

Impact of concurrent aerobic and resistance training on body composition, lipid metabolism and physical function in patients with type 2 diabetes and overweight/obesity: a systematic review and meta-analysis

Sameer Badri AL-Mhanna^{1,2}, Abdullah F. Alghannam³,
Nouf H. Alkhamees⁴, Bodor Bin Sheeha⁴, Norsuhana Omar²,
Hani Albalawi⁵, Mehmet Güllü⁶, Umut Canli⁷, Hafeez Abiola Afolabi⁸,
Bishir Daku Abubakar⁹, Georgian Badicu¹⁰, Rozaziana Ahmad²,
Gerasimos V. Grivas¹¹ and Alexios Batrakoulis^{12,13}

¹ Center for Global Health Research, Saveetha Medical College and Hospitals, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, India

² Department of Physiology, School of Medical Sciences, Universiti Sains Malaysia, Kubang Kerian, Kelantan, Malaysia

³ Lifestyle and Health Research Center, Health Sciences Research Center, Princess Nourah bint Abdulrahman University, Riyadh, Saudi Arabia

⁴ Department of Rehabilitation Sciences, College of Health and Rehabilitation Sciences, Princess Nourah bint Abdulrahman University, Riyadh, Saudi Arabia

⁵ Department of Health Rehabilitation Sciences, Faculty of Applied Medical Sciences, University of Tabuk, Tabuk, Saudi Arabia

⁶ Department of Sports Management, Faculty of Sport Sciences, Kirikkale University, Kirikkale, Turkey

⁷ Sports Science Faculty, Tekirdag Namik Kemal University, Tekirdag, Turkey

⁸ Department of General Surgery, School of Medical Sciences, Universiti Sains Malaysia, Kelantan, Malaysia

⁹ Department of Human Physiology, Federal University Dutse, Jigawa, Nigeria

¹⁰ Department of Physical Education and Special Motricity, Transilvania University of Brasov, Brasov, Romania

¹¹ Physical Education and Sports, Division of Humanities and Political Sciences, Hellenic Naval Academy, Piraeus, Greece

¹² Department of Physical Education and Sport Science, School of Physical Education, Sport Science and Dietetics, University of Thessaly, Karies, Trikala, Greece

¹³ School of Physical Education and Sport Science, Department of Physical Education and Sport Science, Komotini, Greece

Submitted 13 January 2025

Accepted 7 May 2025

Published 11 June 2025

Corresponding author

Norsuhana Omar,
suhanakk@usm.my

Academic editor

Yung-Sheng Chen

Additional Information and
Declarations can be found on
page 23

DOI 10.7717/peerj.19537

© Copyright

2025 AL-Mhanna et al.

Distributed under

Creative Commons CC-BY 4.0

OPEN ACCESS

ABSTRACT

Background: The potential advantages of concurrent aerobic and resistance training (CART) for enhancing cardiometabolic health-related outcomes appear to surpass the outcomes of engaging in aerobic or resistance training alone. The present study aimed to synthesize the available scientific evidence on the effects of CART on body composition, lipid metabolism, and physical function in patients with type 2 diabetes and overweight/obesity.

Methods: PubMed, Scopus, ScienceDirect, Cochrane Library, and Google Scholar were searched from inception to August 7, 2024. The review focused on randomized controlled trials and controlled clinical trials of CART. The Cochrane risk of bias tool

was used to assess eligible studies, and the GRADE method to evaluate the reliability of evidence. A random-effects model was used and data were analyzed using standardized mean differences (SMD) and 95% confidence intervals (CI).

Results: A total of 22,878 studies were retrieved; only 20 studies were included, and data were extracted from 1,289 participants (57.0 ± 7.0 years; 31.1 ± 4.6 kg/m²) who met the eligibility criteria. CART group significantly reduced body fat percentage (SMD -0.42 , 95% CI $[-0.70$ to $-0.15]$), low-density lipoprotein-cholesterol (SMD -0.32 , 95% CI $[-0.62$ to $-0.02]$), triglycerides (SMD -0.48 , 95% CI $[-0.71$ to $-0.24]$), total cholesterol (SMD -0.35 , 95% CI $[-0.58$ to $-0.12]$), and fasting blood glucose levels compared to standard treatment (non-exercising controls). CART significantly increased high-density lipoprotein-cholesterol (SMD 0.44 , 95% CI $[0.05$ – $0.82]$) and improved physical function (cardiorespiratory fitness: SMD 78.78 , 95% CI $[46.30$ – $111.25]$; muscular fitness: SMD 5.19 , 95% CI $[1.80$ – $8.59]$) compared to standard treatment. There were no significant differences in body mass, waist-to-hip ratio, fat mass, and lean body mass between CART and standard treatment. An uncertain risk of bias and poor quality of evidence were observed in the eligible studies.

Conclusions: The present results indicate clear evidence that CART has a beneficial role in the improvement of several cardiometabolic health-related parameters in patients with type 2 diabetes and concomitant overweight/obesity. More trials with robust methodological design are needed to investigate the dose-response effects, training parameters formation, and potential mechanisms.

Subjects Diabetes and Endocrinology, Sports Medicine

Keywords Aerobic exercise, Resistance training, Overweight, Obesity, Metabolic syndrome, Cardiometabolic health

INTRODUCTION

Type 2 diabetes mellitus (T2DM) and obesity are currently major public health concerns globally, significantly increasing the risk of cardiovascular disease morbidity and mortality (Al-Mhanna et al., 2023). As a result, individuals with T2DM and overweight/obesity often experience metabolic and cardiovascular dysfunction due to factors such as sedentary behavior, elevated visceral fat, and disrupted lipid homeostasis (Al-Mhanna et al., 2024a; Bhupathiraju & Hu, 2016). Moreover, these populations often face physical limitations and reduced functional capacity, which negatively impact musculoskeletal health and quality of life (Pataky et al., 2014; Warburton, Gledhill & Quinney, 2001). The economic burden of obesity-related comorbidities is also rising at a concerning rate, posing a significant financial strain on healthcare systems worldwide, and it was estimated to be US \$2.0 trillion (Al-Mhanna et al., 2024b; Tremmel et al., 2017). Consequently, investigating cost-effective, non-pharmaceutical interventions has become a key priority for clinicians, practitioners, and public health policymakers, who aim to raise awareness of the essential role of physical exercise in improving community health (Albert et al., 2020).

Physical exercise is recognized as a key element in preventing, managing, and treating individuals who are overweight or obese and have T2DM (Colberg et al., 2016;

Kanaley et al., 2022; Kemps et al., 2019; Kim et al., 2019; Umpierre et al., 2011; Zhao et al., 2021). Additionally, exercise has been identified as one of the fastest-growing health and fitness trends globally for people affected by metabolic diseases (*Al-Mhanna et al., 2022b; Kercher et al., 2023*). According to current international guidelines from the American College of Sports Medicine (ACSM), combining aerobic and resistance training (CART) is highly recommended for improving cardiometabolic health, even without weight loss, in individuals with metabolic health issues (*American College of Sports Medicine et al., 2021*). Specifically, CART appears to be the most effective training approach for producing positive changes in various cardiometabolic health indicators in adults who are overweight or obese but do not have comorbidities (*Al-Mhanna et al., 2024c, 2023; Batrakoulis et al., 2022a*). Moreover, both aerobic and/or resistance training can lead to improvements in individuals with T2DM, particularly in terms of glycemic control, cardiovascular health, chronic inflammation, and mental well-being (*Al-Mhanna et al., 2024d, 2025; Kanaley et al., 2022; Mendes et al., 2016; Pesta et al., 2017; Qadir et al., 2021; Sabag et al., 2017; Zhao et al., 2021*). However, CART has been shown to be more effective than either aerobic or resistance training alone in improving glycemic control in this population (*Church et al., 2010; Güngör et al., 2024; Jamka et al., 2022; Sigal et al., 2007*), although the optimal CART protocols have yet to be fully established (*Kadoglou et al., 2013*). Therefore, further research is required, as there is currently no comprehensive scientific evidence regarding the benefits of CART for various health outcomes in T2DM patients with concurrent overweight/obesity.

While it is well-established that physical exercise plays a crucial role in reducing cardiometabolic risk in obesity and T2DM (*American College of Sports Medicine et al., 2021*), the specific effectiveness of CART in achieving this benefit remains unclear. Therefore, this systematic review and meta-analysis aimed to assess the impact of CART on a wide range of cardiometabolic health parameters in individuals with overweight/obesity and T2DM, including anthropometrics (*i.e.*, body mass and waist-to-hip ratio), body composition (*i.e.*, body fat, fat mass, and lean body mass), lipid metabolism (*i.e.*, high-density lipoprotein cholesterol (HDL-C), low-density lipoprotein cholesterol (LDL-C), total cholesterol (TC), and triglycerides (TG)), glucose metabolism (fasting blood glucose (FBG)), and physical function.

METHODS

The methodology employed in the present systematic review and meta-analysis was previously delineated (*Al-Mhanna et al., 2023*), following the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (*Page et al., 2021*).

Registration

The study protocol was registered on the Open Science Framework (https://osf.io/evt3w/?view_only=e4b33d370929417ab12c8a3a9e4e9d03).

Literature search strategy

Following a systematic electronic search, articles were gathered from six databases (*e.g.*, PubMed, Scopus, Web of Science, Cochrane Library, Science Direct, and Google Scholar). Four authors (S.B.A.M., A.B.D., H.A., and M.G.) used a combination of keywords and Boolean operators, specifically “OR” and “AND,” to conduct the search until August 7, 2024. The keywords used were (“Diabetes”) AND (“Exercise” OR “Training”), as outlined in [Table S1](#), to retrieve relevant articles. The search strategy was based on keywords related to the PICOS framework (P) Population: T2DM patients with overweight or obesity; (I) Intervention: CART; (C) Comparator: other forms of exercise, non-exercising controls, or standard treatment without exercise; (O) Outcomes: body mass, waist-to-hip ratio, body fat, fat mass, lean body mass, HDL-C, LDL-C, TC, TG, FBG, and physical function; and (S) Study type: randomized controlled trials (RCTs) and controlled clinical trials. A comprehensive examination of the reference lists of the included articles, as well as those of all relevant systematic reviews, was conducted to identify additional articles that met the established inclusion criteria.

Eligibility criteria

The following criteria were used to determine the inclusion of studies in the present analysis: Firstly, the participants were patients diagnosed with T2DM, exhibiting a BMI ranging from 25 to 29.9 kg/m², indicating a state of pre-obesity, or an BMI of 30 kg/m² or higher, categorically designated as obesity. The studies were required to have no specified age limit for participants. The intervention in the studies was required to be CART. The studies were required to investigate at least one of the following primary outcomes in humans: anthropometry (body mass and waist-to-hip ratio), body composition (body fat, fat mass, and lean body mass), lipid metabolism (HDL-C, LDL-C, TC, and TG), and glucose metabolism (FBG). Physical function, as measured by the 6-min walk test and the 30-s sit-to-stand test, was also included as a secondary outcome due to its connection with various cardiometabolic health-related markers. The following criteria were applied to the selection of articles: (v) full-text access was provided, and the articles were published in a peer-reviewed journal from inception until August 7, 2024; (vi) no language restrictions were imposed; and (vii) the studies were RCTs or controlled clinical trials. The following articles were excluded from the analysis: (i) articles that did not assess the relevant outcome measures; (ii) studies involving acute exercise interventions; and (iii) review articles, case reports, studies without a control group, or those with unclear or ambiguous data.

Study selection

Four authors (S.B.A.M., A.B.D., H.A., and M.M.) employed a linear evaluation approach to assess the eligibility criteria. A meticulous examination of the titles, abstracts, and full texts (in instances of uncertainty) was conducted, followed by a thorough evaluation of the remaining articles based on the qualifying criteria. Ultimately, a decision was arrived at. In instances of disagreement or uncertainty, a fifth author (W.S.W.G.) provided assistance by independently implementing the same method. The literature search records were

meticulously organized using literature management software (EndNote X9; Clarivate Analytics, Philadelphia, PA, USA).

Data extraction

Two authors (S.B.A.M. and A.B.D.) independently reviewed the full texts of the relevant studies to sample and extract data. The included studies provided substantial data, which was collected and documented, including the first author, publication year, population, gender, sample size, description of the exercise intervention, study length, and outcomes.

Risk of bias assessment

Two authors (S.B.A.M. and A.B.D.) independently evaluated the risk of bias in individual studies following the Cochrane Handbook for Systematic Reviews of Interventions (Higgins *et al.*, 2019). The overall risk of bias for each eligible study was determined according to the following factors: First, the random sequence generation was assessed. Second, the allocation concealment was evaluated. Third, the blinding of participants and personnel was considered. Fourth, the blinding of outcome assessors was examined. Fifth, the completeness of outcome data was assessed. Sixth, the selectivity of outcome reporting was evaluated. Finally, other biases, as described in the Cochrane Handbook for Systematic Reviews of Interventions (Table S2), were considered. The categorization of eligible studies was conducted into three risk levels (high, some concerns, and low) based on the number of factors exhibiting high, unclear, or low risk of bias.

Data analysis

All analyses were conducted using Review Manager 5.4 software (Cochrane Collaboration, <https://revman.cochrane.org/info>). A random-effects model was employed to present the outcomes, and Cochran's Q test along with the I^2 test were used to evaluate heterogeneity. In instances where I^2 exceeded 50%, a fixed-effects model was implemented to calculate the pooled results, and a subgroup analysis was conducted. The effect size was determined using mean differences (MD) or standardized mean differences (SMD) with 95% confidence intervals (CI). A two-sided p -value of less than 0.05 was considered statistically significant. The GRADEpro methodology (<https://www.gradepro.org>) was employed to assess the reliability of the evidence, classifying studies as low-, moderate-, or poor-quality evidence (Table S3).

RESULTS

Literature search and selection

From the specified databases, PubMed, Web of Science, Scopus, Science Direct, Cochrane Library, and Google Scholar (Fig. 1), a total of 22,878 studies were obtained. After removing duplicate articles, the number of studies eligible for further evaluation was reduced to 21,195. Through a review of the titles and abstracts based on predetermined inclusion and exclusion criteria, 21,159 studies were excluded. Subsequently, the full text of the remaining 36 articles was carefully examined, excluding 14 articles with reasons. However, two records were subsequent studies of eligible trials included in the present

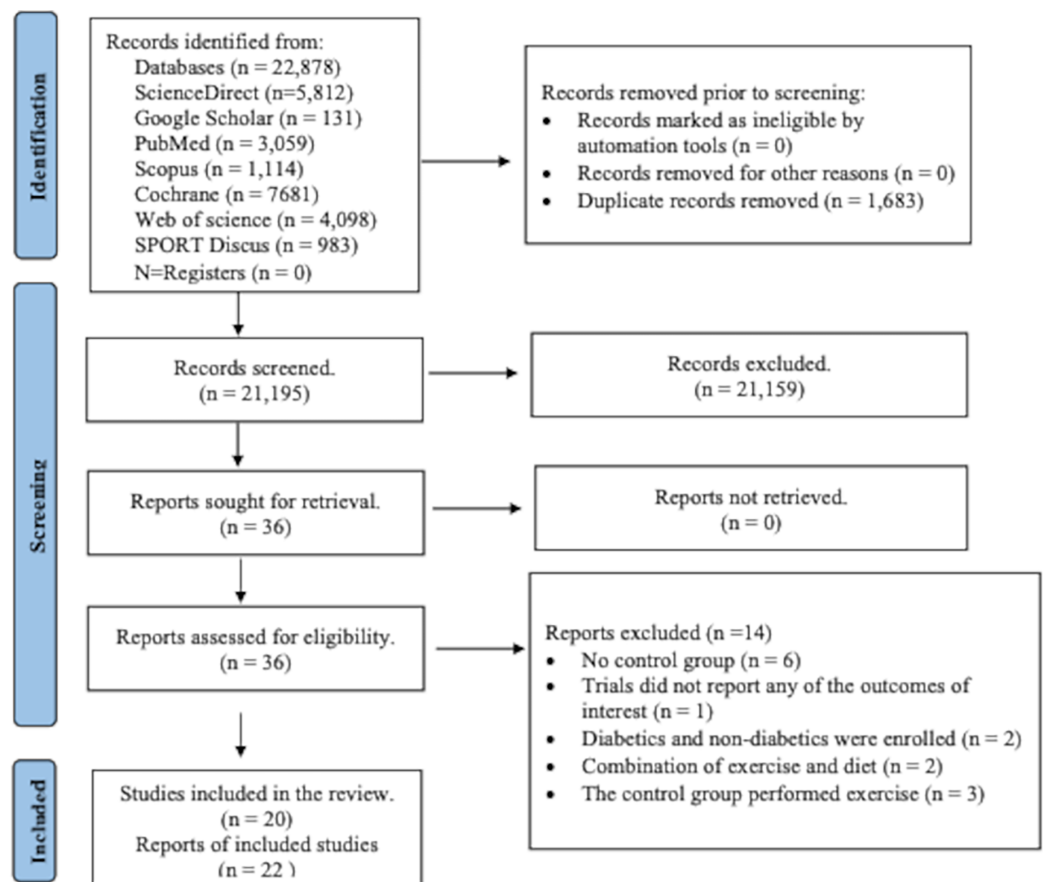


Figure 1 PRISMA flowchart for search strategy. The process of study selection for the systematic review and meta-analysis, including identification, screening, eligibility, and inclusion phases. A total of 22,878 records were identified through database searching, and 1,683 duplicates were removed. After screening 21,195 records, 36 full-text articles were assessed for eligibility. Ultimately, 20 studies (22 reports) met the inclusion criteria, while 14 were excluded for reasons such as lack of control group, irrelevant outcomes, or combined interventions. [Full-size !\[\]\(1679558f37f6db0dd8360a2a7e913e90_img.jpg\) DOI: 10.7717/peerj.19537/fig-1](https://doi.org/10.7717/peerj.19537/fig-1)

review. Thus, a total of 20 studies were finally included in this review, and data were extracted from 1,289 patients (age: 57.0 ± 7.0 ; BMI: $31.1 \pm 4.6 \text{ kg/m}^2$) who met the eligibility criteria (Fig. 1 and Tables S4 and S5).

Literature characteristics

Fourteen out of the 20 studies were from high-income countries (Annibalini et al., 2017; Cuff et al., 2003; Dunstan et al., 1998; Ferrer-García et al., 2011; Gibbs et al., 2012; Hale et al., 2022; Lambers et al., 2008; Loimaala et al., 2003; Magalhães et al., 2019; Maiorana et al., 2002; Scheer et al., 2020; Sigal et al., 2007; Swift et al., 2012; Tessier et al., 2000), two studies, were from upper-middle-income countries (Jorge et al., 2011; Tan, Li & Wang, 2012), and four studies, were from lower-middle-income countries (Motahari Rad et al., 2023; Sabouri et al., 2021; Yavari et al., 2012; Zarei et al., 2021). Only one out of the 20 studies was conducted in a non-clinical setting (home-based intervention). Nine studies conducted short-term exercise interventions lasting 8–12 weeks and 11 studies conducted long-term exercise interventions lasting 16–60 weeks (Table 1).

Table 1 Characteristics of included trials. The table summarizes key details such as participants' demographics (age, BMI), comorbidities, study design, recruitment methods, intervention types (aerobic, resistance, or combined), duration, and outcome measures assessed across the included studies.

Reference	Participants' age (yrs), BMI (kg/m ²), population	Comorbidities	Study design	Recruitment and grouping	Control intervention	Intervention group	Duration of intervention	Outcome measures	Pro-instrument measures
1. <i>Swift et al. (2012)</i>	55.8 ± 8.7,	Cancer,	RCT	Over media, mailers, and community events N = 96: CO = 37: EX = 59	No exercise	10 kcal/kg per week expending aerobic and twice a week resistance training. Supervised	36 weeks	1. Fasting glucose 2. Body fat 3. Body mass	1. Immunoassay Siemens, Deerfield 2000 2. – 3. on a GSE 450 electronic scale (GSE Scale Systems, Novi, MI, USA)
2. <i>Ferrer-García et al. (2011)</i>	35.8 ± 6.2, Inter-racial sedentary men and women	Neuropathy, Myocardial infarction, Heart catheterization, And coronary artery bypass surgery —	United States RCT	N = 84: CO = 40: Ex = 44	Dietary and exercise counseling	45 min of moderate physical (particularly aerobic) for 5 days + Strength training at least 2 days/week Home-based physical education program (HPEP) (verbally and in writing recommendation)	24 weeks	1. Lipid profile 2. Body mass 3. In (kg)	1. – 2. In (kg)
3. <i>Maiorana et al. (2002)</i>	31.3 ± 6.2, 52.0 ± 2.0,	—	Spain RCT	Hospital recruitment	They were instructed not to undertake any formal exercise or change in habitual physical activity levels during the study	1 hour of circuit training (a combination of cycle ergometry, treadmill walking, and resistance training)	8 weeks	1. Body mass 2. Body fat 3. Waist-to-hip ratio 4. Plasma lipid profile 5. Plasma fasting glucose	1. Anthropometric steel tape (Luftkin) 3. Hitachi 917 analyzer (Tokyo, Japan)
4. <i>Lambers et al. (2008)</i>	29.6 ± 3.4 55.8 ± 9.7,	—	Australia RCT	N = 16: Ex = 8: CO = 8 Hospital outpatients	Continued with their normal daily activities	Supervised by an experienced exercise physiologist. 40 sessions of circuit training (walking or jogging, elbow flexion, and extension, cycling, knee flexion and extension, stepping, cooling down + stack weight strengthening	12 weeks	1. Physical function 2. Body mass 3. Lipid profile	1. 6-min walk test (6MWT), sit-to-stand test 2. Digital balance, stadiometer 3. HDL-C (PEG β cholesterol oxidase; Roche Diagnostics), triglycerides (glycerol phosphate PAP; Roche Diagnostics), total cholesterol (cholesterol oxidase-PAP; Roche Diagnostics)
	28.9 ± 2.8,	—	Belgium	N = 35: CO = 16: Ex = 19	Exercises				

(Continued)

Table 1 (continued)

Reference	Participants' age (yrs), BMI (kg/m ²), population	Comorbidities	Study design	Recruitment and grouping	Control intervention	Intervention group	Duration of intervention	Outcome measures	Pro-instrument measures
	From two General Practice centres in the Netherlands and Belgium					Supervised			
5. <i>Hale et al. (2022)</i>	62.7 ± 15.3,		Randomized, two-arm, parallel, open-label trial	via general practices (GP), Diabetes NZ, public media advertising, and health agencies that work with Maori and Pacific communities	Usual care	Diabetes Community Exercise Programme (DCEP) twice weekly. It consists of an aerobic exercise warm-up (5 min), an aerobic and resistance exercise circuit with a focus on major muscle groups (30 min), and flexibility exercises (5 min).	12 weeks	1. Body mass	
	N/A,		New Zealand	N = 169; CO = 84; Ex = 85		Supervised			
6. <i>Loimaala et al. (2003)</i>	53.3 ± 5.1,	Hypertension	RCT	Through newspaper advertisement	Conventional treatment only	Conventional treatment together + heart rate-controlled endurance training twice a week + muscle strength training twice a week	60 weeks	1. Physical function	1. Sit to stand test
	29.3 ± 3.7		Finland	N = 50; CO = 25; Ex = 24		Supervised			
7. <i>Tessier et al. (2000)</i>	69.3 ± 4.2,		RCT	Hospital outpatients	Continue with their usual activity regimen	Three times a week of rapid walking, strengthening, and stretching exercise	16 weeks	1. Body mass	1.
	N/A		Canada	N = 39; CO = 20; Ex = 19		Supervised			
8. <i>Dunstan et al. (1998)</i>	50.3 ± 2.0,		RCT	Non-regular vigorous exercising NIDDM volunteers	No formal exercise	60 min circuit weight training (CWT)	8 weeks	1. Fasting serum glucose 2. Waist-to-hip ratio	1. Automated analyzer (Bayer Diagnostics, Sydney, NSW, Australia) Radioimmunoassay using Tosoh analyzer (Tosoh, Kyobashi, Chuo-ku, Tokyo, Japan) 2. Waist-hip ratio was calculated from the umbilicus and hip circumference measurement sites
	28.3 ± 0.8		Australia	N = 27; CO = 12; Ex = 15		3 days a week Supervised			

Table 1 (continued)

Reference	Participants' age (yrs), BMI (kg/m ²), population	Comorbidities	Study design	Recruitment and grouping	Control intervention	Intervention group	Duration of intervention	Outcome measures	Pro-instrument measures
9. <i>Jorge et al. (2011)</i>	57.9 ± 9.8,		RCT	From Diabetes Outpatient Clinic	Continued with their normal daily activities	3 days per week of cycling at the heart rate corresponding to the lactate threshold (30 min) + seven circuit training as follows: leg press, bench press, lat pull down, seated rowing, shoulder press, abdominal curls, and knee curls (30 min).	12 week	1. Waist-to-hip ratio 2. Cholesterol and triglyceride	1. By measuring the waist circumference at the narrowest region between the costal margin and iliac crest and then dividing this measurement by the hip circumference measured at its greatest gluteal protuberance 2. Colorimetric methods using commercial kits (Abbott, Abbott Park, IL)
10. <i>de Oliveira et al. (2012)</i>	31.2 ± 3.9 57.9 ± 9.8,		Brazil	N = 48; CO = 12; Ex = 12				3. Body mass 4. Body fat 5. Fasting blood glucose, LDL-C, and HDL-C	3. in Kg 4. By measuring the waist circumference at the costal margin and iliac crest, dividing by the hip circumference at its greatest gluteal protuberance 5. Colorimetric methods using commercial kits (Abbott, Abbott Park, IL)
11. <i>Sigal et al. (2007)</i>	31.2 ± 3.9 53.5 ± 7.3,		RCT	Recruited through advertising, physicians, and word of mouth	Maintained their lifestyle	3 times weekly progressive treadmills or bicycle ergometers exercised + seven progressing weight machines resistant exercises Supervised	22 weeks	1. Plasma lipid 2. Body composition 3. Body mass	1. Enzymatic methods on a Beckman-Coulter LX20 analyzer 2. bioelectrical impedance analyser, computed tomography (CT).
	35.0 ± 9.6		Canada.	N = 251; CO = 62; Ex = 64					

(Continued)

Table 1 (continued)

Reference	Participants' age (yrs), BMI (kg/m ²), population	Comorbidities	Study design	Recruitment and grouping	Control intervention	Intervention group	Duration of intervention	Outcome measures	Pro-instrument measures
12. <i>Gibbs et al. (2012)</i>	58.0 ± 5.0,	Hypertension	RCT United States	Recruited via newspaper advertisements from greater Baltimore city	No further intervention	Three times per week of 10–15 min warm-up, 45 min of aerobic exercise at 60–90% maximum heart rate and a cool down + seven weight training exercises of latissimus dorsi pull down, leg extension, leg curl, bench press, leg press, shoulder press, and seated mid-rowing as two sets of 12–15 repetitions at 50% of 1-repetition maximum. Supervised	24 weeks	1. Body fat 2. Lipid profile	1. Dual X-ray absorptiometry, magnetic resonance imaging 2. Lipids (Cholestech Corp.), insulin (Linco Research Inc.), glucose (Beckman Diagnostics), and HbA1c (Med. Computer Systems).
13. <i>Yavari et al. (2012)</i>	32.3 ± 5.3, Multi-racial 50.9 ± 9.8,		RCT	N = 140; CO = 70; Ex = 70 Clinic DM out-patients	Maintained their lifestyle	Three times per week of a warm-up stage, they worked for 20–30 min on a treadmill or bicycle plus two sets each of eight exercises with 8–10 repetitions on weight machines. Supervised	52 weeks	1. Blood glucose, total cholesterol, HDL-c, and triglyceride 2. Body fat	1. Photometric End Point method using Pars Azmoon* enzyme kits (made in Iran) 2. Body composition monitor (model BF500, OMRON*, 2007)
14. <i>Cuff et al. (2003)</i>	28.8 ± 5.4 63.4 ± 2.2	Obese postmenopausal women	Iran RCT	N = 80; CO = 20; Ex=20 Hospital recruitment		Warm-up, an aerobic phase, a resistance training phase, and a cooldown to total class time of 75 min. Supervised	16 weeks	1. Serum total cholesterol, LDL, apolipoprotein B and HDL cholesterol 2. Abdominal adipose tissue & mid-thigh skeletal	1. Enzymatic colorimetric test 2. Computed tomography scans
15. <i>Scheer et al. (2020)</i>	33.3 ± 1.5 60.9 ± 9.6 35.3 ± 6.8		Canada Australia Control Trial	N = 28; CO = 9; Ex = 10 Recruited from the community using local media advertising	Maintained usual activities	Three times a week in a heated community pool of eight aerobic stations alternating with eight resistance stations supervised	8 week	1. Waist-to-hip ratio 2. Plasma glucose, total cholesterol, HDL, LDL and triglycerides	1. Triplicate measures using an anthropometric steel tape (Lufkin, Missouri City, TX, USA) 2. –

Table 1 (continued)

Reference	Participants' age (yrs), BMI (kg/m ²), population	Comorbidities	Study design	Recruitment and grouping	Control intervention	Intervention group	Duration of intervention	Outcome measures	Pro-instrument measures
16. <i>Tan, Li & Wang (2012)</i>	65.9 ± 4.2,		RCT	Recruited via local medical practitioners.	Maintain their usual physical activity habits	Three sessions per week of warm-up period (30 min), moderate aerobic exercise, resistance training (10 min) with five leg muscle exercises (two sets of 10–12 repetitions) and a cool-down Supervised	24 week	1. Body composition 2. Body mass and 3. Waist-to-hip ratio 4. Blood glucose 5. Lipid profile	1. GE Prodigy direct digital DEXA bone densitometry (GE Healthcare, Chicago, IL, USA) 2. Kgm ⁻² Waist girth was measured at the level of the umbilicus horizontally without clothing, while the hip girth at the level of the greatest protrusion of the gluteal muscles with underwear 3. Using Glucose analyzer (YS2300; Yellow Springs, OH, USA) 4. By Cobas Integra Bio-analyzer (Roche, USA) using the standard kits
17. <i>Zarei et al. (2021)</i>	N/A 48.7 ± 10.1,		China RCT	N = 30; CO = 12; Ex = 18 N = 26; CO = 13; Ex = 13	Received no intervention	Three sessions per week of aerobic exercise (walking or running) + weight training Supervised	12 weeks	1. Body composition 2. Glucose, lipid profile	1. Body composition analyzer (InBody 270; South Korea) 2. Enzymatic assay kits
18. <i>Magalhães et al. (2019)</i>	26.7 ± 4.0 59.7 ± 6.5,	Hypertension	Iran RCT	Using media advertisements and e-mail	No intervention	Aerobic exercise on cycling at 40–60% of the heart rate reserve (HRR) + RT included 1 set of 10–12 repetitions.	1 year	1. Body fat 2. Lean body mass 2. Lipid profile 3. Body mass	1. Dual-energy X-ray absorptiometry (Hologic Explorer W, Waltham, USA) 2. Colored enzymatic tests in an automated analyzer (auto analyzer Olympus AU640, Beckman Coulter). 3. Electronic scale with a stadiometer (Seca, Hamburg, Germany).
19. <i>Magalhães et al. (2020)</i>	31.0 ± 5.1		Portugal	N = 38; CO = 22; EX = 16 CO = 27; EX = 28				4. Fasting glucose	4. Auto analyzer Olympus AU640, Beckman Coulter

(Continued)

Table 1 (continued)

Reference	Participants' age (yrs), BMI (kg/m ²), population	Comorbidities	Study design	Recruitment and grouping	Control intervention	Intervention group	Duration of intervention	Outcome measures	Pro-instrument measures
20. Annibolini <i>et al.</i> (2017)	60.0 ± 6.8, -	-	RCT	-	Usual care (No intervention)	Aerobic exercise performed on a treadmill with (40% to 65% of heart rate (HR) reserve) and duration (30 to 60 min) + RT gradually increased from 2 to 4 sets of 20 to 12 repetitions from 40% to 60% of 1-repetition maximum (1-RM) for 3 times per week Supervised	16 weeks	1. Body mass 2. Body composition 3. Fasting glucose 4. Lipid profile	1. - 2. Dual-energy X-ray absorptiometry (DXA LUNAR® GE Healthcare, Milan, Italy) 3. Routine laboratory methods in the local clinic by an auto-analyzer (Beckman Coulter, Milan, Italy). 4. -
21. Sabouri <i>et al.</i> (2021)	29.0 ± 3.8 52.5 ± 4.8, -	-	Italy RCT	N = 16; EX = 8; CO = 8 N = 28; EX = 15; CO = 13	Subjects in the CON group were asked to retain their habitual physical activity without participating in any exercise program throughout the study.	Aerobic exercise on cycle ergometers + RT for 70 min was performed three training sessions/week Supervised	12 weeks	1. Body mass 2. Lipid profile 3. HbA1c	1. Body composition analyzer (InBody 570, Korea) 2. An automated analyzer (CobasC111; Roche Diagnostics, Indianapolis, IN, USA) 3. Anion exchange chromatography. 4. East Bio-Pharm,
22. Kanaley <i>et al.</i> (2022)	26.6 ± 2.3 43.9 ± 2.5, -	-	Iran RCT	N = 34; EX = 17; CO = 17	No exercise	Instructed to maintain their current lifestyles. The RT was 40–80% of 1RM with 15–18 reps. The AE was performed at 75–95% heart rate maximum (HRmax) for 3/week.	12 weeks	1. Body mass 2. Body fat	1. In (kg) 2. Body composition monitor (model BF500; OMRON®, 2007)
29.6 ± 1.7			Iran						

Note:

EX, exercise; CO, control.

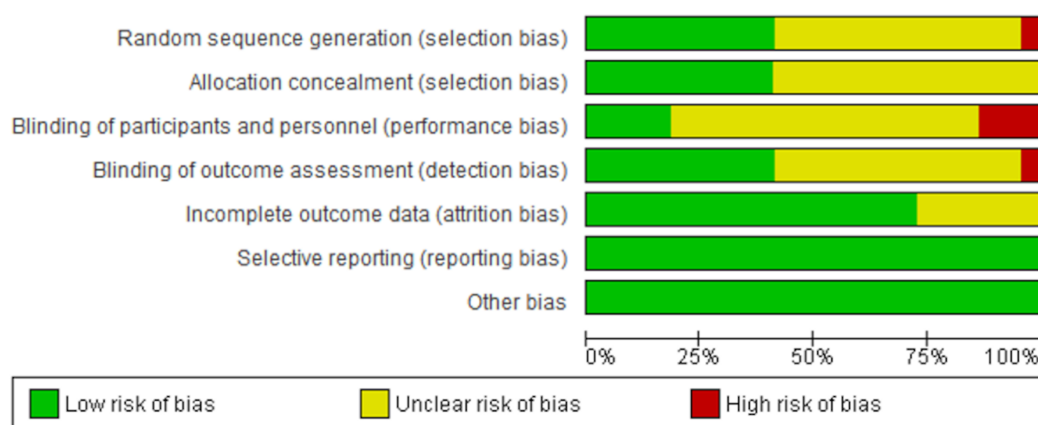


Figure 2 Summary of the risk of bias assessment. Summary of risk of bias across all included studies based on the Cochrane risk-of-bias tool. The figure presents the proportion of studies showing low (green), unclear (yellow), and high (red) risk of bias for each domain assessed.

Full-size DOI: 10.7717/peerj.19537/fig-2

Risk of bias assessment results

The summary of the risk of bias assessment is shown in Fig. 2. Details of the risk of bias judgment per domain for each study are provided in Fig. 3. Specifically, the large majority of eligible studies showed concerns about the randomization, allocation concealment, blinding of participants/personnel and outcome assessment. On the other side, the majority of studies demonstrated a low risk of bias in missing outcome data and a selective reporting process.

Primary outcomes

Anthropometry

Body mass was reported in 15 trials involving 795 participants, showing no differences between CART and ST (SMD -0.05 , 95% CI $[-0.66$ to $0.56]$; $I^2 = 93\%$; $p = 0.94$) following either short- (≤ 16 weeks) or long-term (> 16 weeks) interventions (Fig. 4 and Table S3). The waist-to-hip ratio was assessed in six trials ($n = 152$), demonstrating no meaningful change between CART and ST (SMD -0.26 , 95% CI $[-0.69$ to $0.17]$; $I^2 = 41\%$; $p = 0.24$) (Fig. 5 and Table S3).

Body composition

Body fat was measured in ten trials ($n = 551$). CART demonstrated a significant reduction in body fat (SMD -0.42 , 95% CI $[-0.70$ to $-0.15]$; $I^2 = 56\%$; $p = 0.002$) compared to standard treatment, showing low-quality evidence (Fig. 6 and Table S3). Fat mass and lean body mass were included in three trials, involving 168 and 179 participants, respectively. No differences were found in both fat mass (SMD -0.19 , 95% CI $[-0.50$ to $0.11]$; $I^2 = 0\%$; $p = 0.22$) and lean body mass (SMD -0.02 , 95% CI $[-0.33$ to $0.30]$; $I^2 = 0\%$; $p = 0.92$) between CART and standard treatment (Figs. 7 and 8, Table S3).

	Random sequence generation (selection bias)	Allocation concealment (selection bias)	Blinding of participants and personnel (performance bias)	Blinding of outcome assessment (detection bias)	Incomplete outcome data (attrition bias)	Selective reporting (reporting bias)	Other bias
Annibalini et al., 2017	?	?	?	?	+	+	+
Cuff et al., 2003	?	?	?	?	+	+	+
Dunstan et al., 1998	+	+	?	?	+	+	+
García et al., 2011	?	?	?	?	?	+	+
Gibbs et al., 2012	?	?	?	?	?	+	+
Hale et al., 2022	+	+	+	+	+	+	+
Jorge et al., 2011	?	?	?	?	?	+	+
Lambers et al., 2008	+	+	+	+	+	+	+
Loimaala et al., 2003	?	+	?	?	+	+	+
Magalhães et al., 2020	+	+	+	+	+	+	+
Magalhães et al., 2019	+	+	+	+	+	+	+
Maiorana et al., 2002	?	?	?	+	?	+	+
Motahari Rad et al., 2023	+	+	?	+	+	+	+
Oliveira et al., 2012	?	?	?	?	?	+	+
Sabouri et al., 2021	+	?	?	?	+	+	+
Scheer et al., 2020	-	?	?	+	+	+	+
Sigal et al., 2007	+	+	-	+	+	+	+
Swift et al., 2012	?	?	-	+	+	+	+
Tan et al., 2012	?	?	?	?	+	+	+
Tessier et al., 2000	?	?	?	?	+	+	+
Yavari et al., 2012	?	?	-	-	?	+	+
Zarei et al., 2021	+	+	?	?	+	+	+

Figure 3 Risk of bias assessment results. Each study was evaluated across seven domains: random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome

Figure 3 (continued)

assessment, incomplete outcome data, selective reporting, and other sources of bias. Green (+) indicates low risk of bias, yellow (?) indicates unclear risk, and red (–) indicates high risk. Most studies demonstrated low or unclear risk in most domains, with a few showing high risk, particularly in performance bias and allocation concealment (Anniballini et al., 2017; Cuff et al., 2003; Dunstan et al., 1998; Ferrer-García et al., 2011; Gibbs et al., 2012; Hale et al., 2022; Jorge et al., 2011; Lambers et al., 2008; Loimaala et al., 2003; Magalhães et al., 2020, 2019; Maiorana et al., 2002; Motahari Rad et al., 2023; de Oliveira et al., 2012; Sabouri et al., 2021; Scheer et al., 2020; Sigal et al., 2007; Swift et al., 2012; Tan, Li & Wang, 2012; Tessier et al., 2000; Yavari et al., 2012; Zarei et al., 2021).

Full-size  DOI: 10.7717/peerj.19537/fig-3

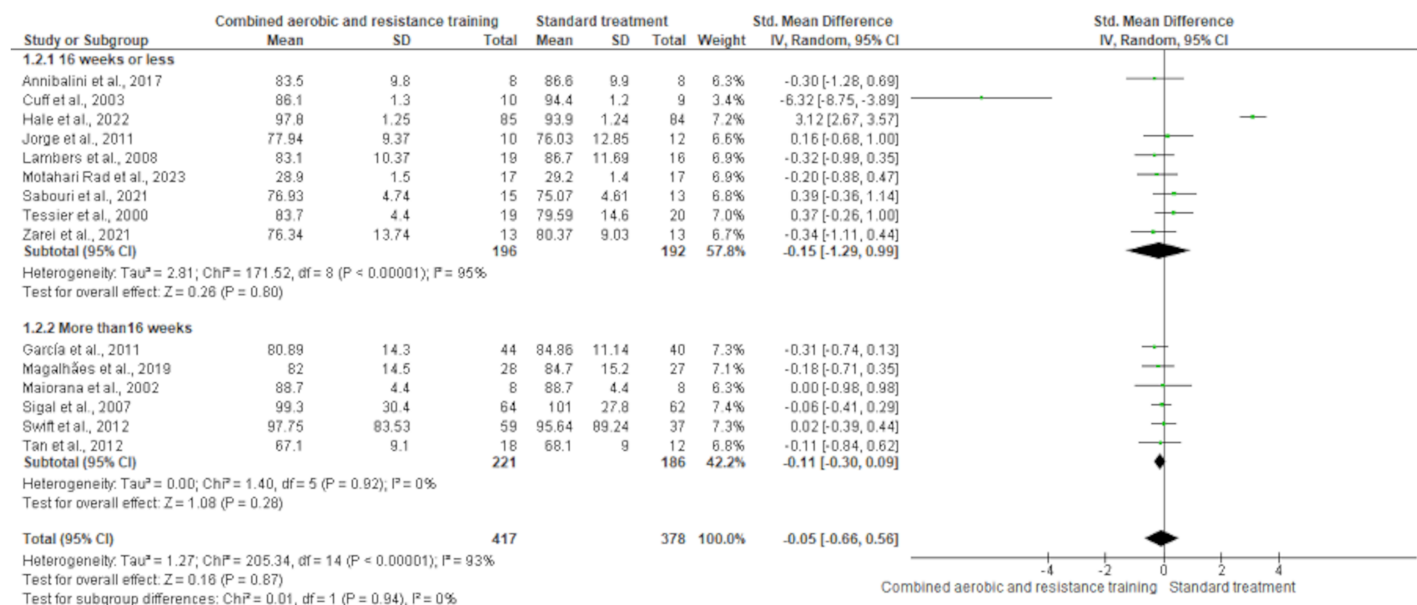


Figure 4 The effect of CART on body mass. The forest plot displays standardized mean differences (SMD) and 95% confidence intervals (CI) across studies, with subgroup analysis based on intervention duration (≤ 16 weeks and > 16 weeks). No statistically significant reduction in body mass was observed (SMD = -0.05 , 95% CI $[-0.66, 0.56]$; $p = 0.87$), and the overall heterogeneity was high ($I^2 = 93\%$) (Anniballini et al., 2017; Cuff et al., 2003; Ferrer-García et al., 2011; Hale et al., 2022; Jorge et al., 2011; Lambers et al., 2008; Loimaala et al., 2003; Magalhães et al., 2019; Maiorana et al., 2002; Motahari Rad et al., 2023; Sabouri et al., 2021; Sigal et al., 2007; Swift et al., 2012; Tan, Li & Wang, 2012; Tessier et al., 2000; Zarei et al., 2021).

Full-size  DOI: 10.7717/peerj.19537/fig-4

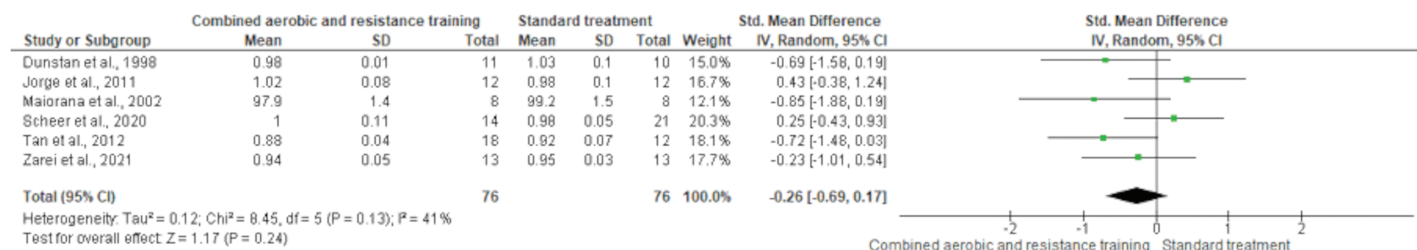


Figure 5 The effect of CART on the waist-to-hip ratio. Forest plot illustrating the effect of combined aerobic and resistance training (CART) on waist-to-hip ratio in individuals with type 2 diabetes and overweight/obesity. No significant effect was observed compared to standard treatment (SMD = -0.26 , 95% CI $[-0.69, 0.17]$, $p = 0.24$), with moderate heterogeneity ($I^2 = 41\%$) (Dunstan et al., 1998; Jorge et al., 2011; Maiorana et al., 2002; Scheer et al., 2020; Tan, Li & Wang, 2012; Zarei et al., 2021).

Full-size  DOI: 10.7717/peerj.19537/fig-5

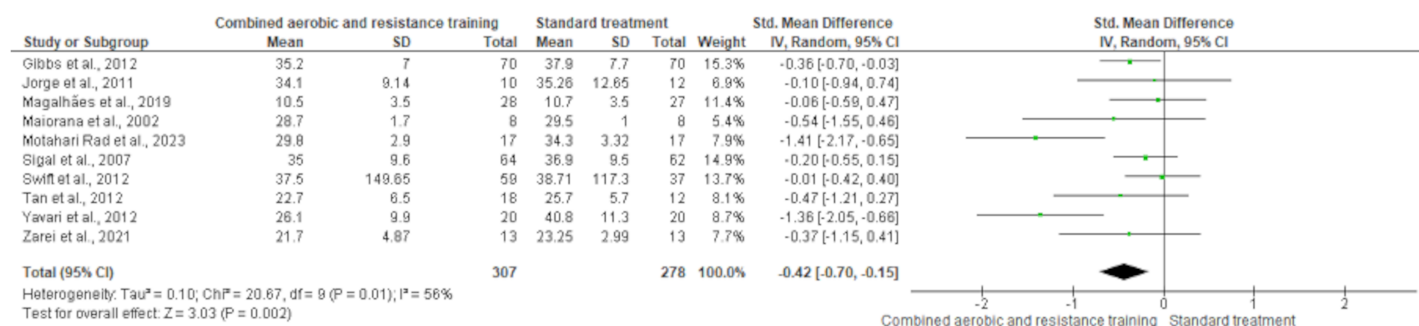


Figure 6 The effect of CART on body fat. The forest plot presents standardized mean differences (SMD) with 95% confidence intervals (CI) for each study and the overall pooled estimate. A statistically significant reduction in body fat was observed in the CART group compared to standard treatment (SMD = -0.42 , 95% CI $[-0.70$ to -0.15]; $p = 0.002$), with moderate heterogeneity ($I^2 = 56\%$) (Gibbs et al., 2012; Jorge et al., 2011; Magalhães et al., 2019; Maiorana et al., 2002; Motahari Rad et al., 2023; Sigal et al., 2007; Swift et al., 2012; Tan, Li & Wang, 2012; Yavari et al., 2012; Zarei et al., 2021). Full-size [DOI: 10.7717/peerj.19537/fig-6](https://doi.org/10.7717/peerj.19537/fig-6)

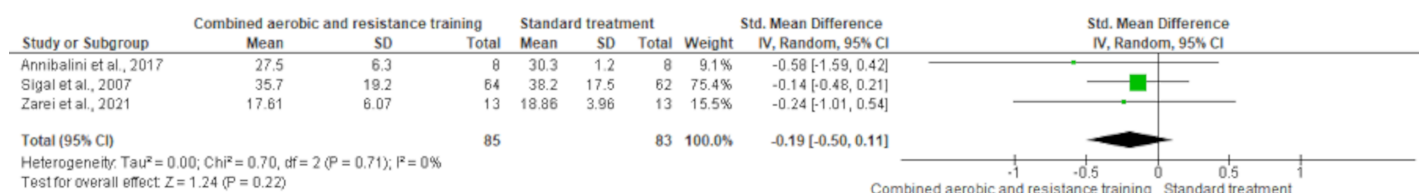


Figure 7 The effect of CART on fat mass. The forest plot shows standardized mean differences (SMD) with 95% confidence intervals (CI). No significant reduction in fat mass was observed following CART compared to standard treatment (SMD = -0.19 , 95% CI $[-0.50$ to 0.11]; $p = 0.22$), with low heterogeneity across studies ($I^2 = 0\%$) (Annibalini et al., 2017; Sigal et al., 2007; Zarei et al., 2021). Full-size [DOI: 10.7717/peerj.19537/fig-7](https://doi.org/10.7717/peerj.19537/fig-7)

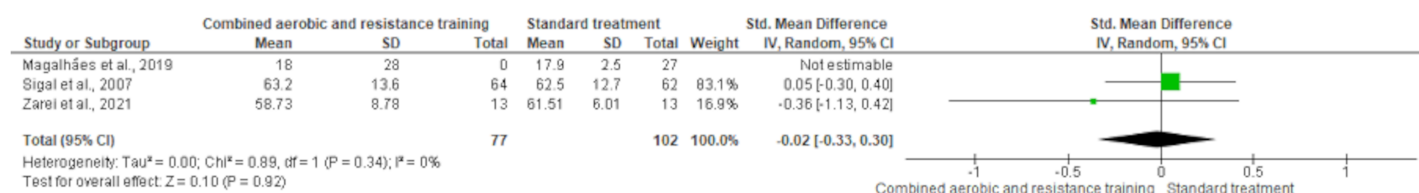


Figure 8 The effect of CART on lean body mass. The forest plot shows standardized mean differences (SMD) with 95% confidence intervals (CI). No significant effect of CART on lean body mass was observed compared to standard treatment (SMD = -0.02 , 95% CI $[-0.33$ to 0.30]; $p = 0.92$), with no observed heterogeneity ($I^2 = 0\%$) (Magalhães et al., 2019; Sigal et al., 2007; Zarei et al., 2021). Full-size [DOI: 10.7717/peerj.19537/fig-8](https://doi.org/10.7717/peerj.19537/fig-8)

Lipid metabolism

HDL-C, LDL-C, TC and TG were reported in 11 trials, involving 576, 589, 376 and 626 participants, respectively. CART induced a meaningful increase in HDL-C (SMD 0.44, 95% CI $[0.05$ – 0.82]; $I^2 = 76\%$; $p = 0.03$) compared to standard treatment, showing very low-quality evidence (Fig. 9, Table S3). CART exhibited significant reductions in LDL-C (SMD -0.32 , 95% CI $[-0.62$ to -0.02]; $I^2 = 63\%$; $p = 0.03$), TC (SMD -0.35 , 95% CI $[-0.58$ to -0.12]; $I^2 = 16\%$; $p = 0.003$), and TG (SMD -0.48 , 95% CI $[-0.71$ to -0.24]; $I^2 = 44\%$; $p < 0.001$) with low-quality evidence between CART and standard treatment (Figs. 10–12, Table S3).

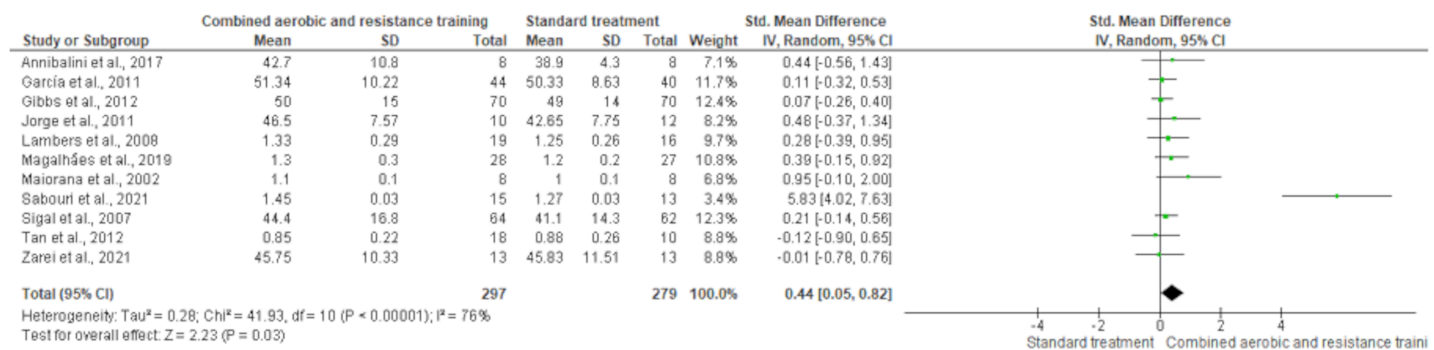


Figure 9 The effect of CART on HDL-C. The forest plot illustrates a significant improvement in HDL-C following CART compared to standard treatment (SMD = 0.44, 95% CI [0.05–0.82]; $p = 0.03$), despite moderate heterogeneity among studies ($I^2 = 76\%$) (Annibalini et al., 2017; Ferrer-García et al., 2011; Gibbs et al., 2012; Jorge et al., 2011; Lambers et al., 2008; Magalhães et al., 2019; Maiorana et al., 2002; Sabouri et al., 2021; Sigal et al., 2007; Tan, Li & Wang, 2012; Zarei et al., 2021). Full-size [DOI: 10.7717/peerj.19537/fig-9](https://doi.org/10.7717/peerj.19537/fig-9)

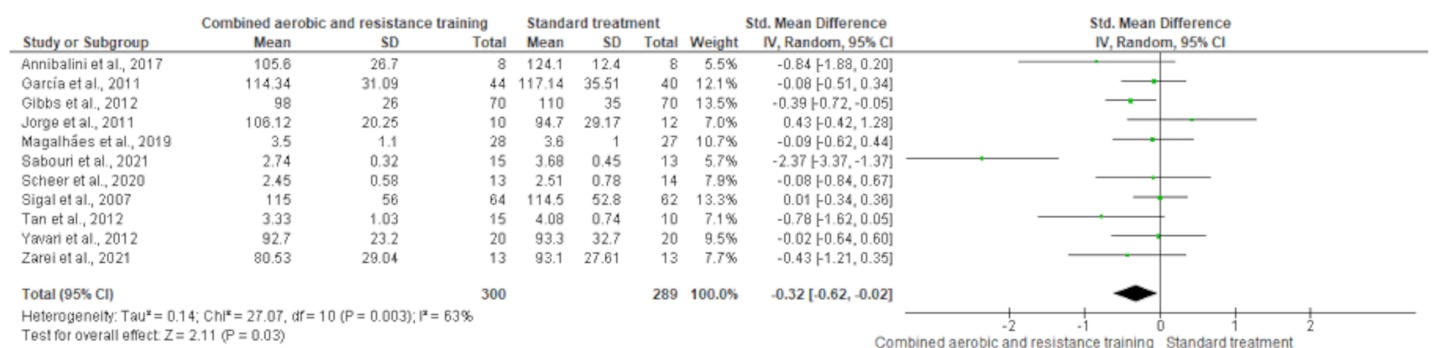


Figure 10 The effect of CART on LDL-C. The forest plot shows a statistically significant reduction in LDL-C levels following CART compared to standard treatment (SMD = -0.32, 95% CI [-0.62 to -0.02]; $p = 0.03$), with moderate heterogeneity observed among studies ($I^2 = 63\%$) (Annibalini et al., 2017; Ferrer-García et al., 2011; Gibbs et al., 2012; Jorge et al., 2011; Magalhães et al., 2019; Sabouri et al., 2021; Scheer et al., 2020; Sigal et al., 2007; Tan, Li & Wang, 2012; Yavari et al., 2012; Zarei et al., 2021). Full-size [DOI: 10.7717/peerj.19537/fig-10](https://doi.org/10.7717/peerj.19537/fig-10)

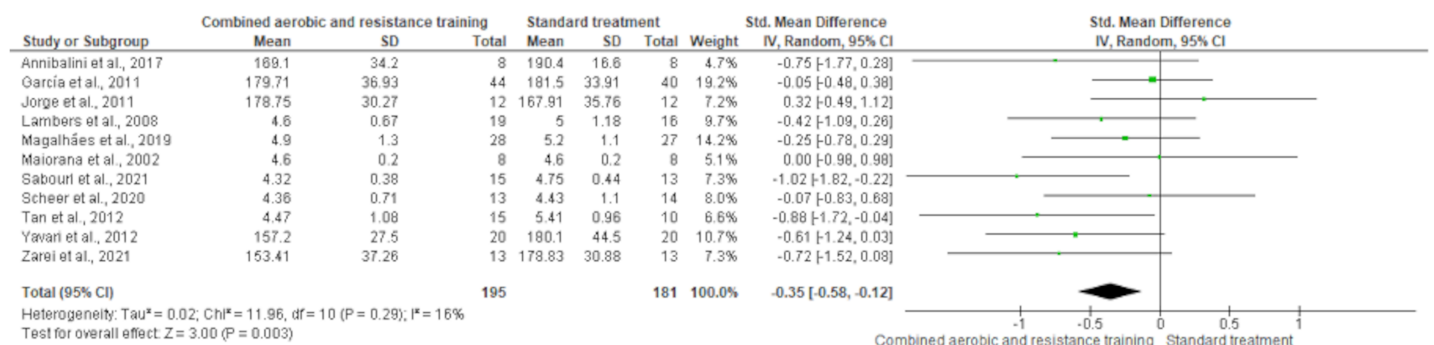


Figure 11 The effect of CART on TC. The forest plot demonstrates a significant reduction in TC following CART compared to standard treatment (SMD = -0.35, 95% CI [-0.58 to -0.12]; $p = 0.003$), with low heterogeneity ($I^2 = 16\%$) indicating consistent findings across studies (Annibalini et al., 2017; Ferrer-García et al., 2011; Jorge et al., 2011; Lambers et al., 2008; Magalhães et al., 2019; Maiorana et al., 2002; Sabouri et al., 2021; Scheer et al., 2020; Tan, Li & Wang, 2012; Yavari et al., 2012; Zarei et al., 2021). Full-size [DOI: 10.7717/peerj.19537/fig-11](https://doi.org/10.7717/peerj.19537/fig-11)

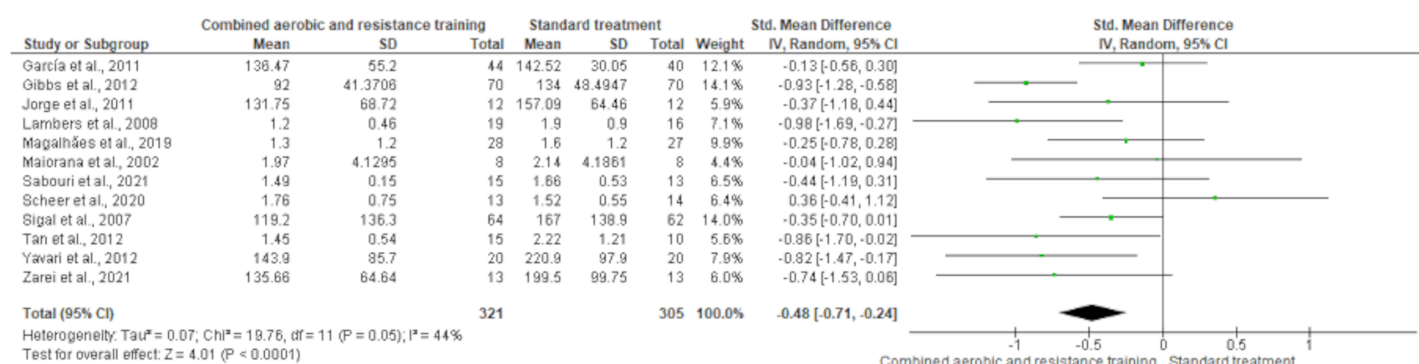


Figure 12 The effect of CART on TG. The meta-analysis revealed a significant reduction in TG following CART compared to standard treatment (SMD = -0.48, 95% CI [-0.71 to -0.24]; $p < 0.0001$), with moderate heterogeneity ($I^2 = 44\%$) (Ferrer-García et al., 2011; Gibbs et al., 2012; Jorge et al., 2011; Lambers et al., 2008; Magalhães et al., 2019; Maiorana et al., 2002; Sabouri et al., 2021; Scheer et al., 2020; Sigal et al., 2007; Tan, Li & Wang, 2012; Yavari et al., 2012; Zarei et al., 2021). Full-size [DOI: 10.7717/peerj.19537/fig-12](https://doi.org/10.7717/peerj.19537/fig-12)

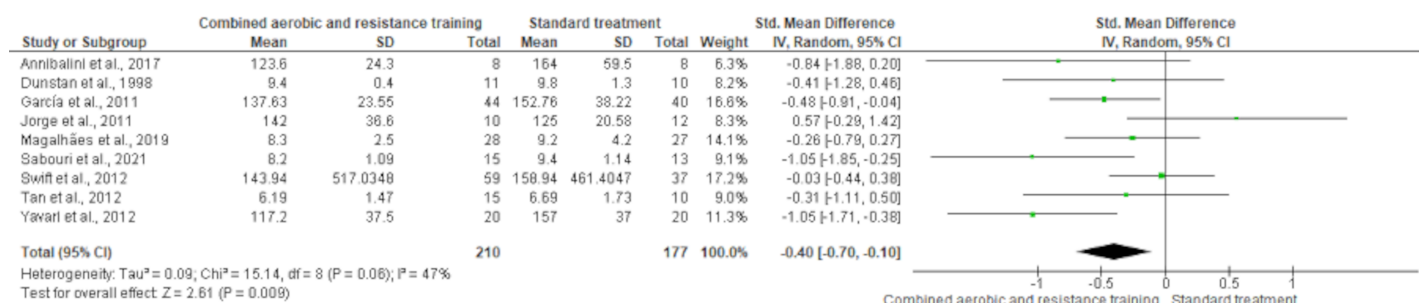


Figure 13 The effect of CART on FBG. The meta-analysis showed a significant reduction in FBG following CART compared to standard treatment (SMD = -0.40, 95% CI [-0.70 to -0.10]; $p = 0.009$), with moderate heterogeneity ($I^2 = 47\%$) (Annibalini et al., 2017; Dunstan et al., 1998; Ferrer-García et al., 2011; Jorge et al., 2011; Magalhães et al., 2019; Sabouri et al., 2021; Swift et al., 2012; Tan, Li & Wang, 2012; Yavari et al., 2012). Full-size [DOI: 10.7717/peerj.19537/fig-13](https://doi.org/10.7717/peerj.19537/fig-13)

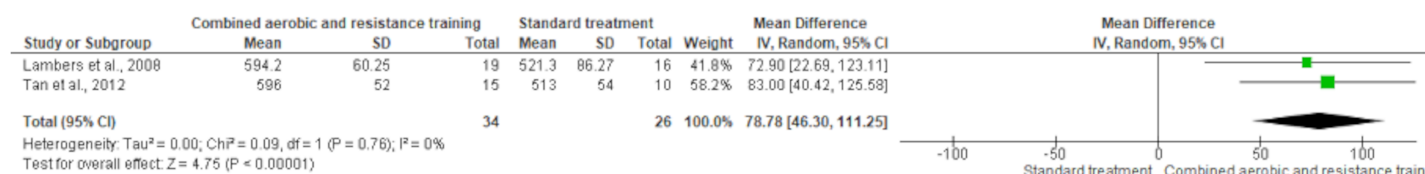


Figure 14 The effect of CART on cardiorespiratory fitness. The meta-analysis revealed a significant improvement in cardiorespiratory fitness in the CART group compared to standard treatment (Mean Difference = 78.78, 95% CI [46.30–111.25]; $p < 0.00001$), with no observed heterogeneity ($I^2 = 0\%$) (Lambers et al., 2008; Tan, Li & Wang, 2012). Full-size [DOI: 10.7717/peerj.19537/fig-14](https://doi.org/10.7717/peerj.19537/fig-14)

Glucose metabolism

FBG reported nine trials involving 387 participants and showing high-quality evidence. CART demonstrated a reduction in FBG (SMD -0.40, 95% CI [-0.70 to -0.10]; I^2 statistic = 47%; $p = 0.009$) (Fig. 13 and Table S3) compared to standard treatment.

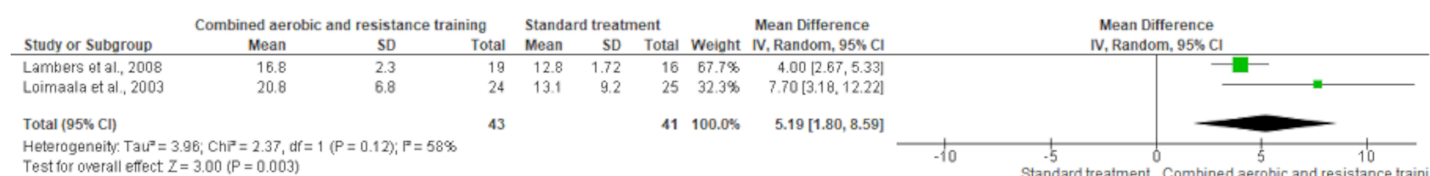


Figure 15 The effect of CART on lower body muscular strength. A significant increase in lower body strength was observed in the CART group compared to standard treatment (Mean Difference = 5.19, 95% CI [1.80–8.59]; $p = 0.003$), with moderate heterogeneity ($I^2 = 58\%$) (Lambers et al., 2008; Loimaala et al., 2003). Full-size DOI: 10.7717/peerj.19537/fig-15

Secondary outcomes

Physical function

6-min walk test

The 6-min walk test was reported in two trials ($n = 60$). CART exerted a meaningful increase in cardiorespiratory fitness (SMD 78.78, 95% CI [46.30–111.25]; I^2 statistic = 0%; $p < 0.001$ compared to standard treatment, demonstrating moderate-quality evidence (Fig. 14 and Table S3).

30-s sit to stand test

The 30-s sit-to-stand test was used in two trials ($n = 84$). CART exhibited a significant improvement in lower body muscular strength (SMD 5.19, 95% CI [1.80–8.59]; I^2 statistic = 59%; $p = 0.003$) compared to standard treatment, showing low-quality evidence (Fig. 15 and Table S3).

PUBLICATION BIAS

Despite including 22 reports, we were unable to create a funnel plot to detect bias or heterogeneity for specific outcomes due to insufficient studies (less than 10 studies of varying sizes) contributing to each outcome (Higgins, 2008). Therefore, a funnel plot using random effects was generated to explore potential publication bias in studies assessing HDL-C, LDL-C, TG, TC, BMI, and body fat. The number of studies for each outcome varied (with 10 or more studies of various sizes) (Higgins, 2008). The funnel plot illustrating the impact of exercise on HDL-C, LDL-C, TG, TC, BMI, and body fat shows a symmetrical distribution on both sides, indicating minimal publication bias in the results, as depicted in Figs. S1–S6.

DISCUSSION

Our study aimed to evaluate the influence of CART on a wide-ranging range of cardiometabolic health-related indicators in individuals with overweight/obesity and T2DM. The main findings show that CART leads to favorable changes in body composition, lipid and glucose metabolism, and physical function in patients with T2DM and concurrent overweight/obesity. While aerobic and resistance training have been recognized as effective exercise strategies for improving cardiovascular disease risk factors

in people with T2DM ([Grace et al., 2017](#); [Kelley & Kelley, 2007](#); [Nery et al., 2017](#); [Yang et al., 2014](#)), our results suggest that CART may be the optimal exercise approach for individuals with poor metabolic health due to the combined presence of T2DM and overweight/obesity.

Anthropometry and body composition

Populations with metabolic dysregulation often experience abdominal obesity, which is associated with visceral and ectopic fat, contributing to chronic inflammation that exacerbates insulin resistance ([Moore & Shah, 2020](#)). This review suggests that CART improves body fat but does not significantly affect other anthropometric or body composition parameters in individuals with T2DM and overweight/obesity. These findings highlight the need for further investigation into these important variables, as the observed changes remain uncertain. Given that weight management is crucial for individuals with poor metabolic health, our results are particularly relevant for people with T2DM and concomitant overweight/obesity.

CART has been recognized as the most effective form of exercise for improving various anthropometric and body composition measures in individuals with excess weight ([Batrakoulis et al., 2018, 2022a](#); [Yapici et al., 2023](#)). Other relevant studies have shown similar effects of CART on anthropometry and body composition in individuals with T2DM and concurrent overweight/obesity ([Pan et al., 2018](#); [Zhao et al., 2021](#)). However, further randomized controlled trials (RCTs) are needed to determine whether CART can induce beneficial changes in visceral adiposity, which is linked to higher cardiovascular disease morbidity and mortality risks ([Moore & Shah, 2020](#)).

Lipid metabolism

Individuals with T2DM and concurrent overweight/obesity are likely to experience poor lipid profile, promoting cardiovascular complications ([Costanzo et al., 2015](#); [Tan et al., 2023](#)). Following the current guidelines published by the American Diabetic Association, it is crucial for these people to maintain normal blood lipid levels, aiming to reduce the risk of developing comorbidities ([Colberg et al., 2016](#)). In our review, CART exhibited meaningful improvements in blood lipids. In general, various exercise modes induce favorable alterations in lipid homeostasis in people with T2DM ([Kelley & Kelley, 2007](#); [Magalhães et al., 2020](#)), which is an observation aligned with the present results. Such an outcome cannot be explained here; however, the presence of excessive weight in conjunction with T2DM may play some role in the simultaneous control of glucose and lipid metabolism due to a complex, low-grade chronic inflammation. Also, CART appears the best exercise mode for improving lipid profile among individuals with an unhealthy weight ([Batrakoulis, 2022a](#)) however, several alternative types of exercise induce positive alterations in blood lipids and lipoproteins among populations with metabolic health impairments and excessive weight ([Batrakoulis, 2022a, 2022b, 2022c](#); [Batrakoulis & Fatouros, 2022](#)) promoting time-efficient and positive experiences in this population within real-world gym settings.

Glucose metabolism

Our results indicate that CART significantly reduces FBG in individuals with T2DM and concurrent overweight/obesity. Notably, these reductions in FBG are associated with a decreased risk of developing T2DM-related morbidity and mortality ([Moore & Shah, 2020](#)). This finding is consistent with previous meta-analyses that have explored the impact of exercise training on glucose homeostasis in individuals with T2DM, both with and without concurrent overweight/obesity ([Zhao et al., 2021](#)). It is important to note that long-term exercise interventions (greater than 12 weeks) appear to be more effective than short-term ones (12 weeks or less), underscoring the enduring benefits of exercise training in glucose control for individuals with T2DM and overweight/obesity ([Zou et al., 2016](#)). Moreover, CART has been identified as the most effective exercise modality for improving glycemic management in populations with impaired metabolic health, outperforming other types of exercise like endurance, resistance, or high-intensity interval training ([Batrakoulis, Jamurtas & Fatouros, 2021](#); [Batrakoulis et al., 2022a](#); [Zhao et al., 2021](#)). In summary, the positive impact of CART on glucose metabolism may be partly explained by the high prevalence of visceral adiposity in individuals with T2DM and concurrent overweight/obesity ([Bays et al., 2008](#)). Consequently, the beneficial changes observed after CART interventions could be linked to the activation of key molecular mechanisms that regulate whole-body glucose homeostasis, particularly those associated with visceral and ectopic fat.

Physical function

Individuals with impaired metabolic health often have low cardiorespiratory fitness and functional capacity, which increases their risk of developing comorbidities ([Al-Mhanna et al., 2022a](#); [Colberg et al., 2010](#); [Jensen et al., 2014](#)). In contrast, high cardiorespiratory fitness is linked to a lower risk of cardiovascular disease morbidity and mortality in apparently healthy individuals. This has been identified as a more influential factor for cardiometabolic health than improvements in anthropometrics and body composition ([Afolabi et al., 2023](#); [McAuley et al., 2016](#)). Additionally, cardiorespiratory fitness is inversely related to liver fat accumulation and insulin resistance, although no significant differences were found between individuals with T2DM and those without T2DM in terms of cardiorespiratory fitness levels ([Sabag et al., 2021](#)). Regarding the positive effects of exercise training on cardiorespiratory fitness, CART has been recognized as the optimal form of exercise for improving aerobic capacity in individuals with overweight/obesity but without comorbidities ([Batrakoulis et al., 2022a](#); [O'Donoghue et al., 2021](#)). Notably, exercise protocols combining endurance and resistance training in a single session have proven effective in improving various physical fitness measures in sedentary individuals with excess body weight ([Batrakoulis et al., 2018, 2022b, 2021](#)). The significant increase in aerobic capacity may be attributed to the favorable mitochondrial adaptations, increased skeletal muscle capillarization, and enhanced oxidative metabolism induced by CART ([Murlasits, Kneffel & Thalib, 2018](#)). However, the findings supporting the positive role of CART in improving cardiorespiratory fitness should be interpreted cautiously, as only two eligible studies were included in the meta-analysis.

With regard to muscular fitness, CART demonstrated a substantial increase in lower body strength. However, the paucity of available data precludes the presentation of compelling evidence regarding the effectiveness of CART on muscular strength and functionality among individuals with T2DM and concurrent overweight/obesity. Nevertheless, this is an important observation given that muscular strength has been documented as a prognosticator of all-cause mortality in adults with no chronic diseases (Carbone *et al.*, 2020). Despite the absence of substantial evidence supporting the pivotal role of muscular fitness in cardiometabolic health among individuals with excessive weight, favorable changes in muscular strength have been associated with a reduced risk of cardiovascular disease in these populations (Carbone *et al.*, 2020). However, CART is in line with the current physical activity guidelines recommending the integration of cardiovascular and neuromuscular stimulus into either a single session or separate sessions weekly (Bull *et al.*, 2020). Interestingly, CART has been reported as a more effective type of exercise for improving musculoskeletal fitness-related parameters compared to aerobic, interval, or resistance training alone (Batrakoulis, 2022a).

The inclusion of the muscle-strengthening component in CART may be the factor that explains the meaningful CART-induced strength increases due to neural adaptations (Strasser, Arvandi & Siebert, 2012), increased muscle fiber activation, mitochondrial biogenesis and glucose transport commonly observed among individuals with metabolic health impairments and excessive weight (Schjerve *et al.*, 2008)

Implications for future research

Although CART appears to be a promising exercise modality for individuals with T2DM and concurrent overweight/obesity, particularly in improving various cardiovascular disease risk factors, there is a lack of strong evidence regarding its effectiveness in real-world settings. Despite recent exercise prescription guidelines for individuals with T2DM (Aschner, 2017; Colberg *et al.*, 2010; Mendes *et al.*, 2016), further studies are needed to determine the optimal training parameters, such as frequency, intensity, and duration. These studies would help guide physicians and exercise professionals in prescribing evidence-based CART programs for individuals with T2DM and overweight/obesity (Batrakoulis, Jamurtas & Fatouros, 2022). Among the 20 eligible RCTs reviewed, the most common CART protocol used either inter- or intra-session formats, typically 2–3 times per week. Circuit-based CART was also widely utilized, combining cardiorespiratory and muscle-strengthening exercises in an efficient manner. Furthermore, additional research should focus on exploring the dose-response relationship between CART and cardiometabolic health parameters, particularly in real-world exercise contexts, as previously suggested (Batrakoulis *et al.*, 2019). Such studies would help optimize the application of CART, determining whether it can serve as the most comprehensive exercise solution for individuals with poor metabolic health in everyday environments.

Limitations

Our meta-analysis has several limitations, and therefore, the results should be interpreted with caution. The included studies displayed inconsistencies in the training parameters

used during the interventions, leading to considerable heterogeneity among the studies. Additionally, the present study indicates that beneficial adaptations from CART do not occur in younger individuals, as the mean age of participants was 57 ± 7 years. Therefore, the findings cannot be generalized to younger age groups with T2DM and excess weight. Furthermore, given the outcome measures included, the role of CART in improving cardiometabolic health in this specific population remains unclear, due to the lack of data on factors such as glucose homeostasis, blood pressure, inflammation, and oxidative stress.

CONCLUSIONS

This meta-analysis provides valuable evidence on the use of CART for patients with T2DM and concurrent overweight/obesity as a supportive element in the comprehensive management of poor metabolic health. The findings offer clear evidence that CART plays a beneficial role in improving various cardiometabolic health markers, such as anthropometrics, body composition, lipid profile, fasting glucose levels, and physical function in individuals with T2DM and concomitant overweight/obesity. However, further studies with robust methodologies are needed to explore the dose-response relationship, optimal training parameters, and the mechanisms underlying these positive adaptations. This review also emphasizes the need for additional RCTs to assess more comprehensive glucose metabolism outcomes, as well as resting cardiovascular function, inflammation, and oxidative stress markers, to better understand the effects of CART in individuals with T2DM and concurrent overweight/obesity.

ADDITIONAL INFORMATION AND DECLARATIONS

Funding

The authors received no funding for this work.

Competing Interests

The authors declare that they have no competing interests.

Author Contributions

- Sameer Badri AL-Mhanna conceived and designed the experiments, prepared figures and/or tables, and approved the final draft.
- Abdullah F. Alghannam conceived and designed the experiments, prepared figures and/or tables, and approved the final draft.
- Nouf H. Alkhamees conceived and designed the experiments, prepared figures and/or tables, and approved the final draft.
- Bodor Bin Sheeha conceived and designed the experiments, prepared figures and/or tables, and approved the final draft.
- Norsuhana Omar conceived and designed the experiments, prepared figures and/or tables, and approved the final draft.
- Hani Albalawi performed the experiments, authored or reviewed drafts of the article, and approved the final draft.

- Mehmet Gülu performed the experiments, authored or reviewed drafts of the article, and approved the final draft.
- Umut Canli performed the experiments, authored or reviewed drafts of the article, and approved the final draft.
- Hafeez Abiola Afolabi performed the experiments, authored or reviewed drafts of the article, and approved the final draft.
- Bishir Daku Abubakar performed the experiments, authored or reviewed drafts of the article, and approved the final draft.
- Georgian Badicu analyzed the data, prepared figures and/or tables, and approved the final draft.
- Rozaziana Ahmad analyzed the data, prepared figures and/or tables, and approved the final draft.
- Gerasimos V. Grivas analyzed the data, prepared figures and/or tables, and approved the final draft.
- Alexios Batrakoulis analyzed the data, prepared figures and/or tables, and approved the final draft.

Data Availability

The following information was supplied regarding data availability:

This is a systematic review/meta-analysis.

Supplemental Information

Supplemental information for this article can be found online at <http://dx.doi.org/10.7717/peerj.19537#supplemental-information>.

REFERENCES

- Afolabi HA, Zakaria Z, Salleh SM, Ch'ng ES, Nafi SNM, Aziz AABA, Al-Mhanna SB, Irekeola AA, Wada Y, Daku AB. 2023. Obesity: a prerequisite for major chronic illnesses. In: *Obesity-Recent Insights and Therapeutic*. London, UK: IntechOpen.
- Al-Mhanna SB, Batrakoulis A, Mohamed M, Alkhamees NH, Sheeha BB, Ibrahim ZM, Aldayel A, Muhamad AS, Rahman SA, Afolabi HA, Zulkifli MM, Hafiz Bin Hanafi M, Abubakar BD, Rojas-Valverde D, Ghazali WSW. 2024a. Home-based circuit training improves blood lipid profile, liver function, musculoskeletal fitness, and health-related quality of life in overweight/obese older adult patients with knee osteoarthritis and type 2 diabetes: a randomized controlled trial during the COVID-19 pandemic. *BMC Sports Science, Medicine and Rehabilitation* 16(1):125 DOI 10.1186/s13102-024-00915-4.
- Al-Mhanna SB, Batrakoulis A, Wan Ghazali WS, Mohamed M, Aldayel A, Alhussain MH, Afolabi HA, Wada Y, Gulu M, Elkholi S, Abubakar BD, Rojas-Valverde D. 2024b. Effects of combined aerobic and resistance training on glycemic control, blood pressure, inflammation, cardiorespiratory fitness and quality of life in patients with type 2 diabetes and overweight/obesity: a systematic review and meta-analysis. *PeerJ* 12(1):e17525 DOI 10.7717/peerj.17525.
- Al-Mhanna SB, Franklin BA, Jakicic JM, Stamatakis E, Pescatello LS, Riebe D, Thompson WR, Skinner J, Colberg SR, Alkhamees NH, Bin Sheeha B, Gulu M, Alghannam AF, Batrakoulis A. 2025. Impact of resistance training on cardiometabolic health-related indices in patients with type 2 diabetes and overweight/obesity: a systematic review and meta-analysis of

randomised controlled trials. *British Journal of Sports Medicine* **59**(10):733–746
DOI 10.1136/bjsports-2024-108947.

Al-Mhanna SB, Ghazali WSW, Mohamed M, Rabaan AA, Santali EY, Alestad JH, Santali EY, Arshad S, Ahmed N, Afolabi HA. 2022a. Effectiveness of physical activity on immunity markers and quality of life in cancer patient: a systematic review. *PeerJ* **10**(3):e13664
DOI 10.7717/peerj.13664.

Al-Mhanna SB, Leão C, Wan GWS, Mohamed M, Batrakoulis A, Abiola AH, Daku Abubakar BI, Güllü M, Hilal YF. 2024c. Impact of exercise on high-density lipoprotein cholesterol in adults with overweight and obesity: a narrative review. *Annals of Applied Sport Science* **12**:e1300.

Al-Mhanna SB, Mohamed M, Mohd NN, Aldhahi MI, Afolabi HA, Mutalub YB, Irekeola AA, Bello KE, Wan Ghazali WS. 2022b. Effects of circuit training on patients with knee osteoarthritis: a systematic review and meta-analysis. *Healthcare* **10**:2041
DOI 10.3390/healthcare10102041.

Al-Mhanna SB, Rocha-Rodriguesc S, Mohamed M, Batrakoulis A, Aldhahi MI, Afolabi HA, Yagin FH, Alhussain MH, Güllü M, Abubakar BD, Ghazali WSW, Alghannam AF, Badicu G. 2023. Effects of combined aerobic exercise and diet on cardiometabolic health in patients with obesity and type 2 diabetes: a systematic review and meta-analysis. *BMC Sports Science, Medicine and Rehabilitation* **15**(1):165 DOI 10.1186/s13102-023-00766-5.

Al-Mhanna SB, Wan Ghazali WS, Batrakoulis A, Alkhamees NH, Drenowatz C, Mohamed M, Güllü M, Afolabi HA, Badicu G. 2024d. The impact of various types of exercise on lipid metabolism in patients with type 2 diabetes and concurrent overweight/obesity: a narrative review. *Annals of Applied Sport Science* **12**:2467–4918 DOI 10.61186/aassjournal.1324.

Albert FA, Crowe MJ, Malau-Aduli AEO, Malau-Aduli BS. 2020. Physical activity promotion: a systematic review of the perceptions of healthcare professionals. *International Journal of Environmental Research and Public Health* **17**:4358 DOI 10.3390/ijerph17124358.

American College of Sports Medicine, Liguori G, Feito Y, Fountaine C, Roy BA. 2021. *ACSM's guidelines for exercise testing and prescription*. Philadelphia, PA: Wolters Kluwer Health.

Annibalini G, Lucertini F, Agostini D, Vallorani L, Gioacchini A, Barbieri E, Guescini M, Casadei L, Passalia A, Del Sal M, Piccoli G, Andreani M, Federici A, Stocchi V. 2017. Concurrent aerobic and resistance training has anti-inflammatory effects and increases both plasma and leukocyte levels of IGF-1 in late middle-aged type 2 diabetic patients. *Oxidative Medicine and Cellular Longevity* **2017**:3937842 DOI 10.1155/2017/3937842.

Aschner P. 2017. New IDF clinical practice recommendations for managing type 2 diabetes in primary care. *Diabetes Research and Clinical Practice* **132**:169–170
DOI 10.1016/j.diabres.2017.09.002.

Batrakoulis A. 2022a. Psychophysiological adaptations to pilates training in overweight and obese individuals: a topical review. *Diseases* **10**:71 DOI 10.3390/diseases10040071.

Batrakoulis A. 2022b. Psychophysiological adaptations to yoga practice in overweight and obese individuals: a topical review. *Diseases* **10**:107 DOI 10.3390/diseases10040107.

Batrakoulis A. 2022c. Role of mind-body fitness in obesity. *Diseases* **11**:1
DOI 10.3390/diseases11010001.

Batrakoulis A, Fatouros IG. 2022. Psychological adaptations to high-intensity interval training in overweight and obese adults: a topical review. *Sports* **10**:64 DOI 10.3390/sports10050064.

Batrakoulis A, Fatouros IG, Chatzinikolaou A, Draganidis D, Georgakouli K, Papanikolaou K, Deli CK, Tsimeas P, Avloniti A, Syrou N, Jamurtas AZ. 2019. Dose-response effects of high-intensity interval neuromuscular exercise training on weight loss, performance, health and

quality of life in inactive obese adults: study rationale, design and methods of the DoIT trial. *Contemporary Clinical Trials Communications* 15(3):100386
DOI 10.1016/j.conctc.2019.100386.

Batrakoulis A, Jamurtas AZ, Fatouros IG. 2021. High-intensity interval training in metabolic diseases: physiological adaptations. *ACSM'S Health & Fitness Journal* 25(5):54–59
DOI 10.1249/fit.0000000000000703.

Batrakoulis A, Jamurtas AZ, Fatouros IG. 2022. Exercise and type II diabetes mellitus: a brief guide for exercise professionals. *Strength & Conditioning Journal* 44(6):64–72
DOI 10.1519/SSC.0000000000000731.

Batrakoulis A, Jamurtas AZ, Georgakouli K, Draganidis D, Deli CK, Papanikolaou K, Avloniti A, Chatzinikolaou A, Leontsini D, Tsimeas P, Comoutos N, Bouglas V, Michalopoulou M, Fatouros IG. 2018. High intensity, circuit-type integrated neuromuscular training alters energy balance and reduces body mass and fat in obese women: a 10-month training-detraining randomized controlled trial. *PLOS ONE* 13(8):e0202390
DOI 10.1371/journal.pone.0202390.

Batrakoulis A, Jamurtas AZ, Metsios GS, Perivoliotis K, Liguori G, Feito Y, Riebe D, Thompson WR, Angelopoulos TJ, Krstrup P, Mohr M, Draganidis D, Poullos A, Fatouros IG. 2022a. Comparative efficacy of 5 exercise types on cardiometabolic health in overweight and obese adults: a systematic review and network meta-analysis of 81 randomized controlled trials. *Circulation: Cardiovascular Quality and Outcomes* 5(6):e008243
DOI 10.1161/CIRCOUTCOMES.121.008243.

Batrakoulis A, Jamurtas AZ, Tsimeas P, Poullos A, Perivoliotis K, Syrou N, Papanikolaou K, Draganidis D, Deli CK, Metsios GS, Angelopoulos TJ, Feito Y, Fatouros IG. 2022b. Hybrid-type, multicomponent interval training upregulates musculoskeletal fitness of adults with overweight and obesity in a volume-dependent manner: a 1-year dose-response randomised controlled trial. *European Journal of Sport Science* 23(3):1–12
DOI 10.1080/17461391.2021.2025434.

Batrakoulis A, Tsimeas P, Deli CK, Vlachopoulos D, Ubago-Guisado E, Poullos A, Chatzinikolaou A, Draganidis D, Papanikolaou K, Georgakouli K, Batsilas D, Gracia-Marco L, Jamurtas AZ, Fatouros I. 2021. Hybrid neuromuscular training promotes musculoskeletal adaptations in inactive overweight and obese women: a training-detraining randomized controlled trial. *Journal of Sports Sciences* 39(5):503–512
DOI 10.1080/02640414.2020.1830543.

Bays HE, Gonzalez-Campoy JM, Bray GA, Kitabchi AE, Bergman DA, Schorr AB, Rodbard HW, Henry RR. 2008. Pathogenic potential of adipose tissue and metabolic consequences of adipocyte hypertrophy and increased visceral adiposity. *Expert Review of Cardiovascular Therapy* 6(3):343–368 DOI 10.1586/14779072.6.3.343.

Bhupathiraju SN, Hu FB. 2016. Epidemiology of obesity and diabetes and their cardiovascular complications. *Circulation Research* 118(11):1723–1735
DOI 10.1161/CIRCRESAHA.115.306825.

Bull FC, Al-Ansari SS, Biddle S, Borodulin K, Buman MP, Cardon G, Carty C, Chaput J-P, Chastin S, Chou R, Dempsey PC, Dipietro L, Ekelund U, Firth J, Friedenreich CM, Garcia L, Gichu M, Jago R, Katzmarzyk PT, Lambert E, Leitsmann M, Milton K, Ortega FB, Ranasinghe C, Stamatakis E, Tiedemann A, Troiano RP, van der Ploeg HP, Wari V, Willumsen JF. 2020. World Health Organization 2020 guidelines on physical activity and sedentary behaviour. *British Journal of Sports Medicine* 54(24):1451–1462
DOI 10.1136/bjsports-2020-102955.

- Carbone S, Kirkman DL, Garten RS, Rodriguez-Miguel P, Artero EG, Lee D-C, Lavie CJ. 2020. Muscular strength and cardiovascular disease: an updated state-of-the-art narrative review. *Journal of Cardiopulmonary Rehabilitation and Prevention* 40(5):302–309 DOI 10.1097/hcr.0000000000000525.
- Church TS, Blair SN, Cocroham S, Johannsen N, Johnson W, Kramer K, Mikus CR, Myers V, Nauta M, Rodarte RQ, Sparks L, Thompson A, Earnest CP. 2010. Effects of aerobic and resistance training on hemoglobin A1c levels in patients with type 2 diabetes: a randomized controlled trial. *The Journal of the American Medical Association* 304(20):2253–2262 DOI 10.1001/jama.2010.1710.
- Colberg SR, Sigal RJ, Fernhall B, Regensteiner JG, Blissmer BJ, Rubin RR, Chasan-Taber L, Albright AL, Braun B. 2010. Exercise and type 2 diabetes: the american college of sports medicine and the american diabetes association: joint position statement. *Diabetes Care* 33(12):e147–e167 DOI 10.2337/dc10-9990.
- Colberg SR, Sigal RJ, Yardley JE, Riddell MC, Dunstan DW, Dempsey PC, Horton ES, Castorino K, Tate DF. 2016. Physical activity/exercise and diabetes: a position statement of the american diabetes association. *Diabetes Care* 39(11):2065–2079 DOI 10.2337/dc16-1728.
- Costanzo P, Cleland JG, Pellicori P, Clark AL, Hepburn D, Kilpatrick ES, Perrone-Filardi P, Zhang J, Atkin SL. 2015. The obesity paradox in type 2 diabetes mellitus: relationship of body mass index to prognosis: a cohort study. *Annals of Internal Medicine* 162(9):610–618 DOI 10.7326/M14-1551.
- Cuff DJ, Meneilly GS, Martin A, Ignaszewski A, Tildesley HD, Frohlich JJ. 2003. Effective exercise modality to reduce insulin resistance in women with type 2 diabetes. *Diabetes Care* 26(11):2977–2982 DOI 10.2337/diacare.26.11.2977.
- de Oliveira VN, Bessa A, Jorge ML, Oliveira RJ, de Mello MT, De Agostini GG, Jorge PT, Espindola FS. 2012. The effect of different training programs on antioxidant status, oxidative stress, and metabolic control in type 2 diabetes. *Applied Physiology Nutrition Metabolism* 37(2):334–344 DOI 10.1139/h2012-004.
- Dunstan DW, Puddey IB, Beilin LJ, Burke V, Morton AR, Stanton K. 1998. Effects of a short-term circuit weight training program on glycaemic control in NIDDM. *Diabetes Research and Clinical Practice* 40(1):53–61 DOI 10.1016/s0168-8227(98)00027-8.
- Ferrer-García JC, López PS, Pablos-Abella C, Albalat-Galera R, Elvira-Macagno L, Sánchez-Juan C, Pablos-Monzó A. 2011. Benefits of a home-based physical exercise program in elderly subjects with type 2 diabetes mellitus. *Endocrinología y Nutrición (English Edition)* 58(8):387–394 DOI 10.1016/j.endoen.2011.05.007.
- Gibbs BB, Dobrosielski DA, Bonekamp S, Stewart KJ, Clark JM. 2012. A randomized trial of exercise for blood pressure reduction in type 2 diabetes: effect on flow-mediated dilation and circulating biomarkers of endothelial function. *Atherosclerosis* 224(2):446–453 DOI 10.1016/j.atherosclerosis.2012.07.035.
- Grace A, Chan E, Giallauria F, Graham PL, Smart NA. 2017. Clinical outcomes and glycaemic responses to different aerobic exercise training intensities in type II diabetes: a systematic review and meta-analysis. *Cardiovascular Diabetology* 16(1):1–10 DOI 10.1186/s12933-017-0518-6.
- Güngör AK, Topçu H, Aldhahi MI, Al-Mhanna SB, Güllü M. 2024. Resistance training to muscle failure with variable load intensities: implications for post-exercise blood pressure and heart rate variability in trained men. *Journal of Clinical Medicine* 13(8):2296 DOI 10.3390/jcm13082296.
- Hale L, Higgs C, Gray A, Mann J, Mani R, Sullivan T, Terry J, Keen D, Stokes T. 2022. The diabetes community exercise programme plus usual care versus usual care in patients with type 2

- diabetes: a randomised, two-arm, parallel, open-label trial. *EClinical Medicine* **46(1)**:101361 DOI [10.1016/j.eclinm.2022.101361](https://doi.org/10.1016/j.eclinm.2022.101361).
- Higgins JP. 2008.** Cochrane handbook for systematic reviews of interventions version 5.0.1. The Cochrane collaboration.
- Higgins JP, Thomas J, Chandler J, Cumpston M, Li T, Page MJ, Welch VA. 2019.** *Cochrane handbook for systematic reviews of interventions*. New Jersey, USA: John Wiley & Sons.
- Jamka M, Makarewicz-Bukowska A, Bokayeva K, Smidowicz A, Geltz J, Kokot M, Kaczmarek N, Zok A, Kononets V, Cielecka-Piontek J, Madry E, Walkowiak J. 2022.** Comparison of the effect of endurance, strength and endurance-strength training on glucose and insulin homeostasis and the lipid profile of overweight and obese subjects: a systematic review and meta-analysis. *International Journal of Environmental Research and Public Health* **19**:14928 DOI [10.3390/ijerph192214928](https://doi.org/10.3390/ijerph192214928).
- Jensen MD, Ryan DH, Apovian CM, Ard JD, Comuzzie AG, Donato KA, Hu FB, Hubbard VS, Jakicic JM, Kushner RF, Loria CM, Millen BE, Nonas CA, Pi-Sunyer FX, Stevens J, Stevens VJ, Wadden TA, Wolfe BM, Yanovski SZ, Jordan HS, Kendall KA, Lux LJ, Mentor-Marcel R, Morgan LC, Trisolini MG, Wnek J, Anderson JL, Halperin JL, Albert NM, Bozkurt B, Brindis RG, Curtis LH, DeMets D, Hochman JS, Kovacs RJ, Ohman EM, Pressler SJ, Sellke FW, Shen WK, Smith SC Jr., Tomaselli GF, American College of Cardiology, American Heart Association Task Force on Practice Guidelines, Obesity Society. 2014.** 2013 AHA/ACC/TOS guideline for the management of overweight and obesity in adults: a report of the American College of Cardiology/American Heart association task force on practice guidelines and the obesity society. *Circulation* **129**:S102–S138 DOI [10.1161/01.cir.0000437739.71477.ee](https://doi.org/10.1161/01.cir.0000437739.71477.ee).
- Jorge MLMP, de Oliveira VN, Resende NM, Paraiso LF, Calixto A, Diniz ALD, Resende ES, Ropelle ER, Carnevalheira JB, Espindola FS, Jorge PT, Geloneze B. 2011.** The effects of aerobic, resistance, and combined exercise on metabolic control, inflammatory markers, adipocytokines, and muscle insulin signaling in patients with type 2 diabetes mellitus. *Metabolism* **60(9)**:1244–1252 DOI [10.1016/j.metabol.2011.01.006](https://doi.org/10.1016/j.metabol.2011.01.006).
- Kadoglou N, Fotiadis G, Kapelouzou A, Kostakis A, Liapis C, Vrabas I. 2013.** The differential anti-inflammatory effects of exercise modalities and their association with early carotid atherosclerosis progression in patients with type 2 diabetes. *Diabetic Medicine* **30(2)**:e41–e50 DOI [10.1111/dme.12055](https://doi.org/10.1111/dme.12055).
- Kanaley JA, Colberg SR, Corcoran MH, Malin SK, Rodriguez NR, Crespo CJ, Kirwan JP, Zierath JR. 2022.** Exercise/physical activity in individuals with type 2 diabetes: a consensus statement from the American College of Sports medicine. *Medicine & Science in Sports & Exercise* **54(2)**:353–368 DOI [10.1249/MSS.0000000000002800](https://doi.org/10.1249/MSS.0000000000002800).
- Kelley GA, Kelley KS. 2007.** Effects of aerobic exercise on lipids and lipoproteins in adults with type 2 diabetes: a meta-analysis of randomized-controlled trials. *Public Health* **121(9)**:643–655 DOI [10.1016/j.puhe.2007.02.014](https://doi.org/10.1016/j.puhe.2007.02.014).
- Kemps H, Krankel N, Dorr M, Moholdt T, Wilhelm M, Paneni F, Serratos L, Ekker Solberg E, Hansen D, Halle M, Guazzi M. 2019.** Exercise training for patients with type 2 diabetes and cardiovascular disease: what to pursue and how to do it. A position paper of the European Association of Preventive cardiology (EAPC). *European Journal of Preventive Cardiology* **26(7)**:709–727 DOI [10.1177/2047487318820420](https://doi.org/10.1177/2047487318820420).
- Kercher VM, Kercher K, Levy P, Bennion T, Alexander C, Amaral PC, Batrakoulis A, Chávez LFJG, Cortés-Almanzar P, Haro JL, Zavalza ARP, Rodríguez LEA, Franco S, Santos-Rocha R, Ramalho F, Simões V, Vieira I, Ramos L, Veiga OL, Valcarce-Torrente M, Romero-**

- Caballero A. 2023. 2023 fitness trends from around the globe. *ACSM'S Health & Fitness Journal* 27(1):19–30 DOI 10.1249/FIT.0000000000000836.
- Kim KB, Kim K, Kim C, Kang SJ, Kim HJ, Yoon S, Shin YA. 2019. Effects of exercise on the body composition and lipid profile of individuals with obesity: a systematic review and meta-analysis. *Journal of Obesity & Metabolic Syndrome* 28(4):278–294 DOI 10.7570/jomes.2019.28.4.278.
- Lambers S, Van Laethem C, Van Acker K, Calders P. 2008. Influence of combined exercise training on indices of obesity, diabetes and cardiovascular risk in type 2 diabetes patients. *Clinical Rehabilitation* 22(6):483–492 DOI 10.1177/0269215508084582.
- Loimaala A, Huikuri HV, Koobi T, Rinne M, Nenonen A, Vuori I. 2003. Exercise training improves baroreflex sensitivity in type 2 diabetes. *Diabetes* 52(7):1837–1842 DOI 10.2337/diabetes.52.7.1837.
- Magalhães JP, Júdice PB, Ribeiro R, Andrade R, Raposo J, Dores H, Bicho M, Sardinha LB. 2019. Effectiveness of high-intensity interval training combined with resistance training versus continuous moderate-intensity training combined with resistance training in patients with type 2 diabetes: a one-year randomized controlled trial. *Diabetes, Obesity and Metabolism* 21(3):550–559 DOI 10.1111/dom.13551.
- Magalhães JP, Santos DA, Correia IR, Hetherington-Rauth M, Ribeiro R, Raposo JF, Matos A, Bicho MD, Sardinha LB. 2020. Impact of combined training with different exercise intensities on inflammatory and lipid markers in type 2 diabetes: a secondary analysis from a 1-year randomized controlled trial. *Cardiovascular Diabetology* 19:1–11 DOI 10.21203/rs.3.rs-36837/v2.
- Maiorana A, O'Driscoll G, Goodman C, Taylor R, Green D. 2002. Combined aerobic and resistance exercise improves glycemic control and fitness in type 2 diabetes. *Diabetes Research and Clinical Practice* 56(2):115–123 DOI 10.1016/s0168-8227(01)00368-0.
- McAuley PA, Blaha MJ, Keteyian SJ, Brawner CA, Al Rifai M, Dardari ZA, Ehrman JK, Al-Mallah MH. 2016. Fitness, fatness, and mortality: the FIT (Henry ford exercise testing) project. *The American Journal of Medicine* 129(9):960–965 e961 DOI 10.1016/j.amjmed.2016.04.007.
- Mendes R, Sousa N, Almeida A, Subtil P, Guedes-Marques F, Reis VM, Themudo-Barata JL. 2016. Exercise prescription for patients with type 2 diabetes-a synthesis of international recommendations: narrative review. *British Journal of Sports Medicine* 50(22):1379–1381 DOI 10.1136/bjsports-2015-094895.
- Moore KJ, Shah R. 2020. Introduction to the obesity, metabolic syndrome, and CVD compendium. *Circulation Research* 126(11):1475–1476 DOI 10.1161/circresaha.120.317240.
- Motahari Rad M, Bijeh N, Attarzadeh Hosseini SR, Raouf Saeb A. 2023. The effect of two concurrent exercise modalities on serum concentrations of FGF21, irisin, follistatin, and myostatin in men with type 2 diabetes mellitus. *Archives of Physiology and Biochemistry* 129(2):424–433 DOI 10.1080/13813455.2020.1829649.
- Murlasits Z, Kneffel Z, Thalib L. 2018. The physiological effects of concurrent strength and endurance training sequence: a systematic review and meta-analysis. *Journal of Sports Sciences* 36(11):1212–1219 DOI 10.1080/02640414.2017.1364405.
- Nery C, De Moraes SRA, Novaes KA, Bezerra MA, Silveira PVDC, Lemos A. 2017. Effectiveness of resistance exercise compared to aerobic exercise without insulin therapy in patients with type 2 diabetes mellitus: a meta-analysis. *Brazilian Journal of Physical Therapy* 21(6):400–415 DOI 10.1016/j.bjpt.2017.06.004.
- O'Donoghue G, Blake C, Cunningham C, Lennon O, Perrotta C. 2021. What exercise prescription is optimal to improve body composition and cardiorespiratory fitness in adults

living with obesity? A network meta-analysis. *Obesity Reviews* 22(2):e13137 DOI 10.1111/obr.13137.

- Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, Shamseer L, Tetzlaff JM, Akl EA, Brennan SE, Chou R, Glanville J, Grimshaw JM, Hrobjartsson A, Lalu MM, Li T, Loder EW, Mayo-Wilson E, McDonald S, McGuinness LA, Stewart LA, Thomas J, Tricco AC, Welch VA, Whiting P, Moher D. 2021. The PRISMA, 2020 statement: an updated guideline for reporting systematic reviews. *BMJ* 372:n71 DOI 10.1136/bmj.n71.
- Pan B, Ge L, Xun YQ, Chen YJ, Gao CY, Han X, Zuo LQ, Shan HQ, Yang KH, Ding GW, Tian JH. 2018. Exercise training modalities in patients with type 2 diabetes mellitus: a systematic review and network meta-analysis. *International Journal of Behavioral Nutrition and Physical Activity* 15(1):72 DOI 10.1186/s12966-018-0703-3.
- Pataky Z, Armand S, Muller-Pinget S, Golay A, Allet L. 2014. Effects of obesity on functional capacity. *Obesity (Silver Spring)* 22(1):56–62 DOI 10.1002/oby.20514.
- Pesta DH, Goncalves RLS, Madiraju AK, Strasser B, Sparks LM. 2017. Resistance training to improve type 2 diabetes: working toward a prescription for the future. *Nutrition & Metabolism (London)* 14(1):24 DOI 10.1186/s12986-017-0173-7.
- Qadir R, Sculthorpe NF, Todd T, Brown EC. 2021. Effectiveness of resistance training and associated program characteristics in patients at risk for type 2 diabetes: a systematic review and meta-analysis. *Sports Medicine—Open* 7(1):38 DOI 10.1186/s40798-021-00321-x.
- Sabag A, Keating SE, Way KL, Sultana RN, Lanting SM, Twigg SM, Johnson NA. 2021. The association between cardiorespiratory fitness, liver fat and insulin resistance in adults with or without type 2 diabetes: a cross-sectional analysis. *BMC Sports Science, Medicine and Rehabilitation* 13(1):40 DOI 10.1186/s13102-021-00261-9.
- Sabag A, Way KL, Keating SE, Sultana RN, O'Connor HT, Baker MK, Chuter VH, George J, Johnson NA. 2017. Exercise and ectopic fat in type 2 diabetes: a systematic review and meta-analysis. *Diabetes & Metabolism* 43(3):195–210 DOI 10.1016/j.diabet.2016.12.006.
- Sabouri M, Hatami E, Pournemati P, Shabkhiz F. 2021. Inflammatory, antioxidant and glycemic status to different mode of high-intensity training in type 2 diabetes mellitus. *Molecular Biology Reports* 48(6):5291–5304 DOI 10.1007/s11033-021-06539-y.
- Scheer AS, Naylor LH, Gan SK, Charlesworth J, Benjanuvatra N, Green DJ, Maiorana AJ. 2020. The effects of water-based exercise training in people with type 2 diabetes. *Medicine & Science in Sports & Exercise* 52(2):417–424 DOI 10.1249/mss.0000000000002133.
- Schjerve IE, Tyldum GA, Tjønnå AE, Stølen T, Loennechen JP, Hansen HE, Haram PM, Heinrich G, Bye A, Najjar SM, Smith GL, Slørdahl SA, Kemi OJ, Wisløff U. 2008. Both aerobic endurance and strength training programmes improve cardiovascular health in obese adults. *Clinical Science* 115(9):283–293 DOI 10.1042/cs20070332.
- Sigal RJ, Kenny GP, Boule NG, Wells GA, Prud'homme D, Fortier M, Reid RD, Tulloch H, Coyle D, Phillips P, Jennings A, Jaffey J. 2007. Effects of aerobic training, resistance training, or both on glycemic control in type 2 diabetes: a randomized trial. *Annals of Internal Medicine* 147(6):357–369 DOI 10.7326/0003-4819-147-6-200709180-00005.
- Strasser B, Arvandi M, Siebert U. 2012. Resistance training, visceral obesity and inflammatory response: a review of the evidence. *Obesity Reviews* 13(7):578–591 DOI 10.1111/j.1467-789x.2012.00988.x.
- Swift DL, Johannsen NM, Earnest CP, Blair SN, Church TS. 2012. The effect of exercise training modality on C-reactive protein in type-2 diabetes. *Medicine and Science in Sports and Exercise* 44(6):1028–1034 DOI 10.1249/mss.0b013e31824526cc.

- Tan J, Krasilshchikov O, Kuan G, Hashim HA, Aldhahi MI, Al-Mhanna SB, Badicu G. 2023.** The effects of combining aerobic and heavy resistance training on body composition, muscle hypertrophy, and exercise satisfaction in physically active adults. *Healthcare* **11**(17):2443 DOI [10.3390/healthcare11172443](https://doi.org/10.3390/healthcare11172443).
- Tan S, Li W, Wang J. 2012.** Effects of six months of combined aerobic and resistance training for elderly patients with a long history of type 2 diabetes. *Journal of Sports Science & Medicine* **11**(3):495–501.
- Tessier D, Ménard J, Fülöp T, Ardilouze J-L, Roy M-A, Dubuc N, Dubois M-F, Gauthier P. 2000.** Effects of aerobic physical exercise in the elderly with type 2 diabetes mellitus. *Archives of Gerontology and Geriatrics* **31**(2):121–132 DOI [10.1016/s0167-4943\(00\)00076-5](https://doi.org/10.1016/s0167-4943(00)00076-5).
- Tremmel M, Gerdtham UG, Nilsson PM, Saha S. 2017.** Economic burden of obesity: a systematic literature review. *International Journal of Environmental Research and Public Health* **14**:435 DOI [10.3390/ijerph14040435](https://doi.org/10.3390/ijerph14040435).
- Umpierre D, Ribeiro PA, Kramer CK, Leitao CB, Zucatti AT, Azevedo MJ, Gross JL, Ribeiro JP, Schaan BD. 2011.** Physical activity advice only or structured exercise training and association with HbA1c levels in type 2 diabetes: a systematic review and meta-analysis. *The Journal of the American Medical Association* **305**(17):1790–1799 DOI [10.1001/jama.2011.576](https://doi.org/10.1001/jama.2011.576).
- Warburton DE, Gledhill N, Quinney A. 2001.** Musculoskeletal fitness and health. *Canadian Journal of Applied Physiology* **26**(2):217–237 DOI [10.1139/h01-013](https://doi.org/10.1139/h01-013).
- Yang Z, Scott CA, Mao C, Tang J, Farmer AJ. 2014.** Resistance exercise versus aerobic exercise for type 2 diabetes: a systematic review and meta-analysis. *Sports Medicine* **44**(4):487–499 DOI [10.1007/s40279-013-0128-8](https://doi.org/10.1007/s40279-013-0128-8).
- Yapici H, Güllü M, Yagin FH, Ugurlu D, Comertpay E, Eroglu O, Kocoğlu M, Aldhahi MI, Karayigit R, Badri AL-Mhanna S. 2023.** The effect of 8-weeks of combined resistance training and chocolate milk consumption on maximal strength, muscle thickness, peak power and lean mass, untrained, university-aged males. *Frontiers in Physiology* **14**:1148494 DOI [10.3389/fphys.2023.1148494](https://doi.org/10.3389/fphys.2023.1148494).
- Yavari A, Najafipoor F, Aliasgarzadeh A, Niafar M, Mobasser M. 2012.** Effect of aerobic exercise, resistance training or combined training on glycaemic control and cardio-vascular risk factors in patients with type 2 diabetes. *Biology of Sport* **29**(2):135–143.
- Zarei M, Nakhzari Khodakheyr J, Rashidlamir A, Montazeri A. 2021.** The effect of combined resistance aerobic exercise training on concentrations of asprosin and complement C1q tumor necrosis factor-related protein-1 in men with type 2 diabetes. *Sport Sciences for Health* **17**(4):863–871 DOI [10.1007/s11332-021-00738-7](https://doi.org/10.1007/s11332-021-00738-7).
- Zhao X, He Q, Zeng Y, Cheng L. 2021.** Effectiveness of combined exercise in people with type 2 diabetes and concurrent overweight/obesity: a systematic review and meta-analysis. *BMJ Open* **11**(10):e046252 DOI [10.1136/bmjopen-2020-046252](https://doi.org/10.1136/bmjopen-2020-046252).
- Zou Z, Cai W, Cai M, Xiao M, Wang Z. 2016.** Influence of the intervention of exercise on obese type II diabetes mellitus: a meta-analysis. *Primary Care Diabetes* **10**(3):186–201 DOI [10.1016/j.pcd.2015.10.003](https://doi.org/10.1016/j.pcd.2015.10.003).