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Matthijs Michielsen, Jan Yagiz, Matthijs Hanssens, Jomme Claes, Lieze Geuns, Tin Gojevic, Dominique Hansen, Guido Claessen, Marieke Craemer & Véronique Cornelissen

The effect of exercise characteristics on HbA1c and other cardiovascular risk factors in adults with type 2 diabetes: a systematic review and meta-analysis of randomised controlled trials

Matthijs Michielsen[1,2], Jan Yagiz[1], Matthijs Hanssens[1], Jomme Claes[1], Lieze Geuns[1], Tin Gojevic[6,7], Dominique Hansen[6,7], Guido Claessen[3,5,8], Marieke De Craemer[2], Véronique Cornelissen[1]

[1]Department of Rehabilitation Sciences, KU Leuven, Leuven, Belgium
[2]Department of Rehabilitation Sciences, Ghent University, Gent, Belgium
[3]Department of Cardiovascular Sciences, KU Leuven, Leuven, Belgium
[4]Department of Cardiovascular Diseases, UZ Leuven, Leuven, Belgium
[5]Faculty of Medicine and Life Sciences (LCRC), Hasselt University, Diepenbeek, Belgium
[6]Faculty of Rehabilitation Sciences, Hasselt University, Hasselt Belgium
[7]Rehabilitation Research Center (REVAL) and Biomedical Research Institute (BIOMED), Hasselt University, Diepenbeek, Belgium
[8]Department of Cardiology, Jessa Hospital, Hasselt, Belgium

Address of Correspondence
Matthijs Michielsen
Department of Rehabilitation Sciences
O&N 4 – Flex Offices
Herestraat 49 B 1501
3000 Leuven, Belgium
matthijs.michielsen@kuleuven.be
ORCID : 0000-0001-9816-7359

Abstract

Background: Exercise is a first-line therapy in adults with type 2 diabetes, yet its optimal characteristics remain unclear. Moreover, most meta-analyses focus on glycated haemoglobin (HbA1c), providing limited insight into the concomitant effects of these exercise programmes on the overall cardiovascular risk profile.

Methods: A systematic review and meta-analysis was conducted. Nine electronic databases were searched from inception to January 2025 for randomised controlled trials evaluating the effects of exercise on HbA1c and concomitantly reported cardiovascular risk factors in adults with type 2 diabetes. Outcomes were pooled using random-effects models and analysed by exercise type. Subgroup analyses were performed to explore optimal exercise characteristics for improving HbA1c.

Results: One hundred randomised controlled trials (7195 participants, 136 interventions) were included. All exercise types significantly improved HbA1c, with the largest reductions observed for combined training (–0.74%, 95%CI [-0.91; -0.57], n=38) and high-intensity interval training (HIIT) (-0.71%, 95%CI [-1.07; -0.35], n=13), followed by continuous aerobic training (CAT) (-0.62%, 95%CI [-0.84; -0.41], n=57) and resistance training (-0.36%, 95%CI [-0.51; -0.20], n=38). Supervised interventions and those prescribing a weekly volume of 150–210 minutes were consistently the most effective. Analyses of concomitantly reported cardiovascular risk factors showed improvements in VO_2peak with CAT, combined training and HIIT (+2.77 to +4.19 ml/kg/min) and in muscle strength with resistance and combined training (SMD: +0.44 to +0.66). All modalities reduced fasting plasma glucose (–0.60 to –1.13 mmol/L), LDL cholesterol (–0.18 to –0.31 mmol/L) and systolic blood pressure (–1.24 to –4.15 mmHg), while improvements in body fat were observed only after CAT, combined training and HIIT (SMD: –0.36 to –0.59).

Conclusions: All types of exercise significantly improved HbA1c, with combined training producing the largest reduction. Moreover, each modality provides distinct advantages for other cardiovascular risk factors, with combined training offering the broadest benefits and HIIT serving as a time-efficient alternative. Tailoring exercise programmes based on the patient's individual risk profile, and adjusting exercise types accordingly, may help optimise outcomes.

Trial registration: PROSPERO (CRD42025642391)

Keywords

Exercise, Continuous aerobic training, Resistance training, Combined training, High-intensity interval training, HbA1c, Cardiovascular risk profile, Type 2 diabetes, Meta-analysis

Research insights

What is currently known about this topic?

- Exercise is first-line therapy in adults with T2D and lowers HbA1c.

What is the key research question?

- Which exercise types and characteristics improve HbA1c and cardiovascular risk the most in adults with T2D?

What is new?

- Identification of optimal training mode and characteristics to reduce HbA1c
- Insights into exercise mode-specific cardiovascular risk reduction

How might this study influence clinical practice

- Tailoring exercise to individual risk profiles may improve cardiovascular outcomes in T2D.

Background

Diabetes is a rapidly growing public health concern, projected to affect 853 million individuals by 2050, constituting 13% of the global adult population (1). Approximately 90% of adults with diabetes have type 2 diabetes, a disease frequently accompanied by obesity, hypertension, and hyperlipidaemia, which significantly increase the risk of premature cardiovascular morbidity and mortality (2,3).

Epidemiological studies consistently show that higher levels of physical activity reduce the incidence of type 2 diabetes and result in better health outcomes in those already diagnosed (4,5). Accordingly, structured, planned and repetitive physical activity, hereafter referred to as exercise, is recommended in all guidelines as a key intervention (class IA recommendation) for the management of adults with type 2 diabetes (6,7).

Continuous aerobic training (CAT) is the most extensively studied exercise modality and has consistently been shown to reduce glycated haemoglobin (HbA1c), a key marker of long-term glycaemic control and diabetes-related morbidity (8–10). Meta-analyses report mean reductions of up to 0.50% (8,11). However, in recent years resistance training has also emerged as an effective intervention to lower HbA1c, with mean reductions of up to 0.39% (12). Combining continuous aerobic and resistance training appears additive as demonstrated in a recent meta-analysis by Liang et al. who reported additional HbA1c reductions of 0.12% and 0.25% compared with continuous aerobic or resistance training alone, respectively (8). Moreover, over the past decade high-intensity interval training (HIIT) has gained attention as a time-efficient and potent training method, with meta-analyses indicating greater HbA1c reduction than CAT (8,13).

Despite these clinically meaningful improvements in glycaemic control, most existing meta-analyses in populations with type 2 diabetes have focused almost exclusively on HbA1c (8,9,14), overlooking the broader cardiovascular risk profile (2,15). Furthermore, although research on dose-response relationships has expanded in recent years, significant knowledge gaps persist regarding the optimal FITT (Frequency, Intensity, Type, and Time) parameters (16) for exercise prescription in this population (8,9). Clearer evidence on the efficacy of different exercise parameters is essential for maximising both metabolic and cardiovascular benefits.

Therefore, the primary objective of the current meta-analysis is to summarise and compare the effects of continuous aerobic, resistance, combined and high-intensity interval training on HbA1c in adults with type 2 diabetes, and to examine the effect of different exercise characteristics. Secondary outcomes included the effects of these exercise modalities on the concomitantly reported cardiovascular risk factors. The findings are intended to support clinicians in selecting the most appropriate exercise programme for an adult with type 2 diabetes and one or more other cardiovascular risk factors.

METHODS

This systematic review and meta-analysis was prospectively registered in PROSPERO (CRD42025642391) and conducted in collaboration with KU Leuven Libraries – 2Bergen, Learning Centre Désiré Collen (Leuven, Belgium). Reporting followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (17) guidelines.

Search strategy, selection and eligibility criteria

A comprehensive literature search was performed in nine electronic databases (MEDLINE (PubMed), Embase, Web of Science, Scopus, CENTRAL, CINAHL, SPORTDiscus, PEDro, clinicaltrials.gov) from inception to January 10th, 2025. Reference lists of relevant recent systematic reviews and meta-analyses were also hand-searched for additional studies. The detailed search strategies for each database are provided in the supplementary file, pages 2-20.

After removal of duplicates in EndNote 21 software (Clarivate, Philadelphia, USA), the remaining articles were uploaded to Rayyan (Rayyan Systems, Cambridge, MA, USA) for screening. Titles and abstracts were independently assessed for eligibility by two pairs of reviewers (JY, MH, MM, LG) (18). Full texts of potentially eligible studies were then screened by two independent reviewers (JG and MH) with reasons for exclusion documented. Discrepancies were resolved by consensus with a third reviewer (MM).

Eligibility criteria for inclusion in the meta-analysis were as follows:

i) Randomised controlled trials (RCT), published in English, in a peer-reviewed journal.

ii) Adults (≥18 years) with type 2 diabetes, without established cardiovascular, pulmonary, neurological, oncological or any unstable chronic diseases

iii) Investigating the impact of CAT, resistance, combined or HIIT training, with a minimum duration of 4 weeks. CAT was defined as walking, cycling, jogging, swimming, or other dynamic activities to improve fitness and performed at a constant work rate. Resistance training could include machines and free-weights, own body weight, resistance bands or other activities aimed to improve muscle strength. Combined training was defined as the integration of both aerobic and resistance exercises. HIIT was defined as any exercise session including repeated high-intensity exercise bouts alternated with recovery periods (i.e., including sprint interval training (SIT)). Comparator groups were eligible if they did not receive any exercise and differed from the intervention groups solely in exposure to exercise.

iv) Reporting on changes in HbA1c

Outcomes

The primary outcome was change in HbA1c from baseline to the first follow-up after completion of the exercise intervention. Secondary outcomes included changes in cardiovascular risk factors such as body composition (Body Mass Index (BMI), body weight, body fat, waist circumference), blood pressure, fasting plasma glucose (FPG), total cholesterol, low-density lipoprotein (LDL), high-density lipoprotein (HDL) and triglycerides, as well as health-related physical fitness components (peak oxygen uptake (VO_2peak) and muscle strength) and physical activity. Outcomes were included in the analyses if reported in at least three trials.

Data extraction

Two pairs of reviewers (JY, MH, MM, LG) independently extracted data using a standardised data extraction sheet (Microsoft Excel, Redmond, WA, USA). Extracted variables included: study characteristics (author information, publication year, country of origin, study design, type of analysis and drop-out rate), details of the exercise intervention (type, frequency, intensity, duration, level of supervision and adherence) and control group (content and level of supervision) participant characteristics (sex, age, duration of diabetes, medication intake and smoking status), primary (HbA1c) and secondary (other clinical cardiovascular risk factors) outcomes, reported as either mean or mean difference (MD) and standard deviations (SD) or standard errors of means. Data reported in conventional units were converted to standard units after data extraction.

Quality assessment

Risk of bias and methodological quality of eligible studies were assessed using the Tool for the assESsment of study quality and reporting in EXercise (TESTEX) by two reviewers (JY and MH) and discrepancies were resolved by consensus with a third reviewer (MM) (19). The TESTEX scale is a validated 15-point (12-item) instrument specifically designed to evaluate the quality and reporting of exercise training studies (19). The strength of this tool lies in the incorporation of domains that are relevant to exercise training studies that are not captured by other Risk of Bias tools.

Statistical analysis

Baseline characteristics were described using mean values, calculated by combining mean baseline data from the training group and the control group, weighted by the number of participants in each group.

Comprehensive Meta-Analysis V4, (Biostat Inc, NJ, USA) was used for all meta-analyses. The effect sizes were calculated either from the pre and post mean ± SD of the intervention and control groups or from the mean change ± SD within each group. When SD was not reported, this was derived from standard errors or confidence intervals (20). For analyses based on change scores, a conservative pre–post correlation coefficient of 0.5 was used (20). Each effect size was then weighted by the inverse of its variance. In trials with multiple intervention arms sharing one control group, the control group was proportionally split into smaller subgroups (20).

Pooled outcomes were estimated using random-effects models to account for heterogeneity (20,21). Effect sizes were expressed as mean differences (MD), or standardized mean differences (SMD) when units differed. Analyses were stratified by exercise type with additional subgrouping for the primary outcome by exercise subtype. Between-group differences were tested using Cochran's Q. Subgroup analyses further examined the influence of training characteristics on the primary outcome across all exercise types. For the exercise intensity, classification was made based on ACSM guidelines (22).

Statistical heterogeneity was evaluated with Cochran's Q ($p<0.05$) and the I^2 statistic (>50% indicating substantial heterogeneity) (23). To complement measures of heterogeneity, prediction intervals were added to quantify the expected range of true effects in future studies, providing a clinically interpretable estimate of between-study variability (24). A leave-one-out sensitivity analysis, removing each study in turn to assess the stability of the pooled effect and any change in significance, was performed for the primary outcome for all exercise types. Publication bias was examined through visual inspection of the funnel plots, Egger's regression test ($p<0.10$) (25) and the trim-and-fill method (26).

Results

Study selection and characteristics

A PRISMA flow diagram of the literature search and selection is presented in Figure 1. The initial search identified a total of 11,559 articles. Following deduplication and title/abstract screening, 206 articles remained for full-text review. Of these, 100 RCTs comprising 136 distinct interventions were included.

Study characteristics

The included studies were published between 1986 and 2024 and were conducted in 33 different countries. Most studies were conducted in high-income (n=49) and upper-middle-income (n=37) countries, with fewer from lower-middle-income (n=13) and low-income (n=1) countries. Exercise intervention duration ranged from 4 to 52 weeks. CAT was the most frequently studied exercise intervention (n=57, 42%), followed by combined training (n=38, 28%), resistance training (n=28, 21%) and HIIT (n=13, 10%). Among the HIIT interventions, only one study used a SIT protocol. The mean training frequency was 3.5 sessions per week (range: 1-7), with a mean duration of 49 minutes per session (range: 7.5-120). Resistance training intensity was assessed using 1 repetition maximum (1RM) in 48% of the interventions (n=32) and averaged 68% of 1RM (range: 40-85). For CAT, combined and HIIT interventions, intensity was mostly prescribed as a percentage of VO_2peak (n=30, 28%), heart rate peak (n=35, 32%), heart rate reserve (n=13, 12%) or Borg scale (n=9, 8%). Most interventions were fully supervised (n=100, 74%) or partially supervised (n=22, 16%). Mean adherence across studies was 90% (range 60-100) with a mean dropout rate of 12% (range 0-37). A detailed summary of the data extracted from each study is presented in supplementary file, pages 21-32.

Study quality

Details of the TESTEX risk of bias assessment are provided in the supplementary file, pages 33-37. The median score for study quality was 3 of 5 (range 1-5). Eligibility criteria were reported in 92% of studies, representing the highest-scoring item, whereas blinding of the assessor was the lowest, reported in only 30% of studies. For quality of study reporting, the median score was 6 of 10 (range 3-10), with 61% of studies reporting a study withdrawal rate below 15%. Only 10% of studies included physical activity monitoring in the control groups.

Patient characteristics

A total of 7195 participants (47% male) were analyzed. The mean age of participants was 57.1 years (range: 37.0–71.2), and the time since diagnosis of diabetes was 8.3 years (range: 1.5–21.1). The mean BMI was 29.7 kg/m^2 (range: 22.7–39.7), and the mean baseline HbA1c level was 7.7% (range: 5.9–10.5). Among interventions reporting medication intake (n=56, 41%), 86% of participants used hypoglycaemic medication, and 9% received insulin therapy. Among those reporting smoking status (n=46, 34%), 9% of participants were current smokers. An overview of the aggregated mode-specific baseline age, HbA1c and BMI is provided in supplementary table 2, page 32. No systematic differences were present between the different exercise modalities.

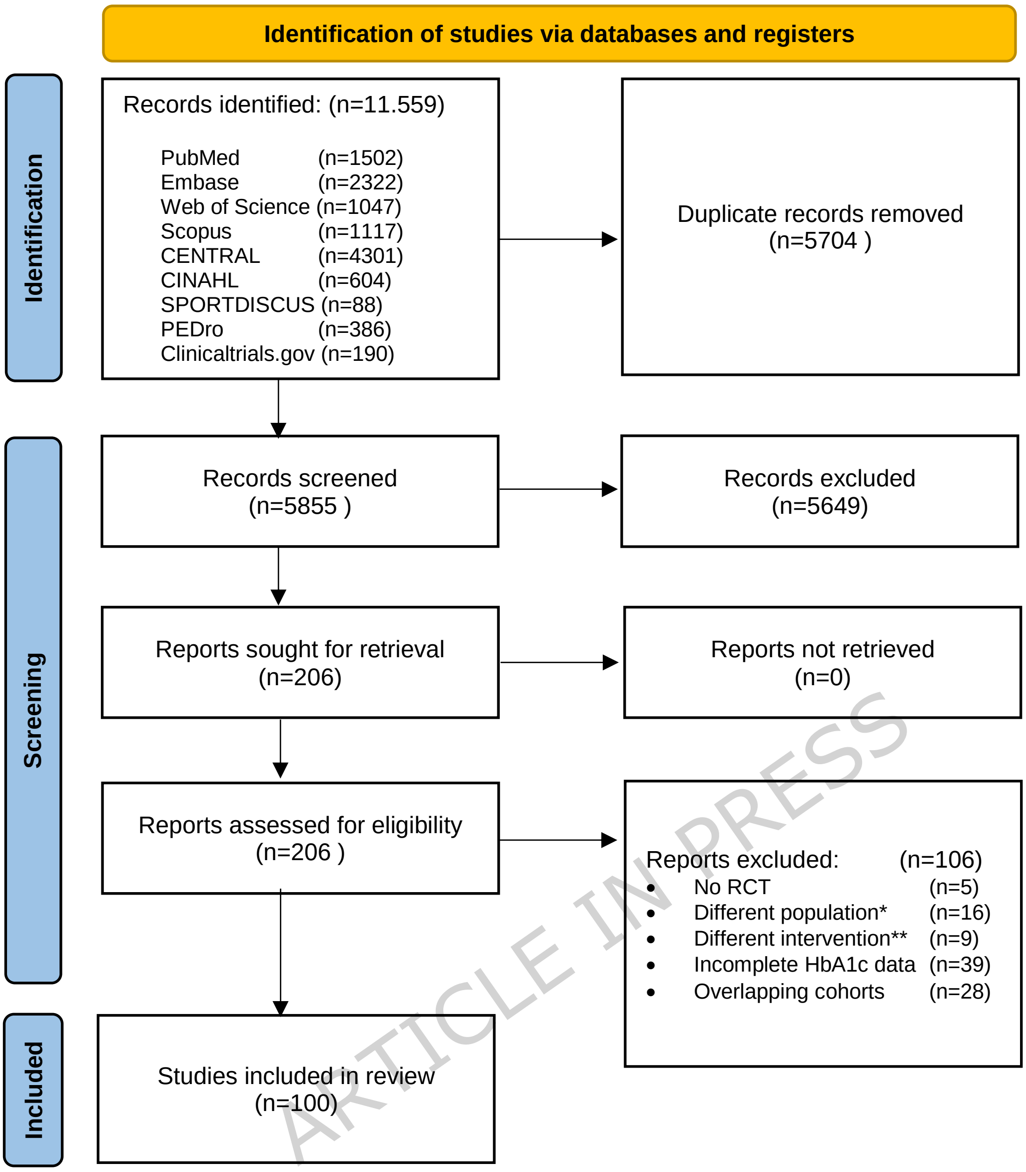

Figure 1. PRISMA flowchart of the study inclusion. RCT randomised controlled trial; *: established cardiovascular, pulmonary, neurological, oncological or other unstable chronic diseases (n=11), not conducted in individuals with type 2 diabetes (n=4), not conducted in adults (n=1); **: combined intervention (n=4), behaviour change intervention (n=2), control group receiving an active intervention (n=3).

Outcomes

HbA1c

All four exercise types significantly reduced HbA1c with mean changes ranging between -0.36% (95%CI [-0.51; -0.20], n=28) following resistance training and -0.74% (95%CI [-0.91; -0.57], n=38) following combined training (Figure 2). These pooled effects were characterised by substantial between-study heterogeneity ($I^2 > 50\%$, Cochrane Q, $p < 0.05$). Across exercise types, resistance training was less effective than combined training (p<0.001), CAT (p=0.05) and HIIT (p=0.08). No significant differences were observed among the different CAT modalities: walking (MD: -0.51%, 95%CI [-0.73; -0.30], n=28), running (MD: -0.54%, 95%CI [-0.91; -0.16], n=6), cycling (MD: -0.54%, 95%CI [-1.07; -0.02], n=7) and combining different CAT modes (MD: -0.82%, 95%CI [-1.46; -0.19], n=9). For resistance training, a significant reduction was observed when using machines and free weights (MD: -0.35%; 95%CI [-0.52; -0.18], n=21), whereas programs using resistance bands did not result in a significant improvement (MD: -0.19%, 95%CI [-1.24; 0.87], n=2). Among HIIT interventions, running-based protocols (MD: -1.20%, 95%CI [-1.51; -0.89], n=4) yielded significantly greater (p<0.001) reductions in HbA1c, than cycling-based programs (MD: -0.38%, 95%CI [-0.65; -0.12], n=9).

Table 1 summarizes subgroup analyses according to the FITT principles and the level of supervision for each of the main exercise types. Overall, supervised programs consistently produced greater effect sizes, although differences from unsupervised programs were not statistically significant. However, for resistance training and HIIT significant reductions in HbA1c were observed only in supervised interventions. Regarding frequency, 3 sessions per week yielded the strongest reductions in HbA1c in all exercise types. Lower frequencies remained effective for combined training, whereas higher frequencies did not further increase changes in HbA1c. Moderate and high intensity training significantly reduced HbA1c in CAT and resistance training, whereas low intensity did not. Session durations >45 minutes were most effective in resistance and combined training, whereas CAT benefited slightly more from shorter sessions (≤45 minutes). Across exercise types, weekly volumes of 150–210 minutes were optimal, with no additional benefit at >210 minutes. Intervention duration did not affect statistical significance of outcomes; both shorter (≤16 weeks) and longer (>16 weeks) interventions were effective, with slightly larger effect sizes in shorter programs.

Exploratory meta-regression analyses indicated that greater reductions in BMI and body fat, as well as higher baseline HbA1c levels and younger age were associated with larger reductions in HbA1c across all studies.

Pooled subgroup analyses across all exercise types, full measures of heterogeneity, a sensitivity analyses restricted to supervised interventions, and all exploratory meta-regression analyses are provided in supplementary file, pages 38-49.

Exercise mode	MD [95%CI]	N effect sizes	N participants	I² %	P-value
Continuous aerobic training	-0.62 [-0.84;-0.41]	57	1474	85.9	<0.001
Walking	-0.51 [-0.73;-0.30]	28	876	6.5	<0.001
Running	-0.54 [-0.91;-0.16]	6	117	10.6	0.005
Cycling	-0.54 [-1.07;-0.02]	7	88	59.1	0.041
Combination	-0.82 [-1.46;-0.19]	9	124	89.6	0.011
Resistance training	-0.36 [-0.51;-0.20]	28	855	49.1	<0.001
Machines + free weight	-0.35 [-0.52;-0.18]	21	700	42.7	<0.001
Resistance bands	-0.19 [-1.24;0.87]	2	57	88.6	0.725
Combined training	-0.74 [-0.91;-0.57]	38	1422	72.7	<0.001
HIIT	-0.71 [-1.07;-0.35]	13	244	86.2	<0.001
Cycling	-0.38 [-0.65;-0.12]	9	167	47.1	0.005
Running	-1.20 [-1.51;-0.89]	4	77	45.9	<0.001

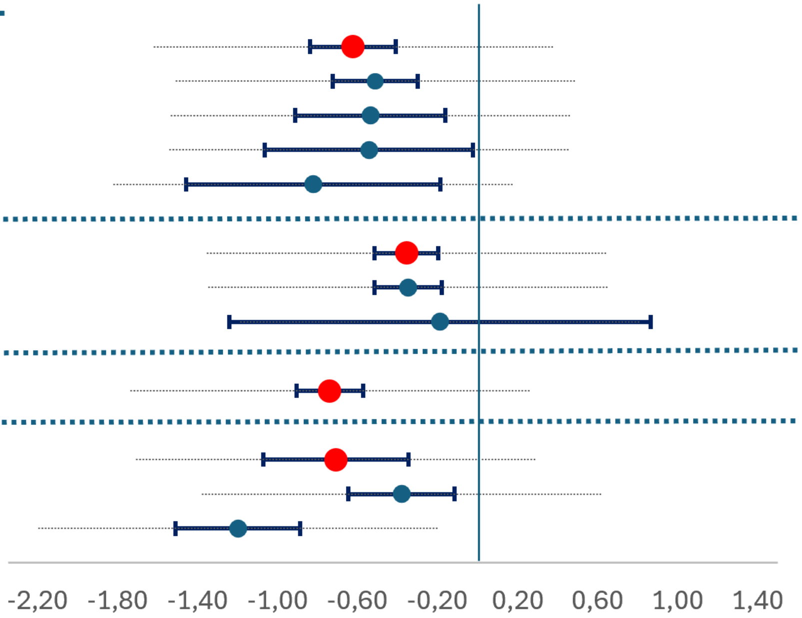

Figure 2. Forest plot including the mean difference, confidence intervals (thick lines) and prediction intervals (thin lines) on HbA1c, for both the primary and secondary exercise mode.

Table 1. Subgroup analyses for the effect of different exercise modalities on HbA1c using a random-effects model

	CAT			Resistance training			Combined training			HIIT		
	N	MD [95 CI]	P	N	MD [95 CI]	P	N	MD [95 CI]	P	N	MD [95 CI]	P
Supervision												
Yes	37	-0.69 [-0.97;-0.42]	<0.001	23	-0.39 [-0.55;-0.22]	<0.001	28	-0.77 [-1.01;-0.54]	<0.001	12	-0.73 [-1.12;-0.34]	<0.001
No	19	-0.46 [-0.73;-0.18]	0.001	5	-0.16 [-0.60; 0.29]	0.481	10	-0.73 [-0.91;-0.55]	<0.001	1	-0.50 [-1.17; 0.17]	0.141
Frequency (x/week)												
<3	2	-0.48 [-1.12; 0.16]	0.140	6	-0.24 [-0.48;-0.00]	0.053	4	-0.26 [-0.43;-0.10]	0.002	/	/	/
3	34	-0.73 [-1.01;-0.46]	<0.001	21	-0.42 [-0.61;-0.24]	<0.001	24	-0.78 [-1.05;-0.51]	<0.001	12	-0.74 [-1.14;-0.34]	<0.001
> 3	21	-0.44 [-0.72;-0.17]	0.002	1	-0.40 [-0.28; 1.08]	0.247	10	-0.79 [-0.92;-0.66]	<0.001	1	-0.42 [-0.84:-0.00]	0.050
Intensity												
Low	2	-1.49 [-2.92; 0.02]	0.053	1	-0.47 [-1.39; 0.45]	0.32	/	/	/	/	/	/
Moderate	22	-0.55 [-0.90;-0.19]	0.003	4	-0.65 [-0.85;-0.45]	<0.001	/	/	/	/	/	/
High	19	-0.55 [-0.87;-0.22]	0.001	9	-0.55 [-0.88;-0.22]	0.001	/	/	/	13	-0.71 [-1.07;-0.35]	<0.001
Session duration (min)												
≤ 30	8	-0.67 [-0.97;-0.37]	<0.001	1	-0.01 [-0.31; 0.29]	0.947	4	-0.49 [-0.88;-0.09]	0.016	8	-0.49 [-0.84;-0.14]	0.006
31-45	17	-0.62 [-0.89;-0.35]	<0.001	5	-0.33 [-0.80; 0.13]	0.160	5	-0.41 [-0.99; 0.16]	0.156	4	-0.90 [-1.61;-0.19]	0.013
> 45	30	-0.57 [-0.90;-0.24]	0.001	13	-0.48 [-0.64;-0.31]	<0.001	26	-0.80 [-1.00;-0.59]	<0.001	1	-1.84 [-2.83;-0.85]	<0.001
Weekly exercise (min/week)												
< 150	17	-0.64 [-0.90;-0.39]	<0.001	8	-0.34 [-0.61;-0.08]	0.011	9	-0.44 [-0.68;-0.21]	<0.001	11	-0.66 [-1.07;-0.26]	0.001
150-210	28	-0.71 [-1.03;-0.40]	<0.001	11	-0.48 [-0.68;-0.27]	<0.001	17	-0.88 [-1.21;-0.55]	<0.001	1	-1.84 [-2.83;-0.85]	<0.001
> 210	9	-0.14 [-0.57; 0.30]	0.545	/	/	/	8	-0.85 [-1.02;-0.68]	<0.001	/	/	/
Intervention duration (weeks)												
≤16	44	-0.63 [-0.86;-0.39]	<0.001	18	-0.41 [-0.58;-0.23]	<0.001	23	-0.80 [-1.06;-0.54]	<0.001	13	-0.71 [-1.07;-0.35]	<0.001
>16	13	-0.60 [-1.02;-0.19]	0.004	10	-0.33 [-0.58;-0.08]	0.011	15	-0.68 [-0.91;-0.45]	<0.001	/	/	/

Other cardiovascular risk factors

Figure 3 presents the pooled effect sizes for concomitantly reported cardiovascular risk factors across exercise types. Full analyses, including heterogeneity assessments and between-type comparisons are provided in the supplementary file, page 49-52.

Physical fitness

VO_2peak improved significantly following CAT (MD: +2.77 ml/kg/min, 95%CI [1.98; 3.56], n=28), combined training (MD: +2.68 ml/kg/min, 95%CI [1.66; 3.70], n=17) and HIIT (MD: +4.19 ml/kg/min, 95%CI [2.59; 5.79], n=5), but did not change after resistance training. Muscle strength increased following resistance training (SMD: 0.44, 95%CI [0.23; 0.64], n=7) and combined training (SMD: 0.66, 95%CI [0.39; 0.94], n=12) with no change after CAT or HIIT.

Blood biochemistry

All four types of exercise reduced FPG with mean changes ranging between -0.60 mmol/L (95%CI [-1.60; -0.03], n=19) after resistance training and -1.13 mmol/L (95%CI [-1.45; -0.81], n=39) after CAT. LDL decreased significantly following all four exercise types with mean differences ranging between -0.19 mmol/L (95%CI [-0.27; -0.11], n=32) for CAT and -0.31 (95%CI [-0.48; -0.15], n=24) for combined training. HDL only significantly improved following CAT (MD: 0.05 mmol/L, 95%CI [-0.01; 0.09], n=35) and combined training (MD: 0.09, 95%CI [0.06; 0.11], n=26). Total cholesterol was significantly reduced following all exercise types except for resistance training, with mean changes ranging between -0.26 mmol/L (95%CI [-0.39; -0.14], n=23) for combined training and -0.42 mmol/L (95%CI [-0.61; -0.23], n=10) for HIIT. Triglycerides only decreased significantly after resistance (MD: -0.18 mmol/L, 95%CI [-0.23; -0.13], n=19) and combined training (MD: -0.20 mmol/L, 95%CI [-0.28; -0.11], n=24).

Blood pressure

All four types of exercise produced significant reductions in SBP and DBP, except for DBP following HIIT. Mean differences for SBP ranged between -4.15 mmHg (95%CI [-8.09; -0.22], n=15) following resistance training and -1.14 mmHg (95%CI [-2.41; -0.07], n=28) following CAT. For DBP, mean differences ranged between -3.03 mmHg (95%CI [-4.96; -1.10], n=15) following resistance training and -0.17 mmHg (95%CI [-2.98; 2.64], n=8) following HIIT. No significant differences were observed between exercise types.

Anthropometrics

All four types of exercise decreased body fat, except for resistance training. The largest reduction in BMI was observed following HIIT (MD: -0.47 kg/m^2, 95%CI [-0.84; -0.11], n=9), whereas the most substantial body fat reduction occurred following combined training (SMD: -0.59, 95%CI [-0.92; -0.27], n=17) and CAT (SMD: -0.54, 95%CI [-0.86; -0.21], n=25). Waist circumference significantly decreased following all exercise types, with mean changes ranging from -1.79 cm (95%CI [-2.89; -0.69], n=14) following CAT to -5.89 cm (95%CI [-9.02; -2.75], n=4) following HIIT.

Physical activity

Changes in habitual physical activity outside of the exercise programmes were assessed in 10 interventions (CAT: n=3, resistance training: n=3, combined training: n=4). Physical activity was measured using questionnaires (n=8), an accelerometer (n=1), or a diary converted to MET-hours (n=1). A significant increase in physical activity was only observed after CAT (SMD: 1.00, 95%CI [0.11; 1.89], n=3).

Publication bias and sensitivity analyses

A sensitivity analysis of the primary outcome (HbA1c) was conducted using a leave-one-out approach, which did not influence the effect size for any type of exercise. However, visual inspection of the individual funnel plots and Egger's regression test (supplementary file, pages 38-42) suggested a publication bias for CAT (intercept = 1.65, p=0.003), combined training (intercept = -1.01, p=0.047) and HIIT (intercept = -1.98, p=0.01).

Duval and Tweedie trim-and-fill method was used to estimate the number of potentially missing studies due to bias. For CAT, 13 missing studies were imputed on the left side of the funnel plot, adjusting the effect size from -0.62 [-0.84; -0.41] to -0.85 [-1.05; -0.65]. Similarly for HIIT, imputing one study shifted the effect from -0.71 [-1.07; -0.35] to -0.75 [-1.11; -0.40]. For resistance training 6 missing studies were imputed on the right side of the funnel plot, adjusting the effect size from -0.36 [-0.51; -0.20] to -0.27 [-0.44; -0.11]. No missing studies were identified for combined training.

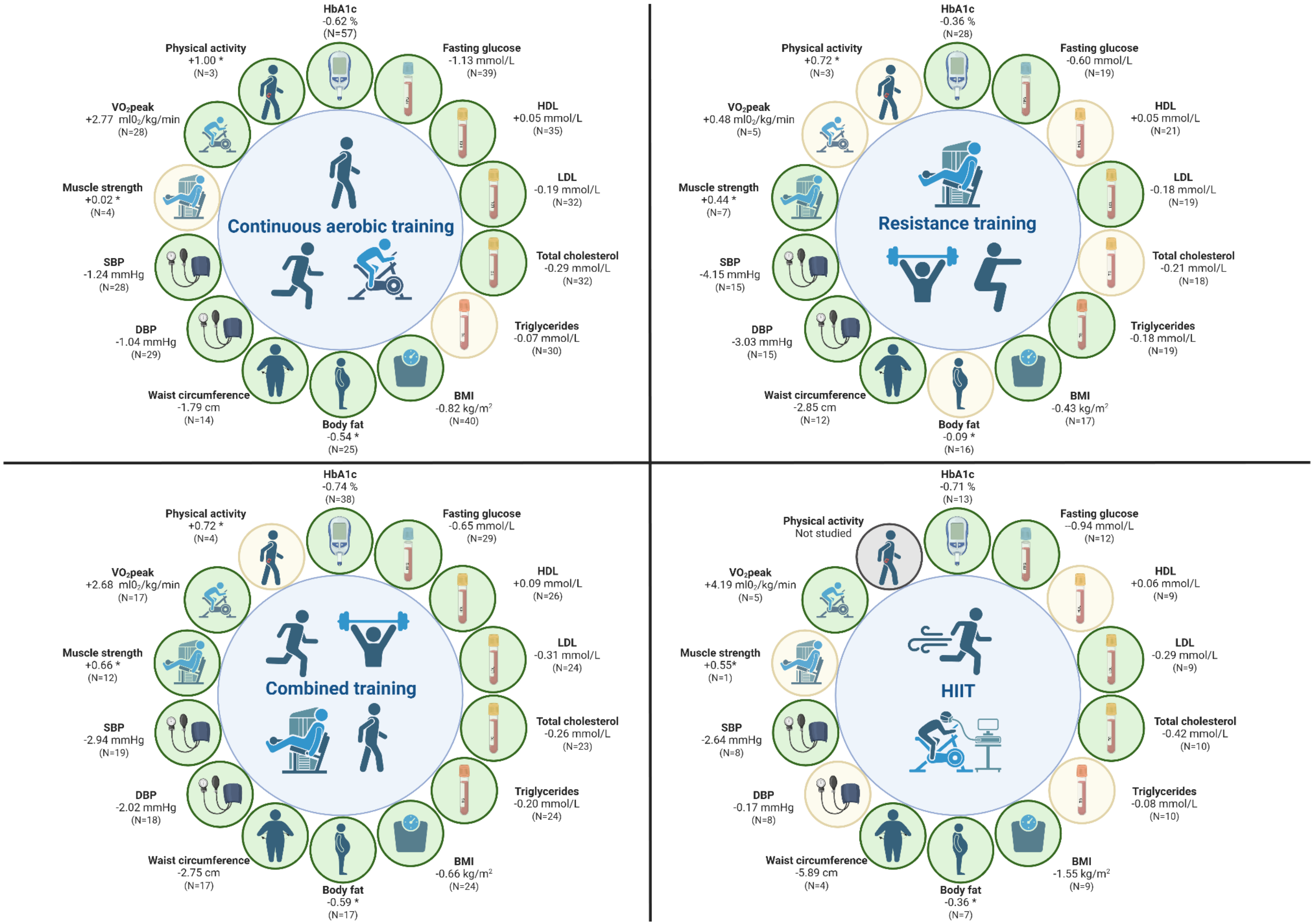

Figure 3. The subgroup analyses for the effect of different exercise modes on other concomitant reported cardiovascular risk factors.*: standardized mean difference; green: significant; yellow: insignificant; grey: not studied

Discussion

Principal findings

This systematic review and meta-analysis, including 100 RCTs with 7195 participants, evaluated the impact of CAT, resistance, combined, and HIIT on HbA1c and concomitantly reported cardiovascular risk factors in adults with type 2 diabetes. All exercise types significantly reduced HbA1c with combined training showing the greatest benefit, followed by HIIT, CAT and resistance training. Across exercise types, supervised interventions proved more effective than unsupervised programs. Beyond glycaemic control, all exercise modalities improved several distinct cardiovascular risk factors, underscoring the importance of tailoring exercise therapy to the individual patient.

Optimal exercise programme characteristics for improving HbA1c

Irrespective of the type of exercise, supervised programmes consistently yielded larger effect sizes compared to unsupervised programs, a finding consistent with previous research and current exercise guidelines (11,27). Supervision may support correct exercise execution and progression, while unsupervised training may be limited by lower adherence and compliance to intensity (27).

All four exercise types produced clinically meaningful improvements in HbA1c ranging between -0.74% and -0.36%. Among these, programs combining CAT with resistance training resulted in the largest reduction in HbA1c. These findings align with prior literature (8,28,29) and may be explained by the additive effects of enhanced mitochondrial oxidative capacity from CAT and improved skeletal muscle glucose storage from resistance training (30). For CAT, no differences were observed between walking, running or cycling interventions. Resistance training was effective when machines and free weights were used, but not resistance bands. However, the latter were evaluated in only two studies, both unsupervised or partially supervised, and one at low intensity, warranting cautious interpretation and further study. Moreover, the smaller HbA1c reductions observed in resistance training may partly reflect the lower reductions in body fat achieved with this modality, which is a known mediator of improvements in glycaemic control (31,32).

A training frequency of three sessions per week appeared optimal in reducing HbA1c, as higher frequencies did not show additional benefits. One possible explanation is that the effect of exercise on insulin sensitivity lasts for up to 72 hours, which could have limited the added value of more frequent sessions on glycaemic control (33,34).

Moderate-intensity programs totaling 150–210 minutes per week were most effective for both CAT and resistance training, with neither higher intensity nor greater volume providing additional benefits. These findings are consistent with earlier meta-analyses reporting flattened dose-responses beyond 210-240 min/week for CAT and 170 min/week for resistance training (8,9). Importantly, when CAT and resistance modalities were combined, an equal training dose (150-210 min/week) resulted in amplified HbA1c reductions, supporting the presence of a additive interaction. Notably, shorter training sessions appeared sufficient for CAT, whereas resistance training required a longer session duration (>45 minutes) to elicit optimal HbA1c reductions.

HIIT offered reductions in HbA1c comparable to combined training, while demanding lower total training volume, making it a promising time-efficient alternative. Running-based HIIT protocols appeared more effective than cycling-based ones, potentially reflecting greater muscle recruitment and energy expenditure (35). However, the small number of trials and substantial similarity in exercise protocols preclude definitive conclusions regarding optimal FITT characteristics. Still, our findings align with previous dose-response analyses showing no plateau for HIIT, suggesting that individuals capable and willing to sustain higher training volumes might achieve even greater HbA1c reductions (8). Yet, as nearly all HIIT interventions were supervised and short in duration, uncertainties remain regarding long-term feasibility, adherence, and effectiveness in unsupervised or home-based contexts.

Overall trial duration did not appear to influence the effect of exercise on HbA1c, with the largest effect sizes observed in the shortest interventions. As changes in HbA1c require at least two to three months to become fully apparent, these findings likely reflect a decline in adherence in longer interventions, rather than an accelerated physiological response in the shorter interventions (14,36,37). This emphasises the need for strategies that promote long-term adherence, such as hybrid or tele-monitored interventions, preferably combined with structured exercise counseling (38).

The benefits of exercise on the broader cardiovascular risk profile

Beyond HbA1c, concomitantly reported cardiovascular risk factors were assessed as secondary outcomes. CAT and combined training both improved VO_2peak beyond the minimal clinically important difference of 1 mL/kg/min. However, the most profound increase was seen following HIIT, where increases exceeded 1 metabolic equivalent (3.5 mL/kg/min), a threshold associated with a 16% reduction in all-cause mortality risk (39). Resistance training alone did not improve VO_2peak, yet it was, together with combined training, the only modality to significantly increase muscular strength. Since reduced strength is associated not only with the prevalence of type 2 diabetes but also with greater morbidity and mortality among affected individuals (40,41), interventions integrating both CAT and resistance components appear to provide the most comprehensive cardiovascular protection. Similarly, while CAT produced the most pronounced improvements in anthropometric measures and resistance training demonstrated more profound effects on blood pressure, combined training merged these benefits, resulting in the most favorable overall cardiovascular risk reduction.

HIIT emerged as a valid and time-efficient alternative, offering broad cardiovascular benefits and showing particular promise if weight loss is prioritised. Nonetheless, most HIIT interventions were short-term and supervised, warranting caution in extrapolating these findings to long-term or unsupervised practice.

Notably, physical activity was only measured in just 10 interventions and showed significant increases only after CAT. This scarcity of data highlights an important gap in the literature, as sustained increases in habitual physical activity could consolidate or extend the benefits of structured exercise. Future studies should therefore not only focus on optimising exercise prescription, but also on strategies that facilitate the translation of structured exercise into lasting lifestyle changes.

Strengths and limitations:

This meta-analysis has several strengths. First, the comprehensive and well-structured search strategy led to the inclusion of a larger number of studies compared to previous reviews, increasing statistical power. Second, we assessed both optimal subtypes and training modalities within each exercise type, refining clinical exercise prescriptions. Third, where possible, we reported mean differences to facilitate clinical interpretation of the results. Lastly, by evaluating not only HbA1c but also a range of concomitantly reported cardiovascular risk factors, this study provides a more holistic view of the cardiovascular benefits of exercise in adults with type 2 diabetes.

Nonetheless, several limitations should be considered. As we aimed to investigate the impact of exercise interventions on concomitantly reported cardiovascular risk factors, outcomes were restricted to those reported in included studies. Additionally, as medication adjustments during interventions are common, they may have confounded observed effect sizes (42,43). Future individual participant data meta-analyses are needed to better account for these influences.

Moreover, there was considerable heterogeneity between studies and the presence of publication bias in combination with the relatively low quality of the included studies suggests that caution is warranted when interpreting the magnitude of effects.

Conclusions

All exercise modalities significantly reduced HbA1c, highlighting the role of exercise as a core component in the management of type 2 diabetes. Combining CAT and resistance training offers the most comprehensive metabolic and cardiovascular benefits. Based on the included studies, an exercise volume of 150-210 minutes of moderate intensity per week, distributed over three sessions, appeared most effective. The superiority of supervised over unsupervised interventions further underscores the value of guided or hybrid programs. HIIT may be considered a valid and time-efficient alternative to combined training, especially in individuals prioritising improvements in cardiorespiratory fitness and weight loss. However, its feasibility should be assessed in long-term and unsupervised or home-based contexts. Finally, tailoring the emphasis of an exercise program based on the patient's metabolic profile, and adjusting FITT parameters accordingly, may help create individualized regimens that yield the greatest benefits for specific patient subgroups.

Abbreviations

HbA1c	Glycated Haemoglobin
CAT	Continuous Aerobic Training
HIIT	High-Intensity Interval Training
SIT	Sprint interval training
FITT	Frequency, Intensity, Type, and Time
BMI	Body Mass Index
FPG	Fasting Plasma Glucose
LDL	Low-Density Lipoprotein
HDL	High-Density Lipoprotein
VO_2peak	Peak oxygen uptake
SBP	Systolic Blood Pressure
DBP	Diastolic Blood Pressure
1RM	One Repetition Maximum
RCT	Randomised Controlled Trial
MD	Mean Difference
SMD	Standardized Mean Difference
CI	Confidence Interval
SD	Standard Deviation
ACSM	American College of Sports Medicine
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PROSPERO	International prospective register of systematic reviews
TESTEX	Tool for the assESsment of study quality and reporting in Exercise
MEDLINE	Medical Literature Analysis and Retrieval System Online
CENTRAL	Cochrane Central Register of Controlled Trials
CINAHL	Cumulative Index to Nursing and Allied Health Literature
PEDro	Physiotherapy Evidence Database

Declarations

Ethics approval and consent to participate
Not applicable

Consent for publication
Not applicable

Data availability
The datasets used during the current study are available from the corresponding author on reasonable request.

Competing interests
All authors declare that they have no competing interests.

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Author Contributions

Study concept and design: V.C., M.d.C. and M.M. Acquisition, analysis, or interpretation of data: J.G., M.H., L.G. and M.M. Drafting of the manuscript: M.M., V.C., J.C., M.d.C. Critical revision of the manuscript for important intellectual content: all authors. All authors read and approved the final manuscript.

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