM, overweight	FBG: 122.13 ± 18.26 mg/dL HbA1c: 7.43 ± 0.87%	AEx: 55.7 ± 7.0 REx: 55.7 ± 6.2 C: 57.8 ± 8.1	AEx: 27.1 ± 2.4 REx: 27.1 ± 2.3 C: 27.4 ± 2.8	12-wk, 5×/wk.; REx: elastic band exercise in 3 sets of 15–20 reps at 40%–50% of maximal exercise capacity, AEx: walking, 60 min at moderate intensity (3.6–5.2 METs)	S	DXA—g
Li et al., 2022 [73]	AEx, C	106 (M, F)	T2DM	FBG: 122.76 ± 32.4 mg/dL HbA1c: 6.97 ± 1.09%	AEx: 65.15 ± 5.00 C: 67.62 ± 5.91	AEx: 24.27 ± 2.76 C: 24.77 ± 3.02	24-wk, 3×/wk.; aerobic dancing, warmup: 5 min, 50 min at 60%–70% of HR_{max}, cooldown: 5 min	S	MRI—cm^2

(Continues)

TABLE 1 | (Continued)

Source, year	Groups	Sample size (male, female)	Participants characteristics	Glycemic marker (s)	Age (years)	BMI (kg/m^2)	Ex program duration, frequency and type	Supervision	Measurement method and unit
Maillard et al., 2016 [74]	HIIT, AEx	16 (F)	T2DM, postmenopausal, overweight, obese	FBG: 162.9 ± 36.18 mg/dL	HIIT: 68.2 ± 5.37 AEx: 70.1 ± 6.78	HIIT: 32.6 ± 4.8 AEx: 29.7 ± 3.39	16-wk, 2×/wk.; warmup: 5 min, HIIT: 60 × 8s at 77%–85% of HR_{max}, between sets recovery: active 12 s at 20–30 R.P.M., MICT: 40 min at 55%–60% of HRR, cooldown: 5 min	S	DXA—kg
Mavros et al., 2013 [75]	REx, C	84 (M, F)	T2DM, older adult, MetS	HbA1c: 7.16 ± 1.18%	REx: 67.1 ± 4.8 C: 68.9 ± 6.0	REx: 31.3 ± 4.6 C: 31.6 ± 6.1	48-wk, 3×/wk.; pneumatic resistance equipment, power training: concentric phase: as quickly as possible, and the eccentric phase: over 4 s in 3 sets of 8 reps at 80% of 1-RM	S	CT—cm^2
Ramos et al., 2020 [76]	$HIIT_1$, $HIIT_2$, AEx	39 (M, F)	PD, MetS	FBG: 112 ± 40.86 mg/dL	$HIIT_1$: 54 ± 10 $HIIT_2$: 57 ± 8 AEx: 54 ± 9	$HIIT_1$: 30.8 ± 6.1 $HIIT_2$: 31.96 ± 4.79 AEx: 34 ± 6.5	16-wk, treadmill or cycle ergometer, unsupervised: outdoor/indoor: large muscle groups; AEx: 5×/wk., 30 min at 60%–70% of HR_{peak}; $HIIT_1$: 38 min, warmup: 10 min, 3×/wk.: 4 × 4 min at 85%–95% of HR_{peak}, between intervals recovery: 3 min at 50%–70% of HR_{peak}, cooldown: 3 min; $HIIT_2$: 17 min, warmup: 10 min, 3×/wk. 1 × 4 min at 85%–95% of HR_{peak}, cooldown: 3 min.	Both	DXA—g

(Continues)

TABLE 1 | (Continued)

Source, year	Groups	Sample size (male, female)	Participants characteristics	Glycemic marker (s)	Age (years)	BMI (kg/m^2)	Ex program duration, frequency and type	Supervision	Measurement method and unit
Sigal et al., 2007 [77]	AEx, REx, CEx, C	251 (M, F)	T2DM	HbA1c: 7.44 ± 1.44%	AEx: 53.9 ± 6.6 REx: 54.7 ± 7.5 CEx: 53.5 ± 7.3 C: 54.8 ± 7.2	AEx: 35.6 ± 10.1 REx: 34.1 ± 9.6 CEx: 35.0 ± 9.6 C: 35.0 ± 9.5	26-wk, 3×/wk.; AEx: treadmills or bicycle ergometer, 15–45 min at 60%–75% of HR_{max}, REx: weight machines in 2–3 sets of maximum weight lifted of 7–9 reps. CEx: AEx + RT	S	CT—cm^2
Stine et al., 2022 [78]	AEx, C	28 (M, F)	PD, NASH	FBG: 130.94 ± 41.49 mg/dL HbA1c: 6.3 ± 1.2	AEx: 52.9 ± 11.5 C: 45.0 ± 10.2	AEx: 34.3 ± 4.9 C: 35.1 ± 4.9	20-wk, 5×/wk.; 30 min at 45%–55% of VO_{2peak}	S	DXA—lbs
Waters et al., 2022 [79]	AEx, REx, CEx, C	160 (M, F)	PD, older adult, obese	FBG: 100.1 ± 16.51 mg/dL 2 h-BG: 154 ± 13.18 mg/dL	AEx: 70 ± 4 REx: 70 ± 5 CEx: 70 ± 5 C: 70 ± 5	AEx: 35.9 ± 4.4 REx: 36.7 ± 5.8 CEx: 35.8 ± 4.5 C: 36.7 ± 5.0	26-wk, 3×/wk.; target: weight loss ~ 10%, 60–90 min, warmup and cooldown: 15 min; AEx: aerobic exercise equipment at ~ 65%–85% of HR_{peak}. REx: weight machines: upper and lower-body exercises in 1–3 sets of 8–12 reps at 65–85-% 1-RM. Weight management program: 1×/wk.: nutritional counseling to achieve a 500–750 kcal deficit/d and 1 g protein/kg/day	S	MRI—cm^2
Willis et al., 2024 [80]	AEx, C	26 (M)	T2DM, MASLD	FBG: 135.9 ± 28.99 mg/dL HbA1c: 6.75 ± 1.29%	AEx: 61 ± 17 C: 63 ± 18	AEx: 34.1 ± 5.6 C: 31.9 ± 4.1	6-wk, 4×/wk.; AEx: 65–50 min, walking or cycling, warmup: 5 min, 70%–75% of HR_{max}, cooldown: 10 min	Both	MRI—mL

(Continues)

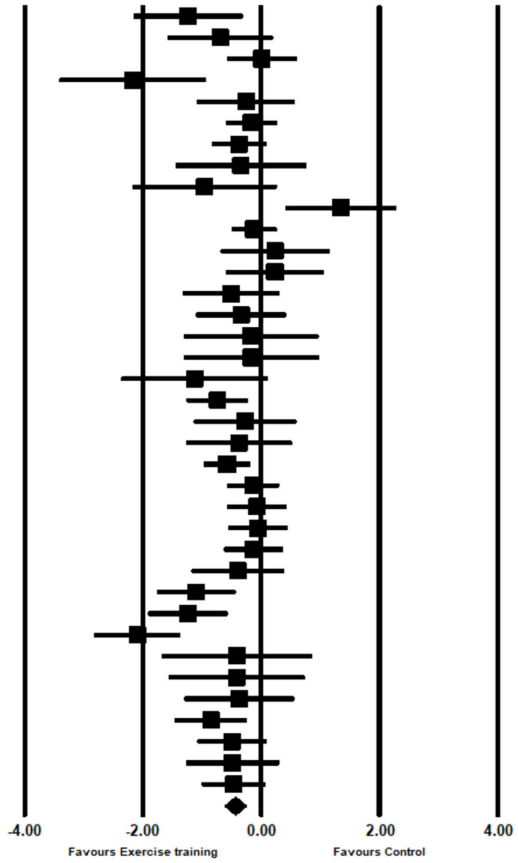
TABLE 1 | (Continued)

Source, year	Groups	Sample size (male, female)	Participants characteristics	Glycemic marker (s)	Age (years)	BMI (kg/m^2)	Ex program duration, frequency and type	Supervision	Measurement method and unit
Winding et al., 2018 [81]	HIIT, AEx, C	32 (M, F)	T2DM	FBG: 152.64 ± 37.62 mg/dL	HIIT: 54 ± 6 AEx: 58 ± 8 C: 57 ± 7	HIIT: 28.1 ± 3.5 AEx: 27.4 ± 3.1 C: 28 ± 3.5	11-wk, 3×/wk.; cycling, AEx: 40 min, warmup: 5 min, 50% of W_{peak}, HIIT: 20 min, 5 min at 40% of W_{peak}, 10 × 1-min intervals at 95% of W_{peak}, between intervals recovery: active 1 min at 20% of W_{peak}	Non	DXA—kg
Yamaguchi et al., 2011 [82]	AEx, C	19 (M, F)	PD, Obese	FBG: 161.37 ± 68.72 mg/dL HbA1c: 9.94 ± 2.53%	AEx: 50 ± 3.1 C: 50 ± 2.7	AEx: 27.9 ± 6.0 C: 27.8 ± 5.6	4-wk, 7×/wk.; treadmill walking, 2 × 30-min bouts at anaerobic threshold by HR.	Non	CT—cm^2
Yan et al., 2019 [84]	AEx, REx, C	105 (M, F)	PD	FBG: 104.22 ± 10.62 mg/dL 2 h-BG: 144.54 ± 82.62 mg/dL HbA1c: 5.94 ± 0.35%	AEx: 64.23 ± 5.75 REx: 62.06 ± 8.11 C: 60:31 ± 7:56	AEx: 23.25 ± 3.59 REx: 24.84 ± 3.12 C: 24.63 ± 4.60	48-wk, 3×/wk.; REx: 50 min in 6–15 reps at 50%–60% of 1-RM. AEx: 60 min, warmup: 5–10 min, aerobic dancing with music at 60%–70% of HR_{max}. C: maintain usual habits.	S	CT—cm^2

Abbreviations: 1H-MRS, proton magnetic resonance spectroscopy; 1-RM, one repetition maximum; 2 h-BG, 2 hour blood glucose; AEx, aerobic exercise training; C, control; CT, computed tomography; DXA, dual energy x-ray absorptiometry; F, female; FBG, fasting blood glucose; HbA1c, glycated hemoglobin; HIIT, HIGH INTENSITY INTERVAL TRAINING; HR_{max}, heart rate maximum; HRR, heart rate reserve; M, male; MET, metabolic equivalent; MetS, metabolic syndrome; MICT, moderate intensity continuous training; MRI, magnetic resonance imaging; MUFA, monounsaturated fatty acids; NAFLD, nonalcoholic fatty liver disease; NASH, nonalcoholic steatohepatitis; PD, prediabetes; PUFA, polyunsaturated fat; R.P.M., revolution per minute; reps, repetitions; REx, resistance exercise training; RIR, repetitions in reserve; RPE, rate of perceived exertion; SAFA, saturated fatty acid; T2DM, type 2 diabetes mellitus; USG, ultrasound sonography; W, watt; W_{peak}, peak power output.

exercise training, including aerobic training, resistance training, combined aerobic and resistance training, and HIIT, were used in the interventions. The details of participant and intervention characteristics are presented in Table 1. The overall quality of included studies was summarized in supplementary Table 2, which reported that PEDro scale scores ranged from 5 to 9.

Model	Study name	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
	Abdelbasset et al, 2020 a	-1.237	0.468	0.219	-2.155	-0.319	-2.641	0.008
	Abdelbasset et al, 2020 b	-0.689	0.449	0.202	-1.569	0.192	-1.532	0.125
	Botton et al, 2018	0.013	0.302	0.091	-0.578	0.604	0.044	0.965
	Boudou et al, 2003	-2.169	0.630	0.397	-3.404	-0.934	-3.443	0.001
	Cassidy et al, 2015	-0.255	0.419	0.176	-1.077	0.566	-0.609	0.543
	Cheng et al, 2017	-0.163	0.218	0.047	-0.589	0.264	-0.748	0.455
	Choi et al, 2012	-0.375	0.233	0.054	-0.832	0.081	-1.610	0.107
	Cuff et al, 2003 a	-0.341	0.561	0.315	-1.441	0.760	-0.607	0.544
	Cuff et al, 2003 b	-0.956	0.619	0.383	-2.168	0.257	-1.545	0.122
	Giannopoulou et al, 2005	1.348	0.472	0.223	0.423	2.274	2.855	0.004
	Gibbs et al, 2012	-0.115	0.191	0.036	-0.489	0.258	-0.604	0.546
	Hallsworth et al, 2011	0.236	0.466	0.217	-0.677	1.150	0.507	0.612
	Hallsworth et al, 2015	0.233	0.419	0.175	-0.588	1.054	0.557	0.577
	Houghton et al, 2016	-0.508	0.415	0.172	-1.321	0.305	-1.224	0.221
	Jung et al, 2012	-0.337	0.385	0.148	-1.091	0.417	-0.877	0.381
	Karstoft et al, 2012 a	-0.168	0.578	0.334	-1.302	0.965	-0.291	0.771
	Karstoft et al, 2012 b	-0.164	0.578	0.334	-1.297	0.969	-0.284	0.777
	Keating et al, 2023	-1.125	0.629	0.396	-2.358	0.108	-1.789	0.074
	Koo et al, 2010	-0.736	0.261	0.068	-1.248	-0.224	-2.816	0.005
	Ku et al, 2010 a	-0.269	0.440	0.193	-1.131	0.592	-0.612	0.540
	Ku et al, 2010 b	-0.375	0.453	0.205	-1.263	0.513	-0.827	0.408
	Li et al, 2021	-0.575	0.198	0.039	-0.963	-0.186	-2.898	0.004
	Mavros et al, 2013	-0.138	0.221	0.049	-0.571	0.295	-0.624	0.533
	Sigal et al, 2007 a	-0.070	0.254	0.064	-0.567	0.427	-0.275	0.783
	Sigal et al, 2007 b	-0.052	0.252	0.063	-0.545	0.441	-0.207	0.836
	Sigal et al, 2007 c	-0.128	0.252	0.063	-0.621	0.365	-0.509	0.611
	Stine et al, 2022	-0.392	0.398	0.158	-1.172	0.388	-0.985	0.325
	Waters et al, 2022 a	-1.099	0.337	0.113	-1.758	-0.439	-3.264	0.001
	Waters et al, 2022 b	-1.238	0.341	0.116	-1.907	-0.570	-3.630	0.000
	Waters et al, 2022 c	-2.093	0.370	0.137	-2.819	-1.368	-5.655	0.000
	Winding et al, 2018 a	-0.408	0.645	0.415	-1.672	0.855	-0.633	0.526
	Winding et al, 2018 b	-0.414	0.582	0.339	-1.555	0.727	-0.711	0.477
	Yamaguchi et al, 201	-0.371	0.469	0.220	-1.290	0.547	-0.793	0.428
	Yan et al, 2019 a	-0.849	0.307	0.094	-1.451	-0.248	-2.766	0.006
	Yan et al, 2019 b	-0.495	0.294	0.086	-1.071	0.081	-1.684	0.092
	Willis et al, 2024	-0.482	0.398	0.158	-1.261	0.298	-1.210	0.226
	Lyngbaek et al, 2024	-0.461	0.272	0.074	-0.993	0.071	-1.697	0.090
Random		-0.438	0.086	0.007	-0.607	-0.269	-5.074	0.000



Meta Analysis

FIGURE 2 | Forest plot of the effects of exercise training versus CON on visceral fat. Data are reported as SMD. SMD: standardized mean difference.

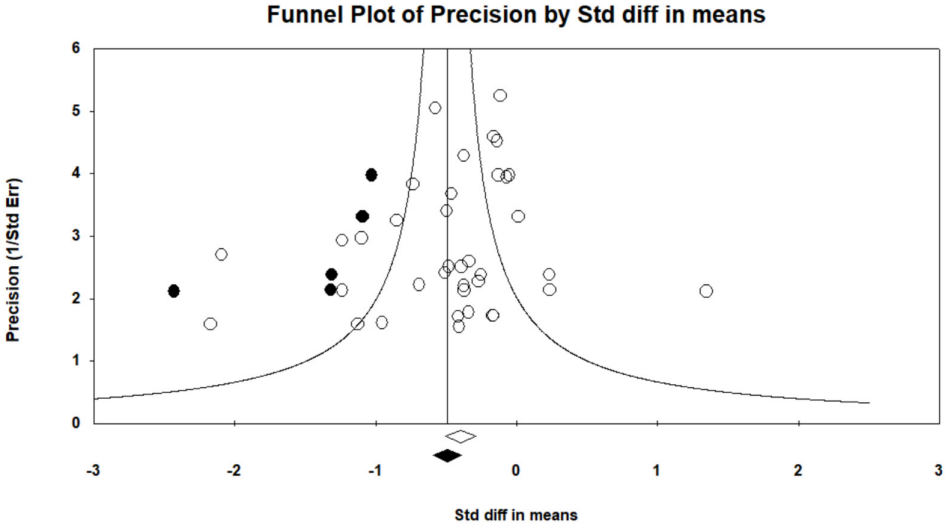


FIGURE 3 | Funnel plots of the meta-analyses of the effects of exercise training on visceral fat.

3.3 | Meta-Analysis

Overall, 37 intervention arms were included in the meta-analysis. Compared with controls, exercise training demonstrated a significant reduction in VAT (−0.43, $p = 0.001$) (Figure 2). The I^2 statistic revealed a high degree of heterogeneity among the included studies ($I^2 = 54.80\%$, $p = 0.001$). In addition, the visual interpretation of funnel plots suggested publication bias, which was not confirmed by the Egger's test ($p = 0.23$) (Figure 3). The trim and fill method identified five missing studies from the left side of the funnel plot. After accounting for the missing studies, the overall effect size increased to (−0.55).

3.3.1 | Subgroup Analyses

Several subgroup analyses were performed with results showing that when compared with a control group, VAT was reduced in both middle-aged (−0.34, $p = 0.001$) and older adults (−0.54, $p = 0.001$), in adults with prediabetes (−0.71, $p = 0.001$) and T2DM (−0.28, $p = 0.001$), with (−0.43, $p = 0.002$) or without obesity (−0.46 [95% CI −0.62 to −0.29], $p = 0.001$), and following short-term (−0.37, $p = 0.009$) and longer-term (−0.49, $p = 0.001$) intervention duration (supplementary Table 3).

3.4 | Network Meta-Analysis

Network geometry for visceral fat is displayed in Figure 4. Thirty-three studies involving 54 pairwise comparisons, 5 treatment arms, and 10 study designs were eligible for NMA. Compared with a control group, combined training (−0.63, $p = 0.001$), HIIT (−0.53, $p = 0.001$), and aerobic training (−0.38, $p = 0.001$) were effective for reducing VAT, but resistance training was not (−0.25, $p = 0.08$) (Figure 5, supplementary Table 4). In addition, the P score–based ranking of interventions is shown in Figure 5. The highest ranking was for combined training (0.89), followed by HIIT (0.76), aerobic training (0.52), and resistance training (0.32) (Figure 5). The results of heterogeneity and inconsistency tests are summarized in supplementary Table 3 and demonstrated considerable heterogeneity with $I^2 = 55.2\%$ (36.0%; 68.6%) (Q statistics in supplementary Table 5). Nevertheless, the node splitting analysis results, which were conducted to compare direct and indirect evidence, demonstrated no significant inconsistency between the direct and indirect estimates (supplementary Table 6). In addition, Egger's test revealed no significant publication bias in the network meta-analysis ($p = 0.66$) (Figure 6).

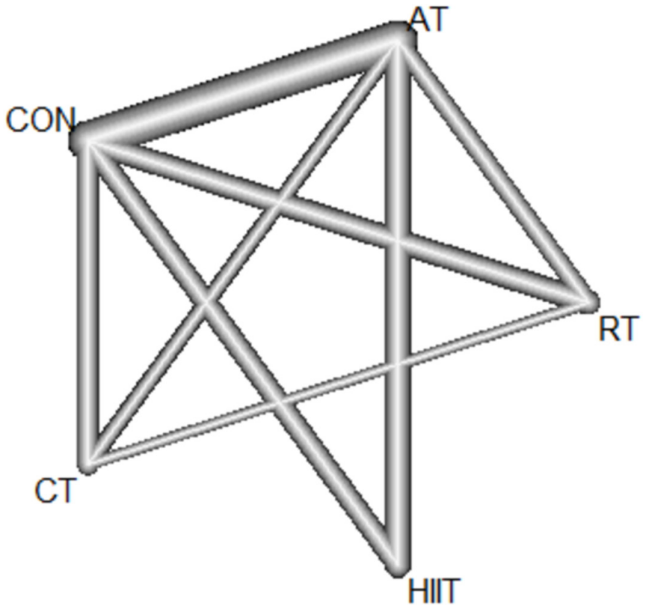


FIGURE 4 | Network geometric map of studies investigating the effects of exercise training on visceral fat.

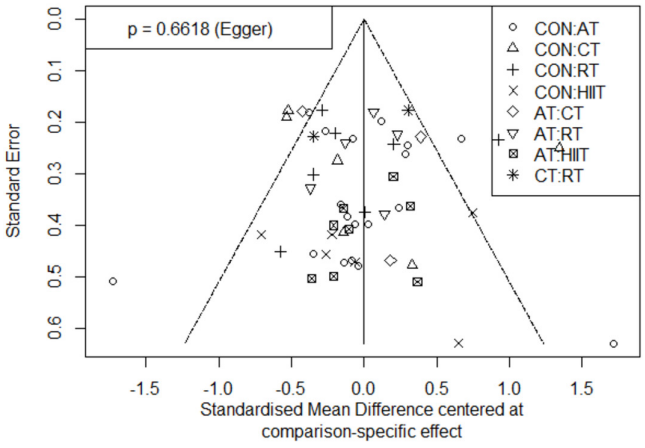


FIGURE 6 | Funnel plots of the network meta-analyses of the effects of exercise training on visceral fat.

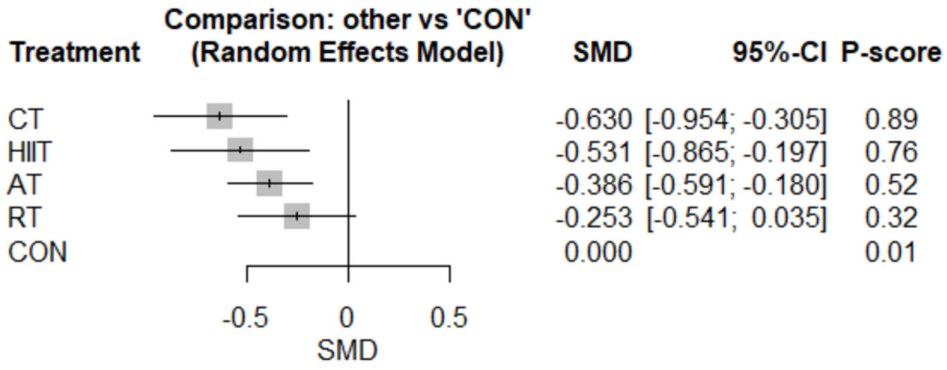


FIGURE 5 | Forest plot of the network meta-analyses of the effects of exercise training on visceral fat.

4 | Discussion

In this systematic review with pairwise and network meta-analyses, we provide strong evidence regarding the advantageous effects of four exercise types on VAT in patients with prediabetes and T2DM. When compared with a control group, combined aerobic and resistance training, aerobic training, and HIIT, but not resistance training, resulted in larger reductions in visceral fat in both patient groups, irrespective of age, health status, BMI, or duration of intervention. This important outcome provides healthcare professionals and public health policymakers with clear evidence of a noninvasive, nonpharmacological, and cost-effective clinical strategy for supporting patients with impaired metabolic health [85].

Reducing visceral fat in patients with prediabetes and T2DM has significant metabolic effects [86]. Regular exercise is an effective lifestyle intervention for reducing VAT among patients with metabolic dysfunction [9–12] and reducing their risk of cardiovascular disease morbidity and mortality [87]. This process improves insulin signaling, inflammation, mitochondrial function, oxidative stress, lipid metabolism, adipokine regulation, cortisol and the hypothalamic–pituitary–adrenal axis, insulin and glucagon, and incretin hormone activity, which are all driven by molecular and hormonal mechanisms [86]. Collectively, these adaptations improve glucose homeostasis, reduce cardiometabolic risk, and delay disease progression. Consequently, the focal point of diabetes management is the targeting of visceral fat through structured lifestyle interventions or pharmacotherapy [88]. Our findings indicate that combined training, HIIT, and aerobic training facilitate reductions in VAT, which is commonly associated with low-grade chronic inflammation in patients with prediabetes and T2DM who have BMIs ranging from 25 to 40 kg m^2. The present outcomes align with other systematic reviews and meta-analyses investigating the effects of different forms of exercise on VAT in various populations with metabolic health dysregulation [9, 12, 18, 22, 30–33].

Combining aerobic and resistance training has been widely reported as the most effective exercise strategy for improving cardiometabolic health-related indicators [25, 34], including body composition and inflammatory markers [24, 89–92]. The present network meta-analysis showed that combined training may be the best exercise strategy for reducing VAT in individuals with prediabetes and T2DM. The combination of resistance training with aerobic exercise has been established as an effective approach for enhancing muscular fitness and bone mass, while aerobic exercise appears to be an effective strategy for reducing VAT [9, 93]. Furthermore, numerous meta-analytical studies have reported that combined training may be the optimal form of exercise for improving chronic low-grade inflammation [91, 93, 94]. Hence, combined training is recommended for cardiometabolic health improvements, including VAT reduction in populations with glucose metabolism derangements.

HIIT appears to be the second-best exercise type for reducing VAT in patients with prediabetes and T2DM. This vigorous and time-efficient exercise strategy has been widely reported to improve body composition, liver fat, chronic inflammation, glycemic markers, and cardiovascular disease risk factors in people with metabolic health dysfunction [25, 27, 95–102]. Vigorous intermittent exercise can increase the secretion of cytokines and myokines, whereas moderate-intensity continuous aerobic exercise does not [9]. This may be the mechanism by which HIIT reduces VAT, as interleukin 6 and other adipo-myokines exert favorable effects on metabolism [103–105]. HIIT seems to augment basal metabolic rate and enhance postexercise oxygen consumption more than moderate-intensity continuous aerobic exercise in participants with a high BMI, promoting beneficial changes in VAT [106–108].

The *P*-score ranking showed that aerobic exercise ranks third, suggesting that aerobic exercise may be the least effective training modality for reducing VAT in patients with prediabetes and T2DM. Nevertheless, substantial evidence demonstrates the positive impact of aerobic exercise on visceral adiposity in populations who are overweight or obese and at high risk of impaired glucose control [9, 28, 31]. Interestingly, a previous meta-analysis found a minimal visceral fat reduction by various aerobic exercise interventions using different training parameters in participants with overweight and obesity [28]. In our study, aerobic exercise interventions were characterized by moderate-intensity protocols and not high-intensity stimulation used in HIIT interventions. This difference may play a key role in activating the molecular and hormonal mechanisms behind visceral fat reduction, even without clinically significant weight loss [28, 109]. Taken together, the present results indicate that vigorous-intensity aerobic exercise may be superior to moderate-intensity in reducing VAT. However, intensity is not the only training parameter affecting the efficacy of aerobic exercise on visceral fat, as volume also plays a key role, because the dose–response relationship between aerobic exercise and VAT reduction occurs in people with excess adiposity but without obesity-related illness [109].

Although resistance training can improve numerous cardiometabolic health-related indicators in populations with prediabetes and T2DM [25, 87], the present results do not confirm its efficacy on the VAT reduction as a standalone exercise. This outcome corroborates previous meta-analyses, showing that muscle-strengthening should be supplemented by some forms of aerobic-based activities to reduce visceral fat in participants with overweight or obesity [28, 31, 32]. However, this finding does not agree with other meta-analyses investigating the influence of resistance training on VAT in individuals with overweight or obesity, but without prediabetes or T2DM [9, 12, 33]. It is worth mentioning that in the meta-analysis by Chen et al. [9], resistance training had a relatively small overall effect and was the least effective form of exercise compared to aerobic training, combined training, and HIIT. Furthermore, the literature on resistance training protocols reveals a considerable diversity in the prescribed training parameters, including frequency, intensity, and duration, that could influence the outcomes of visceral fat.

4.1 | Future Directions and Clinical Implications

The present findings support clinicians, practitioners, and the public health authorities responsible for formulating and implementing policy with robust data of a nonintrusive, nonpharmaceutical, and cost-effective approach for supporting patients with prediabetes and T2DM. Interestingly, different exercise

interventions, such as combined aerobic and resistance training, aerobic training, or HIIT, can be incorporated into a patients' management plan in healthcare settings as a feasible and low-risk clinical strategy for reducing visceral fat in these populations. However, future clinical trials should focus on HIIT-type, resistance-based training protocols [110] or concurrent HIIT and resistance training, aiming to identify whether this popular exercise approach [16] elicits positive alterations in VAT not only in individuals with excess body weight and adiposity [9] but also in those with prediabetes and T2DM.

4.2 | Limitations

The current meta-analysis has several limitations that should be acknowledged. Specifically, limitations include the fact that we did not report other anthropometric, body composition, and chronic inflammatory variables to investigate whether the effects of various types of exercise on these outcome measures were consistent with the effects on VAT, as these were consistently unavailable. Second, the present review aimed to investigate the exclusive role of different forms of exercise in visceral fat reduction. Thus, combined exercise and diet interventions were not included, and therefore, the impact of diet was not considered. Future meta-analyses are suggested to explore the efficacy of various exercise types combined with dietary strategies. Finally, the dose–response effects of different forms of exercise were not examined because of the limited number of original studies, which did not allow for valid subgroup analyses.

5 | Conclusions

The present systematic review with pairwise and network meta-analyses provides evidence that various exercise types, including combined aerobic and resistance training, HIIT, and aerobic training, but not resistance training, can reduce VAT in patients with prediabetes and T2DM. The highest ranking for VAT reduction was reported for combined training, followed by HIIT, and aerobic exercise training. This evidence provides a foundation for clinicians and practitioners to prescribe a range of exercise interventions for patients with prediabetes and T2DM, for whom abdominal adiposity is a common characteristic, resulting in insulin resistance due to low-grade chronic inflammation.

Author Contributions

M.Kh., S.F., M.E.S., A.B., and S.K.R. conceptualized and designed the protocol. M.Kh., S.F., and F.D. carried out the screenings and reviews, and the analysis of the articles. M.Kh. and A.B. drafted the manuscript, and M.E.S., S.K.R., M.Kh., and A.B. revised the manuscript. All authors read and approved the final manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data generated or analyzed during this study is included in this published article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Search strategy. **Table S2:** Quality assessment. **Table S3:** Summary of subgroup analyses. **Table S4:** League table reporting the comparative effects for all interventions for the visceral fat network. **Table S5:** Tests of heterogeneity (within designs) and inconsistency (between designs). **Table S6:** Node-splitting method in comparison between direct and indirect evidence of different specific intervention.