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SYSTEMATIC REVIEW

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Influence of Morning and Afternoon Exercise on Body Composition and Metabolic Health: A Systematic Review and Meta-Analysis

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Abstract

Background Exercise is widely recognized for its beneficial effects on metabolic health and can serve as a non-pharmacological health intervention. However, the effect of morning versus afternoon exercise on various metabolic indicators remains unclear. This study aimed to systematically analyze the effect of exercise at various times of day on body composition, glucose and lipid metabolism.

Methods Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines, this study conducted literature searches in the electronic databases PubMed, Embase, Web of Science, Scopus and SPORTDiscus. Fourteen long-term and five acute studies were analyzed ($n = 765$ participants) that compared exercise performed in the morning versus the afternoon or evening, and assessed body weight, body mass index, fat mass, fasting blood glucose, hemoglobin A1c (HbA1c), insulin, and/or triglycerides. The risk of bias was assessed using the Cochrane tool (RoB 2). The certainty of evidence was assessed using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) framework.

Results In the long-term studies, morning training was associated with a greater reduction in HbA1c (mean difference [MD] − 0.11%, 95% confidence intervals [CI] − 0.19 to − 0.03, $I^2 = 0\%$, $p = 0.009$), an effect primarily observed in populations with type 2 diabetes (T2D) in subgroup analyses. In contrast, afternoon training was associated with a greater reduction in fasting blood glucose (MD 0.13 mmol/L, 95% CI 0.01 to 0.24, $I^2 = 0\%$, $p = 0.03$). No significant timing effects were observed for other body composition or lipid outcomes. In the acute studies, afternoon exercise was associated with greater reductions in glucose levels from pre- to post-exercise (MD 0.53 mmol/L, 95% CI 0.10 to 0.96, $I^2 = 21\%$, $p = 0.02$), but no difference was found for fasting blood glucose. The certainty of evidence ranged from moderate to very low across most outcomes, primarily due to risk of bias and imprecision.

Conclusions Morning and afternoon exercise suggest selective effects on glycemic control, though these findings should be considered preliminary and were primarily observed in populations with T2D. Morning training was associated with a statistically significant reduction in HbA1c, whereas afternoon training was associated with lowering fasting blood glucose. However, these findings should be interpreted with caution, as the result was primarily observed in T2D populations and the overall certainty of evidence was low. No consistent differential effects were observed for body composition or other lipid parameters.

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Key Points

- Morning training was associated with greater HbA1c reduction, particularly in T2D populations, though evidence certainty is low.
- Afternoon training was associated with greater reductions in fasting blood glucose and pre- to post-exercise glucose changes but evidence remains preliminary due to limited studies.
- Exercise timing did not show consistent differential effects on body composition or blood lipids in this analysis.

Keywords Exercise timing, Time-of-day, Glycemic control, Lipid metabolism, Chronobiology

Background

The incidence of obesity and metabolic diseases such as type 2 diabetes (T2D) and cardiovascular disorders is increasing worldwide; therefore, identifying effective methods for managing weight and improving metabolic health has become essential [1–4]. In 2022, approximately 2.5 billion adults worldwide were overweight, accounting for 43% of the global adult population, among whom 890 million suffered from obesity, representing 16% of all adults [5]. Over the past two decades, metabolic diseases have surged globally. According to the latest IDF estimates, 589 million adults have diabetes in 2024, projected to reach 853 million by 2050 [6]. Concurrently, metabolic syndrome (MetS) affects approximately 25% of adults worldwide [7]. Exercise, as a non-pharmacological strategy [8, 9], has been widely acknowledged for its beneficial effects in enhancing body composition [10, 11], glucose metabolism, and lipid profiles [12, 13]. Recently, the effect of exercise timing on metabolic health has been investigated, and the concept of timed exercise has been proposed [14, 15].

Exercise timing may differentially influence metabolic responses. However, findings remain inconsistent. A recent meta-analysis showed that exercise timing did not affect the acute cardiometabolic response to exercise [16]. Another meta-analysis indicated no significant difference in metabolic adaptation between morning training (MT) and afternoon training (AT) but demonstrated the superior efficacy of AT in reducing circulating triglyceride (TG) levels [17]. However, evidence on body composition outcomes remains mixed and appears to differ by sex: morning exercise was more effective for reducing abdominal fat in women, whereas afternoon exercise increased lipid oxidation in men [18]. Mechanistically, exercise-induced catecholamine and growth hormone responses can promote lipolysis [19], yet a consistent timing-dependent advantage across populations has not been established. Notably, previous meta-analyses have focused on either acute [16] or long-term [17] interventions alone, and have largely focused on a narrow set of outcomes, leaving a substantial gap in understanding both immediate and sustained metabolic responses to exercise timing.

The present review addresses this gap by incorporating both acute and long-term study designs and extending the outcome spectrum to include body composition, glycemic control, and lipid metabolism. By synthesizing existing evidence, this study aimed to clarify temporal patterns of exercise and the influence on metabolic health, providing a more holistic evidence base to inform individualized exercise recommendations.

Methods

Search Strategy and Data Selection

This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [20] (Fig. 1). The protocol was registered in the International Prospective Register of Systematic Reviews (PROSPERO) database (CRD420250619379). There were no deviations from the registered protocol. A literature search was conducted using the electronic databases PubMed, Embase, and Web of Science (WOS), Scopus, and SPORTDiscus. The search was first conducted in January 2025, with an update in January 2026. Only articles published in English were included. The following search strategy was used: (“diel rhythm” OR "time-of-day" OR “exercise timing” OR “morning exercise” OR “morning training” OR “circadian” OR “morning vs afternoon” OR “morning vs evening” OR “timing” OR “time-of-day”) AND (“exercis*” OR “training” OR “sport” OR “physical activity” OR “athletics” OR “workout” OR “fitness” OR “play” OR “movement” OR “walking” OR “strength”). The “randomized controlled trial” filter was applied in PubMed and Embase databases, and the term “clinical trial” was added to the WOS search. The search results were imported into EndNote to organize the references and remove duplicates. Positive mean differences (MDs) favor afternoon training and negative MDs favor morning training.

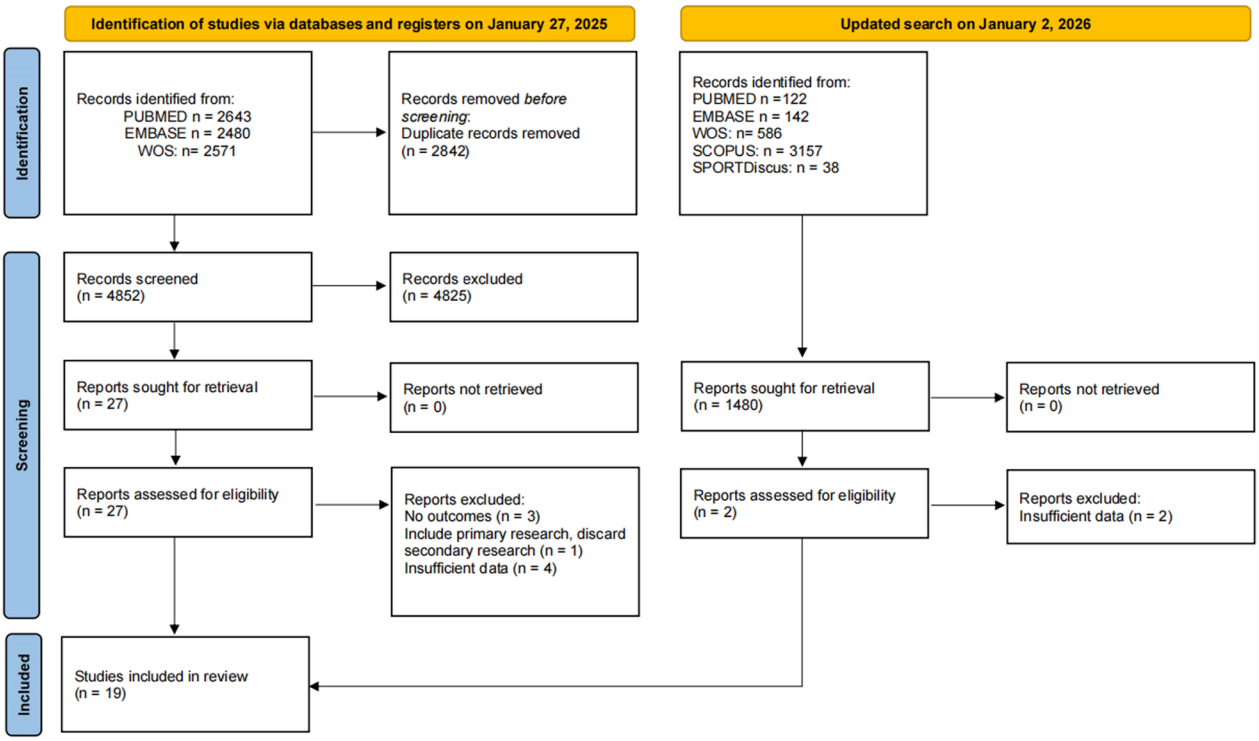

Fig. 1 PRISMA 2020 flowchart

Eligibility Criteria

Studies were included if they met the following criteria based on the PICOS framework:

Population: adults who are sedentary, overweight/obese, or diagnosed with MetS. Studies involving adolescents, pregnant women, or animal models were excluded. Studies focusing exclusively on patients with hypertension (without concurrent metabolic disturbances) were also excluded, as their primary outcome (blood pressure) differs from our prespecified metabolic endpoints (body composition, glucose, and lipid metabolism).

Intervention: structured exercise interventions performed at a fixed time of day, including the morning (typically 07:00–10:00), and the afternoon/evening (typically 16:00–20:30). For the purpose of meta-analysis and to maintain consistency with prior literature, the latter time window is referred to as "afternoon training" throughout the manuscript.

Comparator: comparison groups could involve exercise at a different time of day, such as the morning and the afternoon.

Outcomes: primary outcomes included body composition (weight, body mass index [BMI], fat mass, and waist circumference), glucose metabolic factors (fasting blood glucose [FBG], hemoglobin A1c [HbA1c], insulin, insulin resistance [HOMA-IR]), and lipid profiles (triglycerides [TG], total cholesterol [TC], high-density lipoproteins [HDL] cholesterol, and low-density lipoproteins [LDL cholesterol]).

Study type: randomized controlled trials, including both parallel and crossover designs. Observational studies and non-randomized trials were excluded.

Each article was independently screened and approved based on the criteria.

Data Extraction, Conversion, and Synthesis

Acute and long-term studies were analyzed separately for all outcomes. No data pooling was performed across acute and long-term study designs. The extracted data included: body weight, BMI, fat mass, fat-free mass, waist circumference, body fat, FBG, HbA1c (%), fasting insulin, HOMA-IR, TG, TC, HDL cholesterol, and LDL cholesterol in long-term studies. FBG and pre- to post-exercise glucose changes were included in acute studies. In these acute crossover studies, FBG was assessed as the change in fasting glucose from the morning before the exercise session to the morning after the session (i.e., post-intervention minus pre-intervention), reflecting the carryover effect of the preceding day's exercise on next-morning fasting glucose. The results were extracted using Origin 2025 when they were shown only in graphs and the corresponding authors could not be reached. To ensure accuracy, extractions were performed independently by two reviewers (JW and XZ). Any discrepancies were

reviewed by a third author (SC) and resolved through discussion until consensus was reached. If the studies only presented 95% confidence intervals (CIs), standard deviations (SDs) were calculated using the https://www.math.hkbu.edu.hk/~tongt/papers/median2mean.html website [21, 22]. When ΔSD was not reported, it was calculated by assuming a correlation coefficient of 0.7, as previously suggested [23]:

$$\Delta SD = \sqrt{SD_{PRE}^2 + SD_{POST}^2 - 2^* SD_{PRE}^* SD_{POST}^{*CORR}}.$$

The meta-analysis progression was carried out using RevMan5.4 software. For blood biomarkers (e.g., glucose, lipids, insulin), which are measured using internationally standardized units across studies, we used mean difference (MD) to preserve clinical interpretability. Negative MDs favor morning training (indicating a greater reduction or lower value in the MT group), whereas positive MDs favor afternoon training (indicating a greater reduction or lower value in the AT group). For body composition outcomes (e.g., fat mass, fat-free mass, body fat percentage), where measurement methods (DEXA, bioelectrical impedance, skinfolds) may yield systematically different absolute values despite nominally identical units, we used standardized mean difference (SMD) to harmonize the data. Given the expected heterogeneity among the studies in terms of population and intervention protocols, all meta-analyses adopted the random-effects model [24, 25]. We performed subgroup analyses for long-term glycemic outcomes stratified by health status (T2D vs. non-T2D populations).

Risk of Bias and Methodological Quality

The risk of bias was assessed according to version 2 of the Cochrane tool (RoB2) [26]. Parallel-group studies ($n=12$) were evaluated across six standard domains: randomization process, deviations from intended interventions, missing outcome data, measurement of the outcome, selection of the reported result, and overall bias. Crossover studies ($n=7$) were additionally assessed for bias arising from period and carryover effects, consistent with the RoB 2 framework for crossover trials. The certainty of evidence for the primary outcomes was assessed using the GRADE framework (supplementary material). GRADE assessments were performed independently by two reviewers (JW and XZ), with disagreements resolved through discussion. The certainty was rated across five domains: risk of bias, inconsistency, indirectness, imprecision, and publication bias.

Sensitivity Analysis

For the sensitivity analysis, the leave-one-out method was used to assess whether any of the included studies had a significant influence on the overall effect. If the leave-one-out test yielded positive results, the effect size of the model was reported, and that study was excluded from the analysis.

Publication Bias

Publication bias pertains to the tendency of significant results to be more likely to be published than null results. Egger's test was planned for assessing publication bias but was not performed, as all outcomes included fewer than 10 studies, rendering the test unreliable [27].

Results

Description of Studies

Results for long-term studies ($n=14$) are presented first, followed by acute study findings ($n=5$). Table 1 (long-term studies) and Table 2 (acute studies) present qualitative descriptions of the included studies. In the 14 long-term studies (692 participants), the exercise intervention time ranged from 2 to 16 weeks (Table 1). Three studies focused on patients with T2D, one on patients with cardiovascular arterial disease, three on healthy people, six on healthy overweight and obese people, and one on patients with MetS. In terms of exercise intervention protocols, the studies included one study using strength training, two using combined aerobic and strength training, one using low-intensity walking, three using high-intensity interval training (HIIT), six using aerobic training, and one using a multi-sport training model. Finally, three studies used a randomized crossover design with 2-week wash-out periods, and 11 used a parallel group design. The qualitative analysis of the risk-of-bias assessment showed that all the included studies ranged from moderate to high quality. Visual summaries of the risk of bias are presented in Figs. 2, 3 and 4. GRADE assessment indicated very low certainty for insulin, FBG—acute, glucose before and after exercise—acute, and moderate to low certainty for other outcomes, primarily due to serious imprecision, indirectness, and risk of bias. No serious inconsistency or publication bias was identified. Detailed GRADE assessments are presented in Supplementary Table 1.

In the five acute studies listed in Table 2 (73 participants), the exercise intervention time ranged from 40 to 60 min, and the exercise period varied from 1 to 12 days. Among the studies, two were conducted on healthy individuals, one on participants with obesity, one on patients with T2D, and one on patients with type 1 diabetes (T1D). In terms of exercise intervention protocols, one study implemented a low-intensity walking program, one used HIIT, three employed aerobic training, and one used a resistance training program. Regarding the study design, four studies adopted a crossover design, and

Table 1 Summary of characteristics of included long-term studies

References	Participants	Study design	Exercise protocol	Frequency	Training duration	Time of training	Diet	Results
Carrillo et al.2024[28]	18 participants with T2D (9 M) 61 ± 2 yr BMI: 30.6 ± 0.7 kg/m^2	Randomized crossover trial (2 weeks wash-out)	30 min walking at 70% max-HR	3 sessions/week	6 weeks	Morning: 7:00–10:00 Afternoon: 16:00–19:00	Maintain normal eating habits	Morning moderate-intensity exercise acutely reduces glycemia in people with T2D also being prescribed metformin
Palomo et al.2023[29]	139 participants with MetS (90 M) 57 ± 7 yr BMI: 30.6 ± 3.0 kg/m^2	Randomized parallel-group controlled trial	HIIT: 4 × 4 min intervals at 90% max-HR	3 sessions/week	16 weeks	Morning: 8:00–9:00 Afternoon:16:00–17:00	Maintain normal eating habits Eat an hour before exercise	High-intensity aerobic exercise training in the morning is more efficient at reducing cardiometabolic risk factors
Brooker et al.2023[30]	65 participants with obesity MT: 41 ± 12 yr BMI:31 ± 4.3 kg/m^2 AT: 38 ± 11 yr BMI:32 ± 5.9 kg/m^2	Three-armed randomized parallel-group controlled trial	250 min per week of self-paced aerobic exercise	Not stated	12 weeks	Morning: 6:00–9:00 Afternoon: 16:00–19:00	Maintain normal eating habits	Afternoon group had a more significant weight loss than the morning group
Creasy et al. 2022[31]	33 participants with obesity (10 M) AM: 40.8 ± 8.4 yr BMI: 30.0 ± 3.9 kg/m^2 PM: 36.4 ± 10.8 yr BMI: 30.6 ± 4.7 kg/m^2	Randomized parallel-group controlled trial	From 70 to 80% max-HR and 750–2000 kcal/week supervised aerobic exercise	1 on-own, 3 supervised sessions/week	15 weeks	Morning: 06:00–10:00 Afternoon: 15:00–19:00	Eat freely throughout the study	Afternoon exercise loses more weight
Teo et al. 2021[32]	40 participants with obesity (17 M) 51 ± 13 yr BMI: 30.9 ± 4.2 kg/m^2	Randomized parallel-group controlled trial	30 min of aerobic exercise at 70% VO2 peak and 30 min of resistance exercise	3 sessions/week	12 weeks	Morning: 08:00–10:00 Afternoon 17:00–19:00	Eat at least 1 h before training Maintain normal eating habits	In the absence of dietary manipulation, the effect of diurnal exercise timing on body composition appear trivial
Teo et al. 2020[33]	40 participants with obesity (17 M,20 T2D) 51 ± 13 yr BMI: 30.9 ± 4.2 kg/m^2	Randomized parallel-group controlled trial	Moderate intensity (30 min of treadmill walking at 60–70% of VO2 peak)	3 sessions/week	12 weeks	Morning:08:00–10:00 Afternoon:17:00–19:00	Maintain usual eating habits	AT group exhibited no statistically significant improvement in glucose or insulin levels versus the MT group
Brooker et al. 2019[34]	20 inactive participants with overweight (6 M) 39 ± 13 yr BMI: 30.9 ± 4.2 kg/m^2	Three-armed, randomized parallel-group controlled trial	Self-paced moderate-vigorous walking or running on a treadmill to achieve a weekly total of 250 min	Not stated	12 weeks	Morning: 06:00–09:00 Afternoon: 16:00–19:00	Maintain normal eating habits	Afternoon exercise improves body composition and lowers blood glucose

Table 1 (continued)

References	Participants	Study design	Exercise protocol	Frequency	Training duration	Time of training	Diet	Results
Alizadeh et al. 2017[35]	48 females with overweight MT: 33.56 ± 5.98 yr BMI: 27.3 ± 1.52 kg/m^2 AT: 33.89 ± 6.58 yr BMI: 27.6 ± 1.42 kg/m^2	Randomized parallel-group controlled trial	Aerobic exercise at a target heart rate on the ventilatory threshold for 30 min	3 sessions/week	6 weeks	Morning: 08:00–10:00 Afternoon: 14:00–16:00	Maintain normal eating habits	Aerobic exercise in the morning could be considered a more effective program than afternoon exercise for weight loss
Savikj et al. 2022[36]	8 participants with T2D (8 M) 62 ± 8 yr BMI: 27.4 ± 1.9 kg/m^2	Randomized crossover trial (2 weeks wash-out)	Six one-min pulses at individual maximal load and 75 rpm	3 sessions/week	2 weeks	Morning: 08:00 Afternoon: 16:45	Maintain normal eating habits	Training impact on metabolic parameters was not observed
Lian et al. 2014[37]	178 participants with CAD (133 M) Morning group: 64 ± 9 yr BMI: 24.97 ± 2.71 kg/m^2 Afternoon group: 62 ± 10 yr BMI: 24.59 ± 2.66 kg/m^2	Randomized parallel-group controlled trial	Walk at 2.5 miles/h for 30 min/day	5 days/week	12 weeks	Not stated	All participants were given similar dietary advice by dietitians	Evening walking group gained more benefits in lipids
Arciero et al. 2022[18]	27 exercise-trained women: 42 ± 8 yr BMI: 24 ± 3 kg/m^2 20 exercise-trained men: 45 ± 8 yr BMI: 25.5 ± 3 kg/m^2	Randomized parallel-group controlled trial	RISE training for 1 h	4 sessions/week	12 weeks	Morning: 06:00–08:00 Afternoon: 18:30–20:30	Maintain normal eating habits	Men: TC, HDL cholesterol declined significantly with afternoon exercise Women: both groups exhibited reduced total body fat and increased fat-free mass
Krčmárová et al. 2018[38]	31 healthy women 66 ± 4 yr	Randomized parallel-group controlled trial	Progressive strength training for 8 exercises, with 3 sets for each exercise, and 10–12 repetitions per set	2 sessions/week	12 weeks	Morning: 07:30 Afternoon: 18:00	Follow a diet plan; no significant change in energy intake	Similar circadian effects of exercise on muscle strength and blood glucose
Savikj et al. 2019[39]	11 participants with T2D (11 M) 60 ± 2 yr BMI: 27.5 ± 0.6 kg/m^2	Randomized crossover trial (2 weeks wash-out)	HIIT: on cycle-ergometer 6 × 1 min at maximal load + 1 min low load	3 sessions/week	2 weeks	Morning: 08:00 Afternoon: 16:00	Standardized snack was offered 30 min after the afternoon training; no significant change in energy intake	Afternoon HIIT reduced glucose concentration

Table 1 (continued)

References	Participants	Study design	Exercise protocol	Frequency	Training duration	Time of training	Diet	Results
Shen B et al. 2025[40]	34 sedentary healthy men BMI: 18.5–24.9 kg/m^2 18–28 yr	Randomized parallel-group controlled trial	Moderate-intensity aerobic exercise	≥ 3 sessions/week	12 weeks	Morning: 06:00–08:00 Afternoon: 18:00–20:00	Maintain normal eating habits. Supplements or sports performance aids were prohibited	Aerobic exercise in the morning reduced body fat faster and decreased TC and TG

BMI body mass index, *HR* heart rate, *T2D* type 2 diabetes, *MetS* metabolic syndrome, *HIIT* high-intensity interval training, *VO_2peak* peak oxygen uptake, *CAD* coronary artery disease, *TC* total cholesterol; *HDL cholesterol* high-density lipoprotein, *TG* triglycerides, *MT* morning training, *AT* afternoon training

Table 2 Summary of characteristics of included acute studies

References	Participants	Study design	Exercise protocol	Intervention period	Time of training	Diet	Results
Kim et al. 2022[41]	12 healthy young men 21.8 ± 0.2 yr BMI: 21.3 ± 0.9 kg/m^2	Randomized crossover trial (2 weeks)	60 min on a treadmill at 60% VO_2max	1 week	Morning: 09:00–11:00 Afternoon: 16:00–18:00	Maintain normal eating habits	Endurance exercise in the late afternoon was more effective in improving blood sugar and lipid levels over a 24-h period
Moholdt et al 2021[42]	24 participants with obesity (24 M) 35–36 yr BMI: 31.2 ± 2.3 kg/m^2	Randomized parallel-group controlled trial	DAY 1, 3, 5: HIT, 10 × 1-min workouts and 1-min low-intensity cycling DAY 2, 4: 40、60 min of moderate-intensity continuous cycling	5 days	Morning: 06:30 Afternoon: 18:30	11 days of high-fat diet before and during exercise	Fasting blood glucose, insulin, cholesterol, triacylglycerol, and LDL cholesterol concentrations decreased in afternoon exercise
Tanaka et al. 2021[43]	11 healthy young men 22–30 yr	Randomized crossover trial (2 weeks)	60% of VO_2max for 1 h using a cycle-ergometer	1 day	Morning: 07:00 Afternoon: 16:00	Experimental meals	Glucose levels during exercise were only decreased in the afternoon exercise trial
Munan et al. 2020[44]	14 participants with T2D (8 M) 65 ± 9.0 yr BMI: 27.2 ± 3.5 kg/m^2	Randomized crossover trial (2 weeks)	50 min of walking at 5.0 km/h	12 days	Morning: exercise ending 20 min before breakfast Afternoon: exercise starting 3 or 4 h after lunch and ending 20 min before dinner	Standardized meals are provided on the exercise day and the following day to ensure energy balance	The decrease in blood glucose was more pronounced in the afternoon exercise
Toghi-Eshghi et al. 2019[45]	12 participants with T1D (3 M) 31.3 ± 8.9 yr BMI: 26.6 ± 3.8 kg/m^2	Randomized crossover trial (2 weeks)	40 min of RE at 8RM load for 2 sessions	2 days	Morning: 07:00 Afternoon: 17:00	Morning training: fasting state Before the afternoon training: standardized snack at 16:00	Blood glucose decreased after the afternoon exercise

BMI body mass index, *VO_2max* maximum oxygen uptake, *T2D* type 2 diabetes, *T1D* type 1 diabetes, HIT high-intensity training, *LDL* cholesterol, low-density lipoprotein, *RE* resistance exercise, *RM* repetition maximum

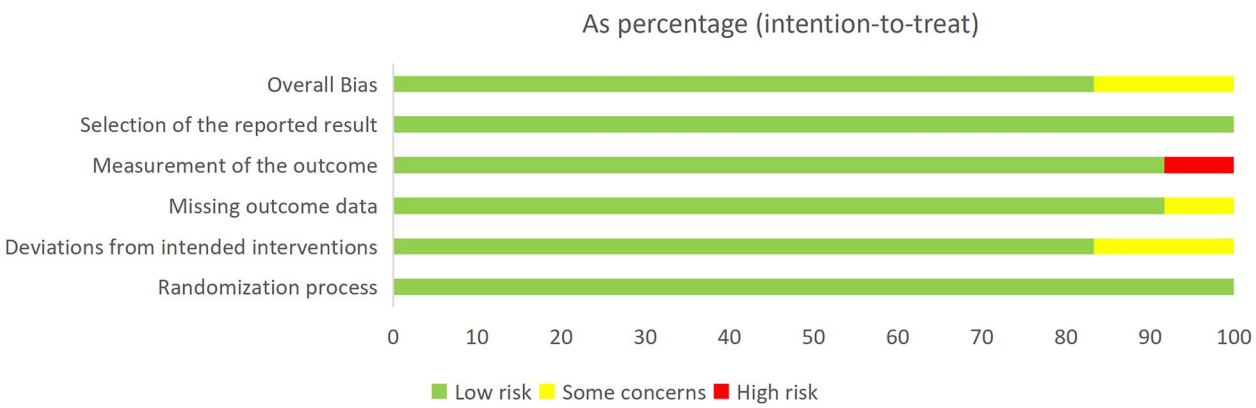

Fig. 2 Overall risk of bias for included parallel-group studies

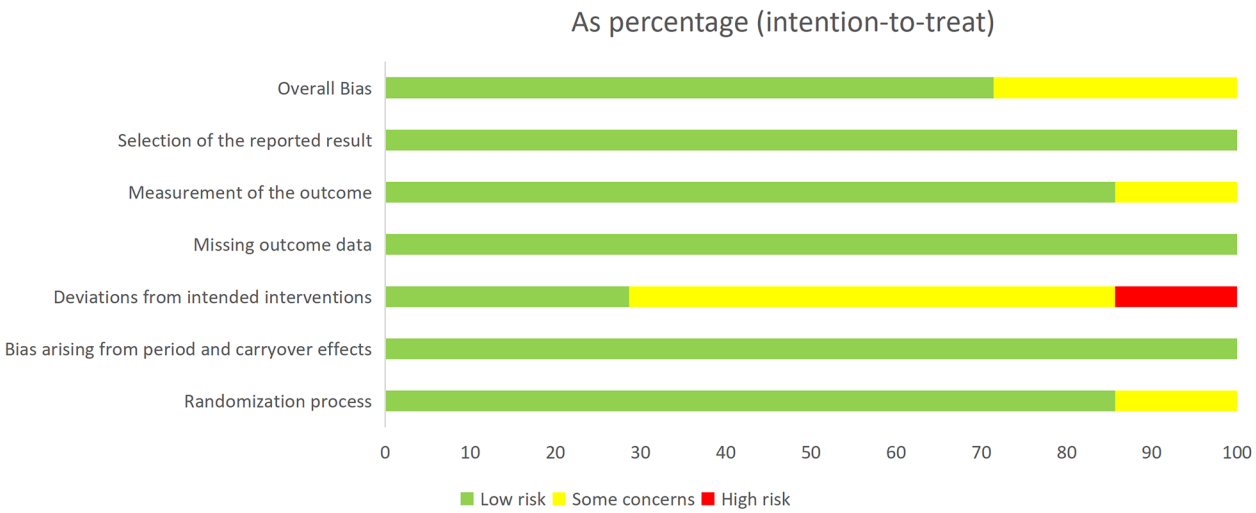

Fig. 3 Overall risk of bias for included crossover studies

one utilized a randomized control trial (RCT) scheme. Notably, Arciero et al. [18] reported data from male and female participants, whereas Teo et al. [33] reported data from patients with T2D and healthy individuals.

Dietary information or control was reported in all included studies, although the level of standardization varied. Briefly, most long-term studies instructed participants to maintain habitual eating patterns, while acute studies typically provided standardized meals. Carrillo et al. [28] enrolled 18 patients with T2D who walked at 70% of their maximum heart rate for 30 min in the morning and afternoon, maintaining their daily eating habits. Caloric intake for breakfast, lunch, and dinner did not differ significantly during the trial period. Brooker et al. [30] conducted a study on 65 patients with obesity who maintained a controlled diet. After 12 weeks, both the MT and AT groups showed a reduction in total energy intake during the intervention period. A significant difference was observed in these groups compared with the control group (MT -3974 kJ, $p<0.001$; AT -3165 kJ, $p=0.001$). Protein intake in the MT group was significantly decreased in the middle and later stages ($p<0.05$), whereas total fat intake in the AT group significantly decreased in the later stages ($p<0.05$). Similarly, Teo et al. [32] included 40 patients with obesity and observed significant reductions in total energy intake in both groups. Alizadeh et al. [35] noted a significant reduction in total energy intake over 6 weeks ($p=0.06$) in the MT group among 48 women with obesity. In contrast, the AT group did not exhibit a significant change in total energy intake.

Body Composition

Body Weight

Six studies across seven different populations assessed body weight (Fig. 5A). No differences were observed between AT and MT in reducing body weight (MD − 0.38 kg, 95% CI − 0.96 to 0.19, $I^2=0\%$, $p=0.19$).

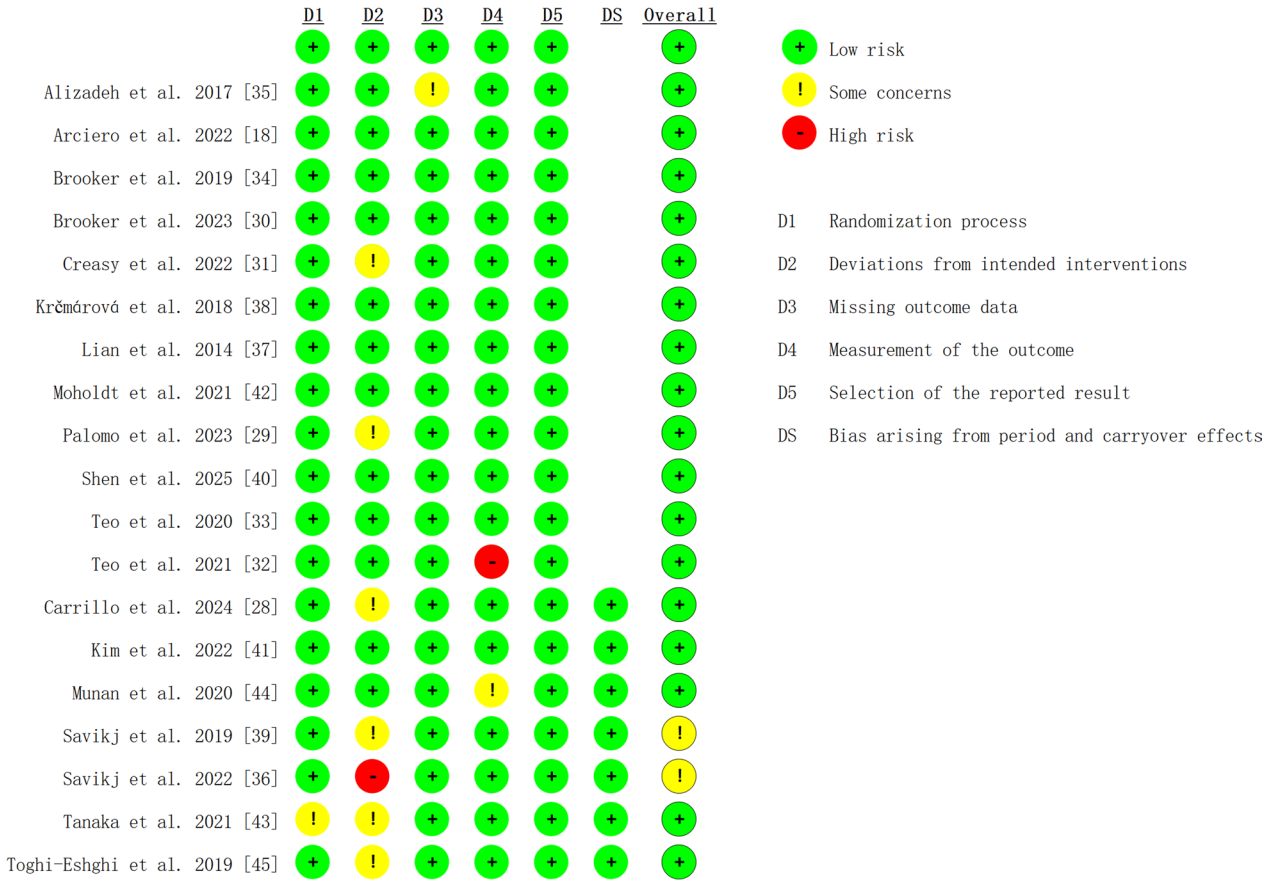

Fig. 4 Detailed risks of bias for studies included in the review. + (Green): Low risk of bias; —(Red): High risk of bias; (Yellow): some concerns (unclear risk)

Leave-one-out analysis showed that none of the studies influenced this effect.

BMI

BMI was evaluated in four studies involving four different populations (Fig. 5B). No differences were noted between AT and MT in reducing BMI (MD − 0.2 kg/m^2, 95% CI − 0.59 to 0.19, I^2 = 67%, p = 0.32). Leave-one-out analysis showed that the BMI result was not influenced by any single study.

Fat Mass

Seven studies involving eight populations evaluated fat mass (Fig. 5E). The results showed no differences between AT and MT in reducing fat mass (SMD 0.09, 95% CI − 0.13 to 0.32, I^2 = 0%, p = 0.42). Sensitivity analysis showed consistent results across studies.

Fat-Free Mass

The fat-free mass was evaluated in six studies involving seven different populations (Fig. 5F). No differences were observed between AT and MT in reducing fat-free mass (SMD 0.04, 95% CI − 0.19 to 0.28, I^2 = 0%, p = 0.71). Leave-one-out analysis confirmed that individual studies did not affect the outcome.

Body Fat

Five studies across six different populations investigated body fat (Fig. 5D). No significant differences were observed between MT and AT in reducing body fat (SMD -0.19, 95% CI − 0.64 to 0.26, I^2 = 51%, p = 0.41). Leave-one-out analysis confirmed that individual studies did not affect the outcome.

Waist Circumference

Waist circumference was evaluated in four studies involving four different populations (Fig. 5C). No significant differences were observed between MT and AT in reducing waist circumferences (MD − 0.21 cm, 95% CI − 1.2 to 0.77, I^2 = 31%, p = 0.68). The leave-one-out analysis showed that none of the studies was influencing the effect.

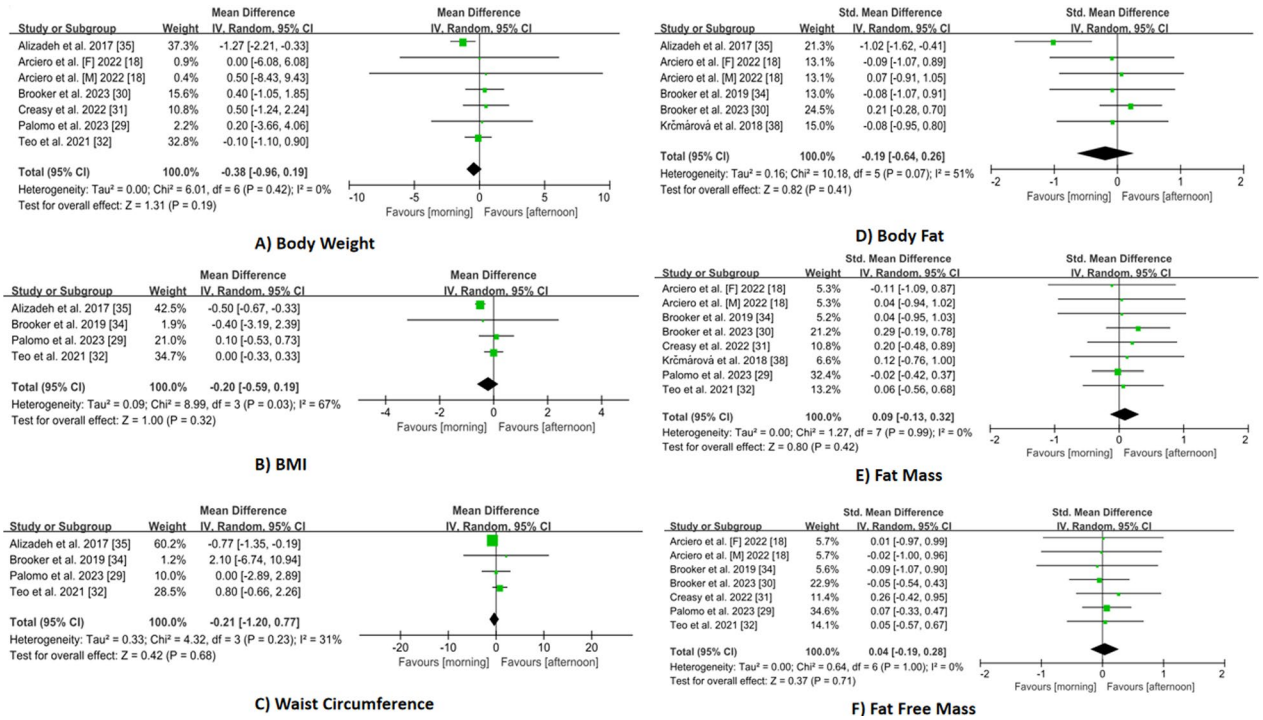

Fig. 5 Long-term effects of exercise on body composition. *BMI* body mass index

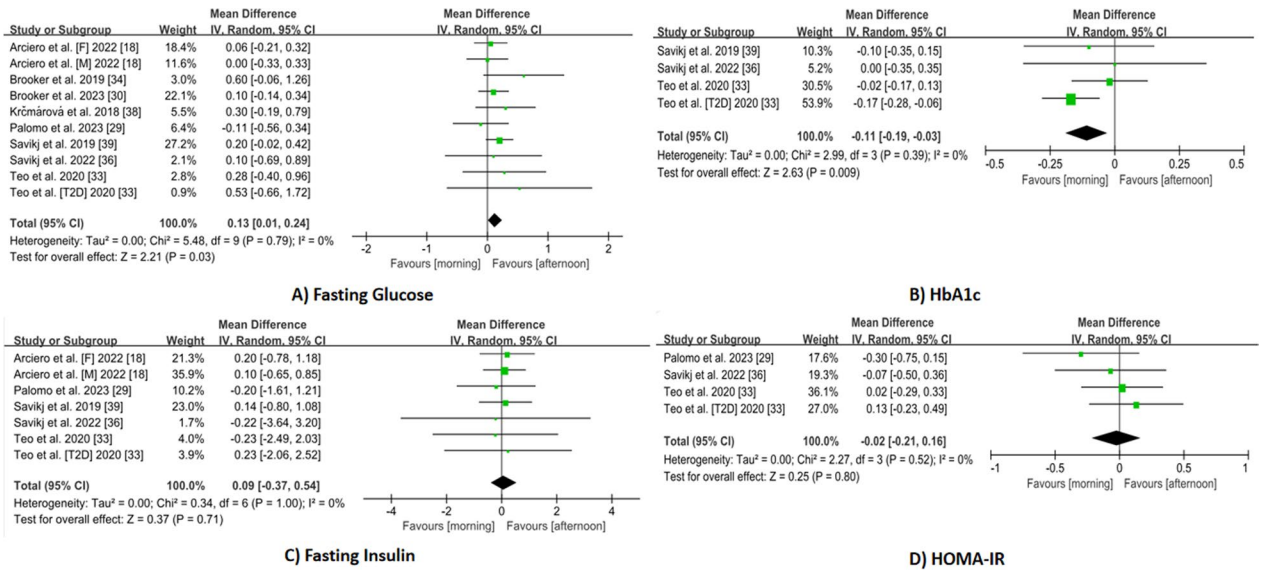

Fig. 6 Long-term effects of exercise on glucose metabolism. *HbA1c* hemoglobin A1c, *HOMA-IR* Homeostatic Model Assessment for Insulin Resistance

Glycemic Control

FBG

Eight studies involving 10 populations analyzed FBG (Fig. 6A), and AT reduced FBG more effectively than MT (MD 0.13 mmol/L, 95% CI 0.01 to 0.24, $I^2 = 0\%$, $p = 0.03$). Leave-one-out analysis showed that the results were no longer significantly biased in favor of AT for reducing blood glucose after excluding the studies by Brooker et al. [34] and Savikj et al. [39]. Subgroup analysis by health status showed a trend toward AT in populations with

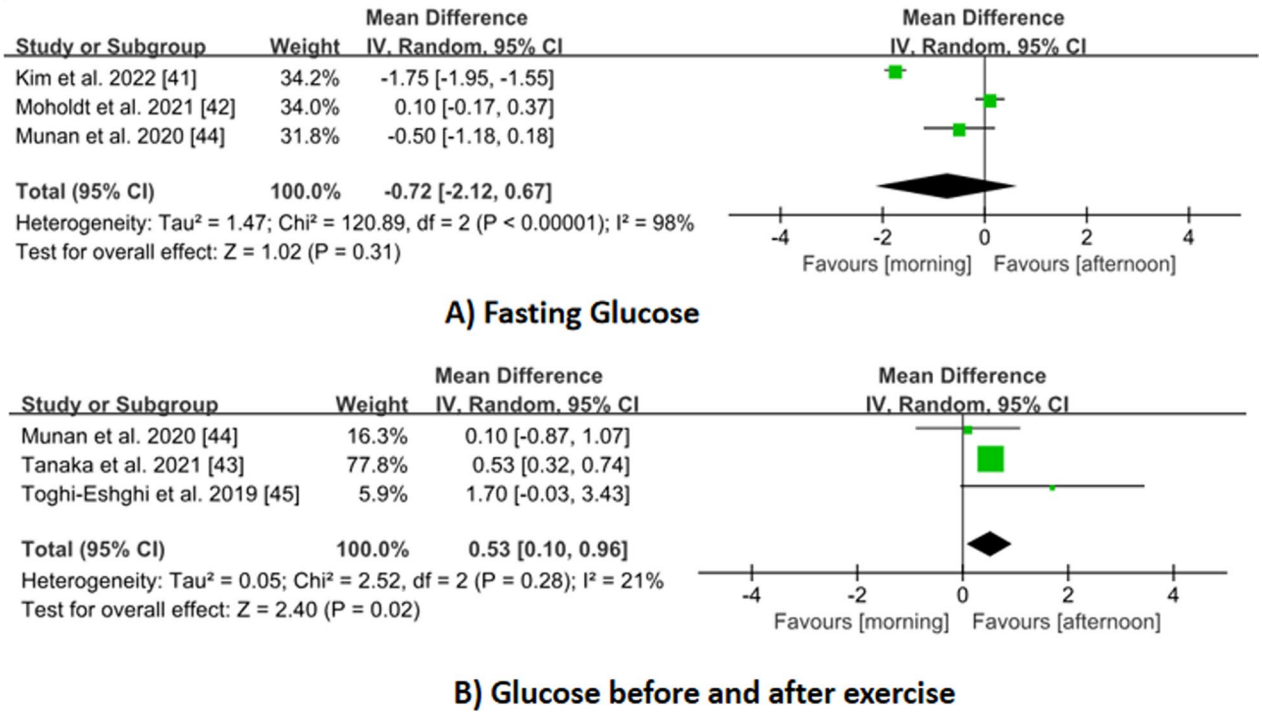

Fig. 7 Acute effects of exercise on glucose metabolism. Glucose before and after exercise: post-exercise minus pre-exercise glucose

T2D (MD 0.20 mmol/L, 95% CI − 0.00 to 0.41, p = 0.06), but not in non-T2D populations (MD 0.10 mmol/L, 95% CI − 0.04 to 0.23, $p = 0.17$), with no significant between-subgroup difference ($p = 0.40$) (Supplementary Figure S1).

In the three acute studies involving three populations that evaluated FBG levels (Fig. 7A), no differences were observed between AT and MT in terms of reducing glucose levels (MD −0.72 mmol/L, 95% CI −2.12 to 0.67, $I^2 = 98\%$, $p = 0.31$). Leave-one-out analysis showed stable outcomes across studies.

For the acute studies, the blood glucose difference before and after exercise in three studies with three different populations (Fig. 7B) was analyzed as exploratory, as it was not a prespecified primary endpoint. AT was more effective than MT at reducing FBG (MD 0.53 mmol/L, 95% CI 0.1 to 0.96, $I^2 = 21\%$, $p = 0.02$). However, when excluding the study by Tanaka et al. [43], the results were no longer significantly biased in favor of AT to reduce the blood glucose difference before and after exercise (MD 0.73 mmol/L, 95% CI − 0.8 to 2.27, $I^2 = 60\%$, $p = 0.35$).

HbA1c

HbA1c was evaluated in four studies involving distinct populations (Fig. 6B), and MT was more effective than AT at reducing HbA1c (MD − 0.11%, 95% CI − 0.19 to − 0.03%, $I^2 = 0\%$, $p = 0.009$). Sensitivity analysis indicated that when excluding the study by Teo et al. [33], the results were no longer significantly biased in favor of MT in reducing HbA1c. Subgroup analysis by health status showed that morning training significantly reduced HbA1c in participants with T2D (MD − 0.15%, 95% CI − 0.24 to − 0.05, $p = 0.003$) but not in individuals without T2D (Supplementary Figure S4).

Fasting Insulin

Fasting insulin was described in five studies with seven different populations (Fig. 6C). There were no differences between AT and MT in reducing insulin levels (MD 0.09 μU mL^{-1}, 95% CI − 0.37 to 0.54, $I^2 = 0\%$, $p = 0.71$). The leave-one-out analysis showed that none of the studies was influencing the effect. Subgroup analysis by health status also showed no significant effects in either T2D or non-T2D populations (Supplementary Figure S2).

HOMA-IR

HOMA-IR was described in three studies with four different populations (Fig. 6D). There were no differences between AT and MT in reducing HOMA-IR levels (MD − 0.02, 95% CI − 0.21 to 0.16, $I^2 = 0\%$, $p = 0.8$). The leave-one-out analysis showed that none of the studies was influencing the effect. Subgroup analysis by health status

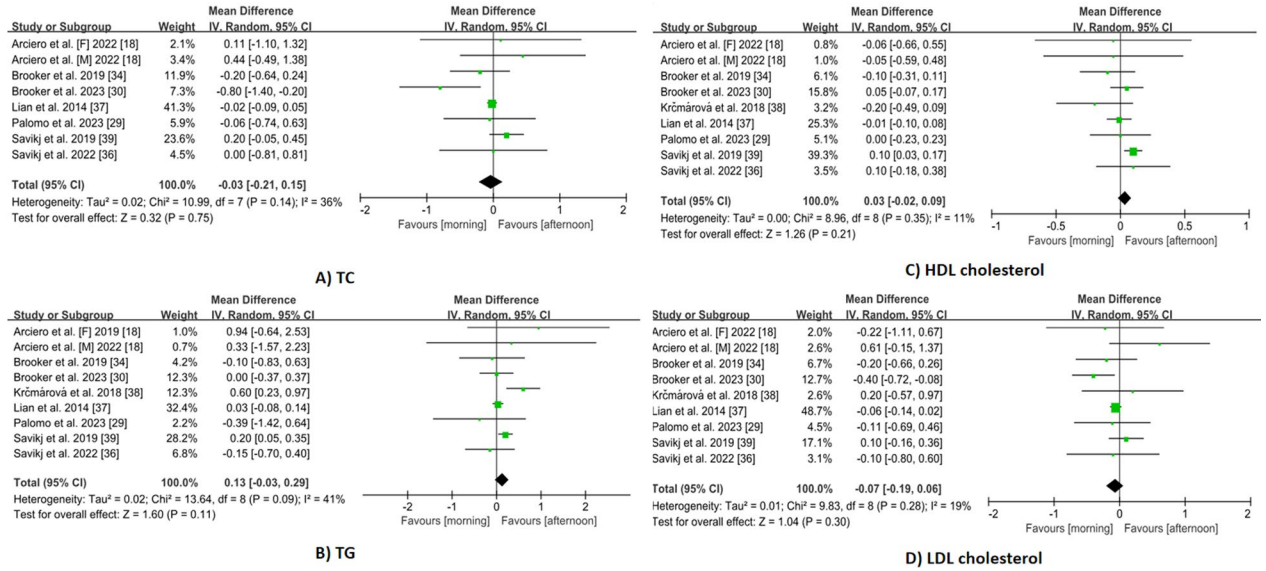

Fig. 8 Long-term effects of exercise on blood lipids. *TC* total cholesterol, *TG* triglycerides, *HDL cholesterol* high-density lipoproteins, *LDL cholesterol* low-density lipoproteins

also showed no significant effects in either T2D or non-T2D populations (Supplementary Figure S3).

Blood Lipids

TG

Analysis of TG across nine independent population studies demonstrated no differences were observed between AT and MT in reducing TG (MD 0.13 mmol/L, 95% CI − 0.03 to 0.29, $I^2 = 41\%$, $p = 0.11$) (Fig. 8-B). The leave-one-out analysis showed that none of the studies was influencing the effect.

TC

TC was evaluated in seven studies with eight different populations (Fig. 8A). There were no differences between AT and MT to reduce TC levels (MD -0.03 mmol/L, 95% CI − 0.21 to 0.15, $I^2 = 36\%$, $p = 0.75$). The leave-one-out analysis showed that none of the studies was influencing the effect.

HDL Cholesterol

HDL cholesterol was evaluated in eight studies involving nine different populations (Fig. 8C). There was no statistically significant difference in HDL cholesterol between AT and MT (MD 0.03 mmol/L, 95% CI − 0.02 to 0.09, $I^2 = 11\%$, $p = 0.21$). The leave-one-out analysis showed that the study by Brooker et al. [34] was influencing the results. When leaving this study out of the analysis, the model estimate changed to MD 0.05 mmol/L(95% CI 0.00 to 0.10, $I^2 = 1\%$, $p = 0.04$). The study by Krčmárová et al. [38] was influencing the results. When leaving this study out of the analysis, the model estimate changed to MD 0.05 mmol/L (95% CI 0.00 to 0.10, $I^2 = 0\%$, $p = 0.04$).

LDL Cholesterol

LDL cholesterol was evaluated in eight studies including nine different populations (Fig. 8D). No differences between AT and MT in reducing LDL cholesterol levels (MD -0.07 mmol/L, 95% CI − 0.19 to 0.06, $I^2 = 19\%$, $p = 0.3$) were observed. The leave-one-out analysis showed that none of the studies was influencing the effect.

Discussion

This meta-analysis suggests a selective influence of exercise timing on metabolic health, with some evidence of timing-related differences for glycemic control, though these findings should be interpreted with caution. AT was superior for lowering both long-term FBG and acute pre- to post-exercise glucose changes, whereas MT led to greater reductions in HbA1c. Our meta-analysis found no consistent differential effects of exercise timing on body composition outcomes.

The analysis of glycemic markers revealed that mid- to long-term (≥2 weeks) AT more effectively improved FBG, whereas MT showed greater benefits for reducing HbA1c. This pattern suggests that AT may capitalize on the circadian peak in insulin sensitivity to acutely lower

glucose, whereas MT might promote longer-term metabolic adaptations that are better reflected in the HbA1c measure. The composition of the analyzed populations offers a plausible, though not definitive, explanation for this dissociation. Studies contributing to the HbA1c pool more frequently involved individuals with T2D, whereas the FBG analysis included a mix of healthy and diabetic cohorts. This aligns with findings such as those of Mancilla et al. [46], which reported greater FBG improvement with AT in men at risk for or with T2D. A notable exception exists: Carrillo et al. [28] demonstrated that MT combined with pre-breakfast metformin significantly reduced FBG in participants with T2D, highlighting a critical interaction between exercise timing and medication schedule. Therefore, while AT appears generally more potent for acute FBG lowering, the optimal timing for glycemic management in clinical populations may be modulated by pharmacotherapy. The acute study data further consolidate the role of AT in eliciting immediate post-exercise glucose reductions. It is worth noting that acute and long-term glucose outcomes were analyzed separately. The acute studies showed greater immediate post-exercise glucose reductions with afternoon exercise, consistent with the long-term FBG findings. However, acute interventions capture immediate metabolic responses while long-term interventions reflect chronic adaptations; these results should therefore be viewed as complementary rather than directly comparable. Of the three acute studies assessing post-exercise glucose changes, a significant reduction with afternoon exercise was observed only in healthy individuals; the two studies in diabetic populations did not show significant effects, and the overall finding was sensitive to exclusion of the largest study. This underscores the exploratory nature of this result and limits its generalizability.

In contrast to a recent meta-analysis which reported a timing effect on TG levels [17], our synthesis did not find a significant differential effect of exercise timing on TG levels, nor on other lipid parameters (TC, HDL-C, LDL-C). This discrepancy may be attributable to differences in the included studies, such as participant characteristics. For example, one cross-sectional study in older adults (mean age 71.8 years) suggested a potential lipid-lowering advantage for morning exercise [47], highlighting age as a potential moderating factor. The null findings in our broader analysis suggest that any effect of exercise timing on lipid metabolism, if it exists, is likely small and may be superseded by other factors like overall exercise volume, diet, or population-specific traits.

The included studies provide mechanistic insights into the differential effects of exercise timing. As indicated by evidence from the reviewed literature, MT is associated with increased sympathetic nervous system activity and catecholamine release, which may enhance lipolysis through β-adrenergic receptor activation in adipose tissue. Furthermore, some studies included in our synthesis reported that MT was linked with elevated resting metabolic rate in the hours following exercise, potentially contributing to greater daily energy expenditure [48]. In contrast, AT correlated with peak diurnal variation in skeletal muscle function and mitochondrial activity, as observed in several physiological studies [39]. This temporal alignment may facilitate more efficient glucose uptake and utilization during and after exercise, which is supported by the acute glucose-lowering effects reported in the included AT trials. However, these mechanisms were examined in individual studies and have not been consistently measured or reported across all included trials. Therefore, while they offer plausible explanations for the observed timing-related differences, the evidence remains indirect and should be interpreted with caution within the context of the overall synthesized outcomes.

An important consideration when interpreting the observed timing effects is the substantial variation in dietary control across the included studies. While most long-term studies instructed participants to maintain habitual eating patterns, acute studies typically provided standardized meals. However, several long-term trials reported significant reductions in total energy intake during the intervention period, with notable differences between morning and afternoon training groups. For instance, Brooker et al. [30] observed a reduction of 3974 kJ in the MT group and 3165 kJ in the AT group, while Alizadeh et al. [35] reported a significant reduction in total energy intake only in the morning exercise group ($p=0.06$). These differential dietary changes may partially explain the greater HbA1c reduction observed with morning training in T2D populations. Conversely, the absence of timing effects on lipid parameters may reflect the predominance of dietary factors over exercise timing in determining lipid outcomes. In acute studies, dietary protocols also varied considerably, with one study employing an 11-day high-fat diet [42], which may have influenced metabolic responses independent of exercise timing.

Although this study provides a comprehensive systematic review and meta-analysis of the effects of exercise duration on metabolic health, some limitations should be addressed. First, variation in baseline health and age across study participants may have affected the consistency of the results. Second, the duration of the included medium- and long-term studies was limited, and there were few acute studies, with the post-exercise glucose finding being particularly sensitive to the exclusion of the single largest study, which may have affected the robustness of the results, and the conceptual heterogeneity

between acute and long-term interventions warrants cautious separate interpretation of these two types of evidence. Third, owing to the limited number of studies included, the sensitivity analyses had low statistical power and several key outcomes were unstable. For example, the differential effects on HbA1c and fasting blood glucose lost statistical significance when individual studies were removed, indicating that these findings should be interpreted as preliminary. Importantly, the HbA1c finding was largely driven by T2D studies, with limited representation of non-T2D populations, precluding generalization to healthy individuals. Fourth, interpretations of our findings must consider the potential confounding effect of diet. It is plausible that the metabolic benefits ascribed to a specific exercise time are, in part, mediated by unintentional modifications in dietary patterns. Fifth, the reliance on SMD for body composition outcomes limits clinical interpretability, and the aggregated estimates should be viewed as indicative of effect direction and relative magnitude rather than as precise absolute changes. In addition, due to the limited number of studies available for specific health statuses, we were unable to conduct stratified subgroup analyses by health status. This limited our ability to explore potential heterogeneity across different populations.

Future research should explore the effects of exercise on metabolic health at different times before or after meals, as well as immediate and long-term effects of exercise of varying intensities, durations, and frequencies in various populations. In addition, other demographic factors such as sex, age, and health status should be examined to better understand the influence of exercise timing on metabolic health.

Conclusions

This meta-analysis suggests that exercise timing may have selective effects on glycemic control, though findings should be considered preliminary. Morning training was associated with a significant reduction in HbA1c, whereas afternoon training was associated with greater lowering of fasting blood glucose. These effects were primarily observed in T2D populations. No consistent timing effects were found for body composition or lipid parameters. However, the overall certainty of evidence was moderate to very low due to risk of bias and imprecision. Therefore, these results should be interpreted with caution and warrant confirmation in larger, well-designed trials.

Supplementary Information

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Supplementary Material 1.

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Author Contributions
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Data Availability
All data generated or analyzed in this study are included in the article and its supplementary information files. The datasets supporting the meta-analysis are available from the corresponding author on reasonable request.

Declarations

Ethics Approval and Consent to Participate
Not applicable.

Consent for Publication
Not applicable.

Competing Interests
Jiayun Wang, Shi Chen, Zhanjia Zhang, Bingqing Yang, and Xiaoyuan Zhang declare that they have no competing interests with the content of this article.

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