



Review Article

Exercise-induced inflammatory and metabolic adaptations in ageing: A meta-analytic compendium

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ABSTRACT

Background: The relationship between metabolic and inflammatory adaptations with exercise training is poorly quantified. We employed a novel meta-analytical approach to provide an evidence-based framework to guide exercise prescription for health in older adults.

Methods: This systematic review (PROSPERO: CRD42025630662) identified controlled exercise training interventions in older adults. We meta-analysed 146 studies assessing body mass, BMI, fat mass, muscle mass, circulating CRP, IL-6, TNF- α , adiponectin, leptin, IGF-1, IL-1 β , fasting glucose, insulin, glycated haemoglobin, HOMA-IR, TG, total cholesterol, LDL-C, HDL-C, and VO₂ max. Our novel analytical approach divided studies into “improved” or “not improved” for each variable based on the significant direction of their standardised mean difference (95% CI), followed by a cross-over subgroup analysis.

Results: Meta-analyses showed that exercise training improved all outcomes, except for IL-1 β . Aerobic training showed the greatest overall benefits—except for IGF-1—while resistance training improved most markers but did not reduce body mass and IL-6. A frequency of at least 3 sessions per week was necessary to reduce body mass, insulin, HOMA-IR, triglycerides, total cholesterol, IL-6, TNF- α , leptin, and to increase adiponectin and IGF-1. Shorter interventions (< 12 weeks) led to greater increases in adiponectin and IGF-1 and stronger reductions

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in TNF- α and IL-1 β , suggesting a transient response. Women, unhealthy individuals, and those who were overweight or obese exhibited greater improvements than their counterparts. Anti-inflammatory effects were more pronounced when accompanied by decreases in body mass, fat mass, and improved glucose and lipid metabolism, but was not dependent on those changes.

Conclusion: Aerobic training is the most effective intervention, followed by resistance training, and at least 3 sessions per week (or twice a week for more than 24 weeks) are needed for metabolic and anti-inflammatory adaptations. This compendium provides a reference point for personalised exercise plans for treatment and prevention of chronic diseases—especially for older adults with metabolic conditions.

1. Introduction

Low-grade chronic inflammation is associated with several age-related diseases including cancer, diabetes mellitus, chronic kidney disease, non-alcoholic fatty liver disease, autoimmune, and neurodegenerative conditions (Roth et al., 2018), contributing to morbidity and mortality worldwide (Kaptoge et al., 2010). The effects of obesity and metabolic syndrome in the same chronic conditions are difficult to distinguish, since metabolic dysfunction and low-grade chronic inflammation are strongly dependent on each other (Schleh et al., 2023). Indeed, the central role of the immune system in regulating metabolism stems from the importance of meeting the energy requirements during an acute immune response (Kotas and Medzhitov, 2015; Straub et al., 2010, 2015; Straub and Schradin, 2016). An immune response triggers various behavioural and physiological changes such as fatigue and social-behaviour withdrawal, as well as insulin resistance and dyslipidaemia to preserve energy for immune cells (Straub et al., 2010; Straub, 2017). However, with ageing and overnutrition, the immune system can become chronically activated – manifesting as inflammation – which drives metabolic dysfunction (Furman et al., 2019).

Currently, it is known that there is a bidirectional relationship between low-grade chronic inflammation and metabolic dysfunction, thus it is believed that by preventing or treating one state we may improve the other, and potentially improve associated disease conditions. In 1993, the elevated production of Tumour Necrosis Factor alpha (TNF- α) by the adipose tissue of obese and diabetic mice, was identified as an important source of insulin resistance (Hotamisligil et al., 1993). In humans, the treatment of rheumatoid arthritis, an auto-immune condition, with a TNF- α inhibitor, improves insulin sensitivity and reduces risk of Alzheimer's disease (Burska et al., 2015). On the other hand, it is well known that drugs interfering with the lipid or glycaemic profile, such as statins and metformin, respectively, have anti-inflammatory properties (Katsiki and Mikhailidis, 2021; Pernicova et al., 2020). In this scenario, exercise training emerges as a powerful lifestyle intervention, reducing inflammation (Sardeli et al., 2018; Khalafi et al., 2023; Xing et al., 2022), improving glucose utilisation (Feng et al., 2025) and lipid metabolism (Kelley et al., 2005; Palazón-Bru et al., 2021); as well as systemic metabolism (Ross et al., 2019). Exercise is often considered to be a “polypill” treatment, and although it cannot replace some therapeutics, such as drugs for cholesterol control (Fiuza-Luces et al., 2013), exercise often outperforms drug treatment for the prevention and treatment of type 2 diabetes and lowering blood pressure (in hypertensive individuals) (Fiuza-Luces et al., 2013). Similarly to many drugs, the molecular mechanisms underlying the effects of exercise are not completely understood and researchers have long sought to identify a single biological factor that could mimic the benefits of exercise training (Katz et al., 2025). To this end, interleukin-6 (IL-6) has received significant interest (Pedersen et al., 2003; Wedell-Neergaard et al., 2019), since it was first discovered that contracting human skeletal muscles can account for the exercise-induced increase in plasma IL-6 (Steensberg et al., 2000). It is now known that muscle-derived IL-6 acts as an endocrine signal that enhances glucose uptake and fatty acid oxidation in skeletal muscle, stimulates hepatic glucose production, and promotes lipolysis in adipose tissue, thereby coordinating energy metabolism during exercise (Wedell-Neergaard

et al., 2019; Lang Lehrslov et al., 2018; Pedersen, 2019; Bay and Pedersen, 2020). Although the reduction in body weight also has a wide range of benefits (Ma et al., 2017), there is robust evidence that maintaining systemic fitness, even in the presence of obesity, is sufficient to lower mortality risks similar to that of a normal-weight individual (Barry et al., 2014).

Our search across six databases identified 28 systematic reviews documenting the role of exercise training in inflammatory and metabolic processes. However, none of these reviews investigated the interaction between those adaptations via meta-analysis. Therefore, in the present study, we focused on older adults (over 50 years) with any health status and analysed the most common circulating markers that participate in inflammatory processes, as well as adaptations related to metabolic responses, such as body composition, lipid and glucose metabolism, and maximal oxygen consumption (VO₂ max). Briefly, C-reactive protein (CRP) is an acute-phase protein induced by IL-6 that promotes complement activation and reflects systemic inflammation. IL-6 acts both as a pro-inflammatory cytokine and a myokine that enhances glucose and lipid metabolism during exercise, while TNF- α drives inflammation, insulin resistance, and endothelial dysfunction. Adiponectin improves insulin sensitivity and fatty acid oxidation, whereas leptin regulates appetite, energy balance, and immune function. Insulin-like growth factor 1 (IGF-1) supports anabolic processes and insulin sensitivity, and interleukin-1 β (IL-1 β) mediates fever and tissue inflammation (Pedersen and Febbraio, 2012). Triglycerides (TG) represent fat storage and cardiovascular risk, total cholesterol (TChol) reflects overall lipid content, HDL-C facilitates reverse cholesterol transport and protects vessels, while LDL-C delivers cholesterol to tissues and contributes to atherosclerosis. Fasting glucose and HbA1c indicate short- and long-term glycaemic control, fasting insulin and HOMA-IR estimate insulin resistance (Grundy et al., 2018; Committee et al., 2024), and VO₂ max measures maximal oxygen uptake, reflecting overall cardiorespiratory fitness (Bassett and Howley, 2000). Rather than classifying these candidate adaptation markers strictly as metabolic or inflammatory, we investigated the interactions between them in the context of exercise training. We acknowledge that several markers are well-known to participate in both inflammatory and metabolic process (e.g., IL-6, adiponectin, leptin, IGF-1) (Bay and Pedersen, 2020; Wolters et al., 2017), and are purported to be central mediators of organ cross-talk.

We leveraged the large number of controlled trials, examining the effects of exercise training on inflammatory and metabolic markers in older adults, to test the association among these adaptations using a novel meta-analytical approach. This approach generated a compendium of interactions drawn from controlled studies, providing a valuable resource for researchers to examine a wide array of confounding factors. Our approach highlights the interdependence between exercise adaptations that will pave the way for future research. For example, to illustrate the translatable applicability of this compendium, in older adults we identified that while a significant increase in muscle mass is not needed for exercise-induced anti-inflammatory effects, a reduction in fat mass led to a larger reduction in CRP, IL-6 and leptin, and was necessary to increase adiponectin. In this example, each of these analyses were based on at least 30 controlled trials, reinforcing the robustness of this compendium and the potential to inform future

research questions.

2. Methods

2.1. Search strategy and selection criteria

The present systematic review with meta-analyses is reported following the PRISMA guidelines (Page et al., 2021) and the PRISMA checklist is provided in Supplementary Table 1. The PICO inclusion criteria were men or women older than 50 years (study average), testing the effects of exercise training intervention(s), compared to a control group (no exercise), on at least one inflammatory marker and one metabolic marker. We included only studies published in peer-reviewed scientific journals in English language, with no restriction regarding the date of publication.

Studies were excluded if they included participants below 40 years and if the type of exercise could not be classified as aerobic, resistance or combined (aerobic and resistance), such as yoga, tai chi, vibration or sports training. Studies (or subgroups of studies) were excluded if they had an additional intervention (besides exercise) in the control group but not in the intervention group, or vice versa, that would not allow isolation of the exercise training effect.

The search was performed in PubMed (MEDLINE), Embase, Web of Science, Scopus, Cochrane CENTRAL, and EBSCOhost, on 5th August 2024. The search combined a comprehensive list of synonyms for inflammatory markers, metabolic markers, exercise and ageing, detailed on the full protocol (PROSPERO: CRD42025630662) Supplementary material. Title/abstract and full-text screening were performed independently by two reviewers using Covidence. Conflicts were resolved by discussion. The risk of bias of primary studies was assessed independently by two reviewers using the PEDro scale, in which 10 is the best score, within a panel of items including randomisation, maintenance of randomised balance between groups, concealed allocation, comparability at baseline, blinding of subjects, therapists and assessors, and analysis completion (Maher et al., 2003).

The certainty of evidence was assessed via GRADE approach (Atkins et al., 2004). The assessment of risk of bias, inconsistency of the results (heterogeneity), indirectness of evidence, imprecision, and publication bias determined the final score of very low, low, moderate or high quality of evidence.

2.2. Data analysis

Data extraction and risk of bias assessment were performed using Microsoft Excel by two independent reviewers (RS, AG, AY, JT, MA, PRHJ, KV, NSMS, OJ, TB, MSHU). Conflicts were resolved by a third

reviewer, with all extracted data verified by RS. The mean, standard deviation (SD) and sample size (n) for each subgroup and outcome variable were extracted for analysis. Where outcomes were reported at multiple time points, the longest time point for the training duration was extracted. Secondary data were collected for subgroup analysis: population baseline characteristics (age, sex, disease status, baseline BMI) and exercise protocols (exercise type [aerobic, resistance, or combined], frequency, duration), quality control variables (time since last meal and exercise prior to blood sampling, PEDro score). Data in studies that was not presented as mean and standard deviation (SD), were converted for analysis. The standard error (SE) was converted to SD ($SD = SE \times (\sqrt{n})$). When median and interquartile range (IQR) were reported, the median was accepted as the mean and SD was estimated ($SD = (IQR/1.35)$) (Hozo et al., 2005). When numerical data were not available, graphical data were extracted from the image pixels and converted using Auto-meris (Rohatgi, 2021), in which the average of three recordings for each data point was used for analysis. If none of these options were available, the authors of the studies were contacted via e-mail.

The standardised mean difference and 95 % CI was calculated between intervention and control for all the outcomes (CRP, IL-6, TNF- α , adiponectin, leptin, IGF-1, IL-1 β , body mass, BMI, fat mass, muscle mass, fasting glucose, glycated haemoglobin, fasting insulin, HOMA-IR, TG, TChol, HDL-C, LDL-C, and VO₂ max) and for body mass (kg) and BMI (kg/m²) raw mean difference and 95 % CI was also calculated for their overall meta-analysis. A conservative pre-post correlation of 0.5 was assumed (Borenstein et al., 2021). For the calculation of summarised effects in the overall meta-analyses, studies were weighted using the inverse-variance method under a random effects model, that included the within studies variance and between studies variances. Publication bias was analysed using Egger's test and a p-value of 5 % ($p < 0.05$) was considered significant (Egger et al., 1997).

The central aim of this study was to investigate the association and interaction between metabolic and inflammatory adaptations with exercise training. Therefore, all studies were divided between improved or not improved, for each variable, according to the significance and direction of their standardised mean difference (95 % CI), for subgroup analyses. Fig. 1 shows the data-analysis pipeline. For example, we tested whether the effects of exercise training on reducing CRP levels were higher in subgroups of studies that significantly reduced body fat or not, and we repeated this type of analysis for each of the 19 remaining outcomes. Subgroup analyses were also performed for other confounding factors, such as exercise protocol (type of training, weekly frequency, length of intervention, training intensity, protocols meeting guidelines) and participants' characteristics (age, sex, presence of type 2 diabetes, overall health status, BMI category). Sensitivity analyses for the following quality control measures were performed: studies scoring

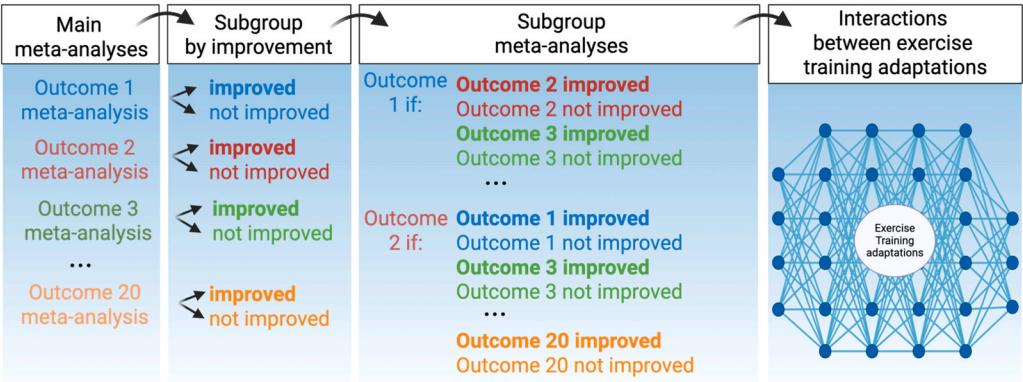


Fig. 1. Data analysis pipeline. This novel meta-analytical approach model was applied for the 20 outcomes: CRP, IL-6, TNF- α , adiponectin, leptin, IGF-1, IL-1 β , body mass, BMI, fat mass, muscle mass, fasting glucose, glycated haemoglobin, fasting insulin, HOMA-IR, Total cholesterol, HDL-Cholesterol, LDL-Cholesterol, Triglycerides, and VO₂ max.

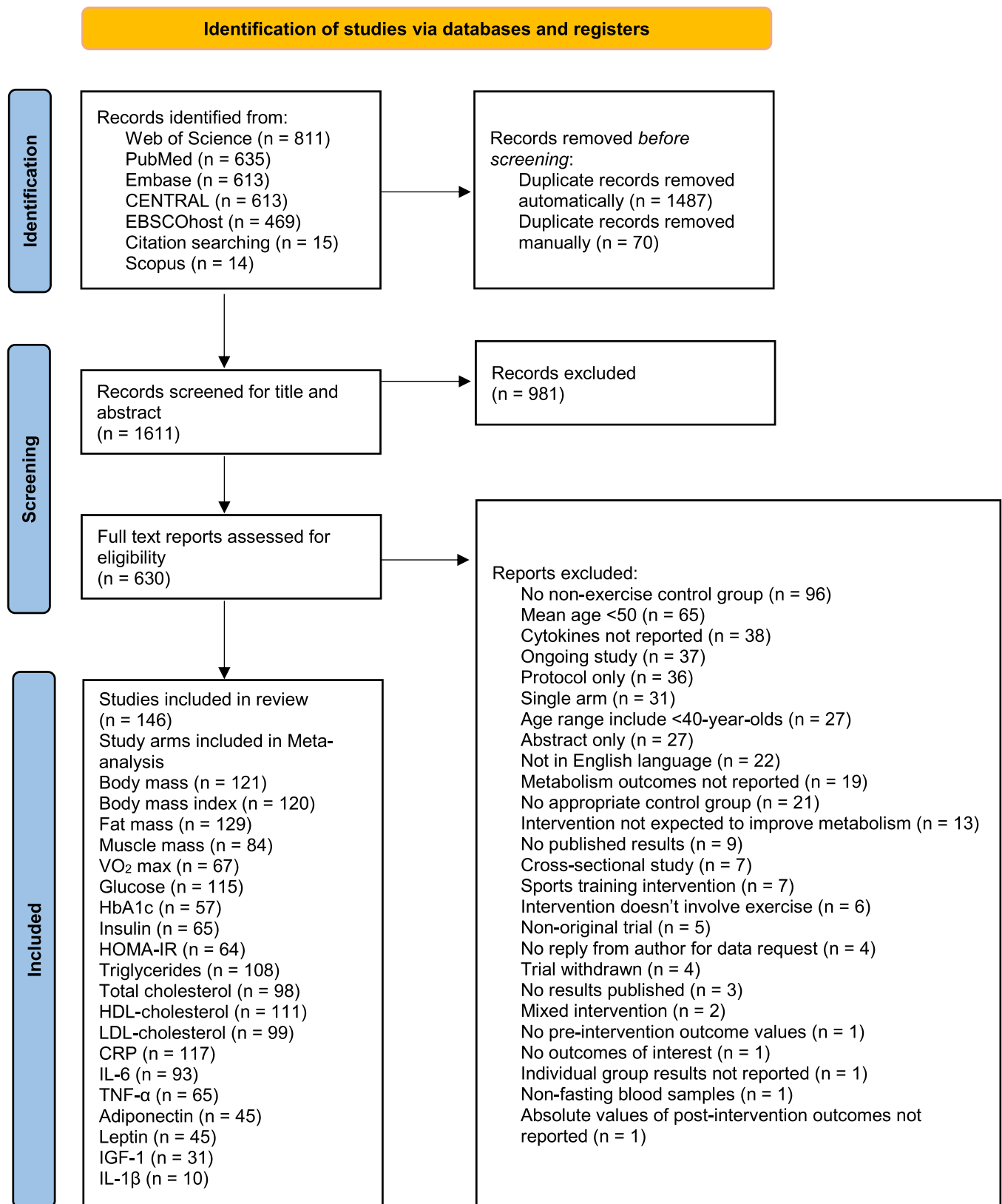


Fig. 2. Flowchart of the selection of the studies. CENTRAL, Cochrane Central Register of Controlled Trials; CRP, C-Reactive Protein; HbA1c, Glycated haemoglobin; HDL, High-density lipoprotein; IGF-1, Insulin-like growth factor 1; IL-1β, Interleukin 1 beta; IL-6, Interleukin 6; LDL, Low-density lipoprotein; TNF-α, Tumour necrosis factor alpha.

Table 1
Characteristics of the studies included.

Author, year (Subgroup)	Sample size	Health status	Age (mean ± SD)	Type of training: number of exercises; muscle groups; equipment/accessories; volume (sets and repetitions or duration); intensity	Duration of each session (time)	Days per week and total number of weeks	Control group activities
Annibalini, 2017	16 F	Type 2 diabetes	Ex: 57 ± 9.1/Con: 60 ± 6.8	RT: 4 ex; whole body; 2–4 sets × 10–12 reps/machine; 40–60 % 1RM; AT: walking; 40–65 % HRR	Walking (30–60 min)	3 d for 16 wk	Non-exercise
Astengo, 2010	17 F/45 M	Stable angina	Ex: 62 ± 7/Con: 65 ± 8	RT: whole body; elastic bands AT: Cycle ergometer; 70 % max capacity	36 (SD 12) mins	5 d for 36 wk	Non-exercise
Azali Alamadari, 2016	30 M	Metabolic syndrome	Ex: 57.93 ± 5.14/Con: 55.78 ± 5.36	AT: walking; 25–40 min; AT: Running; 50–60 % VO ₂ max	120 min	3 d for 8 wk	Non-exercise
Azamian Jazi, 2022	35 F	Older adults	Ex: 73.29 ± 5.44/Con: 74.79 ± 3.87	RT: elastic band; whole body; 1–3 sets × 8–12 reps; Borg RPE 12–14	55 mins	3 d for 12 wk	Non-exercise
Bagheri, 2021	30 F	Postmenopausal women	Overall: 56 ± 3.7	RT: 7 ex; whole body; wk 1–4: 3 sets × 12 reps; 60–65 % of 1RM; wk 5–8: 4 sets × 10 reps (70–75 %) of 1RM	60 min	3 d for 8 wk	Non-exercise
Balducci, 2010 (AT)	17 F/23 M	Type 2 diabetes + metabolic syndrome	Ex: 64.3 ± 8.1/Con: 61.1 ± 7.1	AT: treadmill/cycle ergometer; 70–80 % VO ₂ max; 60 min	60 min	2 d for 48 wk	Sedentary
Balducci, 2010 (CT)	17 F/25 M	Type 2 diabetes + metabolic syndrome	Ex: 60.6 ± 9.3/Con: 61.1 ± 7.1	RT: 4 ex; whole body; 80 % 1RM AT: treadmill/cycle ergometer; 70–80 % VO ₂ max; 40 min 3 stretching positions	60 min	2 d for 48 wk	Sedentary
Balducci, 2012	33 F/40 M	Type 2 diabetes	Ex: 59.6 ± 8.7/Con: 61.6 ± 7.8	RT: 4 ex; major muscle groups; HI group 3 sets × 8 reps at 80 % 1RM; LI group 2 sets × 15 reps at 60 % 1RM AT: HI group 70 % VO ₂ max; LI group 55 % VO ₂ max	75 min	2 d for 48 wk	Non-exercise
Bang, 2023 (Ascend-set RT)	16 F	Obesity	Ex: 59.37 ± 3.2/Con: 60.62 ± 2.77	RT: 8 ex; major muscle groups; 4 sets × 8–12 reps; 40–60 % 1RM (ascend set)	60 min	5 d for 12 wk	Non-exercise
Bang, 2023 (Descend-set)	15 F	Obesity	Ex: 59.42 ± 2.57/Con: 60.62 ± 2.77	RT: 8 ex; major muscle groups; 4 sets × 8–12 reps; 40–60 % 1RM (descend set)	60 min	5 d for 12 wk	Non-exercise
Bang, 2023 (Drop-set RT)	16 F	Obesity	Ex: 60.0 ± 2.97/Con: 60.62 ± 2.77	RT: 8 ex; major muscle groups; 4 sets × 8–12 reps; 40–65 % 1RM (drop set)	60 min	5 d for 12 wk	Non-exercise
Banitalebi, 2019 (CT)	35 F	Type 2 diabetes	Ex: 54.14 ± 5.43/Con: 55.71 ± 6.4	RT: 5 ex; whole body; 1–3 sets × 10–15 reps; max reps AT: treadmill/cycle ergometer; 50–70 % HR max	50 min	3 d for 10 wk	Diabetes self-management
Banitalebi, 2019 (SIT)	35 F	Type 2 diabetes	Ex: 55.36 ± 5.94/Con: 55.71 ± 6.4	AT: cycle ergometer; 4 × 30 s max intervals; 120 rpm; 2 min active recovery	50 min	3 d for 10 wk	Non-exercise
Banitalebi, 2020	63 F	Osteosarcopenic obesity	Ex: 64.11 ± 3.81/Con: 64.05 ± 3.35	RT: Thera-Band (elastic band); whole body; 1–2 ex; 1–2 sets × 12–20 reps	70 min	3 d for 12 wk	Non-exercise
Barcellos, 2018	95 F/55 M	Hypertension + chronic kidney disease	Ex: 65.0 ± 1.2/Con: 65.1 ± 1.3	RT: 7 ex; whole body; 2–6 sets AT: Step aerobics; interval training (30'–1' work/rest)	60 min	3 d for 16 wk	Non-exercise
Bergström, 2009	112 F	Postmenopausal + borderline overweight	Ex: 58.8 ± 4.2/Con: 59.4 ± 3.6	AT: Walking; 30 min aerobic session; self-paced intensity (0–3 walks/wk and 1–2 aerobic sessions/wk)	30 min walk + 60–120 min Aerobic	Varied frequency for 48 wk	Normal physical activity
Bhati, 2023	24 F/32 M	Type 2 diabetes	Ex: 52.8 ± 6.82/Con: 54.0 ± 8.18	RT: 10 ex; whole body; 2–3 sets × 8–12 reps; 65–75 % 1RM AT: cycling; self-paced; 10 min	50 min	3 d for 12 wk	Non-exercise
Biesek, 2021 (Exergames)	36 F	Prefrail older adults	Ex: 71.7 ± 4.8/Con: 73.1 ± 5.3	RT: exergames (weighted vest) on balance platform; whole body; progressive load (5 % body mass + 1–2 % biweekly)	50 min	2 d for 12 wk	Protein supplementation
Biesek, 2021 (Exergames + protein)	36 F	Prefrail older adults	Ex: 71.2 ± 4.2/Con: 70.4 ± 3.9	RT: exergames (weighted vest) on balance platform; whole body; progressive load (5 % body mass + 1–2 % biweekly)	50 min	2 d for 12 wk	Usual activity
Billinska, 2010	120 M	After coronary artery bypass graft surgery	Ex: 53.9 ± 5/Con: 54.1 ± 5.8	AT: cycle ergometer; interval training (4 min work/2 min rest); 70–80 % HR max	60 min	3 d for 6 wk	Non-exercise
Bouchonville, 2014 (CT)	34 F/19 M	Obesity	Ex: 70 ± 4/Con: 69 ± 4	RT: 9 ex; upper/lower extremities ex; 1–2 sets × 6–12 reps; 65–85 % 1RM AT: Treadmill/cycling/stairs; 65–85 % HR max	90 min	3 d for 48 wk	Non-exercise
Bouchonville, 2014 (CT + CR)	33 F/21 M	Obesity	Ex: 70 ± 4/Con: 70 ± 4	RT: 9 ex; upper/lower extremities ex; 1–2 sets × 6–12 reps; 65–85 % 1RM AT: Treadmill/cycling/stairs; 65–85 % HR max	90 min	3 d for 48 wk	Balanced diet 500–750 kcal deficit
Brooks, 2007	22 F/40 M	Type 2 diabetes	Ex: 66 ± 2/Con: 66 ± 1	RT: 5 ex; upper/lower body; 3 sets × 8 reps; 60–80 % 1RM	35 min	3 d for 16 wk	Standard care

(continued on next page)

Table 1 (continued)

Author, year (Subgroup)	Sample size	Health status	Age (mean ± SD)	Type of training: number of exercises; muscle groups; equipment/accessories; volume (sets and repetitions or duration); intensity	Duration of each session (time)	Days per week and total number of weeks	Control group activities
Brunelli, 2024	17 F/13 M	Obesity + type 2 diabetes	Ex: 52 ± 5/Con: 51 ± 4	RT: 10 ex; whole body; 3 sets × 10–12 submax reps; 35 min; 50–75 % 1RM AT: Treadmill/athletics track; walking/trotting/running; 35 min; 50–70 % VO ₂ max RT: 5 ex with elastic bands; whole body; 2–4 sets; RPE 9–11	120–140 min	3 d for 16 wk	Non-exercise
Cai, 2023	21 F/13 M	Prediabetes	Ex: 63.41 ± 5.06/Con: 61.82 ± 4.33	RT: 6 ex; whole body; 2 sets × 8 reps; 80 % 1RM; AT: cycle ergometer; 10 min RT: 6 ex; whole body; 2 sets × 8 reps; 50 % 1RM; AT: cycle ergometer; 10 min	wk1–8: 47 min; wk8–16: 68 min; wk16–24: 76 min	5 d for 24 wk	Non-exercise
Cassilhas, 2007 (High intensity AT)	43 M	Older adults	Ex: 68.4 ± 0.67/Con: 67.04 ± 0.54	RT: 10 ex; whole body; elastic bands + body weight; 3 sets × 10–12 reps; RPE OMNI-RES 7–8 AT: step aerobics; RPE 11–16; 50 min	60 min	3 d for 24 wk	Warmup + stretching w/o overload
Cassilhas, 2007 (Moderate intensity AT)	42 M	Older adults	Ex: 69.01 ± 1.1/Con: 67.04 ± 0.54	RT: 10 ex; whole body; weight training; 3 sets × 8–12 reps at 60–70 % 1RM AT: dance steps; moderate intensity	60 min	3 d for 24 wk	Warmup + stretching w/o overload
Chagas, 2017	82 F	Postmenopausal women	Ex: 61.3 ± 6.4/Con: 59.8 ± 7.1	RT: neuromuscular training; whole body; stretching, isometric, dynamic; 2–4 sets × submax 10 reps; AT: walking; flat surface; 50–60 % VO ₂ max; 50 min	75 min	3 d for 20 wk	Non-exercise
Chang and Namkung, 2021	30 F	Metabolic syndrome	Ex: 57.5 ± 12.20/Con: 60.2 ± 7.9	RT: 10 ex; whole body; weight training; 3 sets × 8–12 reps at 60–70 % 1RM AT: dance steps; moderate intensity	3 50 min	3 d for 12 wk	Non-exercise, usual care
Chen, 2017 (AT)	27 F/3 M	Sarcopenic obesity	Ex: 69.3 ± 3.0/Con: 68.6 ± 3.1	RT: 10 ex; whole body; weight training; 3 sets × 8–12 reps at 60–70 % 1RM	40–45 min	2 d for 8 wk	Non-exercise, usual care
Chen, 2017 (CT)	24 F/6 M	Sarcopenic obesity	Ex: 68.5 ± 2.7/Con: 68.6 ± 3.1	RT: 10 ex; whole body; kettlebell training; 3 sets × 8–12 reps at 60–70 % 1RM	60 min	2 d for 8 wk	Non-exercise, usual care
Chen, 2017 (RT)	25 F/25 M	Sarcopenic obesity	Ex: 68.9 ± 4.4/Con: 68.6 ± 3.1	AT: spin bike; 5 cycles of 3 min high-intensity (90 % HR max, RPE 15) + 3 min low-intensity (70 % HR max, RPE 12)	60 min	2 d for 8 wk	Non-exercise, usual care
Chen, 2018	33 F	Sarcopenia	Ex: 66.7 ± 5.3/Con: 68.3 ± 2.8	AT: cycle ergometer; 4–5 days/week; 75 % VO ₂ max	30 min	2 d for 8 wk	Non-exercise
Chen, 2021	41 F/5 M	Obesity	Overall: 58.3 ± 0.5	AT: cycle ergometer; 4–5 days/week; 50 % VO ₂ max	30 min	NR d for 12 wk	Non-exercise
Choi, 2012	78 F	Type 2 diabetes	Ex: 53.8 ± 7.2/Con: 55.0 ± 6.0	AT: walking; 3.6–6.0 METs	60 min	5 d for 12 wk	Non-exercise
Coker, 2009 (High intensity AT)	6 F/6 M	Overweight-obese	Ex: 73 ± 2/Con: 67 ± 3	AT: cycle ergometer; 4–5 days/week; 75 % VO ₂ max	30 min	4–5 d for 12 wk	Non-exercise
Coker, 2009 (Moderate intensity AT)	6 F/6 M	Overweight-obese	Ex: 70 ± 1/Con: 67 ± 3	AT: cycle ergometer; 4–5 days/week; 50 % VO ₂ max	30 min	4–5 d for 12 wk	Non-exercise
Colli-Risco, 2018	150 F	Peri-menopausal women	Ex: 52.8 ± 4.48/Con: 52.7 ± 4.51	AT: cycle ergometer; 70 % VO ₂ max	60 min	3 d for 16 wk	Non-exercise, usual routine
Cunha, 2019	48 F	Older adults	Ex: 71.40 ± 5.71/Con: 69.04 ± 4.45	RT: 8 ex; whole body; 1 set × 10–15 reps to failure; increase 2–5 % upper limbs, 5–10 % lower limbs	20 min	3 d for 12 wk	Non-exercise
Cunha, 2020 (Multiple sets)	41 F	Older adults	Ex: 63.60 ± 4.44/Con: 68.04 ± 4.38	RT: 8 ex; whole body; 1 set × 10–15 reps max; 60–120 s rest between sets	45 min	3 d for 12 wk	Non-exercise
Cunha, 2020 (Single sets)	42 F	Older adults	Ex: 70.09 ± 5.95/Con: 68.04 ± 4.38	RT: 8 ex; whole body; 1 set × 10–15 reps max; 60–120 s rest between sets	15 min	3 d for 12 wk	Non-exercise
Cunha, 2021 (High volume RT)	43 F	Older adults	Ex: 68.7 ± 4.7/Con: 69.0 ± 4.2	RT: 8 ex; whole body; machines and free weights; 3 sets × 10–15 reps; 10–15RM	45–60 min	3 d for 12 wk	Non-exercise
Cunha, 2021 (Low volume RT)	43 F	Older adults	Ex: 70.3 ± 6.3/Con: 69.0 ± 4.2	RT: 8 ex; whole body; machines and free weights; 1 set × 10–15 reps; 10–15RM	15–20 min	3 d for 12 wk	Non-exercise
Dadrass, 2019 (RT)	12 M	Inactive men with type 2 diabetes + vitamin D deficiency	Ex: 54.91 ± 5.86/Con: 53.16 ± 8.12	RT: 10 ex; whole body; machines and bodyweight; 3 sets × 10 reps; 55–75 % 1RM	70 min	3 d for 12 wk	Non-exercise
Dadrass, 2019 (RT + vitamin D)	12 M	Inactive men with type 2 diabetes + vitamin D deficiency	Ex: 53.75 ± 8/Con: 53.83 ± 6.61	RT: 10 ex; whole body; machines and bodyweight; 3 sets × 10 reps; 55–75 % 1RM	70 min	3 d for 12 wk	Non-exercise
Da Silva, 2020 (RT + HIIT)	18 F/8 M	Metabolic syndrome	Ex: 63.3 ± 7.2/Con: 76.1 ± 9.3	RT: 5 ex; whole body; barbell and bodyweight; 2 sets × 8–15 reps; Borg CR-10 scale 2–5 AT: walking; intervals at 80–90 % HR max (3 × 3 min) with 3 min recovery at 55–65 % HR max	50 min	3 d for 12 wk	Non-exercise

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Table 1 (continued)

Author, year (Subgroup)	Sample size	Health status	Age (mean ± SD)	Type of training: number of exercises; muscle groups; equipment/accessories; volume (sets and repetitions or duration); intensity	Duration of each session (time)	Days per week and total number of weeks	Control group activities
Da Silva, 2020 (RT + MICT)	20 F/6 M	Metabolic syndrome	Ex: 71.1 ± 4.8/Con: 76.1 ± 9.3	RT: 5 ex; whole body; barbell and bodyweight; 2 sets × 8–15 reps; Borg CR-10 scale 2–5 AT: 25 min walking at 60–70 % HR max	50 min	3 d for 12 wk	Non-exercise
Daly, 2005	13 F/16 M	Type 2 diabetes	Ex: 67.6 ± 5.2/Con: 66.9 ± 5.3	RT: Phase 1: 9 ex; whole body; machines; 3 sets × 8–10 min RT: 75–85 % 1RM; Phase 2: dumbbells; 60–80 % 1RM RT: 8 ex; whole body; 3 sets × 8–20 reps; 55–75 % 1RM 100 min AT: treadmill 30 min at 50–80 % HR max	60 min	3 d for 24 wk	Weight loss + flexibility training
de Paulo, 2018	36 F	Breast cancer survivors undergoing aromatase inhibitor therapy	Ex: 63.2 ± 7.1/Con: 66.6 ± 9.6	RT: 8 ex; whole body; 3 sets × 8–20 reps; 55–75 % 1RM 100 min AT: treadmill 30 min at 50–80 % HR max	100 min	3 d for 36 wk	Stretching + relaxation exercise
Dehghan, 2016 (AT)	16 F	Type 2 diabetes	Ex: 58.83 ± 6.79/Con: 50.17 ± 5.34	AT: treadmill jogging: 50–70 % HR max	60 min	3 d for 16 wk	Placebo
Dehghan, 2016 (AT + purslane seeds)	16 F	Type 2 diabetes	Ex: 61.17 ± 4.88/Con: 52.33 ± 4.08	AT: treadmill jogging: 50–70 % HR max	60 min	3 d for 16 wk	Purslane seeds
Deibert, 2011	25 M	Middle-aged men	Ex: 55.5 ± 4.8/Con: 55.8 ± 5.5	RT: 4 + ex; whole body; 25–10 reps (progression); 4 seconds per rep	90 min	2 d for 12 wk	Non-exercise, lifestyle education
Dieli-Conwright, 2018	100 F	Breast cancer survivors	Ex: 52.8 ± 10.6/Con: 53.6 ± 10.1	RT: multiple ex; whole body; 3 sets × 10–15 reps; 80 % 2 days 80 min, 1–1RM lower body, 60 % 1RM upper body AT: aerobic; day 50 min 65–80 % HR max; 30–50 min	80 min	3 d for 16 wk	Usual care
Dos Santos, 2020 (Narrow pyramid RT)	39 F	Older women	Overall: 67.3 ± 4.4	RT: 8 ex; whole body; 3 sets × 8–12 reps; load increase NR +2–5 % for upper and +5–10 % for lower limb	NR	3 d for 8 wk	Non-exercise
Dos Santos, 2020 (Wide pyramid RT)	39 F	Older women	Overall: 67.3 ± 4.4	RT: 8 ex; whole body; 3 sets × 5–15 reps; load increase NR +2–5 % for upper and +5–10 % for lower limb	NR	3 d for 8 wk	Non-exercise
Drapeau, 2011	107 F	Obese post-menopausal women	Ex: 58.0 ± 4.1/Con: 58.5 ± 4.6	RT: 6 ex; whole body; machines; 2–4 sets × 8–15 reps; NR progressive by phase (IRM-based)	NR	3 d for 24 wk	Caloric restriction
Fairey, 2005	53 F	Postmenopausal breast cancer survivors	Ex: 58 ± 6/Con: 59 ± 5	AT: cycling; lower body; cycle ergometer; 15–35 min; 70–75 % VO ₂ max	15 min +5/3 wk to 35 mins	3 d for 15wk	Non-exercise
Fatouros, 2005 (High intensity RT)	24 M	Overweight + inactive	Ex: 70.8 ± 2.8/Con: 69.8 ± 5.1	RT: 8 ex; whole body; machines; 2–4 sets × 6–12 reps; 60 min	60 min	3 d for 24 wk	Non-exercise
Fatouros, 2005 (Low intensity RT)	24 M	Overweight + inactive	Ex: 71.1 ± 3.6/Con: 69.8 ± 5.1	RT: 8 ex; whole body; machines; 2–4 sets × 6–12 reps; 60 min	60 min	3 d for 24 wk	Non-exercise
Fatouros, 2005 (Moderate intensity RT)	22 M	Overweight + inactive	Ex: 69.7 ± 3.8/Con: 69.8 ± 5.1	RT: 8 ex; whole body; machines; 2–4 sets × 6–12 reps; 60 min	60 min	3 d for 24 wk	Non-exercise
Figuerola, 2013	27 F	Obese post-menopausal women	Ex: 54 ± 1/Con: 54 ± 1	RT: 4 ex; lower body; 2–3 sets × 18–22 reps	30 min	3 d for 12 wk	Commercial weight loss program
Frih, 2017	41 M	Chronic haemodialysis	Ex: 64.2 ± 3.4/Con: 65.2 ± 3.1	RT: 5 ex; major muscle groups; 12–15 reps at 50 % 1RM, 60 min load +5 %/month AT: cycling and treadmill walking; 20 min; Borg Score 5–6 and HR based intensity	60 min	4d for 16 wk	Non-exercise
Gargallo, 2024 (Multicomponent training)	60 F	Metabolic syndrome	Ex: 69.30 ± 4.96/Con: 68.00 ± 5.01	RT: 2 ex, 3–4 sets × 15 reps, tempo 2 s concentric/ eccentric, RPE 6–9 Balance: 3 ex, 20–40 s holds AT: walking, jogging, jumping, >100 impacts/session, 65–85 % HR max, RPE 11–15	70–80 min	2 d for 20 wk	Non-exercise
Gargallo, 2024 (Power RT)	60 F	Metabolic syndrome	Ex: 67.24 ± 4.42/Con: 68.00 ± 5.01	RT: 6 ex; whole body; machines; 3–4 sets × 10–12 reps; 40–60 % 1RM; RPE 3–6; 60–90 s rest between sets	70–80 min	2 d for 20 wk	Non-exercise
Gazova, 2019	23 M	Prostate cancer + androgen deprivation therapy	Ex: 69.21 ± 5.8/Con: 70.69 ± 7.5	RT: 5 ex; 2–3 sets × 10–15 reps; resistance at 30 % (wk NR 1–4) and 90–100 % (wk 5–16)	NR	3 d for 16 wk	Non-exercise
Ghodrat, 2022 (Different day RT + HIIT)	16 F	Type 2 diabetes	NR	RT: 12 ex; whole body; 2–4 sets × 10–20 reps; 40–70 % NR 1RM AT: treadmill; 80–90 VO ₂ max	NR	6d for 8 wk	Non-exercise
Ghodrat, 2022 (Same day RT + HIIT)	16 F	Type 2 diabetes	NR	RT: 12 ex; whole body; 2–4 sets × 10–20 reps; 40–70 % NR 1RM AT: treadmill; 80–90 VO ₂ max	NR	3 d for 8 wk	Non-exercise
Gómez-Tomás, 2018	60 F	Postmenopausal women	Ex: 70.89 ± 4.42/Con: 70.45 ± 5.44	RT: 6 ex; major muscle groups; elastic bands; 3 sets × 10 50 min reps; progressive intensity by RPE; 1 s concentric/1 s eccentric	50 min	3 d for 52 wk	Non-exercise

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Table 1 (continued)

Author, year (Subgroup)	Sample size	Health status	Age (mean ± SD)	Type of training: number of exercises; muscle groups; equipment/accessories; volume (sets and repetitions or duration); intensity	Duration of each session (time)	Days per week and total number of weeks	Control group activities
Guzel, 2024	24 F	Postmenopausal with obesity	Ex: 55.67 ± 3.44/Con: 54.42 ± 4.01	AT: treadmill walking/jogging; 50–70 % HRR	25–40 min	3 d for 10 wk	Non-exercise
Hasegawa, 2018	26 F/26 M	Middle-aged and older adults	Ex: 68 ± 7.1/Con: 65.8 ± 8.6	AT: cycle ergometer; intensity 60–70 % VO ₂ max; RPE 12–13 (Borg scale)	55 min	3 d for 8 wk	Non-exercise
Henagan, 2011	23 F	Postmenopausal women	Ex: 65.2 ± 2.6/Con: 66.1 ± 3.0	RT: 10 ex; major muscle groups; machines; 3 sets × 8–12 reps (8RM, last set to failure)	NR	3 d for 12 wk	Non-exercise
Hojan, 2017	66 M	Men with prostate cancer	Ex: 65.7 ± 6.2/Con: 67.9 ± 4.9	RT: 5 ex; major muscle groups; free weights/machines; 2 sets × 8 reps; 70–75 % 1RM AT: cycling/walking/running; 65–80 % HRR	65–70 min	5 d for 8 wk, then 3 d for 44 wk	Non-exercise
Hosseini, 2016	24 M	Sedentary	Ex: 64.2 ± 2.2/Con: 62.7 ± 2.1	RT: 10 ex; whole body; bands/free weights; 2 sets × 10 reps; 70 % 1RM AT: treadmill; 60–70 % HRR	60 min	3 d for 8 wk	Non-exercise
Houghton, 2017	NR	Non-alcoholic steatohepatitis	Ex: 54 ± 12/Con: 51 ± 16	AT: bike intervals; 3 min bouts; RPE 16–18 RT: weights at RPE 14–16	45–60 min	3 d for 12 wk	Non-exercise
Hsieh, 2018	19 F/11 M	Type 2 diabetes	Ex: 70.6 ± 4.2/Con: 71.8 ± 4.5	RT: 8 ex; major muscle groups; free weights/body weight; 3 sets × 8–12 reps; 40–75 % 1RM or RPE 12–16	NR	3 d for 12 wk	Non-exercise
Huffman, 2008 (HA-VI AT)	45 F/53 M	At-risk, overweight, mild obesity, postmenopausal women, dyslipidaemia	Ex: 52.7 ± 4.8/Con: 52.5 ± 7.5	AT: cycling; 32.2 km/wk or 8374 kJ/wk at 65–80 % VO ₂ max	NR	NR d for 24 wk	Non-exercise
Huffman, 2008 (LA-MI AT)	47 F/45 M	At-risk, overweight, mild obesity, postmenopausal women, dyslipidaemia	Ex: 53.4 ± 5/Con: 52.5 ± 7.5	AT: cycling; 19.3 km/wk or 5024 kJ/wk at 40–55 % VO ₂ max	NR	NR d for 24 wk	Non-exercise
Huffman, 2008 (LA-VI AT)	50 F/49 M	At-risk, overweight, mild obesity, postmenopausal women, dyslipidaemia	Ex: 52.7 ± 7.6/Con: 52.5 ± 7.5	AT: cycling; 19.3 km/wk or 5024 kJ/wk at 65–80 % VO ₂ max	NR	NR d for 24 wk	Non-exercise
Huschtscha, 2021 (PRT)	5 F/15 M	Healthy active older adults	Ex: 58.0 (95 % CI 53.0–67.0)/Con: 56.1 (95 % CI 51.5–60.6)	RT: 12 ex; elastic band + free weights; 3 sets × 10–15 reps; 50–95 % 1RM	30 (SD 15) min	3 d for 12 wk	Non-exercise
Huschtscha, 2021 (PRT + milk)	4 F/13 M	Healthy active older adults	Ex: 63.6 (95 % CI 57.4–70.0)/Con: 59.7 (95 % CI 52.9–67.0)	RT: 12 ex; elastic band + free weights; 3 sets × 10–15 reps; 50–95 % 1RM	30 (SD 15) min	3 d for 12 wk	High-protein milk dairy beverage
Hvid, 2016	25 M	Prostate cancer	Ex: 69.8 ± 2.9/Con: 68 ± 6.1	AT: self-selected mode (walking, running, rowing, swimming, bicycling); 50–100 % VO ₂ max	45 min	3 d for 96 wk	Non-exercise
Hwang, 2012	12 F/12 M	Adenocarcinoma + receiving targeted therapy	Ex: 61 ± 6.3/Con: 58.5 ± 8.2	AT: treadmill/cycle; 2–5 min intervals at 80 % VO ₂ max (RPE 11–13)	30–40 min	3 d for 8 wk	Non-exercise
Ihalainen, 2019 (RT 1 day/week)	22 F/22 M	Community-dwelling older adults	Ex: 69.8 ± 2.5/Con: 69.4 ± 2.2	RT: upper and lower limb; machines/free weights; 1 set to failure; 70–90 % 1RM (power training 30–80 % 1RM)	NR	1d for 24 wk	Non-exercise
Ihalainen, 2019 (RT 2 days/week)	23 F/21 M	Community-dwelling older adults	Ex: 68.8 ± 2.9/Con: 69.4 ± 2.2	RT: upper and lower limb; machines/free weights; 1 set to failure; 70–90 % 1RM (power training 30–80 % 1RM)	NR	2 d for 24 wk	Non-exercise
Ihalainen, 2019 (RT 3 days/week)	23 F/23 M	Community-dwelling older adults	Ex: 69.5 ± 2.2/Con: 69.4 ± 2.2	RT: upper and lower limb; machines/free weights; 1 set to failure; 70–90 % 1RM (power training 30–80 % 1RM)	NR	3 d for 24 wk	Non-exercise
Jin, 2015	16 F	Hyperglycaemia	Ex: 74.27 ± 0.62/Con: 76.11 ± 2.01	RT: 9 ex; whole body; 2 sets × 10 reps; RPE 12–13	60 min	3 d for 12 wk	Non-exercise
Johannsen, 2012 (12 KKW AT)	205 F	Sedentary, overweight/obese postmenopausal women	Ex: 56.6 ± 6.5/Con: 57.1 ± 5.7	AT: treadmill/cycle ergometer; 4 kcal/kg/wk first week, +1 kcal/kg/wk per week until 12 kcal/kg/wk reached	NR	3–4d for 24 wk	Non-exercise
Johannsen, 2012 (4 KKW AT)	257 F	Sedentary, overweight/obese postmenopausal women	Ex: 58.1 ± 6.6/Con: 57.1 ± 5.7	AT: treadmill/cycle ergometer; 6 months of 4 kcal/kg/wk	NR	3–4d for 24 wk	Non-exercise
Johannsen, 2012 (8 KKW AT)	206 F	Sedentary, overweight/obese postmenopausal women	Ex: 57.2 ± 6.8/Con: 57.1 ± 5.7	AT: treadmill/cycle ergometer; 4 kcal/kg/wk first week, +1 kcal/kg/wk per week until 8 kcal/kg/wk reached	NR	3–4d for 24 wk	Non-exercise
Jung, 2022	28 F	Obesity + sarcopenia	Ex: 75.36 ± 4.5/Con: 74.64 ± 5.77	AT: 10 circuit training ex; whole body; 2–4 sets; 60–80 % HRR	45–75 min	3 d for 12 wk	Non-exercise

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Table 1 (continued)

Author, year (Subgroup)	Sample size	Health status	Age (mean ± SD)	Type of training: number of exercises; muscle groups; equipment/accessories; volume (sets and repetitions or duration); intensity	Duration of each session (time)	Days per week and total number of weeks	Control group activities
Jung, 2024	28 F	Obesity + sarcopenia	Ex: 78.14 ± 3.72/Con: 78.21 ± 3.72	AT: 10 circuit training ex; whole body; 2–4 sets; 1 min/ 45–75 min ex; 60–85 % HRR	45–75 min	3 d for 12 wk	Non-exercise
Kadoglou, 2010 (AT)	28 F/16 M	Type 2 diabetes	Ex: 56.91 ± 7.09/Con: 60.32 ± 9.28	AT: treadmill, cycling, calisthenics; large muscle groups; 50–80 % VO ₂ max	45–60 min	4d for 52 wk	Non-exercise
Kadoglou, 2010 (AT + rosiglitazone)	29 F/17 M	Type 2 diabetes	Ex: 57.83 ± 7.61/Con: 59.04 ± 7.35	AT: treadmill, cycling, calisthenics; large muscle groups; 50–80 % VO ₂ max	45–60 min	4d for 52 wk	Rosiglitazone supplements
Kadoglou, 2012	35 F/12 M	Type 2 diabetes	Ex: 61.5 ± 5.4/Con: 64.6 ± 4.3	RT: 8 ex; Whole body; Machine weights; 2–3 sets × 6–8 reps; 60–80 % 1RM	45–60 min	3 d for 12 wk	Non-exercise
Kadoglou, 2013 (AT)	32 F/13 M	Type 2 diabetes	Ex: 58.3 ± 5.4/Con: 57.9 ± 7.2	AT: walking, running, cycling, calisthenics; Large muscle groups; 60–75 % HR max	60 min	4d for 24 wk	Low to moderate intensity self-controlled exercise in leisure time
Kadoglou, 2013 (CT)	34 F/12 M	Type 2 diabetes	Ex: 57.9 ± 6.5/Con: 57.9 ± 7.2	RT: 8 ex; major muscle groups; 2–3 sets × 8–10 reps; 60–80 % 1RM	60 min	4d for 24 wk	Low to moderate intensity self-controlled exercise in leisure time
Kadoglou, 2013 (RT)	33 F/14 M	Type 2 diabetes	Ex: 56.1 ± 5.3/Con: 57.9 ± 7.2	RT: 8 ex; upper and lower body; machines; 2–3 sets × 8–10 reps; 60–80 % 1 RM	60 min	4d for 24 wk	Low to moderate intensity self-controlled exercise in leisure time
Kang, 2024	52 M	Prostate cancer	Ex: 63.9 ± 7.5/Con: 62.8 ± 6.9	RT: 8 ex; major muscle groups; Machines; 1–2 sets × 4–5 reps; Intensity 60–80 % 1RM AT: Half volume at 60–75 % HR max	28–40 min	3 d for 12 wk	Non-exercise
Kazemipour, 2022	48 F	Osteosarcopenia + obesity	Ex: 64.11 ± 3.81/Con: 64.05 ± 3.35	RT: elastic band (TheraBand (yellow)); Major muscle groups; Familiarisation sessions included	NR	3 d for 12 wk	Non-exercise
Khosravi, 2018	41 F	Breast cancer	Ex: 58.8 ± 6.4/Con: 55.3 ± 5.2	AT: progression (45–80 % HR max)	15/20 min in wk1 to 50 min on wk8	3 d for 26 wk	Non-exercise
Kim, 2018 (CT)	NR	Older adults	NR	RT: 3 ex; large muscle groups; 1–3 sets × 12–15 reps, RPE 6–8 AT: sky-walk, cross-country (outdoor gym equipment); 2 sets x 5 min; RPE 6–8	90 min	3 d for 6 wk	Non-exercise
Kim, 2018 (RT)	NR	Older adults	NR	RT: 3 ex; large muscle groups; 1–3 sets × 12–15 reps, RPE 6–8	70 min	3 d for 6 wk	Non-exercise
Kim, 2019	20 M	Obesity	Ex: 69.1 ± 0.88/Con: 68.5 ± 0.85	RT: 6 ex; elastic bands; large muscle group; 3 sets × 10–15 reps; 60–70 % 1RM AT: treadmill/bicycle; 60–70 % HR max	90–120 min	3 d for 12 wk	Non-exercise
Kim, 2008	11 F/28 M	Coronary artery disease	Ex: 59.9 ± 1.6/Con: 52.8 ± 3.7	AT: treadmill/cycle ergometer; 50–80 % VO ₂ max	40 min	3 d for 14 wk	Non-exercise
Kohrt, 1996 (AT)	33 F	Healthy sedentary women	Ex: 64 ± 3/Con: 67 ± 4	2 months stretching then AT (9 months): walking, jogging, stair climbing; 60–85 % HR max	45–50 min	3 d for 44 wk	Non-exercise
Kohrt, 1996 (AT + HRT)	28 F	Healthy sedentary women	Ex: 66 ± 3/Con: 66 ± 3	2 months stretching then AT (9 months): walking, jogging, stair climbing; 60–85 % HR max	45–50 min	3 d for 44 wk	Hormone replacement therapy
Kortas, 2020	36 F	Older adults	Ex: 66.78 ± 4.76/Con: 66.12 ± 4.83	AT: Nordic walking (walking with walking poles); 60–70 % HR max	65–75 min	3 d for 12 wk	Non-exercise
Kosydar-Piechma, 2010	64 M	Stable coronary heart disease	Ex: 54.0 ± 4.8/Con: 54.5 ± 5.6	AT: cycle ergometer; 60–80 % HR max	60 min	3 d for 6 wk	Non-training, 30 min walking 3 times per week
Kukuljan, 2009 (PRT)	90 M	Healthy men	Ex: 60.7 ± 7.1/Con: 59.9 ± 7.4	RT: 15 ex; upper and lower body and core; machines and free weights; 2–3 sets × 8–20 reps; 50–65 % 1RM AT: 3 ex; lower body; bodyweight jumps; 3 sets × 10–20 reps	NR	3 d for 72 wk	Non-exercise
Kukuljan, 2009 (PRT + fortified milk)	90 M	Healthy men	Ex: 61.7 ± 7.6/Con: 61.7 ± 7.7	RT: 15 ex; upper and lower body and core; machines and free weights; 2–3 sets × 8–20 reps; 50–65 % 1RM AT: 3 ex; lower body; bodyweight jumps; 3 sets × 10–20 reps	NR	3 d for 72 wk	Fortified milk alone
Kwon, 2012	30 F	Older women with hypertension	Ex: 74.00 ± 2.90/Con: 73.60 ± 2.20	AT: yoga, walking, step aerobics; balance training; 60–70 % HR max; yoga at RPE 12–14	60 min	4d for 24 wk	Non-exercise
Lambert, 2003 (RT + placebo)	13 M	Healthy men ingesting megesterol acetate	Ex: 67.0 ± 6.1/Con: 64.0 ± 5.3	RT: 5 exercises; upper and lower body; Keiser pneumatic machines; 3 sets × 8–12 reps; 80 % 1RM	NR	3 d for 12 wk	Megesterol acetate ingestion

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Table 1 (continued)

Author, year (Subgroup)	Sample size	Health status	Age (mean $\pm$ SD)	Type of training: number of exercises; muscle groups; equipment/accessories; volume (sets and repetitions or duration); intensity	Duration of each session (time)	Days per week and total number of weeks	Control group activities
Lambert, 2003 (RT + testosterone)	15 M	Healthy men ingesting megestrol acetate	Ex: 66.9 $\pm$ 5.5/Con: 66.6 $\pm$ 3.7	RT: 5 exercises; upper and lower body; Keiser pneumatic machines; 3 sets $\times$ 8–12 reps; 80 % 1RM	NR	3 d for 12 wk	Megestrol acetate ingestion + testosterone
Lamina, 2014	323 M	Stage 1 & 2 Hypertension	Ex: 58.40 $\pm$ 6.91/Con: 58.27 $\pm$ 6.24	AT: cycle ergometer; 60–79 % HR max progressive	60 min	3 d for 8 wk	Non-exercise
Leehey, 2009	13 M	Obese with diabetes and chronic kidney disease	Overall: 66 (range 55–81)	AT: walking, treadmill, cycle ergometer, interval training; 25–84 % VO ₂ max	30–55 min	3 d for 24 wk	Non-exercise
Levinger, 2009	10 F/20 M	With metabolic risk factors	Ex: 51.6 $\pm$ 7.1/Con: 52.3 $\pm$ 5.8	RT: 8 ex; major muscle groups; 2–3 sets $\times$ 8–20 reps; 40–85 % 1RM	NR	3 d for 10 wk	Non-exercise
Lim, 2015	20 F	Obesity	Ex: 70.7 $\pm$ 2.2/Con: 71.3 $\pm$ 1.7	AT: walking, jumping, Korean dance (jumping and balancing exercise); whole body; 50–70 % HR max RT: 4 ex, upper body, 50–70 % HR max	45 min	3 d for 12 wk	Non-exercise
Lima, 2015 (AT)	26 F/3 M	Hypertension	Ex: 67.8 $\pm$ 4.3/Con: 69.9 $\pm$ 5.5	AT: 5 min stretches; 20–30 aerobic ex	25–35 min	3 d for 10 wk	Non-exercise
Lima, 2015 (CT)	25 F/4 M	Hypertension	Ex: 67.8 $\pm$ 5.2/Con: 69.9 $\pm$ 5.5	AT: 5 min stretches; 20–30 aerobic ex RT: Machine; 1–2 circuits at 50–60 % RM; 15 reps for upper limb; 20 reps for lower limb	25–35 min + time for RT (NR)	3 d for 10 wk	Non-exercise
Loimaala, 2009	50 M	Type 2 diabetes	Ex: 53.6 $\pm$ 6.2/Con: 54.0 $\pm$ 5.0	AT: jogging, walking; 30 min; 65–75 % VO ₂ max RT: trunk region; 3–4 sets $\times$ 10–12 reps; 60–80 % maximal contraction	30 min	4d for 96 wk	Non-exercise
Luk, 2012	16 F/48 M	Stable coronary heart disease	Ex: 67.7 $\pm$ 9.0/Con: 66.6 $\pm$ 7.9	RT: dumbbell/weight training; increased to 80 % HR max AT: treadmill, ergometers, rowing; 50–80 % HR max	60 min	3 d for 8 wk	Non-exercise
Marrone, 2024 (CT)	6 F/14 M	Chronic kidney disease	Ex: 58.44 $\pm$ 8.28/Con: 65.50 $\pm$ 4.43	RT: 4–6 ex; whole body; bodyweight resistance bands; 2–3 sets $\times$ 8–15 reps; progressive load AT: choreographed movements with music; lower body; 60–75 % HRR	60 min	3 d for 12 wk	Non-exercise
Marrone, 2024 (CT + functional foods)	7 F/13 M	Chronic kidney disease	Ex: 58.00 $\pm$ 8.25/Con: 63.66 $\pm$ 4.61	RT: 4–6 ex; whole body; bodyweight resistance bands; 2–3 sets $\times$ 8–15 reps; progressive load AT: choreographed movements with music; lower body; 60–75 % HRR	60 min	3 d for 12 wk	Daily consumption of 2 functional foods (bars containing grape seed, grape pomace, and olive leaf powders)
Martins, 2010 (AT)	18 F/13 M	Older adults	Ex: 76.2 $\pm$ 7.4/Con: 81.2 $\pm$ 7.9	AT: progression 40–85 % HRR	45 min	3 d for 16 wk	Non-exercise
Martins, 2010 (RT)	16 F/11 M	Older adults	Ex: 73.2 $\pm$ 6.5/Con: 81.2 $\pm$ 7.9	RT: 8 ex; major muscle groups; calisthenics and elastic bands; 1–3 sets $\times$ 8–15 reps	45 min	3 d for 16 wk	Non-exercise
Mavros, 2013	50 F/50 M	Type 2 diabetes	Ex: 67.1 $\pm$ 4.8/Con: 68.9 $\pm$ 9.0	RT: 7 ex; arms, legs, trunk; pneumatic resistance machines; 3 sets $\times$ 8 reps; 80 % 1RM	NR	3 d for 48 wk	Sham exercise: 3 times a week, very low resistance
McNeil, 2015	93 F	Obese postmenopausal women	Overall: 58.1 $\pm$ 4.8	RT: 6 ex; upper and lower body; machines; 2–4 sets $\times$ 8–15 reps; 65–80 % 1RM	NR	3 d for 24 wk	Caloric restriction
Messier, 2013	217 F/87 M	Overweight-obese + knee osteoarthritis	Ex: 65 $\pm$ 6/Con: 66 $\pm$ 6	RT: 7 ex; primarily lower body; 1–2 sets $\times$ 10–12 reps AT: walking; 50–75 % HRR	60 min	3 d for 72 wk	Non-exercise
Moghadam, 2021 (HIIT)	30 F	Obese survivors of breast cancer, postmenopausal	Overall: 57 $\pm$ 1	AT: cycle ergometer; 55–65 % peak power; Borg RPE 9–13	20–30 min	3 d for 12 wk	Non-exercise
Moghadam, 2021 (MICT)	30 F	Obese survivors of breast cancer, postmenopausal	Overall: 57 $\pm$ 1	AT: cycle ergometer; 4–7 $\times$ 30 s intervals (95–115 RPM); $\geq$ 90 % HR max	20–30 min	3 d for 12 wk	Non-exercise
Mohajeri Tehrani, 2015	20 M	Type 2 diabetes	Ex: 50.3 $\pm$ 4.2/Con: 52.1 $\pm$ 4.01	AT: cycle ergometer; 60–70 % HR max	45 min	3 d for 6 wk	Non-exercise
Mojtahedi, 2022 (RT)	24 M	Hypertension	Ex: 63.2 $\pm$ 2.57/Con: 62.5 $\pm$ 2.96	RT: 9 ex; whole body; machine; 2 sets $\times$ 10–15 reps; 40 % RM for upper limb; 60 % RM for lower limb	120 min	3 d for 12 wk	Non-exercise
Mojtahedi, 2022 (RT + saffron)	24 M	Hypertension	Ex: 63.5 $\pm$ 2.57/Con: 63.1 $\pm$ 2.79	RT: 9 ex; whole body; machine; 2 sets $\times$ 10–15 reps; 40 % RM for upper limb; 60 % RM for lower limb	120 min	3 d for 12 wk	Saffron consumption
Muscarri, 2010	58 F/62 M	Healthy older adults	Ex: 68.8 $\pm$ 2.5/Con: 69.9 $\pm$ 2.8	AT: cycle ergometer, treadmill, and free-body activity; full body; 70 % HR max	60 min	3 d for 48 wk	Non-exercise
Nadi, 2019 (RT)	30 F	Diabetic neuropathy	Ex: 56.13 $\pm$ 3.39/Con: 54.80 $\pm$ 3.29	RT: 10 exercises; full body; 30 % 1RM	NR	3 d for 12 wk	Non-exercise
Nazarabadi, 2022	23 F	Postmenopausal females with metabolic syndrome	Ex: 56.01 $\pm$ 2.23	AT: walking, jogging, exercises; 60–75 % HR max	45–60 min	3 d for 8 wk	Vitamin D supplements

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Table 1 (continued)

Author, year (Subgroup)	Sample size	Health status	Age (mean ± SD)	Type of training: number of exercises; muscle groups; equipment/accessories; volume (sets and repetitions or duration); intensity	Duration of each session (time)	Days per week and total number of weeks	Control group activities
Nicklas, 2004 (CT)	95 F/42 M	Community-dwelling, sedentary, overweight-obese adults	Ex: 69 ± 6/Con: 69 ± 6	RT: 4 exercises; lower body; cuff weights, weighted vests; 2 sets × 12 reps AT: walking; 50–75 % HRR	60 min	3 d for 72 wk	Non-exercise
Nicklas, 2004 (CT + CR)	100 F/35 M	Community-dwelling, sedentary, overweight-obese adults	Ex: 68 ± 7/Con: 68 ± 5	RT: 4 exercises; lower body; cuff weights, weighted vests; 2 sets × 12 reps AT: walking; 50–75 % HRR	60 min	3 d for 72 wk	Caloric restriction
Niemiro, 2022 (HIIT)	16 F	Overweight-obese postmenopausal women	Ex: 64.4 ± 6.2/Con: 62.6 ± 7.0	AT: treadmill; 4 × 4 min intervals at 70–90 % HR max and 3 min recovery at 50–70 % HR max	33 min	3 d for 12 wk	Non-exercise
Niemiro, 2022 (MICT)	16 F	Obese-overweight postmenopausal women	Ex: 66.1 ± 13.6/Con: 62.6 ± 7.0	AT: treadmill; 60–70 % HR max	41 min	3 d for 12 wk	Non-exercise
Nishida, 2015	62 F	Postmenopausal women	Ex: 70.4 ± 5.8/Con: 69.7 ± 6.6	AT: bench step ex; lactate threshold intensity	30–60 min	7d for 12 wk	Non-exercise
Nosrani, 2024	21 F/11 M	Overweight	Ex: 71.16 ± 5.91/Con: 73.38 ± 5.81	RT: 4–6 ex; whole body; hand weights, pool noodles; 2–3 sets × 12–16 reps; Borg 6–7 AT: water exercises (running, bouncing, kicking, twister etc.); 60–70 % HRR	40–50 min	2 d for 28 wk	Non-exercise
Nunes, 2016 (High volume RT)	21 F	Postmenopausal women	NR	RT: 8 ex; whole body; free weights/machines; 3 sets × 8–12 reps; 70 % 1RM	3 d for 16 wk	3 d for 16 wk	Non-exercise
Nunes, 2016 (Low volume RT)	21 F	Postmenopausal women	NR	RT: 8 ex; whole body; free weights/machines; 3–6 sets NR × 8–12 reps; 70 % 1RM	3 d for 16 wk	3 d for 16 wk	Non-exercise
Oberbach, 2008	21 F/19 M	Impaired glucose tolerance	Ex: 58.1 (range 50–63)/Con: 59.1 (range 49–63)	AT: running, biking, swimming; whole body; 20 min/activity	60 min	2 d for 48 wk	Non-exercise
Okada, 2010	17 F/21 M	Type 2 diabetes	Ex: 61.9 ± 8.6/Con: 64.5 ± 5.9	RT: 20 min AT: aerobic dance, bicycle; 20 min/activity; training HR per Karvonen's equation at K = 0.6	75 min	3–5 d for 96 wk	Non-exercise
Orsatti, 2008	43 F	Postmenopausal women	Ex: 57.8 ± 8.0/Con: 59.3 ± 6.2	RT: 10 ex; whole body; free weights/machines; 3 sets × 8–12 reps; 60–80 % 1RM	50–60 min	3 d for 16 wk	Non-exercise
Osali, 2020 (AT)	22 F	Metabolic syndrome	Overall: 62.3 ± 1.23	AT: treadmill running/walking; 3 sets × 12–17 min; 65–75 % HRR	36–51 min	NR d for 6 wk	Non-exercise
Osali, 2020 (AT + nano-curcumin)	22 F	Metabolic syndrome	Overall: 62.3 ± 1.23	AT: treadmill running/walking; 3 sets × 12–17 min; 65–75 % HRR	36–51 min	NR d for 6 wk	Non-exercise
Otten, 2017	10 F/19 M	Type 2 diabetes	Overall: 59 ± 8	AT: cross-trainer and cycle ergometer; intervals at 45–100 % max workload RT: 3–5 ex; upper and lower body; 2–4 sets × 10–15 reps	60 min	3 d for 12 wk	Non-exercise
Pérez-López, 2022 (AT)	23 F	Sedentary + obese postmenopausal women	Ex: 56.7 ± 3.7/Con: 56.9 ± 5.8	AT: treadmill, cycle ergometer, elliptical; 55–75 % HRR	60 min	3 d for 12 wk	Non-exercise
Pérez-López, 2022 (CT)	25 F	Sedentary + obese postmenopausal women	Ex: 58.7 ± 2.9/Con: 56.9 ± 5.8	RT: 6 ex; whole body; 3 sets × 8–12 reps; 65 % 1RM AT: treadmill, cycle ergometer, elliptical; 55–75 % HRR	60 min	3 d for 12 wk	Non-exercise
Phillips, 2012	23 F	Obese postmenopausal women	Ex: 66.4 ± 2.8/Con: 64.8 ± 2.4	RT: 10 ex; whole body; 3 sets (first 2 sets 8 reps, last set NR to fatigue); 8RM	NR	3 d for 12 wk	Social interaction 2x/week
Prado, 2024	46 F/31 M	Hypertension	Ex: 66.97 ± 6.99/Con: 66.12 ± 8.03	AT: treadmill; 60–70 % HR max; RPE 5–7 if HR target not reached	50 min (not clear, typo on paper)	3 d for 12 wk	Non-exercise
Praksch, 2019	60 F	Older adults	Overall: 67.4 ± 5	AT: walking, jogging, medicine ball, aerobic exercises, basketball and football; 50–70 % VO ₂ max	45–50 min	3 d for 12 wk	Non-exercise
Rajabi, 2024 (AT + placebo)	22 F	Type 2 diabetes	Overall: 54.12 ± 5.63	AT: self-paced running, aerobic dancing; 40–80 % target HR	50 min	3 d for 12 wk	Non-exercise
Rajabi, 2024 (AT + saffron)	22 F	Type 2 diabetes	Overall: 54.12 ± 5.63	AT: self-paced running, aerobic dancing; 40–80 % target HR	50 min	3 d for 12 wk	Saffron consumption
Rankovic, 2009	23 F/29 M	Ischemic heart disease	Ex: 62.7 ± 7.1/Con: 58.4 ± 7.6	AT: treadmill, room bicycle, walking; 70–80 % HR max	45 min	3 d for 6 wk	Non-exercise
Ruangthai, 2020 (Land-based CT)	18 F/10 M	Hypertension	Ex: 67.3 ± 5.9/Con: 66.7 ± 5.8	AT: walking; 50–60 % HR max RT: 13 ex; whole body; 2 sets × 8–12 reps at 50–80 % RM	60 min	3 d for 24 wk	Non-exercise
Ruangthai, 2020 (Water-based CT)	19 F/6 M	Hypertension	Ex: 69.7 ± 6.5/Con: 66.7 ± 5.8	RT: 10 ex; upper/lower limbs and trunk; 2 sets of 12–8 reps; RPE 4–7 AT: jogging, ankle reaches, knee lifts, jumping jacks, kicks, hamstring curls, pendulums, rocking horse; 50–70 % HR max Both AT and RT underwater	60 min	3 d for 24 wk	Non-exercise

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Table 1 (continued)

Author, year (Subgroup)	Sample size	Health status	Age (mean ± SD)	Type of training: number of exercises; muscle groups; equipment/accessories; volume (sets and repetitions or duration); intensity	Duration of each session (time)	Days per week and total number of weeks	Control group activities
Ryan, 2014	95 F	Sedentary + overweight-obese postmenopausal women	Ex: 60 ± 1/Con: 61 ± 1	AT: treadmill, elliptical trainer; 50–85 % HRR	45 min	3 d for 24 wk	Weight loss
Sabouri, 2021 (HIIT)	14 F/15 M	Sedentary + type 2 diabetes	Ex: 52.02 ± 4.59/Con: 52.28 ± 3.16	AT: cycle ergometer; 10 × 60-s cycling intervals; 85–90 % HR max	30 min	3 d for 12 wk	Non-exercise
Sabouri, 2021 (HIIT + RT)	12 F/15 M	Sedentary + type 2 diabetes	Ex: 52.53 ± 4.8/Con: 52.28 ± 3.16	RT: 7 ex; whole body; machines; 3 sets × 8 reps (abdominal crunch: 3 × 15) at max load AT: cycle ergometer; 10 × 60-s cycling intervals; 85–90 % HR max	70 min	3 d for 12 wk	Non-exercise
Sabouri, 2021 (RT)	15 F/13 M	Sedentary + type 2 diabetes	Ex: 51.31 ± 4.47/Con: 52.28 ± 3.16	RT: 7 ex; whole body; machines; 3 sets × 8 reps (abdominal crunch: 3 × 15) at max load	40 min	3 d for 12 wk	Non-exercise
Sadjapong, 2020	39 F/25 M	Community dwelling older adults	Ex: 76.68 ± 1.14/Con: 78.87 ± 1.32	RT: 10 ex; lower body; elastic band; 2–3 sets × 6–12 reps; 65–100 % of 1RM or RPE 12–13 AT: 6 ex; whole body; chair-based; 40–65 % HR max or RPE 12–13	45–60 min	3 d for 24 wk	Non-exercise
Sardeli, 2022	29 F/15 M	Hypertension	Ex: 65.4 ± 4.3/Con: 65.2 ± 4.6	RT: 7 ex; whole body; machines; 1 set × 15 reps; RPE 5–6 AT: treadmill; 63 % VO ₂ max	50–65 min	3 d for 16 wk	Non-exercise
Seo, 2010 (AT)	14 F	Postmenopausal women	Ex: 55 ± 4.8/Con: 58 ± 4.2	AT: walking and exercises; 60–80 % HRR	60 min	3 d for 12 wk	Non-exercise
Seo, 2010 (CT)	15 F	Postmenopausal women	Ex: 54 ± 3.6/Con: 58 ± 4.2	RT: 8 ex; upper and lower body; machines; 3 sets × 8 reps; 50–70 % 1RM	60 min	3 d for 12 wk	Non-exercise
Shabani, 2018	22 F	Obese-overweight postmenopausal women	Ex: 54.83 ± 4.72/Con: 56.9 ± 4.93	RT: 8 ex; upper and lower body; machines; 3–8 sets × 8 reps; 50–80 % 1RM AT: treadmill and cycle ergometer; 50–80 % HHR	90 min	3 d for 8 wk	Non-exercise
Shakil-Ur-Rehman, 2018 (Female)	47 F	Type 2 diabetes	Ex: 51.31 ± 8.78/Con: 57.96 ± 6.83	AT: treadmill; 30–150 min/week (progressive over 5 phases); incline 0° to 12°	30–150 min	3 d for 25wk	Non-exercise
Shakil-Ur-Rehman, 2018 (Male)	55 M	Type 2 diabetes	Ex: 59.12 ± 5.78/Con: 55 ± 8.03	AT: treadmill; 30–150 min/week (progressive over 5 phases); incline 0° to 12°	30–150 min	3 d for 25wk	Non-exercise
Silva, 2024	29 F/7 M	Sedentary	Ex: 55.15 ± 5.72/Con: 52.24 ± 7.84	RT: 8 ex; whole body; 1–2 sets × 6–15 reps; 45–90 % 1RM AT: brisk walking, stepping, running, circuit training (within enclosed gymnasium); whole body; 60–95 % HR max	75 min	3 d for 16 wk	Non-exercise
Sixt, 2008	6 F/17 M	Prediabetes + coronary artery disease	Ex: 64 ± 6/Con: 64 ± 6	AT: cycle ergometer; 15 min six times/day (week 1), then 30 min/day (home-based for 3 weeks); 70 % HR max or 70 % max exercise capacity	60–90 min	7 d for 4 wk	Non-exercise
Son, 2020	25 F	Postmenopausal women with stage 1 hypertension	Ex: 67.7 ± 1/Con: 67.4 ± 1.1	RT: upper and lower body; resistance bands; 40–80 % 1RM with RPE 11–16	60 min	3 d for 12 wk	Non-exercise
Strandberg, 1985	35 F	Healthy + physically active older women	Ex: 68 ± 2/Con: 68 ± 1	RT: 5 ex; lower and upper body; machines; 3 sets × 8–15 NR	60 min	2 d for 24 wk	Non-exercise
Su, 2022	30 F	Diabetes + cardiovascular autonomic neuropathy	Ex: 64.01 ± 1.98/Con: 63.61 ± 2.56	RT: 3 groups of ex; whole body; dumbbells, elastic belt, 60 min bodyweight; 20 min; 70–85 % 1RM AT: treadmill walking; 65–70 % HR max	60 min	3 d for 12 wk	Non-exercise
Tan, 2018	34 F	Type 2 diabetes	Ex: 63.0 ± 2.3/Con: 62.9 ± 2.6	AT: walking and running; 20–40 min (progressive over 12 weeks); individualised HR max	60 min	3 d for 12 wk	Non-exercise
Tjoe, 2020	58 F	Breast cancer survivors	Ex: 51 ± 7/Con: 56 ± 10	Triathlon training: swimming, biking, running: whole body; 5–8 METs; 0.5-mile open water swim, 12-mile bike ride, and a 3.1-mile walk/run	90 min	6 d for 14 wk	Non-exercise
Tomeleri, 2016	38 F	Obesity	Ex: 66.8 ± 3.2/Con: 69.5 ± 4.7	RT: 8 ex; whole body; free weights and machines; 3 sets × 10–15 reps	45–50 min	3 d for 8 wk	Non-exercise
Tomeleri, 2018	45 F	Metabolic syndrome	Ex: 72.1 ± 6.3/Con: 68.8 ± 4.9	RT: 8 ex; whole body; free weights and machines; 3 sets × 10–15 reps	NR	3 d for 12 wk	Non-exercise
Tomeleri, 2023 (MJ to SJ RT)	29 F	Older women	NR (age range >60)	RT: 8 ex; whole body; free weights and machines; 3 sets × 10–15 reps	NR	3 d for 12 wk	Non-exercise
Tomeleri, 2023 (SJ to MJ RT)	30 F	Older women	NR (age range >60)	RT: 8 ex; whole body; free weights and machines; 3 sets × 10–15 reps	NR	3 d for 12 wk	Non-exercise

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Table 1 (continued)

Author, year (Subgroup)	Sample size	Health status	Age (mean ± SD)	Type of training: number of exercises; muscle groups; equipment/accessories; volume (sets and repetitions or duration); intensity	Duration of each session (time)	Days per week and total number of weeks	Control group activities
Tremblay, 2024	79 F	Postmenopausal + overweight- obese	Ex: 60.0 ± 5.0/Con: 60.0 ± 4.6	RT: 6 ex; upper and lower body; machines; 3 sets × 10 NR reps; 80 % 1RM	10–40 min	3 d for 16 wk	Non-exercise
Tsarouhas, 2011	10 F/29 M	Chronic heart failure	Ex: 66.8 ± 13.1/Con: 67.0 ± 5.6	AT: walking; 40–60 % HR max; 5000–20000+ steps/day	10–40 min	5 d for 12 wk	Non-exercise
Urzi, 2019	20 F	Older women	Ex: 84.4 ± 7.7/Con: 88.9 ± 5.3	RT: 8 ex; upper and lower body; elastic bands and chair; 3 sets × 35–40 min total; Borg RPE 12–14	60 min	3 d for 12 wk	Non-exercise
Vahlberg, 2017	12 F/31 M	Community dwelling older adults after stroke	Ex: 72.7 ± 5.5/Con: 73.7 ± 5.4	RT: circuit training: multiple lower limb strength and balance ex; lower body; weighted belts and bodyweight; >15–10–15 reps per ex	75 min	2 d for 12 wk	Non-exercise, usual care
Venojärvi, 2013 (Nordic walking)	79 F	Impaired glucose regulation + overweight- obese	Ex: 55 ± 6.2/Con: 54 ± 7.2	AT: Nordic walking (walking with walking poles); 55–75 % HRR	60 min	3 d for 12 wk	Non-exercise
Venojärvi, 2013 (RT)	76 F	Impaired glucose regulation + overweight- obese	Ex: 54 ± 6.1/Con: 54 ± 7.2	RT: upper and lower extremity and trunk ex; resistance equipment; 50–85 % 5RM with maximal/high velocity contraction	60 min	3 d for 12 wk	Non-exercise
Wadley, 2014	13 F/6 M	Rheumatoid arthritis patients	Ex: 57 ± 9/Con: 53 ± 12	AT: 3–4 intervals per circuit × 3 circuits; full body; bodyweight; 70 % VO ₂ max	30–40 min	3 d for 12 wk	Non-exercise
Wanderley, 2013 (AT)	32 F/7 M	Community-dwelling older adults, mix of chronic conditions	Ex: 69.9 ± 5.7/Con: 67.8 ± 5.5	AT: walking, stepping, dancing; 50–60 % to 70–80 % HRR	50 min	3 d for 32 wk	Usual lifestyle
Wanderley, 2013 (RT)	22 F/8 M	Community-dwelling older adults, mix of chronic conditions	Ex: 67.3 ± 4.9/Con: 67.8 ± 5.5	RT: 9 ex; upper and lower body; machines; 2 sets × 12–15 reps; 50–60 % 1RM to 80 % 1RM	50 min	3 d for 32 wk	Usual lifestyle
Wang, 2015	70 F	Sedentary, overweight, postmenopausal women	Ex: 58.4 ± 5.2/Con: 58.5 ± 6.1	AT: treadmill walking; 45–75 % HRR	Adjusted by energy expenditure goal	3 d for 20 wk	Caloric restriction alone
Weiss, 2006 (AT)	19 F/10 M	Physically healthy, sedentary adults	Ex: 59 ± 3/Con: 56 ± 3	AT: walking, treadmills and cycling; duration-based to expend 16–20 % TEE	Adjusted by energy expenditure goals	Frequency adjusted by energy expenditure goal, 48 wk	Healthy lifestyle, minimal dietary consultation and yoga classes if participant requested
Weiss, 2016 (AT + CR)	28 F/8 M	Overweight, sedentary adults	Ex: 57 ± 7/Con: 57 ± 5	AT: brisk walking, cycling; duration-based to increase TEE by ~ 20 %	No duration recommended	Recommended 7 d for Caloric restriction alone	Caloric restriction alone
Xiao, 2023	30 F/30 M	Intestinal failure with sarcopenia	Ex: 53.9 ± 14.5/Con: 51.2 ± 12.9	RT: 4 ex; upper and lower limbs, trunk; resistance bands; 3 sets × 30 reps; OMNI scale 6–9	NR	12–16 wk	Daily activity levels without resistance training
Yoon, 2019 (RT + AT)	20 F	Physically healthy older women	Ex: 65.2 ± 5.1/Con: 63.2 ± 2.62	RT: 9 ex; upper and lower body; weights; 3 sets × 8–15 reps; 60–80 % 1RM AT: cycling; stationary bike; 50–60 % HRR	30 min RT, then 30 min	3 d for 12 wk	Non-exercise
Yoon, 2019 (RT + interval training)	20 F	Physically healthy older women	Ex: 64.1 ± 3.35/Con: 63.2 ± 2.62	RT: 9 ex; upper and lower body; weights; 3 sets × 8–15 reps; 60–80 % 1RM AT: interval cycling; stationary bike, 40–90 % HRR	30 min RT, then 30 min AT	3 d for 12 wk	Non-exercise
You, 2004	50 F	Healthy, overweight/ obese post-menopausal women	Ex: 59 ± 1/Con: 57 ± 1	AT: treadmill walking; 50–70 % HRR	20 min increasing to 45–60 min	3 d for 24 wk	Hypocaloric diet alone, non-exercise
Zhang, 2023	35 F/15 M	Pre-diabetes	Ex: 61.12 ± 6.57/Con: 63 ± 4.72	RT: elastic bands; whole body; elastic bands; 2–4 sets; 60–70 % HR max	Increased from 47 min to 76 min	5 d for 24 wk	Daily routines
Ziegler, 2019	7 F/18 M	Healthy	Overall: 67 (range 62–70)	RT: 7 ex; upper and lower body; machines; 1–3 sets × 15 NR reps (adaptation), then 3 sets × 12–6 reps (progressive); 15 RM progressing to 6 RM	47 min to 76 min	3 d for 48 wk	Non-exercise

AT, Aerobic training; CI, Confidence interval; Con, Control; CR, Caloric restriction; CT, Combined training; d, Days/week; Ex, Exercise; F, Female; HA-VI, High amount-vigorous intensity; HIIT, High intensity interval training; HR, Heart rate; HRR, Heart rate reserve; HRT, Hormone replacement therapy; KKW, kcal/kg/week; LA-MI, Low amount-moderate intensity; LA-VI, Low amount-vigorous intensity; M, Male; Max, Maximum; Megestrol acetate, synthetic progesterin hormone therapy that stimulates appetite and weight gain and decreases serum testosterone levels; MET, Metabolic equivalent of task; MICT, Moderate intensity continuous training; Mins, Minutes; MJ, Multiple joint; OMNI-RES, 0–10 numerical scale of an individual's perceived muscular effort during resistance training; PRT, Progressive resistance training; Reps, Repetitions; RM, Repetition maximum; RPE, Rating of Perceived Exertion; RT, Resistance training; SD, Standard deviation; SJ, Single joint; Submax, intensity below the individual's maximum capacity; TEE, Total energy expenditure; THR, Target heart rate; wk, Weeks.

Table 2
Overall effects of exercise training on metabolic and inflammatory markers in older adults.

Variable	Overall hypothesis test			Sample size		Heterogeneity			Egger's
	K	Mean difference [LL; UL]	P-value	Intervention	Control	Q-value	df (Q)	P-value	I ² (%)
Body mass (kg)	121	-0.98 [-1.37; -0.59]	< 0.001	2646	2485	196.4	120	< 0.001	38.89
BMI (kg/m ²)	120	-0.34 [-0.45; -0.23]	< 0.001	2675	2478	427.1	119	< 0.001	72.14
Fat mass (SMD)	129	-0.48 [-0.58; -0.37]	< 0.001	2549	2435	418.9	128	< 0.001	69.44
Muscle mass (SMD)	84	0.26 [0.17; 0.35]	< 0.001	1719	1718	141.9	83	< 0.001	41.50
VO ₂ max (SMD)	67	0.82 [0.65; 0.98]	< 0.001	1601	1406	285.0	66	< 0.001	76.84
Glucose (SMD)	115	-0.49 [-0.62; -0.35]	< 0.001	2399	2236	544.5	114	< 0.001	79.06
HbA1c (SMD)	57	-0.56 [-0.77; -0.36]	< 0.001	1153	1136	295.1	56	< 0.001	81.02
Insulin (SMD)	65	-0.50 [-0.69; -0.31]	< 0.001	1468	1342	351.2	64	< 0.001	81.78
HOMA-IR (SMD)	64	-0.61 [-0.80; -0.42]	< 0.001	1426	1324	355.8	63	< 0.001	82.29
Triglycerides (SMD)	108	-0.46 [-0.61; -0.30]	< 0.001	2214	2106	616.8	107	< 0.001	82.65
Total Cholesterol (SMD)	98	-0.36 [-0.5; -0.21]	< 0.001	2068	1959	462.0	97	< 0.001	79.01
HDL-C (SMD)	111	0.41 [0.28; 0.54]	< 0.001	2256	2136	461.6	110	< 0.001	76.17
LDL-C (SMD)	99	-0.54 [-0.7; -0.37]	< 0.001	2073	1973	609.2	98	< 0.001	83.91
CRP (SMD)	117	-0.42 [-0.53; -0.30]	< 0.001	2913	2736	457.1	116	< 0.001	74.62
IL-6 (SMD)	93	-0.33 [-0.46; -0.20]	< 0.001	2207	2118	387.1	92	< 0.001	76.23
TNF-α (SMD)	65	-0.38 [-0.55; -0.21]	< 0.001	1568	1488	320.3	64	< 0.001	80.02
Adiponectin (SMD)	45	0.39 [0.17; 0.60]	< 0.001	1108	972	232.3	44	< 0.001	81.06
Leptin (SMD)	45	-0.49 [-0.75; -0.24]	< 0.001	843	799	264.6	44	< 0.001	83.37
IGF-1 (SMD)	31	0.44 [0.22; 0.66]	< 0.001	494	493	83.0	30	< 0.001	63.85
IL-1β (SMD)	10	-0.31 [-0.72; 0.11]	0.144	262	270	44.2	9	< 0.001	79.64

BMI, Body mass index; CRP, C-Reactive Protein; df, Degrees of freedom; HbA1c, Glycated haemoglobin; HDL-C, High density lipoprotein cholesterol; HOMA-IR, Homeostasis model assessment of insulin resistance; I², Percentage of inconsistency; IGF-1, Insulin-like growth factor 1; IL-1β, Interleukin-1 beta; IL-6, Interleukin-6; K, Number of studies; LDL-C, Low density lipoprotein cholesterol; LL, Lower limit; Q-value, True heterogeneity; SMD, Standardised mean difference; TG, Triglycerides; TNF-α, Tumour necrosis factor alpha; UL, Upper limit. Confidence intervals and p values in bold are significant (p < 0.05).

6–10 on PEDro scale, studies reporting at least 8 h overnight fasting before tests, studies performing the assessments at least post 48 h from the last exercise session. Heterogeneity between the studies was quantified through the I² statistic, which indicates the percentage of inconsistency between studies (Higgins et al., 2003). Meta-regression analyses using random-effects model (method of moments), two-side p-value, and Z-distribution was conducted to examine whether variations in the standardised mean difference (SMD) of each outcome variable could be explained by differences in volume of training per week (minutes per week) and total volume of training (minutes of training per week multiplied by total number of weeks). All statistical analyses were performed on Biostat's Comprehensive Meta-Analysis software (version 3.0; New Jersey, USA). There was no funding source for this study.

3. Results

From 3170 studies initially identified, 1611 studies remained after duplicate removal. Subsequently, 981 studies were excluded based on title and abstract screening, resulting in 630 studies proceeding to full-text assessment. Fig. 2 shows the reason for exclusion of the 484 studies during full-text screening. The most common reasons for exclusion were the lack of a non-exercise control group (n = 96), a mean age < 50 (n = 65), and no inflammatory marker being reported (n = 38). This resulted in 146 studies being included in the systematic review.

3.1. Study characteristics

The median risk of bias, assessed by PEDro scale, was 5, with an interquartile range (IQR) between 5 and 6, and overall range from 1 to 8. Supplementary Table 2 indicates most studies were rated between fair (4–5) and good quality (6–8). Scores were inherently lowered by the practical difficulties in blinding participants and evaluators between control and exercise groups in intervention studies.

The characteristics of studies are shown in Table 1. Briefly, the median sample size of included studies was 38 (IQR 26–56), while median age and BMI of the intervention groups were 63.2 years (IQR 57.8, 68) and 28.6 kg/m² (IQR 26.8–30.6), respectively. Specifically, there were 26, 104 and 57 studies including normal weight (BMI = 20–24.9 kg/m²), overweight (BMI = 25–29.9 kg/m²) and obese (BMI > 30 kg/m²) participants respectively. Within the included studies, there were 91 studies with female only arms, 30 studies with male only arms and 79 studies mixing sexes. While 90 arms included healthy participants, 110 included participants with chronic conditions, and within those 77 included participants with type 2 diabetes (T2d) specifically. A high number of studies including obese/overweight participants with T2d was expected given the importance of both inflammation and metabolism in the treatment of obesity and T2d. Regarding exercise protocols, 78 study-arms tested aerobic training (AT), 76 resistance tested training (RT) and 46 tested combined training (CT). One-hundred forty-five interventions (79 %) employed an exercise frequency of 3 days/week, and 12 weeks was the median intervention duration (range 4–96 weeks). The median length of intervention and range for each type of exercise was 12 weeks (range 4–96 weeks) for both AT and RT, and 16 weeks (range 6–96 weeks) for CT. Only 53.4 % of AT studies, meet AT guidelines for older adults (Chodzko-Zajko et al., 2009), defined as a minimum of 150 min of moderate exercise per week, or 75 min of high intensity exercise or a mix of both (calculated as a minimum of 150 min, where 1 min of high intensity was computed as 2 min). On the other hand, 97.3 % of RT studies meet the RT guidelines (at least twice a week of moderate intensity RT), and 66 % met both AT and RT guidelines within CT studies (Chodzko-Zajko et al., 2009). Fourteen per cent of all studies did not provide enough detail for this classification and were excluded from these analyses. Adverse events were monitored by 5 studies (Fairey et al., 2005; Messier et al., 2013; Banitalebi et al., 2020; Gómez-Tomás et al., 2018; Kadoglou et al., 2013). One study described the general adverse events in the intervention (lymphedema,

Table 3
Subgroup analysis for the effect of exercise protocol design and participant characteristics on body composition.

	Body mass (RMD)				BMI (RMD)				Fat mass (SMD)				Muscle mass (SMD)			
	K		PE [LL; UL]		K		PE [LL; UL]		K		PE [LL; UL]		K		PE [LL; UL]	
	Diff				Diff				Diff				Diff			
Overall	RE	121	-0.98 [-1.37; -0.59]		120		-0.34 [-0.45; -0.23]		129		-0.48 [-0.58; -0.37]		84		-0.26 [-0.17; 0.35]	
Exercise	AT	48	-1.2 [-1.62; -0.78]	0.06	58		-0.42 [-0.54; -0.29]	0.11	46		-0.69 [-0.89; -0.5]		27		-0.28 [-0.12; 0.44]	0.72
	RT	43	-0.21 [-0.91; 0.5]		32		-0.13 [-0.42; 0.16]		54		-0.24 [-0.38; -0.1]		33		-0.21 [-0.07; 0.35]	
	CT	30	-0.99 [-1.57; -0.41]		30		-0.45 [-0.49; -0.41]		29		-0.59 [-0.84; -0.34]		24		0.3 [0.1; 0.5]	
Frequency (d/week)	<2	11	-0.25 [-1.38; 0.88]	0.37	11		-0.38 [-0.72; -0.03]	0.43	15		-0.22 [-0.39; -0.05]		11		-0.22 [-0.02; 0.42]	0.58
	3	96	-1.03 [-1.5; -0.56]		89		-0.27 [-0.41; -0.12]		93		-0.36 [-0.45; -0.26]		66		-0.21 [-0.11; 0.31]	
	>4	9	-1.15 [-1.7; -0.48]		14		-0.42 [-0.62; -0.22]		13		-1.62 [-2.41; -0.83]		2		1.6 [-1.01; 4.22]	
Duration (weeks)	<12	71	-1.09 [-1.7; -0.48]	0.16	65		-0.36 [-0.55; -0.17]	0.14	75		-0.37 [-0.48; -0.25]		44		-0.24 [-0.09; 0.41]	0.97
	13-24	31	-0.49 [-0.89; -0.09]		33		-0.24 [-0.4; -0.08]		37		-0.59 [-0.84; -0.34]		26		-0.27 [-0.12; 0.43]	
	>24	19	-1.22 [-2.15; -0.28]		22		-0.58 [-0.88; -0.28]		17		-0.68 [-1; -0.35]		14		-0.26 [-0.08; 0.44]	
Healthy	Yes	64	-0.6 [-1.13; -0.07]	0.05	53		-0.13 [-0.27; 0.02]	<0.01	62		-0.26 [-0.37; -0.14]		39		-0.22 [-0.09; 0.35]	0.43
	No	57	-1.3 [-1.77; -0.83]		67		-0.52 [-0.67; -0.37]		67		-0.68 [-0.86; -0.51]		45		-0.29 [-0.16; 0.42]	
Sex	Female	62	-1.12 [-1.47; -0.77]	0.25 ^a	51		-0.37 [-0.58; -0.15]	0.46 ^a	67		-0.43 [-0.56; -0.3]		32		-0.22 [-0.09; 0.36]	0.17 ^a
	Male	18	-0.4 [-1.57; 0.77]		17		-0.23 [-0.53; 0.07]		15		-0.29 [-0.49; -0.09]		11		-0.56 [-0.09; 1.03]	
	Mixed	41	-0.84 [-1.37; -0.31]		52		-0.38 [-0.53; -0.23]		47		-0.58 [-0.8; -0.36]		41		-0.26 [-0.14; 0.38]	0.46
Age	<65 y	70	-0.95 [-1.26; -0.64]	0.42	74		-0.41 [-0.54; -0.28]	0.30	79		-0.6 [-0.75; -0.44]		47		-0.23 [-0.11; 0.35]	
	≥65 y	51	-0.64 [-1.32; 0.05]		46		-0.27 [-0.5; -0.04]		50		-0.3 [-0.44; -0.16]		37		0.3 [0.15; 0.45]	0.56
Diabetes	Yes	80	-0.98 [-1.46; -0.49]	0.71	72		-0.34 [-0.51; -0.18]	0.43	82		-0.39 [-0.5; -0.27]		51		-0.33 [-0.2; 0.45]	
	No	22	-1.21 [-2.3; -0.11]		26		-0.45 [-0.64; -0.25]		25		-1.09 [-1.51; -0.67]		14		-0.23 [-0.05; 0.51]	0.23
BMI (kg/m ²)	18-25	13	-0.69 [-2.15; 0.78]	0.68	17		-0.42 [-0.63; -0.21]	0.57	16		-0.38 [-0.6; -0.17]		9		-0.7 [0.08; 1.32]	
	25-30	60	-1.09 [-1.49; -0.68]		59		-0.47 [-0.7; -0.23]		69		-0.38 [-0.5; -0.26]		44		-0.27 [-0.16; 0.37]	
	>30	44	-0.82 [-1.37; -0.26]		42		-0.32 [-0.48; -0.17]		35		-0.71 [-0.99; -0.44]		24		-0.19 [-0.05; 0.32]	

^a, analysis only between females and males; AT, Aerobic training; BMI, Body mass index; CT, Combined training; Diff, p value of difference between all categories of the sub group; d/week, Days per week; K, Number of studies; LL, Lower limit; PE, Point estimate; RE, Random effects; RT, Resistance training; SMD, Standardised mean difference; UL, Upper limit. Confidence intervals and p values in bold are significant (p < 0.05).

gynaecological complications and influenza) and control groups (fracture and bronchitis) (Fahey et al., 2005). Other studies specifically reported the events occurring during the exercise sessions, such as muscle strain and falls, that resulted in soreness and bruising (Messier et al., 2013) or in the following 48 hours post-exercise, such as muscle soreness, knee pain, and shoulder pain (Banitalebi et al., 2020).

3.2. Overall effects of exercise training on metabolic and inflammatory markers in older adults

Table 2 shows the summarised effects of the overall meta-analysis, and basic characteristics of analysis, confirming that exercise training significantly improved all outcomes tested, except for IL-1 β . A very high number of study arms were included in each meta-analysis, such as 117 for CRP (n = 5649) and 129 for fat mass (n = 4112). Although the precision of the confidence intervals and the directness of the evidence was supported by these large sample sizes and the analysis of controlled studies, respectively; the quality of evidence in each meta-analysis was low (GRADE = 2). The main reasons were the significant heterogeneity (p value < 0.05) and the high risk of publication bias evaluated by Egger's test in each meta-analysis (p < 0.05).

We assumed the risk of bias from some studies (< 6 points on PEDro scale) did not influence the overall quality of the evidence. Nevertheless, we tested subgroup analysis for quality control variables, such as the influence of studies quality (< 6 vs 6–10 on PEDro scale), overnight fasting ($\geq$ 8 h fasting vs no reported fasting) and time post last exercise session ($\geq$ 48 post last exercise session vs not reported). For majority of the variables analysed, these subgroups showed similar results in each low and high-quality group and more importantly, high-quality groups showed the same effects observed for the overall meta-analysis (Supplementary Table 3). Forest plots for each meta-analysis, by exercise type, are presented in the Supplementary material (Supplementary Figs. 1–20). Although there are outliers in the analyses, the inspection of the leave-one-out meta-analyses confirmed the absence of influence of outliers in the main results. This was prevented using random effects models and the high number of studies in each analysis, ultimately leading to very small relative weights (percentual contribution) from each study.

3.3. The effect of exercise protocol design and participant characteristics on body composition, metabolic and inflammatory markers

The effects of exercise training protocol features and participant characteristics on each metabolic and inflammatory marker via subgroup meta-analyses are shown in Tables 3–6b. To facilitate navigation through the large volume of results, all the subgroup meta-analysis are integrated in one single table at OSF HOME (https://osf.io/4jxs5/?view_only=5bd44d7a9a26417ba7a2ce41a06bddf4).

Only AT and CT reduced body mass and BMI, while all types of training increased muscle mass and reduced fat mass significantly, with higher fat mass reduction for AT and CT, compared to RT (Table 3). Although all exercise modalities improved VO₂ max (Supplementary Table 4), RT was less effective (0.28 [0.05–0.51]), compared to AT (0.96 [0.75–1.17] and CT (0.87 [0.49–1.25]). On the other hand, no difference was observed between different exercise modalities for muscle mass gains (Table 3). Similarly, no difference was identified for glucose metabolism (Table 4). Although all three types of exercise modalities led to improvements in lipid metabolism, AT led to greater reductions in TG and greater increases in HDL-C, than RT (Table 5). While AT was the most effective intervention for anti-inflammatory effects, only RT and CT increased IGF-1 (Tables 6a and 6b).

Overall, greater exercise training frequency was associated with a greater reduction in fat mass (Table 3) and training twice a week was not sufficient to reduce fasting insulin, HOMA-IR, TG, TChol, IL-6, TNF- α , Leptin, or increase adiponectin and IGF-1 (Tables 4–6b). Meta-regressions (Supplementary Table 5) showed that higher volume of

Table 4
Subgroup analysis for the effect exercise protocol design and participant characteristics on glucose metabolism.

	Glucose (SMD)				HbA1c (SMD)				Insulin (SMD)				HOMA-IR (SMD)			
	K	PE [LL; UL]		Diff	K	PE [LL; UL]		Diff	K	PE [LL; UL]		Diff	K	PE [LL; UL]		Diff
		RE	AT			RE	AT			RE	AT			RE	AT	
Overall	115	-0.49 [-0.62; -0.35]	-0.5 [-0.75; -0.26]	0.15	57	-0.56 [-0.77; -0.36]	-0.86 [-1.29; -0.43]	0.21	65	-0.5 [-0.69; -0.31]	-0.57 [-0.86; -0.29]	0.80	64	-0.61 [-0.8; -0.42]	-0.66 [-0.97; -0.36]	0.63
Exercise	44	-0.5 [-0.75; -0.26]	-0.61 [-0.85; -0.37]		19	-0.86 [-1.29; -0.43]	-0.44 [-0.76; -0.12]		27	-0.57 [-0.86; -0.29]	-0.45 [-0.8; -0.09]		24	-0.66 [-0.97; -0.36]	-0.49 [-0.81; -0.17]	
RT	39	-0.61 [-0.85; -0.37]	-0.31 [-0.5; -0.12]		19	-0.41 [-0.7; -0.13]	-0.49 [-0.87; -0.12]		21	-0.44 [-0.81; -0.07]	-0.25 [-0.82; -0.32]		18	-0.73 [-1.16; -0.29]	-0.31 [-0.77; -0.16]	
CT	32	-0.31 [-0.5; -0.12]	-0.53 [-0.91; -0.14]	0.71	8	-0.49 [-0.87; -0.12]	-0.43 [-0.63; -0.22]		17	-0.44 [-0.81; -0.07]	-0.4 [-0.58; -0.22]	0.06	6	-0.31 [-0.77; -0.16]	-0.45 [-0.62; -0.28]	0.02
Frequency (d/week)	7	-0.53 [-0.91; -0.14]	-0.47 [-0.62; -0.31]		35	-0.43 [-0.63; -0.22]	-1.07 [-1.71; -0.44]		50	-0.4 [-0.58; -0.22]	-0.65 [-1.04; -0.27]		48	-0.45 [-0.62; -0.28]	-0.64 [-0.89; -0.41]	
≥ 4	11	-0.71 [-1.27; -0.14]	-0.54 [-0.75; -0.32]	0.74	14	-1.07 [-1.71; -0.44]	-0.76 [-1.36; -0.16]		7	-0.6 [-0.9; -0.3]	-0.49 [-0.74; -0.24]	0.61	9	-0.26 [-0.45; -0.07]	-0.64 [-1.01; -0.27]	0.81
Duration (weeks)	65	-0.54 [-0.75; -0.32]	-0.46 [-0.67; -0.26]		29	-0.48 [-0.71; -0.25]	-0.6 [-0.9; -0.3]		32	-0.65 [-1.04; -0.27]	-0.17 [-0.29; -0.05]	< 0.01	33	-0.64 [-0.89; -0.41]	-0.5 [-0.88; -0.12]	< 0.01
13-24	33	-0.46 [-0.67; -0.26]	-0.4 [-0.69; -0.11]	0.03	16	-0.76 [-1.36; -0.16]	-0.08 [-0.31; 0.15]		20	-0.65 [-1.04; -0.27]	-0.75 [-1.08; -0.42]	0.84 ^a	22	-0.64 [-1.01; -0.27]	-0.89 [-1.2; -0.57]	0.23 ^a
> 24	17	-0.4 [-0.69; -0.11]	-0.33 [-0.48; -0.18]		12	-0.6 [-0.9; -0.3]	-0.69 [-0.92; -0.45]		13	-0.49 [-0.74; -0.24]	-0.53 [-0.83; -0.24]		9	-0.5 [-0.88; -0.12]	-0.34 [-0.64; -0.05]	
Healthy	50	-0.33 [-0.48; -0.18]	-0.62 [-0.83; -0.41]	0.58 ^a	11	-0.08 [-0.31; 0.15]	-0.57 [-0.88; -0.25]		30	-0.17 [-0.29; -0.05]	-0.45 [-0.74; -0.15]	0.16	26	-0.21 [-0.33; -0.08]	-0.78 [-1.04; -0.51]	< 0.01
No	65	-0.62 [-0.83; -0.41]	-0.51 [-0.82; -0.2]		46	-0.69 [-0.92; -0.45]	-0.32 [-0.7; 0.06]		35	-0.75 [-1.08; -0.42]	-0.31 [-0.59; -0.03]	0.43	38	-0.89 [-1.2; -0.57]	-0.25 [-0.43; -0.07]	0.01
Sex	54	-0.62 [-0.85; -0.39]	-0.52 [-0.7; -0.34]	0.43	19	-0.57 [-0.88; -0.25]	-0.73 [-0.98; -0.48]		23	-0.53 [-0.83; -0.24]	-0.48 [-0.71; -0.25]	0.33	24	-0.59 [-0.87; -0.31]	-1.07 [-1.52; -0.62]	0.14
Female	15	-0.51 [-0.82; -0.2]	-0.42 [-0.61; -0.22]		7	-0.32 [-0.7; 0.06]	-0.81 [-1.12; -0.5]		10	-0.59 [-0.9; -0.24]	-0.44 [-0.91; 0.03]	0.33	10	-0.34 [-0.64; -0.05]	-0.42 [-0.65; -0.21]	
Mixed	46	-0.34 [-0.52; -0.16]	-0.52 [-0.7; -0.34]	0.01	32	-0.45 [-0.74; -0.15]	-0.15 [-0.44; -0.16]		32	-0.45 [-0.74; -0.15]	-0.37 [-0.67; -0.1]	0.34	30	-0.73 [-1.07; -0.39]	-0.83 [-1.17; -0.48]	
< 65 y	75	-0.52 [-0.7; -0.34]	-0.41 [-0.59; -0.22]		44	-0.73 [-0.98; -0.48]	-0.39 [-0.69; -0.08]		45	-0.57 [-0.8; -0.33]	-0.44 [-0.91; 0.03]	0.33	43	-0.78 [-1.04; -0.51]	-0.42 [-0.65; -0.21]	
≥ 65 y	40	-0.42 [-0.61; -0.22]	-0.41 [-0.59; -0.22]		13	-0.06 [-0.22; 0.1]	-0.15 [-0.44; -0.16]		20	-0.31 [-0.59; -0.03]	-0.37 [-0.67; -0.1]	0.33	21	-0.25 [-0.43; -0.07]	-0.42 [-0.65; -0.21]	
Diabetes	65	-0.41 [-0.59; -0.22]	-0.86 [-1.12; -0.6]	< 0.01	20	-0.39 [-0.69; -0.08]	-0.15 [-0.44; -0.16]		37	-0.48 [-0.71; -0.25]	-0.44 [-0.91; 0.03]	0.33	35	-0.43 [-0.63; -0.22]	-0.42 [-0.65; -0.21]	
No	32	-0.86 [-1.12; -0.6]	-0.05 [-0.27; 0.17]		31	-0.81 [-1.12; -0.5]	-0.37 [-0.67; -0.1]		20	-0.68 [-1.12; -0.24]	-0.44 [-0.91; 0.03]	0.33	23	-1.07 [-1.52; -0.62]	-0.42 [-0.65; -0.21]	
Yes	14	-0.05 [-0.27; 0.17]	-0.38 [-0.54; -0.22]		3	0.15 [-0.16; 0.46]	-0.37 [-0.55; -0.18]		5	-0.44 [-0.91; 0.03]	-0.37 [-0.67; -0.1]	0.33	4	-0.65 [-1.04; -0.27]	-0.42 [-0.65; -0.21]	
BMI (kg/m ²)	18-25	-0.38 [-0.54; -0.22]	-0.73 [-1.01; -0.46]		31	-0.37 [-0.55; -0.18]	-0.15 [-0.44; -0.16]		33	-0.37 [-0.67; -0.1]	-0.37 [-0.67; -0.1]	0.33	31	-0.42 [-0.65; -0.21]	-0.42 [-0.65; -0.21]	
25-30	63	-0.38 [-0.54; -0.22]	-0.73 [-1.01; -0.46]		19	-1.15 [-1.64; -0.67]	-0.37 [-0.55; -0.18]		27	-0.67 [-1.1; -0.34]	-0.37 [-0.67; -0.1]	0.33	27	-0.83 [-1.17; -0.48]	-0.42 [-0.65; -0.21]	
> 30	34	-0.73 [-1.01; -0.46]														

^a, analysis only between females and males; AT, Aerobic training; BMI, Body mass index; CT, Combined training; Diff, p value of difference between all categories of the sub group; d/week, Days per week; HbA1c, Glycated haemoglobin; HOMA-IR, Homeostatic Model Assessment for Insulin Resistance; K, Number of studies; LL, Lower limit; PE, Point estimate; RE, Random effects; RT, Resistance training; SMD, Standardised mean difference; UL, Upper limit; Confidence intervals and p values in bold are significant (p < 0.05).

training in minutes per week, led to higher reduction in fat mass ($r^2 = 0.02$, $p = 0.02$, $k = 95$) and insulin ($r^2 = 0.04$, $p = 0.03$, $k = 53$). Notably, the length of the exercise training intervention did not influence body composition, glucose metabolism, or lipid metabolism adaptations (Table 3-6a). The lack of effect from different lengths of interventions could be due to high variance within studies. However, there was a trend ($p = 0.08$) for higher reduction in fat mass with longer interventions (≤ 12 weeks: -0.37 [-0.48; -0.25], $K = 75$; 13-24 weeks: -0.59 [-0.84; -0.34], $K = 37$; > 24 weeks: -0.68 [-1; -0.35], $K = 17$), that was confirmed via meta-regression (Supplementary Table 5). On the other hand, interventions of shorter durations were significantly more effective than interventions of longer duration to reduce TNF- α , Leptin, IL-1 β and to increase IGF-1 (Tables 6a and 6b).

After classifying the exercise intensity for each study arm according to recent terminology recommendations (Bishop et al., 2024), complementary subgroup analyses for the effects of AT and RT intensity were performed (Supplementary Table 6). Overall, intensity alone did not explain greater changes in metabolic and inflammatory markers, except for the reduction in LDL-C and increase in HDL-C, which were significant only at higher intensities of AT and RT, and the reduction in TC and TG that occurred only with very high intensity RT. These results should be interpreted with caution, given the low number of studies in some categories.

To integrate volume and intensity and allow further comparison with exercise guidelines, a subgroup analysis between studies meeting or not the exercise guidelines for older adults' health (Chodzko-Zajko et al., 2009) was presented in Supplementary Table 7. Interestingly, sufficient or insufficient CT led to improvements in VO₂ max, body composition, glucose and lipid metabolism. Sufficient or insufficient AT increased VO₂ max, reduced body mass, BMI and fat mass, but AT did not increase muscle mass, while only sufficient RT reduced fat and increased muscle mass. Only sufficient AT or RT improved markers of glucose and lipid metabolism, except for a reduction in insulin, HOMA-IR and TChol that was also observed with insufficient AT as well. Only sufficient CT, AT or RT reduced CRP, and sufficient CT or AT reduced IL-6. Only sufficient RT increased adiponectin, IGF-1, and reduced leptin. Insufficient or sufficient RT reduced TNF- α .

Only older adults under 65 years old, significantly reduced body mass and IL-6 in response to exercise interventions (Tables 3 and 6a). Compared to those over 65, interventions in this younger subgroup led to greater reductions in fat mass, HbA1c, HOMA-IR, TG TChol, LDL-C, CRP, and a greater increase in HDL-C (Tables 3-6a).

Within the health status subgroups, only interventions in individuals with diseases (including T2d, metabolic syndrome, obesity, osteo-sarcopenic obesity, hypertension, breast or prostate cancer, chronic kidney disease, and coronary artery disease), and not in disease-free individuals, significantly reduced BMI, HbA1c, TChol, IL-6 and TNF- α (Tables 3-6a). These interventions also led to greater reductions in body mass, fat mass, fasting glucose and insulin, HOMA-IR, TG, CRP, and produced greater increases in HDL-C compared to interventions in healthy individuals (Tables 3-6a). Specifically, in individuals with T2d, interventions led to greater reductions in fat mass, fasting glucose, HOMA-IR, TG, TChol, LDL-C, IL-6, and increased HDL-C and IGF-1, and only people living with T2d exhibited a significant reduction in IL-1 β (Tables 3-6b). Conversely, only people without T2d increased muscle mass and adiponectin, and reduced leptin (Tables 3 and 6b). Normal-weight individuals did not show improvements in reducing body mass, fasting glucose or insulin, HbA1c, TG, TChol, LDL-C, IL-6, TNF- α , or leptin, nor did they exhibit increases in adiponectin (Tables 3-6b). However, obese individuals did not show increases in IGF-1 (Table 6b). Women showed greater improvements than men in LDL-C, CRP, leptin and IGF-1; and the men subgroup did not reduce body mass, BMI, HbA1c, CRP, TNF- α and IL-1 β (Tables 3-6b).

Table 5
Subgroup analysis for the effect of exercise protocol design and participant characteristics on lipid metabolism.

	Triglycerides (SMD)			Total Cholesterol (SMD)			HDL-C (SMD)			LDL-C (SMD)		
	K	PE [LL; UL]	Diff	K	PE [LL; UL]	Diff	K	PE [LL; UL]	Diff	K	PE [LL; UL]	Diff
Overall	108	-0.46 [-0.61; -0.3]		98	-0.36 [-0.5; -0.21]		111	0.41 [0.28; 0.54]		99	-0.54 [-0.7; -0.37]	
Exercise	42	-0.66 [-0.96; -0.37]	0.04	35	-0.37 [-0.61; -0.13]	0.47	42	0.61 [0.36; 0.86]	0.03	35	-0.62 [-0.92; -0.32]	0.79
RT	31	-0.46 [-0.73; -0.2]		28	-0.5 [-0.81; -0.19]		33	0.39 [0.11; 0.67]		30	-0.5 [-0.81; -0.19]	
CT	35	-0.22 [-0.42; -0.01]		35	-0.26 [-0.48; -0.04]		36	0.24 [0.13; 0.35]		34	-0.49 [-0.74; -0.24]	
Frequency (d/week)	9	-0.16 [-0.56; 0.24]	< 0.01	9	-0.34 [-0.85; 0.17]	0.04	10	0.65 [0.2; 1.09]	0.04	9	-1.02 [-1.72; -0.32]	< 0.01
3	75	-0.28 [-0.42; -0.14]		68	-0.26 [-0.4; -0.11]		78	0.29 [0.16; 0.43]		69	-0.32 [-0.46; -0.18]	
≥ 4	17	-1.66 [-2.39; -0.93]		16	-0.98 [-1.52; -0.44]		16	0.89 [0.36; 1.42]		16	-1.53 [-2.31; -0.74]	
Duration (weeks)	55	-0.28 [-0.43; -0.13]	0.05	46	-0.34 [-0.55; -0.12]	0.58	54	0.34 [0.19; 0.5]	0.57	45	-0.44 [-0.66; -0.22]	0.31
13-24	35	-0.77 [-1.13; -0.41]		37	-0.44 [-0.7; -0.18]		37	0.51 [0.23; 0.79]		36	-0.51 [-0.79; -0.24]	
> 24	18	-0.4 [-0.78; -0.02]		15	-0.25 [-0.51; 0.01]		20	0.4 [0.13; 0.68]		18	-0.85 [-1.33; -0.37]	
Healthy	39	-0.21 [-0.35; -0.06]	< 0.01	32	-0.19 [-0.39; 0.01]	0.07	40	0.56 [0.37; 0.75]	< 0.01	34	-0.39 [-0.58; -0.2]	0.13
No	69	-0.64 [-0.86; -0.41]		66	-0.45 [-0.64; -0.26]		71	0.56 [0.37; 0.75]	0.54 ^a	65	-0.63 [-0.86; -0.39]	0.05 ^a
Female	47	-0.43 [-0.65; -0.21]	0.24 ^a	39	-0.44 [-0.69; -0.2]	0.25 ^a	46	0.44 [0.23; 0.64]		41	-0.54 [-0.77; -0.32]	
Male	11	-0.25 [-0.45; -0.05]		12	-0.26 [-0.46; -0.06]		15	0.35 [0.15; 0.55]		13	-0.26 [-0.43; -0.09]	
Mixed	50	-0.55 [-0.81; -0.29]		47	-0.32 [-0.53; -0.11]		50	0.41 [0.2; 0.63]		45	-0.63 [-0.94; -0.33]	
Age	70	-0.62 [-0.86; -0.39]	< 0.01	64	-0.47 [-0.66; -0.27]	0.04	72	0.54 [0.34; 0.73]	< 0.01	64	-0.67 [-0.91; -0.44]	0.02
< 65 y	38	-0.25 [-0.36; -0.13]		34	-0.18 [-0.38; 0.03]		39	0.21 [0.11; 0.32]		35	-0.32 [-0.51; -0.13]	< 0.01
Diabetes	62	-0.36 [-0.53; -0.2]	0.01	52	-0.28 [-0.46; -0.1]	0.01	60	0.33 [0.17; 0.48]	0.01	50	-0.35 [-0.52; -0.19]	< 0.01
No	24	-1.21 [-1.82; -0.61]	< 0.01	26	-0.84 [-1.24; -0.44]	< 0.01	28	0.87 [0.5; 1.24]	0.01	28	-1.29 [-1.8; -0.78]	< 0.01
Yes	14	-0.09 [-0.26; 0.08]		10	0 [-0.19; 0.18]		13	0.23 [0.03; 0.43]	0.01	10	-0.07 [-0.32; 0.17]	< 0.01
BMI (kg/m ²)	59	-0.33 [-0.48; -0.18]		60	-0.28 [-0.44; -0.13]		63	0.28 [0.16; 0.4]		61	-0.46 [-0.64; -0.28]	
18-25	26	-1.14 [-1.66; -0.63]		21	-0.75 [-1.19; -0.31]		26	0.95 [0.5; 1.4]		20	-1.03 [-1.6; -0.46]	

^a, analysis only between females and males; AT, Aerobic training; BMI, Body mass index; CT, Combined training; Diff, p value of difference between all categories of the sub group; d/week, Days per week; HDL-C, High density lipoprotein cholesterol; K, Number of studies; LDL-C, Low density lipoprotein cholesterol; LL, Lower limit; PE, Point estimate; RE, Random effects; RT, Resistance training; SMD, Standardised mean difference; UL, Upper limit. Confidence intervals and p values in bold are significant (p < 0.05).

3.4. The effect of secondary adaptations on body composition, glucose metabolism, lipid metabolism and inflammatory markers

The SMDs for all variables from each study are presented in [Supplementary Table 8](#). For each outcome we performed subgroup analyses by dividing studies into two categories, whether they showed a statistically significant improvement in the outcomes or not. This approach allowed us to explore associations and dependency between metabolic and inflammatory adaptations ([Tables 7–10b](#)).

3.4.1. Body composition

[Table 7](#) shows subgroup body composition meta-analyses. Changes in body composition occurred with or without improvements in glucose or lipid metabolism; however, there was greater reduction in fat mass in interventions that led to reductions in fasting glucose and insulin, HbA1c, HOMA-IR, TG, TChol and LDL-C, and increases in HDL-C. The increase in muscle mass was greater in interventions that reduced insulin and TG and tended to be greater in interventions that reduced TChol (p=0.07). Only interventions that elicited a statistically significant increase in VO₂ max reduced BMI and increased muscle mass; and the interventions that increased VO₂ max elicited a higher fat mass reduction. Interventions that significantly reduced CRP, IL-6, leptin and increased adiponectin also elicited greater reductions in fat mass. There was a trend (p=0.06) for interventions increasing IGF-1 to result in greater increases in muscle mass. Only interventions reducing leptin, significantly reduced body mass.

3.4.2. Glucose metabolism

[Table 8](#) shows subgroup glucose metabolism meta-analyses. Significant improvements in glucose metabolism occurred even without significant improvements in body composition. However, interventions causing a significant reduction in BMI led to greater reductions in fasting glucose and insulin, HbA1c and HOMA-IR, whilst the significant reduction in fat mass led to a greater reduction in fasting insulin, HbA1c and HOMA-IR. Interventions significantly improving lipid metabolism (TG, TChol, HDL-C and LDL-C) elicited greater improvements in glucose metabolism (fasting glucose and insulin, HbA1c and HOMA-IR). There was a significantly greater reduction in glucose metabolism (all markers) when VO₂ max was significantly increased. Greater improvements in fasting insulin and HOMA-IR occurred when interventions brought about an anti-inflammatory effect (i.e., a reduction in CRP, TNF-α, IL-6 and leptin), but fasting glucose and HbA1c were not influenced as much by the modulation of inflammatory markers.

3.4.3. Lipid metabolism

[Table 9](#) shows subgroup lipid metabolism meta-analyses. Although improvements in lipid metabolism were significant even without significant improvements in body composition; interventions reducing fat mass elicited greater reductions in TG, TChol, LDL-C and increases in HDL-C; and interventions increasing muscle mass elicited greater reductions in TG and TChol. Interventions improving glucose metabolism, or increasing VO₂ max, or reducing CRP results in greater improvements in all lipid markers. Interventions increasing IGF-1 elicited greater reductions in TChol and LDL-C, while interventions reducing IL-6 elicited a greater reduction in TChol and a greater increase in HDL-C. Within the small set of interventions testing IL-1β, only interventions reducing IL-1β also elicited significant reductions in TG, TChol, LDL-C and tended to increase HDL-C (p=0.07).

3.4.4. Inflammatory markers

[Tables 10a and 10b](#) show subgroup inflammatory markers meta-analyses. Interventions significantly reducing fat mass elicited greater reductions in CRP and leptin and tended to reduce IL-6 to a greater extent. Only interventions reducing fat mass increased adiponectin. Increase in muscle mass did not explain the improvements in inflammatory markers, although CRP reduced the most in interventions that

Table 6a

Subgroup analysis for the effect of exercise protocol design and participant characteristics on inflammatory markers.

		CRP SMD			IL-6 SMD			TNF- α SMD		
		K	PE [LL; UL]	P diff	K	PE [LL; UL]	P diff	K	PE [LL; UL]	P diff
Overall	RE	117	-0.42 [-0.53; -0.3]		93	-0.33 [-0.46; -0.2]		65	-0.38 [-0.55; -0.21]	
Exercise	AT	42	-0.64 [-0.87; -0.42]	0.02	38	-0.54 [-0.78; -0.3]	0.05	26	-0.38 [-0.66; -0.1]	0.45
	RT	43	-0.25 [-0.39; -0.11]		39	-0.16 [-0.35; 0.03]		29	-0.44 [-0.72; -0.16]	
	CT	32	-0.33 [-0.5; -0.16]		16	-0.25 [-0.48; -0.01]		10	-0.19 [-0.48; 0.09]	
		12	-0.32 [-0.5; -0.14]		10	-0.17 [-0.47; 0.13]		3	-0.22 [-0.74; 0.31]	
Frequency (d/week)	≤ 2	83	-0.39 [-0.52; -0.26]	0.21	71	-0.4 [-0.56; -0.23]	0.23	53	-0.42 [-0.62; -0.22]	0.66
	3	14	-0.84 [-1.38; -0.29]		7	-0.13 [-0.47; 0.21]		5	-0.54 [-1.02; -0.07]	
	≥ 4	57	-0.43 [-0.58; -0.29]		52	-0.37 [-0.58; -0.16]		34	-0.53 [-0.81; -0.25]	
Duration (weeks)	≤ 12	38	-0.45 [-0.69; -0.21]	0.54	26	-0.28 [-0.53; -0.04]	0.79	20	-0.29 [-0.58; 0]	0.04
	13–24	22	-0.32 [-0.49; -0.16]		15	-0.27 [-0.48; -0.06]		11	-0.11 [-0.28; 0.07]	
	> 24	42	-0.26 [-0.38; -0.13]		37	-0.16 [-0.33; 0]		25	-0.14 [-0.34; 0.06]	
Healthy	No	75	-0.5 [-0.66; -0.34]	0.02	56	-0.45 [-0.64; -0.25]	0.03	40	-0.54 [-0.79; -0.29]	0.01
	Yes	47	-0.57 [-0.77; -0.37]		41	-0.51 [-0.77; -0.25]		27	-0.63 [-0.97; -0.29]	
Sex	Female	12	-0.18 [-0.48; 0.13]	0.04^a	16	-0.38 [-0.71; -0.04]	0.54 ^a	11	-0.44 [-0.9; 0.01]	0.52 ^a
	Male	36	-0.09 [-0.19; 0.02]		27	-0.09 [-0.22; 0.04]		27	-0.09 [-0.22; 0.04]	
Age	< 65 y	75	-0.51 [-0.67; -0.34]	0.02	61	-0.5 [-0.67; -0.32]	< 0.01	43	-0.47 [-0.71; -0.24]	0.12
	≥ 65 y	42	-0.28 [-0.37; -0.18]		32	-0.05 [-0.23; 0.13]		22	-0.23 [-0.43; -0.03]	
Diabetes	No	62	-0.46 [-0.62; -0.3]	0.39	60	-0.31 [-0.5; -0.13]	0.04	41	-0.37 [-0.61; -0.13]	0.16
	Yes	30	-0.6 [-0.87; -0.33]		18	-0.66 [-0.94; -0.38]		12	-0.73 [-1.15; -0.3]	
BMI (kg/m ²)	18–25	13	-0.43 [-0.63; -0.23]	0.28	13	-0.22 [-0.6; 0.17]	0.41	8	-0.36 [-0.75; 0.02]	1.00
	25–30	60	-0.31 [-0.42; -0.2]		46	-0.27 [-0.4; -0.13]		36	-0.37 [-0.6; -0.15]	
	> 30	34	-0.53 [-0.81; -0.24]		28	-0.48 [-0.78; -0.18]		16	-0.38 [-0.77; 0.02]	

^a, analysis only between females and males; AT, Aerobic training; BMI, Body mass index; CRP, C reactive protein; CT, Combined training; d/week, Days per week; IL-6, Interleukin 6; K, Number of studies; LL, Lower limit; P diff, p value of difference between all categories of the sub group; PE, Point estimate; RE, Random effects; RT, Resistance training; SMD, Standardised mean difference; TNF- α , Tumour necrosis factor alpha; UL, Upper limit. Confidence intervals and p values in bold are significant (p < 0.05).

increased muscle mass. Interventions improving glucose metabolism (varied markers) had greater anti-inflammatory effects (e.g., larger CRP reduction). Interestingly, TNF- α was only reduced in interventions reducing HbA1c, or Insulin, or HOMA-IR; and leptin was only reduced when there was a significant reduction in HOMA-IR. Interventions improving TG, TChol, HDL-C and LDL-C had the largest reductions in CRP and IL-6. While interventions reducing TChol had the largest reductions in TNF- α and IL-1 β . Only interventions reducing LDL-C increased IGF-1 and reduced IL-1 β . Numerous interactions were observed between changes in inflammatory markers, with interventions that reduced IL-6 consistently showing overall improvements in anti-inflammatory profiles.

4. Discussion

This study is the first to integrate a comprehensive range of metabolic and inflammatory adaptations that take place with exercise training in older adults. We showed that AT was the most effective mode of exercise training, and that a minimum of 3 sessions a week were required for greater anti-inflammatory effects in the short-term (i.e., < 12 weeks), and greater fat mass reduction in the long-term (i.e., ≥ 13 weeks). Although RT resulted in changes to most outcomes, AT led to a greater magnitude of changes. Combined training was the least effective modality for anti-inflammatory effects, contrasting the evidence from a previous meta-analysis in younger overweight and obese adults, showing that CT was the most effective type of exercise for improving cardiometabolic health (body composition, lipid profile, glucose control, blood pressure, VO₂ max, muscle fitness) (Batrakoulis et al., 2022). It is possible that an insufficient frequency of the aerobic component (only 39 % met AT guidelines) within the CT in the trials included in the present analyses explains the smaller magnitude of change. Indeed, a complementary analysis (Supplementary Table 9) showed that only AT improved all glucose and lipid markers when performed twice a week, while RT and CT required a higher training frequency. In addition, since there was high heterogeneity in the studies included here, the lower number of CT studies (46) in comparison with AT (78) could reduce the power in the CT meta-analyses. In fact, when addressing exercise

recommendations for older adults (Bull et al., 2020), insufficient CT (insufficient for both AT and RT) was enough for most metabolic adaptations, likely due to the sum effect of AT and RT. Conversely, AT and RT had to meet recommendations to generate significant metabolic adaptations. Meeting AT and CT recommendations was fundamental for CRP and IL-6 reduction, while meeting RT recommendations was necessary for CRP and leptin reduction, and adiponectin and IGF-1 increase.

The robust evidence for no reduction in IL-6 with RT (meta-analysis of 39 trials) could be linked with the lower caloric demand of this type of exercise compared to AT or CT; IL-6 functions as a metabolic sensor, which increases when intramuscular glycogen is low (Pedersen, 2012). In support of this, RT did not reduce body mass and BMI and elicited less than half of the reduction in fat mass compared to AT and CT. Overall, reductions in fat mass were more strongly associated with metabolic and inflammatory changes, and these changes were not dependent on increases in muscle mass. It is possible that both metabolic and inflammatory adaptations share a common mediator, namely the increase in caloric expenditure during exercise, via enhanced utilisation of circulating glucose and lipids, or activation of metabolic sensors (e.g., IL-6) that regulate inflammation. For example, persistent production of IL-6 leads to chronic NF- κ B and STAT3 activation, contributing to metabolic and inflammatory diseases (Hunter and Jones, 2015). Meanwhile, the acute increase in IL-6 during exercise stimulates IL-10 and IL-1 receptor antagonist (IL-1ra) production, inhibits TNF- α release from monocytes/macrophages, and activates AMP-activated protein kinase (AMPK) and Signal Transducer and Activator of Transcription 3 (STAT3), suppressing systemic inflammation (Pedersen and Febbraio, 2008). Currently, it is very well known that metabolic changes in immune cells are key modulators of chronic inflammation, and chronic changes in the metabolism of immune cells with physical activity can prevent their hyperinflammatory responses in older adults, such as the production of IL-6 by T cells (Hazeldine et al., 2025).

The increase in muscle mass was modest (SMDs ≤ 0.3) and similar across different exercise modalities. This finding raises the question of how RT regulates metabolism and chronic inflammation if not via increases in muscle mass and fat mass reduction. The significant changes

Table 6b
Subgroup analysis for the effect of exercise protocol design and participant characteristics on inflammatory markers.

	Adiponectin SMD			Leptin SMD			IGF-1 SMD			IL-1 β SMD		
	K	PE [LL; UL]	P diff	K	PE [LL; UL]	P diff	K	PE [LL; UL]	P diff	K	PE [LL; UL]	P diff
Overall	45	0.39 [0.17; 0.6]		45	-0.49 [-0.75; -0.24]		31	0.44 [0.22; 0.66]		10	-0.31 [-0.72; 0.11]	
Exercise	20	0.5 [0.13; 0.86]	0.05	14	-0.86 [-1.54; -0.18]	0.07	11	0.33 [-0.07; 0.73]	0.29	4	0.14 [-0.31; 0.59]	0.11
RT	17	0.47 [0.13; 0.8]		20	-0.42 [-0.7; -0.13]		13	0.4 [0.09; 0.7]		4	-1.05 [-2.13; 0.02]	
CT	8	-0.01 [-0.31; 0.3]		11	-0.14 [-0.35; 0.07]		7	0.77 [0.33; 1.22]		2	-0.33 [-1.05; 0.4]	
Frequency (d/week)	4	0.15 [-0.19; 0.49]	0.48	6	-0.07 [-0.34; 0.19]	0.04	5	0.25 [-0.21; 0.71]	0.49	2	-0.45 [-0.89; -0.01]	0.46
	33	0.39 [0.12; 0.65]		33	-0.61 [-0.95; -0.27]		24	0.44 [0.18; 0.71]		5	-0.8 [-1.63; 0.02]	
	7	0.44 [-0.03; 0.91]		6	-0.16 [-0.46; 0.13]		2	0.97 [-0.18; 2.13]				
Duration (weeks)	20	0.56 [0.22; 0.89]	0.39	22	-0.5 [-0.87; -0.13]	0.28	24	0.44 [0.21; 0.67]	0.36	3	-1.59 [-2.65; -0.53]	< 0.01
	18	0.22 [-0.14; 0.57]		15	-0.63 [-1.18; -0.08]		6	0.52 [-0.14; 1.18]		4	0.24 [-0.17; 0.65]	
	7	0.38 [0.14; 0.62]		8	-0.24 [-0.47; 0]		1	-0.24 [-1.18; 0.69]		3	-0.26 [-0.62; 0.1]	0.12
Healthy	27	0.22 [0.05; 0.4]	0.22	22	-0.32 [-0.53; -0.1]	0.22	15	0.36 [0.08; 0.63]	0.40	1	0.25 [-0.41; 0.9]	
	18	0.54 [0.07; 1.02]		23	-0.62 [-1.06; -0.18]		16	0.55 [0.19; 0.9]		9	-0.38 [-0.83; 0.07]	
Sex	22	0.52 [0.16; 0.89]	0.86 ^a	20	-0.85 [-1.35; -0.34]	0.06 ^a	15	0.56 [0.22; 0.9]	0.69 ^a	2	-2.18 [-3.1; -1.26]	< 0.01 ^a
	7	0.59 [0.01; 1.16]		14	-0.3 [-0.58; -0.02]		8	0.45 [0; 0.9]		1	-0.01 [-0.49; 0.47]	
	16	0.12 [-0.08; 0.33]		11	-0.07 [-0.26; 0.12]		8	0.22 [-0.21; 0.65]		7	-0.06 [-0.44; 0.33]	
Age	30	-0.53 [-0.87; -0.2]	0.63	30	-0.53 [-0.87; -0.2]	0.63	17	0.49 [0.1; 0.88]	0.75	9	-0.37 [-0.84; 0.11]	0.30
	18	0.41 [0.13; 0.69]		15	-0.41 [-0.79; -0.03]		14	0.42 [0.22; 0.62]		1	-0.01 [-0.49; 0.47]	
Diabetes	34	0.43 [0.18; 0.69]	0.75	33	-0.57 [-0.9; -0.23]	0.52	20	0.37 [0.12; 0.61]	0.01	5	0.19 [-0.14; 0.53]	0.01
	8	0.34 [-0.14; 0.83]		9	-0.38 [-0.84; 0.08]		5	1.23 [0.65; 1.82]		4	-1.13 [-2; -0.27]	
BMI (kg/m ²)	2	1.03 [-0.41; 2.47]	0.45	3	-0.22 [-1.05; 0.61]	0.69	7	0.43 [0.13; 0.73]	0.84			
	23	0.23 [0.02; 0.43]		30	-0.44 [-0.69; -0.18]		15	0.42 [0.11; 0.73]		6	0.13 [-0.18; 0.44]	0.03
	19	0.38 [0.01; 0.75]		12	-0.68 [-1.36; -0.01]		5	0.2 [-0.5; 0.91]		1	-0.64 [-1.26; -0.01]	

^a, analysis only between females and males; AT, Aerobic training; BMI, Body mass index; CT, Combined training; d/week, Days per week; IGF-1, Insulin-like growth factor 1; IL-1 β , Interleukin 1 beta; K, Number of studies; LL, Lower limit; P diff, p value of difference between all categories of the sub group; PE, Point estimate; RE, Random effects; RT, Resistance training; SMD, Standardised mean difference; UL, Upper limit. Confidence intervals and p values in bold are significant (p < 0.05).

we observed in inflammatory markers with RT could result from a summatory effect from each exercise bout. Indeed, during exercise, muscles release anti-inflammatory cytokines (myokines) (Katz et al., 2025), which could regulate anti-inflammatory adaptations, independently of hypertrophic gains. However, the question remains as to why IL-6 was not reduced by RT. Only RT increased IGF-1, and this increase was associated with greater increases in muscle mass, reductions in fasting glucose, reductions in CRP, and an 8 times greater reduction in TC and LDL-C. While AT improves muscle metabolism (e.g., mitochondrial biogenesis and lipid oxidation) mainly via AMPK/SIRT1/PGC-1 α signalling, RT enhances protein synthesis via the IGF-1/PI3K/AKT/mTOR pathway. Therefore, if on one hand RT does not lead to sufficient nutrient depletion to acutely increase IL-6 and promote robust weight loss – unlike AT – the anabolic effects of RT, mainly via increased muscle mass, may also increase resting metabolic rate (Campbell et al., 1994). In addition, IGF-1 has been linked to improved glucose uptake (Schiaffino and Mammucari, 2011), and might indirectly contribute to reduced inflammation. However, alternative mechanisms by which IGF-1 can induce anti-inflammatory effects with RT remain unknown (Witkowska-Sędek and Pyrzak, 2021).

The small improvement in muscle mass shown in the present analyses with RT could be driven by anabolic resistance with obesity and T2d (Henson et al., 2025). Indeed, T2d participants did not increase muscle mass, similar to a meta-analysis in sarcopenic obese older adults, in which AT, CT and RT significantly reduced fat mass without any increase in muscle mass (Zhuang et al., 2022). Although muscle atrophy with T2d is mediated via dysfunction of IGF1–PI3K–AKT signalling pathway (Sandri et al., 2006), the increase in IGF-1 elicited by exercise was three times higher in T2d (1.23 [0.65; 1.82]) than non-T2d (0.37 [0.12; 0.61]). This anabolic resistance, even under IGF-1 increase, could be linked to the absence of an increase in adiponectin and lack of a reduction in leptin in T2d. These adipokines increase fatty acid (FA) oxidation and decrease triglyceride storage in muscle (Dyck, 2009), and the resistance to FA oxidation in muscle could impair muscle gains via an induction of insulin resistance, thus disrupting nutrient signalling critical for muscle growth (Zhang et al., 2010).

Importantly, our study identified that a minimum of 3 sessions of exercise per week is required to trigger many metabolic and anti-inflammatory adaptations (i.e., reduction in body mass, insulin, HOMA-IR, triglycerides, total cholesterol, IL-6, TNF- α , leptin, and to increase adiponectin and IGF-1) in older adults. More than 4 sessions per week led to a greater magnitude of metabolic benefits (i.e., reduction in fat mass, insulin, HOMA-IR, and all lipid markers), but not anti-inflammatory effects. These findings provide more support for the concept that to treat obesity and T2d, the physical activity undertaken needs to promote an energy deficit (Chodzko-Zajko et al., 2009). Indeed, negative energy balance triggers body mass and fat mass loss (Petridou et al., 2019) and this was particularly true for the effects that AT had on glucose metabolism which occurred only in subgroups with fat mass loss (data not shown). In addition, our study showed that longer interventions tended (p = 0.08) to double the reduction in fat mass (< 12 weeks: -0.37 [-0.48; -0.25], > 24 weeks: -0.68 [-1; -0.35]), while the small muscle mass gains were similar for any length of intervention (SMDs $\leq$ 0.3). Interestingly, shorter interventions (< 12 weeks) led to greater increases in adiponectin and IGF-1 and stronger reductions in TNF- α and IL-1 β , suggesting a transient response. It is difficult to sustain behavioural changes long-term, thus a lower adherence to exercise training long-term could reduce its anti-inflammatory effects. However, given reductions in fat mass and TG were greater with increasing intervention lengths, it is more likely that other homeostatic mechanisms explain the long-term attenuation we see here. For example, after a short-term response to exercise stress, the chronic effect of trained immunity (Bekkering et al., 2020) and the epigenetic obesogenic memory (Hinte et al., 2024) would allow some magnitude of low-grade inflammation to persist even under exercise training effects.

The present analyses also considered whether the characteristics of

Table 7
Subgroup analysis for the effect of exercise training adaptations on body composition.

	Improve	Body mass (kg)				BMI (kg/m ²)				Fat mass (SMD)				Muscle mass (SMD)			
		K	PE [LL; UL]	P diff	K	PE [LL; UL]	P diff	K	PE [LL; UL]	P diff	K	PE [LL; UL]	P diff	K	PE [LL; UL]	P diff	
VO ₂ max	No	25	-1.63 [-2.6; -0.67]	0.08	22	-0.32 [-0.81; 0.17]	0.85	19	-0.27 [-0.44; -0.1]	<0.01	15	0.09 [-0.08; 0.27]	0.08				
Body mass	Yes	20	-0.72 [-1.08; -0.37]		28	-0.37 [-0.51; -0.22]		21	-1.18 [-1.65; -0.7]		12	0.44 [0.1; 0.78]					
	No	110	0.16 [-0.1; 0.41]	<0.01	82	-0.24 [-0.36; -0.12]	<0.01	80	-0.3 [-0.37; -0.23]	<0.01	59	0.2 [0.1; 0.3]	0.70				
BMI	Yes	11	-2.52 [-3.39; -1.65]		9	-0.79 [-1.13; -0.45]		9	-1.07 [-1.51; -0.63]		3	0.32 [-0.27; 0.91]					
	No	83	-0.87 [-1.19; -0.56]	0.02	106	-0.16 [-0.26; -0.06]	<0.01	73	-0.4 [-0.52; -0.27]	<0.01	45	0.2 [0.1; 0.3]	0.73				
Fat mass	Yes	7	-3.28 [-5.36; -1.21]		13	-0.59 [-0.79; -0.39]		9	-2 [-2.91; -1.09]		1	0.33 [-0.44; 1.11]					
	No	73	-0.81 [-1.39; -0.23]	0.01	63	-0.1 [-0.25; 0.04]	<0.01	102	-0.21 [-0.27; -0.14]	<0.01	66	0.13 [0.05; 0.21]	<0.01				
Muscle mass	Yes	16	-1.77 [-2.29; -1.26]		20	-0.49 [-0.68; -0.31]		27	-1.53 [-1.87; -1.2]		14	0.65 [0.37; 0.94]					
	No	55	-0.7 [-1.13; -0.28]	0.24	44	-0.25 [-0.42; -0.09]	0.91	69	-0.25 [-0.33; -0.18]	<0.01	71	0.12 [0.04; 0.19]	<0.01				
Glucose	Yes	7	0.1 [-1.18; 1.39]		3	-0.29 [-0.95; 0.36]		11	-0.96 [-1.28; -0.64]		13	1.16 [0.8; 1.52]					
	No	50	-0.93 [-1.36; -0.5]	0.16	51	-0.61 [-0.78; -0.44]	<0.01	53	-0.35 [-0.47; -0.23]	0.01	38	0.15 [0.04; 0.26]	0.40				
HbA1c	Yes	17	-1.68 [-2.64; -0.72]		24	-0.23 [-0.4; -0.06]		26	-0.94 [-1.37; -0.5]		10	0.26 [0.02; 0.5]					
	No	19	-1.17 [-1.66; -0.69]	0.13	18	-0.44 [-0.64; -0.24]	0.93	24	-0.27 [-0.41; -0.12]	<0.01	17	0.15 [-0.06; 0.37]	0.86				
Insulin	Yes	9	-0.43 [-1.26; 0.41]		16	-0.43 [-0.63; -0.23]		15	-1.3 [-1.93; -0.68]		7	0.12 [-0.12; 0.37]					
	No	37	-0.81 [-1.18; -0.44]	0.54	35	-0.17 [-0.38; 0.03]	0.02	35	-0.31 [-0.52; -0.09]	<0.01	29	0.12 [0; 0.24]	0.06				
HOMA-IR	Yes	7	-1.3 [-2.8; 0.21]		11	-0.53 [-0.75; -0.31]		11	-1.82 [-2.58; -1.07]		6	0.4 [0.13; 0.67]					
	No	38	-0.73 [-1.12; -0.34]	0.95	36	-0.36 [-0.48; -0.23]	0.19	32	-0.35 [-0.5; -0.2]	0.01	26	0.17 [0.03; 0.31]	0.10				
TG	Yes	9	-0.7 [-1.69; 0.28]		12	-0.19 [-0.4; 0.02]		17	-1.23 [-1.88; -0.59]		10	0.45 [0.15; 0.74]					
	No	49	-0.96 [-1.34; -0.58]	0.16	53	-0.32 [-0.53; -0.11]	0.58	55	-0.27 [-0.38; -0.17]	<0.01	35	0.21 [0.1; 0.32]	0.01				
TChol	Yes	10	-1.48 [-2.1; -0.86]		13	-0.4 [-0.6; -0.21]		22	-1.39 [-1.83; -0.94]		12	0.67 [0.33; 1.01]					
	No	39	-1.31 [-1.74; -0.87]	0.58	48	-0.4 [-0.64; -0.15]	0.79	49	-0.36 [-0.51; -0.21]	<0.01	36	0.25 [0.13; 0.37]	0.07				
HDL-C	Yes	9	-0.91 [-2.21; 0.39]		10	-0.35 [-0.58; -0.12]		19	-1.25 [-1.74; -0.76]		7	0.68 [0.23; 1.13]					
	No	46	-1.24 [-1.67; -0.81]	0.88	53	-0.33 [-0.57; -0.11]	0.69	60	-0.33 [-0.45; -0.22]	<0.01	37	0.28 [0.14; 0.42]	0.20				
LDL-C	Yes	11	-1.31 [-2.05; -0.58]		17	-0.39 [-0.57; -0.22]		15	-1.76 [-2.4; -1.11]		7	0.57 [0.15; 0.99]					
	No	40	-1.03 [-1.44; -0.62]	0.77	49	-0.31 [-0.54; -0.08]	0.68	46	-0.31 [-0.45; -0.16]	<0.01	32	0.22 [0.09; 0.36]	0.22				
CRP	Yes	7	-0.91 [-1.6; -0.23]		11	-0.37 [-0.57; -0.18]		21	-1.18 [-1.63; -0.73]		8	0.48 [0.09; 0.87]					
	No	52	-0.75 [-1.11; -0.39]	0.33	53	-0.11 [-0.14; -0.08]	<0.01	56	-0.35 [-0.47; -0.22]	0.01	45	0.26 [0.14; 0.37]	0.20				
IL-6	Yes	8	-1.37 [-2.56; -0.17]		13	-0.36 [-0.51; -0.2]		19	-1.11 [-1.63; -0.59]		8	0.51 [0.14; 0.87]					
	No	45	-0.75 [-1.44; -0.07]	0.08	40	-0.32 [-0.47; -0.18]	0.03	46	-0.35 [-0.45; -0.24]	0.05	37	0.26 [0.09; 0.42]	0.78				
TNF-α	Yes	12	-2.16 [-3.57; -0.75]		14	-0.8 [-1.2; -0.4]		15	-0.66 [-0.96; -0.37]		7	0.3 [0.01; 0.6]					
	No	30	-0.93 [-1.76; -0.09]	0.31	29	-0.32 [-0.47; -0.18]	0.28	32	-0.41 [-0.54; -0.27]	0.96	23	0.39 [0.13; 0.65]	0.81				
Adiponectin	Yes	11	-1.82 [-3.35; -0.3]		9	-1 [-2.21; 0.21]		13	-0.39 [-0.81; 0.02]		8	0.35 [0.12; 0.58]					
	No	28	-0.54 [-0.95; -0.12]	0.23	22	-0.18 [-0.35; 0]	0.04	24	-0.21 [-0.35; -0.08]	0.02	22	0.2 [0.07; 0.33]	0.31				
Leptin	Yes	6	-2.1 [-4.63; 0.43]		6	-1.05 [-1.85; -0.25]		6	-0.84 [-1.34; -0.34]		3	0.45 [-0.02; 0.92]					
	No	26	-0.58 [-1.56; 0.41]	0.15	21	-0.42 [-0.75; -0.09]	0.10	28	-0.22 [-0.36; -0.09]	<0.01	22	0.22 [-0.01; 0.44]	0.57				
IGF-1	Yes	9	-1.79 [-3.1; -0.48]		7	-0.91 [-1.4; -0.42]		8	-0.9 [-1.31; -0.49]		5	0.33 [0.01; 0.64]					
	No	16	-0.41 [-1.34; 0.53]	0.65	15	-0.24 [-0.55; 0.08]	0.37	16	-0.46 [-0.74; -0.18]	0.16	13	0.34 [0.15; 0.53]	0.06				
IL-1β	Yes	3	-0.01 [-1.44; 1.41]		2	0.06 [-0.52; 0.65]		4	-1.05 [-1.81; -0.29]		4	1.19 [0.31; 2.08]					
	No	3	-3.37 [-8.79; 2.05]	0.22	3	-0.93 [-2.18; 0.32]	0.45	4	-0.67 [-1.28; -0.06]	0.70	4	0.65 [0.03; 1.27]	0.44				
	Yes	1	0.2 [-1.5; 1.9]		1	-0.4 [-0.99; 0.19]		6	-0.82 [-1.32; -0.33]		5	1 [0.35; 1.66]					

BMI, Body mass index; CRP, C-Reactive Protein; HbA1c, Glycated haemoglobin; HDL-C, High density lipoprotein cholesterol; HOMA-IR, Homeostasis model assessment of insulin resistance; IGF-1, Insulin-like growth factor 1; IL-1β, Interleukin-1 beta; IL-6, Interleukin-6; K, Number of studies; LDL-C, Low density lipoprotein cholesterol; LL, Lower limit; P diff, p value of difference between all categories of the sub group; PE, Point estimate; SMD, Standardised mean difference; TChol, Total cholesterol; TG, Triglycerides; TNF-α, Tumour necrosis factor alpha; UL, Upper limit. Confidence intervals and p values in bold are significant (p < 0.05).

participants influence metabolic and inflammatory adaptations with exercise. We identified greater effect sizes in adults <65 years, as well as in unhealthy or obese individuals. Adults aged under 65 years showed greater improvements in body composition, glucose and lipid metabolism, and IL-6. Although there is some evidence of reduced metabolic responsiveness to exercise with ageing (i.e., attenuated exercise-induced fat oxidation and impaired adipocyte differentiation) (Ou et al., 2022; Frandsen et al., 2021), we believe these findings were caused by selection bias. Within the studies included in the present analyses, most participants under 65 years of age had chronic diseases, compared to the relatively healthier populations over 65 years old. Healthier older adults with low baseline values of TNF- α , IL-6, CRP, IL-1 α , leptin, and higher adiponectin do not improve inflammation with exercise training as much as in populations with unhealthy baseline values (Sardeli et al., 2022). To prove this hypothesis, we compared the SMD and 95 %CI of healthy and unhealthy (chronic disease) older adults above 65 years. Both subgroups improved fat mass (healthy: $-0.22[-0.44; 0.006]$, $K = 28$; unhealthy: $-0.38[-0.53; -0.24]$, $K = 22$), CRP (healthy: $-0.28[-0.4; -0.16]$, $K = 25$; unhealthy: $-0.27[-0.42; -0.11]$, $K = 17$), adiponectin (healthy: $0.23[0.044; 0.42]$, $K = 13$; unhealthy: $0.82[0.001; 1.64]$, $K = 5$), leptin (healthy: $-0.32[-0.67; 0.04]$, $K = 12$; unhealthy: $-0.66[-1.89; 0.56]$, $K = 3$), and IGF-1 (healthy: $0.37[0.14; 0.61]$; unhealthy: $0.49[0.19; 0.78]$, $K = 7$), while only groups with chronic disease significantly reduced IL-6 (healthy: $0.03[-0.12; 0.18]$, $K = 17$; unhealthy: $-0.21[-0.38; -0.037]$, $K = 15$) and TNF- α (healthy: $-0.19[-0.58; 0.21]$, $K = 9$; unhealthy: $-0.25[-0.46; -0.04]$, $K = 13$). This reinforces that the anti-inflammatory effects of exercise training are more pronounced in individuals with potentially higher baseline inflammation. Similarly, we also observed that normal-weight individuals showed minimal changes in glucose metabolism, lipid metabolism, and inflammatory markers despite reduced BMI and fat mass. Individuals without chronic disease or obesity may benefit from some metabolic improvements, but baseline values within normal ranges limits the ability to detect significant changes (Barnett et al., 2005). Sex differences were also noted, with female participants exhibiting greater reductions in CRP, TNF- α , IL-1 β , and body fat. There is some evidence of greater fat oxidation in women, which could explain higher reductions in fat mass (Beckner et al., 2023). In addition, men are known to experience greater increases in muscle strength and muscle quality (Da Boit et al., 2016), and although no significant difference between men and women was shown, the mean increase in muscle mass was more than twice as large in men ($0.56[0.09; 1.03]$) than women ($0.22[0.09; 0.36]$). Taken together, it is possible that women exhibited greater anti-inflammatory effects given that inflammation is most strongly associated with fat mass, rather than muscle mass.

The present analyses also explored whether change in metabolic variables were dependent on change in inflammatory variables and *vis-à-vis*. Although most anti-inflammatory effects were not dependent on metabolic adaptations, it was clear that greater metabolic improvement (from body composition, glucose metabolism and lipid metabolism) was associated with more pronounced anti-inflammatory effects in older adults. Reductions in circulating inflammatory markers may occur due to reduced secretion from the reduced volume of visceral adipose tissue mass (IL-6 and TNF- α), reduced infiltration of immune cells into adipose tissue, reduced liver CRP production, and reduced hyperinsulinemia (Ryan and Nicklas, 2004). Although reductions in TNF- α are classically known to reduce insulin resistance (Hotamisligil et al., 1993), the reduction in other inflammatory markers (CRP, IL-6, and leptin) and increase in adiponectin were associated with greater reductions in insulin and HOMA-IR. While fat mass is often seen as a key driver of metabolic and inflammatory changes, the evidence suggests a more nuanced picture. Short-term interventions tend to produce stronger anti-inflammatory effects, whereas long-term interventions lead to greater improvements in body composition. This indicates that inflammatory markers may be regulated earlier, possibly alongside initial changes in glucose and lipid metabolism, unless even small reductions in

fat mass are sufficient to trigger these anti-inflammatory effects.

Improvements in glucose control markers were strongly aligned with reductions in inflammatory markers, with some markers being dependent of each other. For example, exercise-induced reduction in insulin and HOMA-IR were associated with reduced CRP, IL-6 and leptin, and only studies reducing insulin or HOMA-IR reduced TNF- α . There is evidence to support the notion of a pathophysiological feedback loop between TNF- α and insulin resistance (Plomgaard et al., 2005; Krogh-Madsen et al., 2004), but defining a causal relationship is beyond the capacity of this study. In addition, only studies reducing leptin and increasing adiponectin also reduced insulin, which could be an effect of improved insulin sensitivity on the regulation of these adipokines, dependently or independently of reduced adiposity (Gao et al., 2013).

Only improvements in lipid metabolism were affected by exercise intensity, independent of the volume of intervention. Lipid improvements, particularly the reduction of TG, TChol, and LDL-C were associated with a reduced inflammatory burden (i.e., CRP, IL-6, TNF- α , leptin, IL-1 β , and increased IGF-1). Diet-derived fatty acids can act as damage-associated molecular patterns (DAMP) and trigger cytokine production (e.g., IL-1 β , IL-6, TNF- α , leptin) by immune, fat, and endothelial cells, ultimately contributing to the development of autoimmune and metabolic conditions (Radzikowska et al., 2019). Since it is difficult to isolate a causal relationship in humans and exercise-induced metabolic adaptations were tightly associated with anti-inflammatory changes, it seems plausible to conclude that an efficient therapy to treat metabolic or anti-inflammatory conditions should have multiple targets. Although exercise interventions are not considered the best therapeutic approach to improve lipid metabolism (Fiuza-Luces et al., 2013), one can conclude that exercise-induced changes in plasma lipids could be sufficient to contribute to important metabolic and anti-inflammatory adaptations. A study in mice taking a high-fat diet demonstrated a reduction in TG and TChol with AT, in parallel with the reduction of inflammatory markers such as TNF- α , IL-1 β , and improved insulin sensitivity (Li et al., 2022), concluding that exercise training reduced inflammation by suppressing the activation of the NF- κ B pathway within skeletal muscles. The higher energy expenditure and glucose and insulin sensitivity with exercise contribute to a reduction in circulating glucose and TG, which not only activate immune response (Radzikowska et al., 2019), but can directly regulate metabolism of adipocytes (higher oxidative capacity) and immune cells (Hazeldine et al., 2025; Park et al., 2014; Andersen, 2022). There is incipient evidence that higher concentrations of circulating LDL-C increase lipid content in immune cells, driving immunosenescence and consequently a pro-inflammatory phenotype (DeConne et al., 2025; Rodrigues et al., 2018). Additionally, exercise training could reduce the fat content in immune cells by reducing circulating TG and cholesterol (Ramkrapes et al., 2025). Furthermore, since aerobic interventions promoted more robust improvements in lipid metabolism (i.e., reduction in TG and increase in HDL-C), further analysis to identify mediators of exercise responsiveness in older adults could be explored. In fact, we showed that increasing VO_2 max, the main adaptation obtained via AT, is associated with higher improvements in glucose control, lipid metabolism, body composition and inflammatory status.

4.1. Limitations, considerations, future research

The low number of studies increasing muscle mass and similar gains with all types of training (AT, RT, and CT) suggest low sensitivity in muscle mass assessment, usually by DEXA, air plethysmography, bioimpedance, or skinfold measurements (Mckendry et al., 2018). Smaller (non-significant effects) gains could have a considerable impact, since there is a linear negative association between muscle mass and TNF- α , IL-6 and CRP (Tuttle et al., 2020). Therefore, the limited effect of exercise training on muscle mass and link with metabolic and inflammatory markers should be interpreted with caution. Although the use of SMD across all meta-analyses allowed the integration of a high number

Table 8
Subgroup analysis for the effect of exercise training adaptations on glucose metabolism.

	Improve	Glucose SMD				HbA1c SMD				Insulin SMD				HOMA-IR SMD			
		K	PE [LL; UL]	P diff	K	PE [LL; UL]	P diff	K	PE [LL; UL]	P diff	K	PE [LL; UL]	P diff	K	PE [LL; UL]	P diff	
VO ₂ max	No	22	-0.31 [-0.51; -0.11]	0.02	11	-0.38 [-0.6; -0.16]	<0.01	11	-0.28 [-0.52; -0.04]	0.03	13	-0.38 [-0.58; -0.17]	0.01	13	-0.38 [-0.58; -0.17]	0.01	
Body mass	Yes	22	-0.72 [-1.02; -0.43]		16	-1.4 [-1.97; -0.84]		19	-0.78 [-1.16; -0.4]		20	-1 [-1.43; -0.57]		20	-1 [-1.43; -0.57]		
	No	60	-0.32 [-0.44; -0.19]	0.35	26	-0.38 [-0.56; -0.2]	0.50	39	-0.23 [-0.39; -0.07]	0.07	43	-0.33 [-0.47; -0.19]	0.06	43	-0.33 [-0.47; -0.19]	0.06	
BMI	Yes	7	-0.95 [-2.26; 0.37]		2	-1.03 [-2.92; 0.86]		5	-1.1 [-2.03; -0.18]		4	-1.27 [-2.26; -0.29]		4	-1.27 [-2.26; -0.29]		
	No	66	-0.41 [-0.56; -0.27]	0.04	27	-0.54 [-0.75; -0.33]	0.03	39	-0.33 [-0.47; -0.18]	0.01	40	-0.38 [-0.52; -0.24]	0.01	40	-0.38 [-0.52; -0.24]	0.01	
Fat mass	Yes	9	-1.14 [-1.83; -0.45]		6	-2.27 [-3.82; -0.72]		7	-1.69 [-2.76; -0.61]		7	-2.45 [-3.95; -0.95]		7	-2.45 [-3.95; -0.95]		
	No	61	-0.43 [-0.59; -0.27]	0.14	29	-0.32 [-0.5; -0.14]	<0.01	32	-0.21 [-0.39; -0.03]	<0.01	34	-0.33 [-0.51; -0.15]	<0.01	34	-0.33 [-0.51; -0.15]	<0.01	
Muscle mass	Yes	18	-0.89 [-1.46; -0.31]		9	-2 [-2.94; -1.07]		14	-1.43 [-2.01; -0.85]		14	-1.91 [-2.59; -1.23]		14	-1.91 [-2.59; -1.23]		
	No	44	-0.22 [-0.42; -0.02]	0.13	21	-0.41 [-0.69; -0.12]	0.62	32	-0.35 [-0.61; -0.09]	0.67	29	-0.43 [-0.7; -0.16]	0.39	29	-0.43 [-0.7; -0.16]	0.39	
Glucose	Yes	4	-1 [-1.98; -0.02]		3	-0.55 [-1.02; -0.07]		3	-0.54 [-1.38; 0.3]		7	-0.63 [-0.98; -0.28]		7	-0.63 [-0.98; -0.28]		
	No	79	-0.1 [-0.21; 0.01]	<0.01	31	-0.3 [-0.48; -0.11]	<0.01	43	-0.33 [-0.52; -0.13]	0.01	41	-0.36 [-0.55; -0.16]	<0.01	41	-0.36 [-0.55; -0.16]	<0.01	
HbA1c	Yes	36	-1.3 [-1.55; -1.05]		14	-1.64 [-2.25; -1.02]		18	-0.9 [-1.31; -0.49]		17	-1.32 [-1.81; -0.83]		17	-1.32 [-1.81; -0.83]		
	No	29	-0.26 [-0.42; -0.09]	0.06	38	-0.11 [-0.22; -0.01]	<0.01	19	-0.21 [-0.37; -0.05]	<0.01	20	-0.14 [-0.29; 0.01]	<0.01	20	-0.14 [-0.29; 0.01]	<0.01	
Insulin	Yes	16	-0.91 [-1.56; -0.26]		19	-1.52 [-1.95; -1.1]		14	-1.34 [-1.95; -0.73]		15	-1.67 [-2.34; -1.01]		15	-1.67 [-2.34; -1.01]		
	No	47	-0.28 [-0.4; -0.17]	0.18	24	-0.33 [-0.52; -0.14]	<0.01	50	-0.12 [-0.21; -0.04]	<0.01	38	-0.26 [-0.38; -0.13]	<0.01	38	-0.26 [-0.38; -0.13]	<0.01	
HOMA-IR	Yes	14	-0.79 [-1.51; -0.06]		9	-2.13 [-2.95; -1.31]		15	-1.81 [-2.29; -1.33]		10	-2.32 [-3.19; -1.45]		10	-2.32 [-3.19; -1.45]		
	No	44	-0.33 [-0.47; -0.2]	0.11	25	-0.26 [-0.43; -0.09]	<0.01	36	-0.14 [-0.23; -0.04]	<0.01	47	-0.18 [-0.27; -0.09]	<0.01	47	-0.18 [-0.27; -0.09]	<0.01	
TG	Yes	14	-0.94 [-1.69; -0.2]		10	-1.92 [-2.68; -1.16]		12	-1.73 [-2.35; -1.11]		17	-1.86 [-2.4; -1.32]		17	-1.86 [-2.4; -1.32]		
	No	61	-0.28 [-0.43; -0.13]	0.02	32	-0.22 [-0.36; -0.08]	<0.01	29	-0.22 [-0.4; -0.04]	<0.01	32	-0.31 [-0.5; -0.13]	<0.01	32	-0.31 [-0.5; -0.13]	<0.01	
TChol	Yes	19	-0.89 [-1.41; -0.38]		13	-1.4 [-2.11; -0.69]		12	-1.32 [-2.03; -0.61]		13	-1.76 [-2.53; -0.98]		13	-1.76 [-2.53; -0.98]		
	No	54	-0.23 [-0.38; -0.09]	0.03	33	-0.2 [-0.33; -0.07]	<0.01	28	-0.29 [-0.47; -0.1]	<0.01	30	-0.31 [-0.5; -0.12]	<0.01	30	-0.31 [-0.5; -0.12]	<0.01	
HDL-C	Yes	14	-0.94 [-1.57; -0.32]		12	-1.59 [-2.34; -0.83]		9	-1.66 [-2.57; -0.74]		10	-2.26 [-3.21; -1.32]		10	-2.26 [-3.21; -1.32]		
	No	64	-0.38 [-0.53; -0.24]	0.02	33	-0.22 [-0.34; -0.1]	<0.01	29	-0.21 [-0.34; -0.07]	0.01	28	-0.17 [-0.29; -0.04]	<0.01	28	-0.17 [-0.29; -0.04]	<0.01	
LDL-C	Yes	17	-0.97 [-1.44; -0.5]		12	-1.37 [-2.13; -0.61]		11	-1.17 [-1.88; -0.47]		14	-1.55 [-2.21; -0.89]		14	-1.55 [-2.21; -0.89]		
	No	52	-0.19 [-0.32; -0.06]	<0.01	33	-0.22 [-0.37; -0.08]	<0.01	29	-0.26 [-0.45; -0.08]	<0.01	26	-0.28 [-0.5; -0.06]	<0.01	26	-0.28 [-0.5; -0.06]	<0.01	
CRP	Yes	18	-1.01 [-1.51; -0.5]		14	-1.37 [-2; -0.74]		8	-1.86 [-2.83; -0.88]		12	-1.93 [-2.78; -1.07]		12	-1.93 [-2.78; -1.07]		
	No	58	-0.32 [-0.44; -0.19]	0.02	34	-0.36 [-0.56; -0.16]	<0.01	31	-0.22 [-0.38; -0.05]	<0.01	33	-0.28 [-0.45; -0.11]	<0.01	33	-0.28 [-0.45; -0.11]	<0.01	
IL-6	Yes	19	-1.06 [-1.68; -0.44]		9	-1.65 [-2.48; -0.82]		9	-1.64 [-2.41; -0.88]		12	-1.79 [-2.46; -1.13]		12	-1.79 [-2.46; -1.13]		
	No	39	-0.44 [-0.61; -0.28]	0.30	21	-0.31 [-0.54; -0.09]	0.18	25	-0.3 [-0.48; -0.11]	0.04	26	-0.26 [-0.39; -0.13]	0.05	26	-0.26 [-0.39; -0.13]	0.05	
TNF-α	Yes	16	-0.79 [-1.42; -0.15]		9	-0.67 [-1.15; -0.19]		9	-0.98 [-1.59; -0.36]		9	-0.89 [-1.5; -0.27]		9	-0.89 [-1.5; -0.27]		
	No	22	-0.38 [-0.57; -0.19]	0.61	11	-0.26 [-0.46; -0.05]	0.26	14	-0.14 [-0.28; 0]	0.03	15	-0.25 [-0.4; -0.11]	0.01	15	-0.25 [-0.4; -0.11]	0.01	
Adiponectin	Yes	13	-0.57 [-1.24; 0.1]		6	-0.68 [-1.4; 0.03]		7	-1.03 [-1.79; -0.26]		9	-1.01 [-1.58; -0.44]		9	-1.01 [-1.58; -0.44]		
	No	24	-0.05 [-0.29; 0.19]	0.19	13	-0.43 [-0.78; -0.08]	0.06	19	-0.23 [-0.49; 0.03]	<0.01	20	-0.31 [-0.56; -0.06]	0.08	20	-0.31 [-0.56; -0.06]	0.08	
Leptin	Yes	6	-0.78 [-1.84; 0.28]		1	-1 [-1.48; -0.52]		4	-1.24 [-1.77; -0.72]		3	-1.13 [-2.01; -0.26]		3	-1.13 [-2.01; -0.26]		
	No	19	-0.25 [-0.44; -0.06]	0.72	12	-0.29 [-0.5; -0.09]	0.11	14	-0.15 [-0.38; 0.07]	0.01	15	-0.24 [-0.49; 0]	0.02	15	-0.24 [-0.49; 0]	0.02	
IGF-1	Yes	8	-0.08 [-0.98; 0.81]		3	-1.09 [-2.03; -0.14]		7	-1.13 [-1.82; -0.44]		5	-1.29 [-2.13; -0.45]		5	-1.29 [-2.13; -0.45]		
	No	13	-0.43 [-0.76; -0.1]	<0.01	3	-0.15 [-0.51; 0.2]	0.59	8	-0.36 [-0.82; 0.11]		5	-0.56 [-0.93; -0.19]	0.23	5	-0.56 [-0.93; -0.19]	0.23	
IL-1β	Yes	1	-2.81 [-4.05; -1.58]		2	-0.38 [-1.12; 0.36]		1	-0.36 [-1.02; 0.3]		3	-1.1 [-1.9; -0.3]		3	-1.1 [-1.9; -0.3]		
	No	1	-0.31 [-0.97; 0.35]	0.18	2	-0.44 [-0.9; 0.02]	0.75	1	-0.36 [-1.02; 0.3]	0.21	2	-0.53 [-0.99; -0.07]	0.21	2	-0.53 [-0.99; -0.07]	0.21	
	Yes	1	0.36 [-0.36; 1.08]		3	-0.55 [-1.02; -0.07]		3	-1 [-1.57; -0.42]		3	-1 [-1.57; -0.42]		3	-1 [-1.57; -0.42]		

BMI, Body mass index; CRP, C-Reactive Protein; HbA1c, Glycated haemoglobin; HDL-C, High density lipoprotein cholesterol; HOMA-IR, Homeostasis model assessment of insulin resistance; IGF-1, Insulin-like growth factor 1; IL-1β, Interleukin-1 beta; IL-6, Interleukin-6; K, Number of studies; LDL-C, Low density lipoprotein cholesterol; LL, Lower limit; P diff, p value of difference between all categories of the sub group; PE, Point estimate; SMD, Standardised mean difference; TC, Total cholesterol; TG, Triglycerides; TNF-α, Tumour necrosis factor alpha; UL, Upper limit. Confidence intervals and p values in bold are significant (p < 0.05).

Table 9
Subgroup analysis for the effect of exercise training adaptations on lipid metabolism.

	Improve	Triglycerides SMD				Total Cholesterol SMD				HDL-C SMD				LDL-C SMD			
		K	PE [LL; UL]	P diff	K	PE [LL; UL]	P diff	K	PE [LL; UL]	P diff	K	PE [LL; UL]	P diff	K	PE [LL; UL]	P diff	
VO ₂ max	No	17	-0.18 [-0.33; -0.02]	<0.01	15	-0.19 [-0.35; -0.03]	<0.01	18	0.28 [0.06; 0.5]	<0.01	17	-0.18 [-0.34; -0.03]	<0.01	17	-0.18 [-0.34; -0.03]	<0.01	
Body mass	Yes	21	-1.52 [-2.18; -0.86]		17	-1.16 [-1.78; -0.55]		23	0.98 [0.56; 1.41]		18	-1.92 [-2.71; -1.13]		18	-1.92 [-2.71; -1.13]		
	No	52	-0.2 [-0.33; -0.06]	0.02	43	-0.23 [-0.39; -0.08]	0.22	52	0.31 [0.14; 0.48]	0.14	43	-0.31 [-0.51; -0.11]	0.53	43	-0.31 [-0.51; -0.11]	0.53	
BMI	Yes	6	-1.67 [-2.9; -0.45]		5	-0.88 [-1.9; 0.14]		5	1.53 [-0.06; 3.12]		4	-0.76 [-2.19; 0.66]		4	-0.76 [-2.19; 0.66]		
	No	59	-0.32 [-0.51; -0.12]	<0.01	50	-0.23 [-0.37; -0.08]	0.01	62	0.45 [0.26; 0.63]	0.09	52	-0.32 [-0.49; -0.15]	0.02	52	-0.32 [-0.49; -0.15]	0.02	
Fat mass	Yes	7	-3.22 [-4.95; -1.5]		7	-1.71 [-2.89; -0.52]		7	1.47 [0.31; 2.62]		7	-2.45 [-4.24; -0.65]		7	-2.45 [-4.24; -0.65]		
	No	57	-0.15 [-0.27; -0.02]	<0.01	50	-0.2 [-0.37; -0.03]	<0.01	56	0.21 [0.1; 0.32]	<0.01	50	-0.35 [-0.53; -0.17]	<0.01	50	-0.35 [-0.53; -0.17]	<0.01	
Muscle mass	Yes	18	-2.38 [-3.15; -1.61]		17	-1.44 [-2; -0.87]		18	1.46 [0.84; 2.08]		16	-2.12 [-2.97; -1.27]		16	-2.12 [-2.97; -1.27]		
	No	36	-0.2 [-0.37; -0.02]	0.01	36	-0.21 [-0.43; 0.02]	0.04	34	0.2 [0.05; 0.35]	0.14	34	-0.37 [-0.64; -0.09]	0.10	34	-0.37 [-0.64; -0.09]	0.10	
Glucose	Yes	10	-1.2 [-1.94; -0.47]		7	-0.98 [-1.67; -0.3]		10	0.82 [0; 1.63]		6	-1.39 [-2.58; -0.2]		6	-1.39 [-2.58; -0.2]		
	No	58	-0.25 [-0.37; -0.13]	<0.01	49	-0.19 [-0.35; -0.03]	<0.01	57	0.22 [0.1; 0.34]	<0.01	50	-0.25 [-0.43; -0.08]	<0.01	50	-0.25 [-0.43; -0.08]	<0.01	
HbA1c	Yes	22	-1.45 [-2.11; -0.8]		19	-1.06 [-1.52; -0.61]		24	1 [0.54; 1.45]		20	-1.38 [-1.91; -0.84]		20	-1.38 [-1.91; -0.84]		
	No	32	-0.24 [-0.39; -0.09]	<0.01	32	-0.16 [-0.36; 0.04]	0.01	33	0.23 [0.07; 0.39]	<0.01	33	-0.17 [-0.33; -0.01]	<0.01	33	-0.17 [-0.33; -0.01]	<0.01	
Insulin	Yes	13	-1.82 [-2.79; -0.85]		13	-1.33 [-2.16; -0.5]		12	1.5 [0.81; 2.18]		14	-2.3 [-3.31; -1.29]		14	-2.3 [-3.31; -1.29]		
	No	33	-0.32 [-0.52; -0.13]	<0.01	29	-0.17 [-0.36; 0.02]	0.01	32	0.26 [0.08; 0.44]	<0.01	28	-0.19 [-0.38; 0.01]	<0.01	28	-0.19 [-0.38; 0.01]	<0.01	
HOMA-IR	Yes	8	-3.24 [-4.93; -1.56]		8	-1.93 [-3.16; -0.71]		8	2.08 [0.95; 3.2]		9	-2.44 [-3.81; -1.08]		9	-2.44 [-3.81; -1.08]		
	No	32	-0.38 [-0.59; -0.18]	0.01	27	-0.18 [-0.35; -0.02]	0.01	31	0.27 [0.09; 0.45]	<0.01	26	-0.28 [-0.52; -0.03]	<0.01	26	-0.28 [-0.52; -0.03]	<0.01	
TG	Yes	13	-2.03 [-3.18; -0.89]		13	-1.45 [-2.36; -0.53]		11	1.93 [0.96; 2.9]		12	-2.51 [-3.75; -1.26]		12	-2.51 [-3.75; -1.26]		
	No	83	-0.09 [-0.16; -0.02]	<0.01	70	-0.12 [-0.22; -0.01]	<0.01	81	0.25 [0.15; 0.35]	<0.01	71	-0.26 [-0.39; -0.12]	<0.01	71	-0.26 [-0.39; -0.12]	<0.01	
TChol	Yes	25	-2.03 [-2.55; -1.5]		23	-1.23 [-1.68; -0.77]		23	1.12 [0.62; 1.62]		21	-1.67 [-2.27; -1.07]		21	-1.67 [-2.27; -1.07]		
	No	75	-0.2 [-0.31; -0.09]	<0.01	79	-0.07 [-0.15; 0.02]	<0.01	77	0.24 [0.14; 0.33]	<0.01	75	-0.23 [-0.36; -0.11]	<0.01	75	-0.23 [-0.36; -0.11]	<0.01	
HDL-C	Yes	17	-1.97 [-2.72; -1.22]		17	-1.78 [-2.27; -1.29]		16	1.36 [0.69; 2.03]		16	-2.2 [-2.93; -1.46]		16	-2.2 [-2.93; -1.46]		
	No	83	-0.2 [-0.27; -0.13]	<0.01	76	-0.18 [-0.28; -0.08]	<0.01	90	0.12 [0.06; 0.19]	<0.01	80	-0.21 [-0.3; -0.13]	<0.01	80	-0.21 [-0.3; -0.13]	<0.01	
LDL-C	Yes	21	-1.96 [-2.75; -1.17]		18	-1.15 [-1.67; -0.62]		21	1.82 [1.34; 2.3]		17	-2.23 [-3.04; -1.41]		17	-2.23 [-3.04; -1.41]		
	No	70	-0.15 [-0.24; -0.07]	<0.01	71	-0.07 [-0.17; 0.02]	<0.01	75	0.19 [0.11; 0.28]	<0.01	76	-0.1 [-0.17; -0.02]	<0.01	76	-0.1 [-0.17; -0.02]	<0.01	
CRP	Yes	22	-1.5 [-2.1; -0.91]		22	-1.35 [-1.8; -0.9]		22	1.01 [0.6; 1.42]		23	-2.1 [-2.65; -1.55]		23	-2.1 [-2.65; -1.55]		
	No	62	-0.31 [-0.45; -0.17]	<0.01	60	-0.23 [-0.36; -0.11]	0.01	65	0.26 [0.14; 0.38]	<0.01	60	-0.33 [-0.48; -0.19]	<0.01	60	-0.33 [-0.48; -0.19]	<0.01	
IL-6	Yes	23	-1.31 [-1.94; -0.68]		20	-1.03 [-1.6; -0.47]		21	1.22 [0.66; 1.78]		18	-1.74 [-2.51; -0.97]		18	-1.74 [-2.51; -0.97]		
	No	34	-0.2 [-0.33; -0.07]	0.23	33	-0.07 [-0.18; 0.04]	0.05	35	0.29 [0.13; 0.45]	0.01	31	-0.28 [-0.49; -0.08]	0.12	31	-0.28 [-0.49; -0.08]	0.12	
TNF-α	Yes	14	-0.6 [-1.23; 0.04]		12	-0.69 [-1.3; -0.09]		14	1.06 [0.47; 1.66]		13	-0.79 [-1.4; -0.18]		13	-0.79 [-1.4; -0.18]		
	No	24	-0.12 [-0.31; 0.06]	0.33	25	-0.11 [-0.28; 0.06]	0.33	25	0.45 [0.19; 0.71]	0.80	24	-0.41 [-0.74; -0.09]	0.72	24	-0.41 [-0.74; -0.09]	0.72	
Adiponectin	Yes	12	-0.45 [-1.08; 0.18]		12	-0.44 [-1.09; 0.2]		11	0.54 [-0.11; 1.19]		11	-0.55 [-1.23; 0.13]		11	-0.55 [-1.23; 0.13]		
	No	17	-0.15 [-0.38; 0.08]	0.33	16	-0.27 [-0.71; 0.18]	0.98	17	0.29 [-0.03; 0.61]	0.32	15	-0.7 [-1.3; -0.11]	0.13	15	-0.7 [-1.3; -0.11]	0.13	
Leptin	Yes	3	-1.48 [-4.16; 1.21]		3	-0.25 [-1.66; 1.16]		2	2.06 [-1.41; 5.52]		2	0.18 [-0.8; 1.16]		2	0.18 [-0.8; 1.16]		
	No	15	-0.03 [-0.25; 0.18]	0.14	17	-0.16 [-0.42; 0.1]	0.39	18	0.43 [0.15; 0.72]	0.50	17	-0.48 [-0.89; -0.06]	0.85	17	-0.48 [-0.89; -0.06]	0.85	
IGF-1	Yes	5	-1.11 [-2.5; 0.28]		5	-0.74 [-2.05; 0.57]		3	1.29 [-1.2; 3.79]		4	-0.64 [-2.25; 0.98]		4	-0.64 [-2.25; 0.98]		
	No	12	-0.56 [-1.2; 0.07]	0.14	8	-0.33 [-0.78; 0.12]	0.02	13	0.55 [-0.09; 1.18]	0.41	8	-0.29 [-0.54; -0.04]	0.03	8	-0.29 [-0.54; -0.04]	0.03	
IL-1β	Yes	2	-2.98 [-6.15; 0.18]		2	-2.78 [-4.76; -0.81]		2	0.97 [0.19; 1.75]		2	-2.27 [-4.02; -0.52]		2	-2.27 [-4.02; -0.52]		
	No	5	-0.1 [-0.86; 0.65]	0.15	5	-0.03 [-0.37; 0.31]	0.02	5	0.45 [-0.22; 1.12]	0.48	5	-0.66 [-1.58; 0.25]	0.21	5	-0.66 [-1.58; 0.25]	0.21	
	Yes	5	-0.98 [-1.88; -0.07]		4	-1.66 [-3.04; -0.28]		5	0.87 [-0.08; 1.82]		4	-2.18 [-4.34; -0.02]		4	-2.18 [-4.34; -0.02]		

BMI, Body mass index; CRP, C-Reactive Protein; HbA1c, Glycated haemoglobin; HDL-C, High density lipoprotein cholesterol; HOMA-IR, Homeostasis model assessment of insulin resistance; IGF-1, Insulin-like growth factor 1; IL-1β, Interleukin-1 beta; IL-6, Interleukin-6; K, Number of studies; LDL-C, Low density lipoprotein cholesterol; LL, Lower limit; P diff, p value of difference between all categories of the sub group; PE, Point estimate; SMD, Standardised mean difference; TChol, Total cholesterol; TG, Triglycerides; TNF-α, Tumour necrosis factor alpha; UL, Upper limit. Confidence intervals and p values in bold are significant (p < 0.05).

Table 10a

Subgroup analysis for the effect of exercise training adaptations on inflammatory markers.

	Improve	CRP SMD			P diff	IL-6 SMD			P diff	TNF- α SMD			P diff
		K	PE [LL; UL]			K	PE [LL; UL]			K	PE [LL; UL]		
VO ₂ max	No	15	-0.3 [-0.47; -0.14]		0.01	17	-0.25 [-0.41; -0.09]		0.31	12	-0.36 [-0.66; -0.06]		0.36
	Yes	22	-0.85 [-1.22; -0.49]			15	-0.41 [-0.65; -0.16]			11	-0.17 [-0.44; 0.1]		
Body mass	No	54	-0.17 [-0.28; -0.05]		0.01	51	-0.22 [-0.36; -0.08]		0.01	36	-0.26 [-0.47; -0.04]		0.02
	Yes	6	-1.5 [-2.54; -0.47]			8	-1.56 [-2.55; -0.58]			7	-1.08 [-1.76; -0.4]		
BMI	No	58	-0.38 [-0.53; -0.22]		0.06	49	-0.49 [-0.69; -0.29]		0.89	32	-0.32 [-0.54; -0.1]		0.38
	Yes	6	-1.49 [-2.64; -0.33]			5	-0.54 [-1.11; 0.04]			6	-0.5 [-0.86; -0.15]		
Fat mass	No	55	-0.29 [-0.43; -0.14]		< 0.01	51	-0.32 [-0.49; -0.15]		0.07	37	-0.38 [-0.61; -0.14]		0.30
	Yes	19	-1.12 [-1.6; -0.63]			12	-0.93 [-1.57; -0.29]			10	-0.73 [-1.36; -0.11]		
Muscle mass	No	43	-0.19 [-0.34; -0.03]		0.02	38	-0.32 [-0.48; -0.16]		0.59	25	-0.42 [-0.75; -0.08]		0.57
	Yes	10	-0.88 [-1.44; -0.31]			8	-0.09 [-0.89; 0.7]			8	-0.23 [-0.79; 0.32]		
Glucose	No	52	-0.25 [-0.36; -0.13]		< 0.01	37	-0.41 [-0.6; -0.23]		0.22	23	-0.55 [-0.96; -0.15]		0.71
	Yes	25	-0.91 [-1.31; -0.51]			18	-0.72 [-1.18; -0.27]			12	-0.67 [-1.11; -0.22]		
HbA1c	No	29	-0.19 [-0.31; -0.07]		0.03	21	-0.35 [-0.59; -0.1]		0.06	12	-0.3 [-0.62; 0.02]		0.01
	Yes	14	-0.87 [-1.47; -0.28]			9	-0.79 [-1.17; -0.4]			5	-1.65 [-2.66; -0.65]		
Insulin	No	31	-0.18 [-0.33; -0.04]		0.03	25	-0.29 [-0.51; -0.08]		0.04	17	-0.23 [-0.53; 0.06]		< 0.01
	Yes	9	-1.42 [-2.51; -0.33]			9	-0.95 [-1.52; -0.38]			4	-1.77 [-2.66; -0.89]		
HOMA-IR	No	32	-0.19 [-0.32; -0.07]		0.01	27	-0.31 [-0.52; -0.1]		0.03	17	-0.24 [-0.51; 0.04]		< 0.01
	Yes	13	-1.27 [-2.08; -0.46]			8	-1.01 [-1.63; -0.4]			7	-1.55 [-2.21; -0.89]		
TG	No	64	-0.34 [-0.47; -0.22]		0.01	42	-0.39 [-0.55; -0.23]		0.08	31	-0.53 [-0.76; -0.31]		0.58
	Yes	22	-0.95 [-1.4; -0.5]			7	-1.33 [-2.38; -0.28]			6	-0.8 [-1.74; 0.13]		
TChol	No	63	-0.29 [-0.4; -0.18]		< 0.01	40	-0.24 [-0.38; -0.11]		< 0.01	32	-0.41 [-0.63; -0.19]		0.01
	Yes	16	-1.19 [-1.77; -0.6]			5	-1.79 [-2.76; -0.81]			6	-1.45 [-2.25; -0.65]		
HDL-C	No	66	-0.33 [-0.42; -0.24]		0.01	40	-0.36 [-0.53; -0.19]		0.03	30	-0.44 [-0.65; -0.23]		0.51
	Yes	20	-1.05 [-1.58; -0.53]			9	-1.32 [-2.19; -0.45]			6	-0.64 [-1.2; -0.09]		
LDL-C	No	57	-0.23 [-0.33; -0.14]		< 0.01	35	-0.33 [-0.51; -0.16]		0.05	28	-0.45 [-0.71; -0.19]		0.12
	Yes	21	-0.88 [-1.26; -0.5]			9	-0.72 [-1.05; -0.38]			7	-0.97 [-1.58; -0.36]		
CRP	No	92	-0.17 [-0.23; -0.11]		< 0.01	45	-0.21 [-0.34; -0.09]		< 0.01	30	-0.15 [-0.31; 0.02]		< 0.01
	Yes	25	-1.41 [-1.81; -1]			13	-1.16 [-1.68; -0.65]			11	-1.25 [-1.71; -0.8]		
IL-6	No	41	-0.19 [-0.27; -0.1]		0.01	70	-0.06 [-0.16; 0.03]		< 0.01	46	-0.15 [-0.29; -0.02]		< 0.01
	Yes	15	-0.98 [-1.55; -0.41]			21	-1.36 [-1.74; -0.99]			13	-1.23 [-1.68; -0.78]		
TNF- α	No	27	-0.23 [-0.35; -0.11]		0.09	44	-0.11 [-0.23; 0]		< 0.01	47	-0.03 [-0.12; 0.07]		< 0.01
	Yes	12	-0.86 [-1.58; -0.15]			15	-1.03 [-1.46; -0.61]			16	-1.41 [-1.74; -1.07]		
Adiponectin	No	19	-0.18 [-0.34; -0.02]		0.66	44	-0.11 [-0.23; 0]		< 0.01	14	-0.36 [-0.77; 0.04]		0.05
	Yes	2	-1.21 [-5.83; 3.41]			15	-1.03 [-1.46; -0.61]			3	-1.45 [-2.44; -0.46]		
Leptin	No	15	-0.19 [-0.36; -0.01]		0.44	18	-0.15 [-0.37; 0.08]		0.09	14	-0.22 [-0.47; 0.02]		0.01
	Yes	3	-1.18 [-3.67; 1.31]			4	-1.19 [-2.37; -0.01]			4	-1.69 [-2.75; -0.63]		
IGF-1	No	6	-0.88 [-2.03; 0.28]		0.84	8	-0.61 [-1.51; 0.3]			5	-0.57 [-1.63; 0.5]		
	Yes	2	-1.02 [-1.8; -0.24]										
IL-1 β	No	3	-0.28 [-0.54; -0.02]		0.21	5	-0.01 [-0.29; 0.27]		0.64	5	-0.09 [-0.41; 0.22]		0.67
	Yes	5	-0.52 [-0.81; -0.24]			3	-0.16 [-0.76; 0.43]			3	-0.23 [-0.8; 0.33]		

BMI, Body mass index; CRP, C-Reactive Protein; HbA1c, Glycated haemoglobin; HDL-C, High density lipoprotein cholesterol; HOMA-IR, Homeostasis model assessment of insulin resistance; IGF-1, Insulin-like growth factor 1; IL-1 β , Interleukin-1 beta; IL-6, Interleukin-6; K, Number of studies; LDL-C, Low density lipoprotein cholesterol; LL, Lower limit; P diff, p value of difference between all categories of the sub group; PE, Point estimate; SMD, Standardised mean difference; TChol, Total cholesterol; TG, Triglycerides; TNF- α , Tumour necrosis factor alpha; UL, Upper limit. Confidence intervals and p values in bold are significant ($p < 0.05$).

of studies, it limited the identification of the clinical significance of those changes. However, SMDs are particularly useful for inflammatory markers due to variation in their assessments even when the same unit of measurement is reported. In addition, the ideal and most sensitive approach for examining whether change in one variable is dependent on change in another variable would be to use continuous data, rather than a binary/dichotomous analytical approach. However, despite the large volume of data per outcome variable, combining variables into a common multivariate meta-regression was not possible due to a high proportion of missing data points. Although our tests of quality showed similar effects were observed for low- and high-quality studies for most variables, the increase in HDL-C was much higher in studies not confirming the minimum 48-hour interval from the last exercise session, suggesting part of the effects observed for HDL-C could be an effect of the last exercise session, rather than a chronic effect. To shed some light on the overall number of sessions, we built a multivariate table combining the length of intervention and the frequency of training per week (Supplementary Table 10). Although there are a low number of

studies testing exercise frequencies < 2 times per week and > 4 times per week, we did find evidence that training less than 2 times a week can generate significant metabolic and anti-inflammatory benefits if interventions last longer than > 24 weeks (BMI, muscle mass, HbA1c, LDL-C, HDL-C, VO₂ max, CRP, IL-6, TNF- α , Adiponectin, IL-1 β).

5. Summary, conclusion and implications

The immediate implications of this study for practical guidelines facilitation of policies are (1) the preference for aerobic training when aiming metabolic and inflammatory regulation in older adults, although resistance training also led to significant improvements; and (2) the need for a minimum frequency of exercise for three times a week, or twice a week for longer than 24 weeks. Furthermore, since these exercise adaptations are all closely linked, (3) interventions aimed at addressing all these holistically may be more effective than narrow targeted interventions to a specific component. Overall, although some metabolic adaptations can be obtained even with CT load prescribed below

Table 10b
Subgroup analysis for the effect of exercise training adaptations on inflammatory markers.

	Improve	Adiponectin SMD				Leptin SMD				IGF-1 SMD				IL-1 β SMD			
		K	PE [LL; UL]	P diff	K	PE [LL; UL]	P diff	K	PE [LL; UL]	P diff	K	PE [LL; UL]	P diff	K	PE [LL; UL]	P diff	
VO ₂ max	No	13	0.2 [-0.1; 0.49]	0.96	13	-0.3 [-0.61; 0.01]	0.71	4	0.26 [-0.2; 0.72]	0.05	1	-0.76 [-1.5; -0.02]	0.90				
	Yes	14	0.21 [-0.02; 0.44]		5	-0.22 [-0.5; 0.07]		3	1.32 [0.38; 2.26]		5	-0.83 [-1.61; -0.04]					
Body mass	No	32	0.28 [0.09; 0.46]	0.47	31	-0.36 [-0.56; -0.16]	0.03	20	0.53 [0.36; 0.7]	< 0.01	3	-0.23 [-0.72; 0.27]	0.54				
	Yes	2	1.73 [-2.2; 5.67]		4	-2.42 [-4.3; -0.54]		1	-0.64 [-1.06; -0.22]		1	-0.01 [-0.49; 0.47]					
BMI	No	27	0.47 [0.16; 0.77]	0.23	27	-0.6 [-0.95; -0.25]	0.66	19	0.38 [0.11; 0.64]		3	-0.23 [-0.72; 0.27]					
	Yes	1	1 [0.18; 1.81]		1	-0.79 [-1.56; -0.02]					1	-0.01 [-0.49; 0.47]	0.54				
Fat mass	No	24	0.17 [-0.04; 0.39]	0.07	28	-0.19 [-0.33; -0.06]	0.01	17	0.45 [0.21; 0.69]	0.96	3	-0.24 [-0.78; 0.31]					
	Yes	6	1.24 [0.12; 2.35]		8	-1.63 [-2.68; -0.58]		5	0.47 [-0.43; 1.38]		6	-0.48 [-1.14; 0.18]	0.59				
Muscle mass	No	21	0.08 [-0.12; 0.29]	0.15	23	-0.36 [-0.66; -0.06]	0.51	15	0.34 [0.06; 0.62]	0.39	3	-0.24 [-0.78; 0.31]					
	Yes	4	1.19 [-0.32; 2.71]		4	-1.19 [-3.61; 1.24]		4	0.92 [-0.37; 2.21]		6	-0.48 [-1.14; 0.18]	0.59				
Glucose	No	22	0.17 [-0.02; 0.36]	0.17	22	-0.47 [-0.8; -0.14]	0.46	12	0.13 [-0.18; 0.43]	0.77	2	-0.24 [-1.22; 0.74]	1.00				
	Yes	8	0.75 [-0.06; 1.55]		5	-1.14 [-2.89; 0.61]		2	0.48 [-1.8; 2.76]								
HbA1c	No	9	-0.16 [-0.37; 0.05]	0.06	9	-0.09 [-0.3; 0.12]	0.21	5	0.71 [-0.07; 1.5]		3	-1.3 [-3.14; 0.54]	0.38				
	Yes	5	0.39 [-0.13; 0.91]		6	-0.73 [-1.72; 0.25]					2	-0.45 [-0.89; -0.01]					
Insulin	No	19	-0.03 [-0.18; 0.12]	0.09	17	-0.18 [-0.35; -0.01]	0.03	7	0 [-0.48; 0.48]	0.83	1	0.25 [-0.41; 0.9]	1.00				
	Yes	4	1.38 [-0.23; 2.98]		4	-2.32 [-4.29; -0.36]		2	-0.13 [-1.21; 0.96]								
HOMA-IR	No	18	0.01 [-0.14; 0.15]	0.09	14	-0.21 [-0.48; 0.05]	0.06	4	0.53 [-0.25; 1.31]	0.78	3	-1.3 [-3.14; 0.54]	0.38				
	Yes	5	1.08 [-0.15; 2.31]		6	-1.61 [-3.01; -0.21]		4	0.73 [-0.48; 1.94]		2	-0.45 [-0.89; -0.01]					
TG	No	16	0.06 [-0.17; 0.29]	0.17	17	-0.18 [-0.33; -0.03]	0.01	10	0.24 [0; 0.48]	0.38	6	-0.13 [-0.49; 0.23]	0.24				
	Yes	4	1.25 [-0.42; 2.91]		3	-3 [-5.14; -0.86]		4	0.75 [-0.35; 1.85]		4	-0.8 [-1.86; 0.26]					
TCchol	No	15	0.14 [-0.1; 0.39]	0.40	18	-0.24 [-0.39; -0.09]	0.15	7	0.12 [-0.24; 0.47]	0.41	6	0.13 [-0.18; 0.44]	0.01				
	Yes	5	0.8 [-0.73; 2.32]		4	-1.97 [-4.31; 0.36]		3	0.96 [-0.99; 2.91]	0.65	8	-0.29 [-0.78; 0.2]	0.63				
HDL-C	No	16	0.01 [-0.19; 0.21]	0.15	18	-0.15 [-0.31; 0.01]	0.26	11	0.21 [-0.13; 0.55]		2	-0.45 [-0.89; -0.01]					
	Yes	3	1.55 [-0.53; 3.63]		3	-1.69 [-4.35; 0.98]		4	0.44 [-0.5; 1.38]	< 0.01	5	0.19 [-0.14; 0.53]	0.01				
LDL-C	No	14	0.03 [-0.26; 0.33]	0.64	18	-0.21 [-0.37; -0.05]	0.31	8	0.1 [-0.23; 0.43]	0.96	7	-0.44 [-1.02; 0.14]	0.66				
	Yes	3	0.18 [-0.34; 0.69]		3	-1.26 [-3.27; 0.75]		2	1.85 [0.97; 2.72]	0.01	4	-1.13 [-2; -0.27]	0.06				
CRP	No	17	-0.08 [-0.2; 0.04]	0.09	14	-0.07 [-0.25; 0.11]	0.02	6	0.4 [-0.12; 0.93]	0.76	1	-0.64 [-1.26; -0.01]	0.88				
	Yes	4	1.25 [-0.28; 2.78]		4	-2.28 [-4.2; -0.36]		2	0.46 [-1.82; 2.74]	0.16	3	-0.23 [-0.72; 0.27]	1.00				
IL-6	No	16	0 [-0.19; 0.18]	0.05	18	-0.18 [-0.35; 0]	0.03	7	0.12 [-0.32; 0.55]	0.08	3	-0.23 [-0.72; 0.27]	1.00				
	Yes	5	1.36 [0.04; 2.67]		4	-2.28 [-4.2; -0.36]		1	-0.64 [-1.06; -0.22]	< 0.01	2	-2.18 [-3.1; -1.26]	1.00				
TNF- α	No	13	0.03 [-0.14; 0.21]	0.20	14	-0.24 [-0.44; -0.04]	0.03	3	-0.38 [-1.28; 0.52]	0.76	1	-0.64 [-1.26; -0.01]	0.88				
	Yes	4	1.14 [-0.55; 2.83]		4	-2.37 [-4.34; -0.41]		2	-0.16 [-1.26; 0.94]	0.16	3	-0.23 [-0.72; 0.27]	1.00				
Adiponectin	No	37	0.04 [-0.07; 0.15]	< 0.01	25	-0.33 [-0.62; -0.04]	0.01	3	-0.16 [-0.67; 0.34]	0.08	3	-0.23 [-0.72; 0.27]	1.00				
	Yes	8	1.79 [1.08; 2.5]		5	-2.15 [-3.5; -0.8]		1	-0.64 [-1.06; -0.22]	0.08	3	-0.23 [-0.72; 0.27]	1.00				
Leptin	No	23	0.06 [-0.09; 0.22]	0.03	36	-0.14 [-0.26; -0.03]	< 0.01	4	-0.13 [-0.52; 0.27]	0.08	3	-0.23 [-0.72; 0.27]	1.00				
	Yes	7	1.17 [0.17; 2.16]		9	-1.82 [-2.71; -0.93]		1	-0.64 [-1.06; -0.22]	< 0.01	2	-2.18 [-3.1; -1.26]	1.00				
IGF-1	No	4	1.03 [-0.98; 3.05]		5	-1.16 [-2.94; 0.63]		22	0.19 [-0.03; 0.41]	0.04	5	0.08 [-0.3; 0.45]	0.04				
	Yes							6	1.13 [0.78; 1.48]								
IL-1 β	No	2	0.03 [-0.73; 0.79]	0.36	2	-0.4 [-1.01; 0.21]	0.80	2	1.85 [0.97; 2.72]		5	-0.93 [-1.83; -0.03]					
	Yes	1	0.5 [-0.12; 1.11]		1	-0.29 [-0.9; 0.32]											

BMI, Body mass index; CRP, C-Reactive Protein; HbA1c, Glycated haemoglobin; HDL-C, High density lipoprotein cholesterol; HOMA-IR, Homeostasis model assessment of insulin resistance; IGF-1, Insulin-like growth factor 1; IL-1 β , Interleukin-1 beta; IL-6, Interleukin-6; K, Number of studies; LDL-C, Low density lipoprotein cholesterol; LL, Lower limit; P diff, p value of difference between all categories of the sub group; PE, Point estimate; SMD, Standardised mean difference; TCchol, Total cholesterol; TG, Triglycerides; TNF- α , Tumour necrosis factor alpha; UL, Upper limit. Confidence intervals and p values in bold are significant (p < 0.05).

recommended levels, the anti-inflammatory response depends on the minimum AT and RT frequency, volume, and intensity of exercise training.

CRedit authorship contributors statement

RS designed and conducted the search and acted as first reviewer for screening, data extraction, and quality appraisal. AG and AVS assisted in the design and performance of the search. AG, JT, AY, MA, PRHJ, KV, NSMS, OJ, SHU, and TB acted as second reviewers for article screening, data extraction, and quality appraisal. RS prepared extracted data for meta-analysis which was conducted by AVS. AVS and RS prepared the first draft of the manuscript, while JET and SWJ revised the interpretation. AG, AY, and KV assisted in the creation of tables and figures. All authors were involved in reviews and revisions of the manuscript.

Declaration of competing interests

We declare no competing interests.

Data sharing

Dataset available at OSF HOME (https://osf.io/4jxs5/?view_only=5bd44d7a9a26417ba7a2ce41a06bddf4).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

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