Diabetes, Metabolic Syndrome and Obesity

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REVIEW

Effect of Exercise Based on American College of Sports Medicine Recommendations on Glycemic Management in Patients with Type 1 Diabetes: A Systematic Review and Meta-Analysis of Randomized Controlled Trials

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Abstract: Exercise is a crucial lifestyle management strategy for individuals with type 1 diabetes (T1DM) to improve overall health, yet its benefits for glycemic control remain controversial. Although clinical trials have designed various exercise regimens, no studies have systematically demonstrated or compared which exercise program yields optimal outcomes for individuals with T1DM. To visually compare and identify a more reasonable exercise program, we used the comprehensive exercise prescription established by the American College of Sports Medicine (ACSM) as a foundation to compare the impact of glycemic management about exercise doses with different compliance to ACSM recommendations. We systematically searched for studies from PubMed, Embase, Web of Science, Cochrane, and OVID. Randomized controlled trials (RCTs) investigating the impact of exercise on glycemic management published between January 2000 and July 11, 2025 were included. The quality of the study was assessed by the Cochrane Collaboration Risk of Bias Tool. Subgroup analyses were performed by categorizing the interventions into high adherence versus low/uncertainty adherence to the exercise prescription developed by ACSM. To compare the results between subgroups, weighted mean difference (WMD) or standardized mean difference (SMD) were adopted, using random or fixed effects models accordingly. Fourteen studies were included in the meta-analysis, with 452 participants. Of which, 7 studies were categorized as high adherence with ACSM and 7 studies were categorized as low or uncertain adherence. Results showed exercise had significant effect on reducing Glycated Hemoglobin (HbA1c) (WMD = −0.52; 95% CI = [−0.74, −0.29]). The WMD for the high adherence group was −0.74 (95% CI: −1.04, −0.44), while for the low or uncertain adherence group was −0.21 (95% CI: [−0.56, 0.13]). Exercise programs with high adherence to the ACSM resulted in a markedly greater reduction in HbA1c compared to those with low adherence ($p = 0.02$). Data on triglyceride levels also showed greater improvements in the high adherence group. These findings collectively indicated that the ACSM prescription serves as an effective exercise guideline for individuals with type 1 diabetes.

Keywords: type 1 diabetes mellitus, exercise dose, ACSM recommendations, blood glucose, HbA1c

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Introduction

Type 1 diabetes mellitus (T1DM) is an endocrine disorder characterized by the almost complete loss of pancreatic β-cells due to immune-mediated destruction, resulting in absolute endogenous insulin deficiency. It can occur at any stage of life but is most commonly diagnosed in childhood and adolescence.[1,2] Moreover, there were approximately 8.4 million patients with T1DM worldwide in 2021, and the prevalent cases is projected to increase to 13.5–17.4 million by 2040.[3] Patients with type 1 diabetes suffer from a range of serious complications, such as nephropathy, neuropathy, retinopathy, coronary heart disease, cerebrovascular disease, peripheral artery disease, etc.[4] A 10-year-old kid diagnosed with T1DM has an average life expectancy of only 13 years.[3] It is evident that T1DM and its complications have caused detrimental impacts on the living quality of patients and increased mortality rates, making it imperative to address this significant global health issue promptly.

Regular exercise is essential for the management and lifestyle of patients with T1DM. Exercise prolongs the "honeymoon period" in the early stages of T1DM and facilitates the reduction of exogenous insulin requirements.[5] Sufficient data to demonstrate that exercise contributes to reducing the risk of vascular disease, insulin resistance, and enhancing insulin sensitivity, physical fitness, and quality of life in individuals with T1DM have been reported.[6] However, more than 60% of adults with T1DM rarely exercise and fail to achieve recommended levels,[7] which may be due to the major barrier—control of glycemic fluctuation.[5]

Previous meta-analyses and systematic evaluations have been conducted to examine the impact of exercise on glycemic control (HbA1c) in patients with T1DM. However, current studies have shown conflicting conclusions, making it unable to demonstrate the benefit of exercise on glycemic management.[6,8–11] Moreover, existing studies have diverse conclusions about the optimal duration, frequency, and intensity of exercise. For example, Rivera et al[12] believed that exercise 1–3 times per week could be beneficial in patients with T1DM, while Quirk et al[13] agreed that the minimum dosage to produce a clinical benefit of exercise required to be ≥3 days per week. A study suggested that exercise training longer than 24 weeks was more effective in reducing HbA1c,[14] while another suggested that exercise programs longer than 8 weeks could show more beneficial effects.[15] The randomized control studies examining the effects of exercise on T1DM have been conducted on a limited scale and therefore do not provide reliable guidance on the intensity, duration, frequency, or type of exercise that could offer the greatest benefit.[6,14] A large amount of experimental data is still needed to ascertain the optimal dose of exercise for the treatment of T1DM.

For different individuals, including patients with diabetes mellitus, the American College of Sports Medicine (ACSM) has established detailed exercise prescriptions, including recommended doses of cardiorespiratory, resistance, and flexibility exercises.[16,17] Since no one has yet determined the ideal type or dosage of exercise to verify the validity and reliability of these recommendations, this systematic review aimed to explore the effects of the ACSM-recommended exercise program on patients with T1DM. We compared the effects of exercise intervention with high adherence and low or uncertain adherence to the ACSM on glycemic management in patients with T1DM. Hopefully, this will provide an effective exercise prescription for patients with T1DM.

Materials and Methods

Protocol and Registration

In accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement,[18] systematic reviews and meta-analyses will be registered and reported in PROSPERO (CRD42024524738).

Search Strategy

Considering study populations, interventions, outcomes, and methods of intervention as key research aspects based on the PICOS principle,[19] we searched PubMed, Embase, Web of Science, OVID, and Cochrane from 1 January 2000 to 11 July 2025. Partial search terms are as follows: ("Diabetes" or "type 1 diabetes" or "insulin dependent diabetes" or "Juvenile Onset Diabetes" or "sudden onset diabetes" or "ketosis-prone diabetes") AND ("Exercise" or "Physical Activity" or "Activity" or "Acute Exercise" or "Isometric Exercise" or "Aerobic Exercise" or "Tai Chi" or "Exercise Training" or "Yoga" or "Wuqinxi" or "Baduanjin" or "Yijinjing" or "Kickboxing" or "Pilates") AND ("blood glucose" or

"Blood Sugar" or "Sugar, Blood" or "Glucose, Blood" or "HbA1c" or "Glycated Hemoglobin") AND ("randomized controlled trials" or "controlled clinical trials" or "randomized" or "placebo" or "randomly"). Detailed search strategies are provided in Supplementary Table S1. We also looked through relevant reviews and bibliographies of retrieved articles and contacted the study authors for more information when necessary.

Criteria for Selection of Studies

Eligibility criteria were set based on the PICOS scheme (Population, Control, Intervention, Study Design, and Outcome), and the inclusion criteria were as follows: ① T1DM Patients of any sex, age, or duration of diabetes. ② Randomized controlled trial. ③ Intervention in at least one of the experimental groups was any kind of exercise, including resistance training, aerobic exercise, flexibility exercise, etc. ④ No intervention, self-administration, or exercise intervention in the control group. ⑤ Only studies with outcomes on glycemic control were eligible.

The exclusion criteria were as follows: ① not type 1 diabetic patients. ② not RCT. ③protocol, reports, conference proceedings, reviews. ④ Comparisons of different exercises and techniques. ⑤ Duplicate experimental data from multiple publications of the same study were excluded. ⑥ Patients with serious complications that affect exercise. ⑦ Studies published before 2000. ⑧ Mind-body exercises such as yoga.

Two authors (RC and YYQ) independently screened the titles and abstracts of articles that met the inclusion criteria. If one of the authors found the study matching, the full text of the article would be accepted. The two authors then independently assessed whether the full text met the requirements. If a controversy arose, the third author (YYH) would intervene to make the decision till the consensus was reached through discussion. No restrictions on the age, sex, duration of diabetes for eligible cases. A flowchart depicts the study selection process (Figure 1).

Interventions and Subgroup

To testify the possible impact of the recommended exercise program by ACSM, individuals were divided into two groups in the meta-analysis: high adherence and low or uncertain adherence according to ACSM recommendations. A narrative approach was used to synthesize exercise intervention on dose and adherence.

The ACSM recommended three types of exercise programs for intervention: resistance exercise (RE), flexibility exercise, and cardiorespiratory exercise. Based on the corresponding criteria provided by the ACSM, two authors (RC and YYQ) respectively assessed the level of adherence in each research. Every type of exercise has a specific dosage range for each aspect of the exercise prescription, including the frequency, intensity, and duration of the exercise (Table 1). Each aspect was scored on a range of 0–2 points (2 points for compliance, 1 point for basic compliance but with some uncertainty, and 0 points for non-compliance). If a certain component was not included in the research or failed to fully meet the standard, it would be defined as "uncertainty of fulfillment" and given 1 point. The scores of each aspect were ultimately pooled to calculate a total score. This total score was then divided by the maximum possible score to calculate a ratio. Finally, the adherence to the suggested exercise dosage by the ACSM was assessed based on this ratio. For example, if the cardiorespiratory exercise intervention was within the dose range recommended by the ACSM in all aspects, such as frequency, intensity, and duration, 6 points would be given to this group. Given that the maximum score is 6, the adherence percentage would be 100%. If one of the indications deviated significantly from the suggested dose range while the other two remained within the acceptable limits, a score of 4 points would be assigned, resulting in a ratio of 67%. With this scoring method, studies with a proportion ≥80% were classified as high adherence to ACSM recommendations; studies with a proportion <80% were classified as low or uncertain adherence to ACSM recommendations. Specific scores reflecting adherence are presented in Table 2. If the two authors held different views, the third author (XTL) would come to discuss till an agreement was made.

Data Extraction (Selection and Coding)

The primary indicators we included in the meta-analysis were HbA1c. In addition, we conducted a meta-analysis of the following secondary outcomes with more than four reported studies: Insulin dose, Body Mass Index (BMI), weight, VO_{2max}, total cholesterol (TC), triglycerides (TG), Fat Free Mass (FFM), High-density lipoprotein (HDL), Low-density lipoprotein (LDL), Diastolic blood pressure (DBP), and Systolic blood pressure (SBP). We designed an Excel

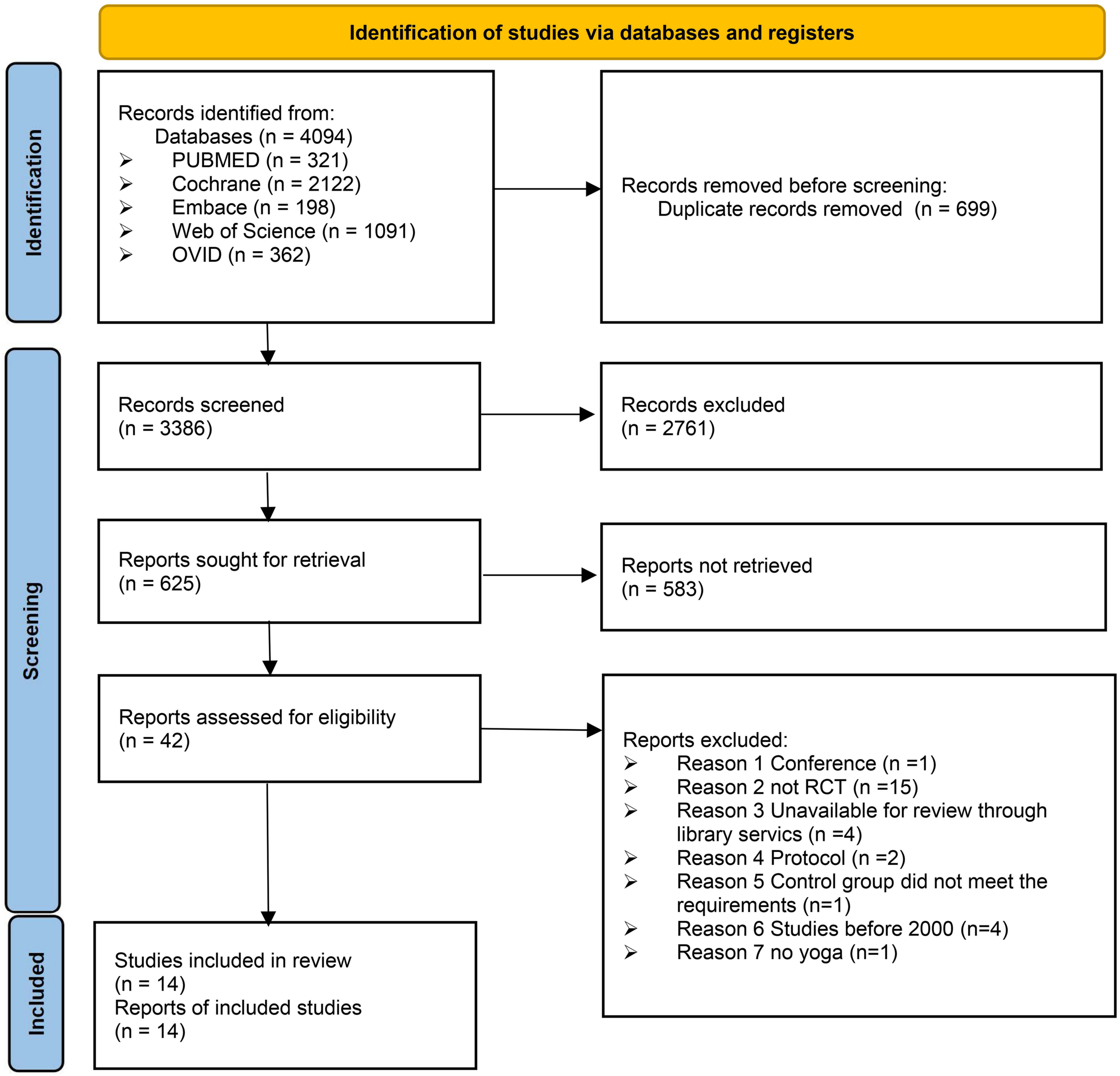

Figure 1 PRISMA Study flow diagram.
Notes: The PRISMA flowchart illustrates the screening process of RCTs evaluating the effect of exercise on glycemic improvement in patients with T1DM, indicating the final numbers of identified, screened, and included studies (n = 14).

spreadsheet (Table 3) to extract relevant data from all eligible trials, including features of publication (title, country, author names, year of publication), characteristics of participants (age, gender ratio, duration of diabetes), characteristics of methodology (design of each group, intervention measures, sample size), characteristics of exercise intervention (single treatment duration, intensity, number of treatments per week, total number of treatments and total intervention duration) and features of results.

When the data were incomplete or ambiguous, we asked for details from the relevant authors. If a study was lack of data, we would remove the study from the group and proceed to present the results in a narrative fashion. When extracting outcome data, if it were presented in graphical form, the Engauge Digitizer software would be used to extract the data. For studies with multiple follow-up assessments, we collected real-time data to catch up with timely changes

Table 1 American College of Sports Medicine (ACSM) Recommendations for Cardiorespiratory Fitness, Muscular Strength, and Flexibility

Exercise Dose	Cardiorespiratory Exercise	Flexibility Exercise	Resistance Exercise
Frequency	3-5 days per week	≥2-3 days per week	2-3 days per week
Intensity/ workload	55-90% of maximal heart rate	Stretch to the point of feeling tightness or slight discomfort	55-90% of maximal heart rate
Duration	20-60 min	10-30 s. 2–4 reps or 60s total stretching time	8-12 repetitions or the number of repetitions needed to induce muscle fatigue but not exhaustion in 2–4 sets

caused by the intervention. If the summary of the two reviewers were inconsistent, a third reviewer would intervene to get a consensus.

Strategy for Data Synthesis

Meta-analyses were performed using Review Manager 5.4 to extract the baseline mean, follow-up value, and the associated standard deviation (SD). If the experiment only provided the standard error of the reported mean (SEM), we transformed it into the SD by multiplying the square root of the group's sample size. The included studies were categorized into two groups based on high and low or uncertain compliance with ACSM recommendations. Heterogeneity between studies was assessed by the Higgins I^2 statistic and interpreted by the recommendations of the Cochrane Handbook.[34] Larger values of I^2 indicate a greater degree of inconsistency. $I^2 < 50\%$ is low heterogeneity, 50–75% is moderate heterogeneity, >75% is high heterogeneity. A descriptive analysis would be applied to identify sources of heterogeneity if $I^2 > 50\%$. In the heterogeneity test, a fixed effect model was carried out to test the effect size if $I^2 \leq 50\%$, while a random effect model was performed if $I^2 > 50\%$.

Effect sizes were expressed as standardized mean difference (SMD) or weighted mean difference (WMD) and 95% confidence interval (CI), with $p < 0.05$ indicating significance. WMD is used for combined statistics if the measures of the indicators and units of measurement are harmonized, and SMD is chosen if the units are inconsistent to eliminate the effects of the unit.

The possibility of publication bias was assessed by constructing a funnel plot for each study's effect size. Egger's test was used to detect publication bias when the number of studies was ≥10, with $p < 0.05$ indicating the presence of bias and $p \geq 0.05$ showing no bias. Furthermore, a sensitivity analysis was conducted to test the robustness of the study results through excluding each study one by one.

Quality Assessment

The quality of the study was independently assessed by two reviewers (RC and YYQ), and conflicts were resolved through discussion. The Cochrane Collaboration's recommended quality assessment criteria[35] and the Risk of Bias tool (Rob 2)[36] were used to examine the risk of bias in included studies. Assessment metrics include randomized sequence generation (selection bias), allocation concealment (performance bias), blinding of participants and personnel (performance bias), outcome assessment (detection bias), incomplete outcome data (attrition bias), selective reporting (reporting bias), etc. We would consult the corresponding authors when further information was necessary. The Cochrane Handbook categorizes the risk of bias for each domain into three levels: "low risk", "uncertain risk", and "high risk".[37] If all domains were assessed as "low risk", the overall risk of bias was characterized as low. If some domains were assessed as "uncertain risk" and no one was "high risk", the overall risk of bias was categorized as "uncertain risk". However, if any single domain was classified as "high risk", the overall risk of bias was designated as "high risk".

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Table 2 Exercise Interventions Evaluated According to ACSM Recommendations

Author, Year	Cardiorespiratory Exercise						Resistance Exercise								Flexibility Exercise						ACSM Adherence
	Frequency 3–5/d wk		Intensity/Workload 55–90% of max HR		Duration 20–60min		Frequency 1–2/ d wk, Gradually INCREASING to 2–3/d wk		Intensity/Workload 60–80% of 1RM		Repetitions 8-12		Sets 2-4		Frequency 2–3/d wk		Intensity/ Workload Stretch Until You Feel Your Muscles Being Pulled Tight or a Slight Discomfort		Duration Stretching for 10–30 s, (Repeated 2–4 Times)		Points (Percent)
Alarcon-Gomez, J 2021[20]	3	H	85% PPO:high-intensity cycling 40% PPO:recovery	H	18-30	M															5/6 (83%)
Gusso, S 2017[21]	3-4	H	85% of max HR	H	40-60	H	1 for 12 week 4 for 8 week	M	NR	M	NR	M	NR	M							10/14 (71%)
Roberts, L 2002[22]	3	H	HR:160 beats /min	H	45	H	3	H	NR	M	NR	M	NR	M							11/14 (78.5%)
Laaksonen, D. E 2000[23]	4-5	H	50–80% of VO_2 peak	M	20-60	H															5/6 (83%)
Petschnig, R. 2020[24]							2	H	30% of 1 RPM (Individualized rate of progress)	M	NR	M	NR	M							5/8 (62%)
Tomar, R 2014[25]	3	H	40-70% of max HR	M	50-60	H															5/6 (83%)
Xin Liu 2019[26]															2	H	NR	M	90min	M	4/6 (67%)
Mohammed, M.H.H. 2021[27]	2	L	80% of max HR	H	90	L															2/6 (33%)
Salem, M. A. 2010[28]	3	H	65-85% of max HR	H	30	H	3	H	One set at 50% of the 10 RM; second set at 75% of the 10 RM; final set at the full 10 RM	M	10	H	3	H	3	H	NR	M	5min	H	18/22 (82%)
Nazari, M. 2023[29]	3	H	50-75% of max HR	M	10-20	M	3	H	NR	M	8-12	H	2-3	H	3	H	NR	M	10-20min	H	16/20 (80%)
Zimmer, R. T. 2023[30]	3	H	NR	M	60	H															5/6 (83%)
Boff, W 2019[31]	3	H	50-80% of max HR	M	30-40	H															5/6 (83%)
Farrell, C. M. 2023[32]	3	H	≥90% of max HR	L	20	H															4/6 (67%)
Lee, A. S. 2020[33]	3	H	50-95% of max HR	L	33	H															4/6 (67%)

Notes: In the final score column, studies with a ratio greater than 80% were categorized as high adherence, and studies with a ratio less than 80% were categorized as low adherence.

Abbreviations: ACSM, American College of Sports Medicine; max HR, Maximum Heart Rate; PPO, peak power output; RM, repetition maximum;1 RPM, one-repetition maximum; NR, not reported; H, fully meets recommendation (2 points); M, Incomplete or uncertain fulfilment of recommendations (1 point); L, do not meet the recommendation at all (0 points);

Table 3 Characteristics of the Study Intervention

Author, Country, Year	Population	Age (mean + SD)	Total/Male/Female	Intervention	Control	Outcome	Duration of Diabetes (mean + SD)
Alarcon-Gomez, J Spain 2021[20]	Type 1 Diabetes	IG:38(5.5) CG:35(8.2)	IG:11/5/6 CG:8/4/4	Cardiorespiratory exercise (HIIT) Length of Intervention: 6 weeks Freq: 3 times a week Duration: 18–30 min	CON	BG; VO2max; FFM; FM,	IG:20.5±8.4 CG:21.1±6.5
Gusso, S New Zealand 2017[21]	Type 1 Diabetes	IG:15.6(1.3) CG:15.5(0.9)	IG: 37/19/18 CG: 13/7/6	Cardiorespiratory and Resistance exercise Length of Intervention: 20 weeks Freq: 4 times a week Duration: 60 min	CON	HbA1c; Insulin; Weight; BMI FFM; SBP; DBP; VO2max	IG:5.4±3.4 CG:7.5±4
Roberts, L Australia 2002[22]	Type 1 Diabetes	IG+CG:14.0(1.2)	IG+CG: 24/12/12 IG:12/NA/NA CG:12/NA/NA	Cardiorespiratory exercise Length of Intervention: 12 weeks Freq: 3 times a week Duration: 45 min	CON	HbA1c; Body mass; BMI	IG+CG:5.0 (3.1)
Laaksonen, D. E Finland 2000[23]	Type 1 Diabetes	IG: 31.7(5.8) CG: 29.8(6.4)	IG: 20/20/0 CG: 22/22/0	Cardiorespiratory exercise Length of Intervention: 12–16 weeks Freq: 3–5 times a week Duration: 20–60 min (Individualized Adjustment Time)	CON	BG; HbA1c; TC; HDL; LDL; TC; TG; insulin; VO_{2max}; BMI	IG:13.8 (9.2) CG:10.8 (5.8)
Petschnig, R Austria 2020[24]	Type 1 Diabetes	IG: 11.0(0.8) CG: 11.30(0.7)	IG: 11/NA/NA CG: 10/NA/NA	Resistance exercise Length of Intervention: 32 weeks Freq: 2 times a week Duration: 50 min	CON	BG; HbA1c	IG:2.63(1.85) CG:2.80 (2.07)
Tomar, R Saudi Arabia 2014[25]	Type 1 Diabetes	IG:14.27(1.73) CG:14.27(1.95)	IG: 11/11/0 CG: 11/11/0	Cardiorespiratory exercise Length of Intervention: 12 weeks Freq: 3 times a week Duration:50–60min	CON	HbA1c; insulin; TC; HDL; LDL; TG	IG:4.36(2.4) CG:4.63(2.06)
Xin Liu China 2019[26]	Type 1 Diabetes	IG+CG: 26(10.75)	IG+CG: 13/7/6 T: 6/NA/NA C: 7/NA/NA	Flexibility exercise (Tai Chi) Length of Intervention: 12 weeks Freq: 2 times a week Duration:60–90 min	CON	HbA1c; BMI; SBP; DBP;	T:16(7.25)
Mohammed, M.H.H. Saudi Arabia 2021[27]	Type 1 Diabetes	IG: 17.8 (0.42) CG: 14.4 (2.0)	T: 10/10/0 C: 10/10/0	Cardiorespiratory exercise Length of Intervention: 12 weeks Freq:2 times a week Duration: 90 min	CON	BG; HbA1c; insulin; TC; HDL; LDL; TG; SBP; DBP;	NA (>1)
Salem, M. A. Egypt 2010[28]	Type 1 Diabetes	IG:14.5(2.4) CG:15(2.35)	IG: 73/NA/NA CG: 48/NA/NA	Cardiorespiratory, Resistance and Flexibility exercise Length of Intervention: 6 months Freq: 3 times a week Duration: 72 min	CON	HbA1c; Insulin does; Weight; BMI; SBP; DBP; TC; HDL-c; LDL-c; TG	IG:5.5(2) CG:4.9(1.9)
Nazari, M Iran 2023[29]	Type 1 Diabetes	IG:11.22 (1.90) CG:11.00 (2.67)	IG: 20/8/12 CG: 20/11/9	Cardiorespiratory and Resistance exercises Length of Intervention: 16 weeks Freq: 3 times a week Duration:30–60 min	CON	BG; HbA1c	IG:3.04(1.83) CG:3.07 (1.87)
Zimmer, R.T. Germany 2023[30]	Type 1 Diabetes	IG: 15.5(1) CG:14.7(1.2)	IG: 8/6/2 CG: 10/5/5	Cardiorespiratory exercises Length of Intervention:4 weeks Freq:3 times a week Duration:60 min	CON (intensive glycaemic management)	BG; HbA1c; insulin; Body; mass; CGM; FFM	IG:5.8 (3.8) CG:5.0 (4.9)
Boff, W Brazil 2019[31]	Type 1 Diabetes	IG:26.1(7.8) CG:20.8(2.6)	IG:9/3/6 CG:9/4/5	Cardiorespiratory exercises (HIIT) Length of Intervention:8 weeks Freq:3 times a week Duration:30–40 min	CON	BG; HbA1c; TC; HDL; LDL; TG; VO2max; SBP; DBP; Weight;	IG:9.1(2.9) CG:9.7(2.7)
Farrell, C. M. UK 2023[32]	Type 1 Diabetes (IAH)	IG:NA CG:NA IG+CG:20-54	IG:9/NA/NA CG:9/NA/NA T:18/9/9	Cardiorespiratory exercises (HIIT) Length of Intervention:4 weeks Freq:3 times a week Duration: 20 min	CON	CGM	27(3.313)
Lee, A. S. Australia 2020[33]	Type 1 Diabetes	IG:40.5(10.0) CG:46.1(10.5)	IG:12/6/6 CG:15/10/5	Cardiorespiratory exercises (HIIT) Length of Intervention: 12 weeks Freq: 3 times a week Duration: 33 min	CON	BG; HbA1c; insulin; VO_{2max}; TC; HDL; LDL; TG; SBP; DBP; CGM	IG:15.8(12.2) CG:22.5 (10.0)

Abbreviations: CON, control group with routine care (no exercise); IG, experimental group; CG, control group; IG+CG, The ages of the experimental and control groups were not reported separately in the study, only the overall age was reported; NA, unavailable; Freq, frequency; SBP, Systolic blood pressure; DBP, Diastolic blood pressure; BG, Blood glucose; TC, Serum total cholesterol; LDL, Low-density lipoprotein; HDL, High-density lipoprotein; TG, Triglycerides; CGM, The metrics measured by CGM; HIIT, High-Intensity Interval Training.

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Results

Study Selection

Our search strategy identified 4094 articles from 5 databases until July 2025, including Pubmed (n = 321), Cochrane (n = 2122), Embace (n = 198), Web of Science (n = 1091), and OVID (n = 362). The titles and abstracts of 3386 articles were screened after removing duplicates. Only 42 articles were assessed as meeting the basic eligibility criteria. After full-text reading, 14 trial reports were ultimately included in this meta-analysis.[20–26,27–29,30–33] More details of the procedure are shown in the PRISMA flow diagram in Figure 1. An included study adopted a randomized crossover experimental design.[33] In order to eliminate the interference caused by the delayed effects of the final outcome data, we only obtained randomized controlled results prior to their elution period for meta-analysis. There were three investigations with more than two study arms.[27,28,31] In those studies, only data from the exercise group versus the wait-list control/routine care were adopted.

Study Characteristics

Characteristics of Study Participants

This study analyzed a total of 14 studies involving 452 patients with T1DM (249 in the exercise intervention group and 203 in the control group). The age range of the participants was 9–46 years. There were three studies that included only males.[23,25,27] Overall, approximately 57% of participants were male. The mean diabetes duration of the participants varied from 2.63 to 22.5 years. Only one study did not describe a detailed disease duration.[27] The characteristics of participants are presented in Table 3.

Characteristics of Exercise in the Included Studies

There are multiple types of exercise included High-Intensity Interval Training (HIIT), bicycle exercise, running, football, Tai Chi, etc (Table 3). The length of interventions ranged from 4[30,32] to 32[24] weeks, and the frequency ranged from 2[24,26,27] to 5[23] days per week. Activity sessions ranged between 10 min[29] and 90 min.[27] In addition, there was a great deal of variability in the intensity of exercise interventions, which ranged from 40%[25] to more than 90%[32] of max HR.

After categorizing the interventions through the ACSM criteria, eight studies[20,23,25,27,30–33] evaluated only Cardiorespiratory exercise, one study[24] evaluated only Resistance exercise, one[26] evaluated only Flexibility exercise, and four[21,22,28,29] evaluated more than two exercises.

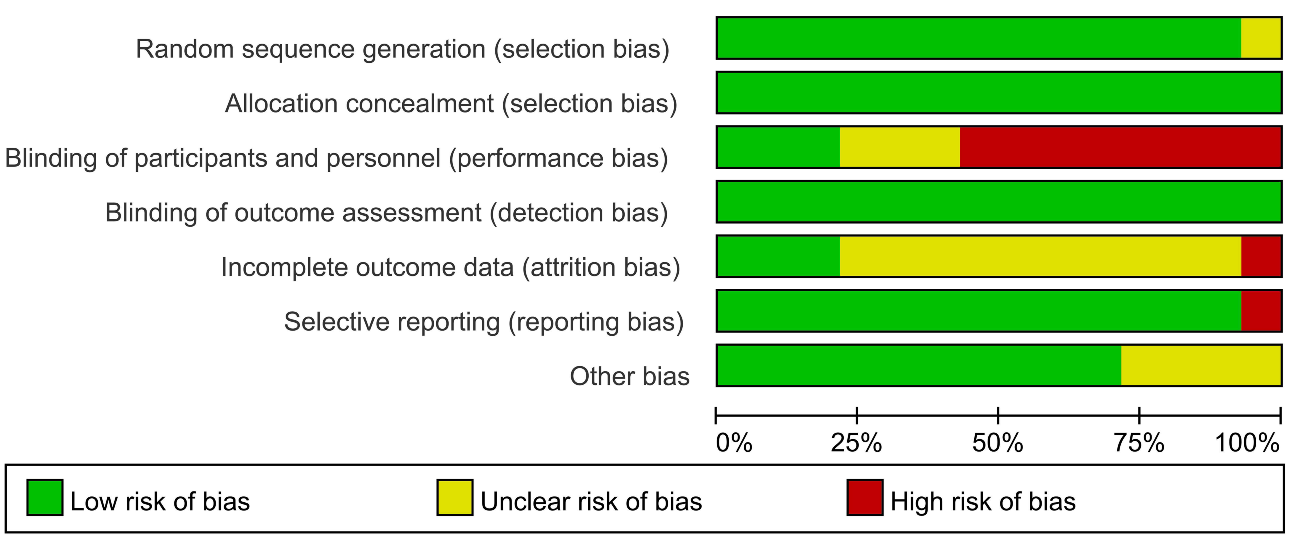

Figure 2 Combined percentage risk of bias in each risk domain of all included RCTs.
Notes: This stacked bar chart presents the overall proportion of studies rated as having low risk (green), some concerns (yellow), or high risk (red) of bias within each domain of the Cochrane Risk of Bias tool.

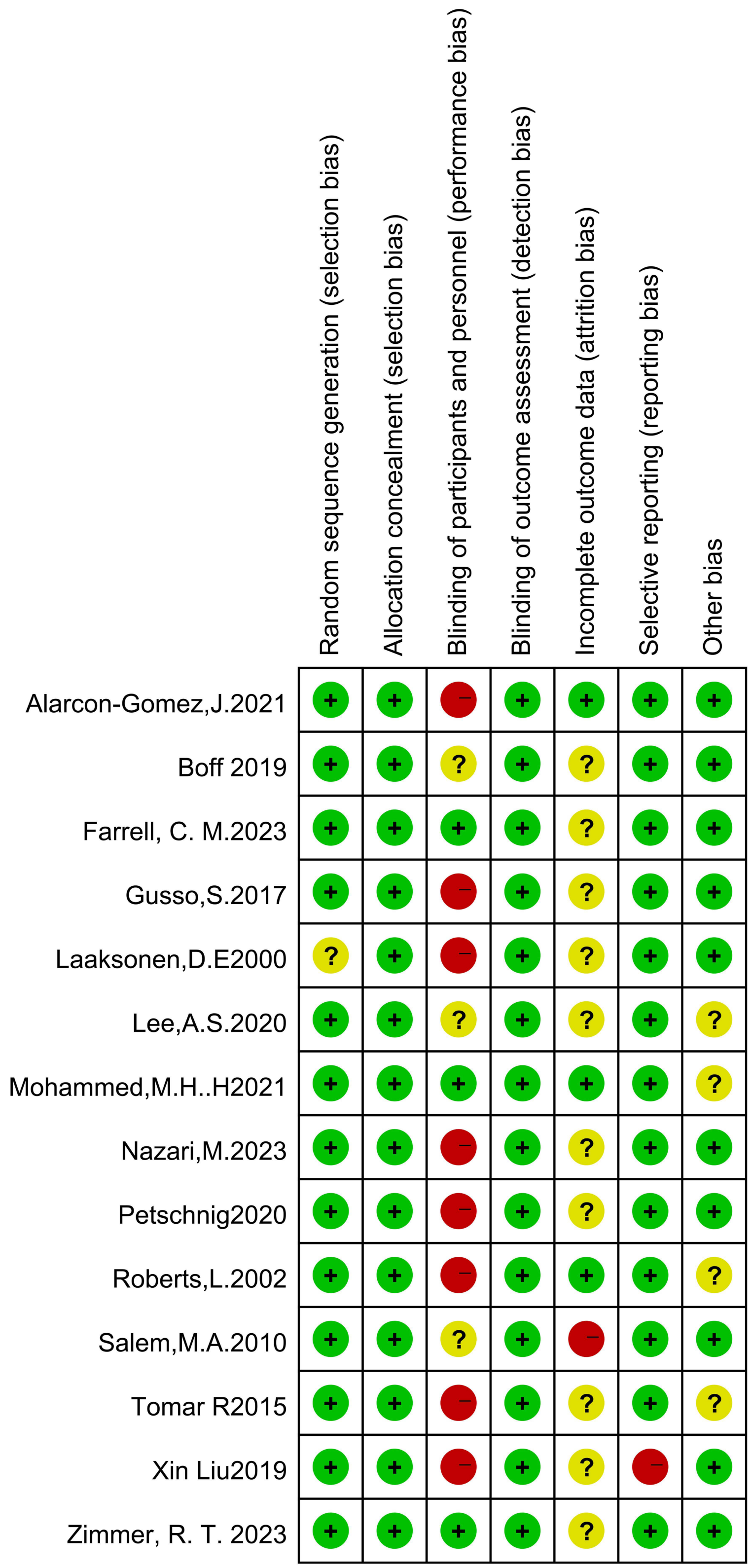

Figure 3 Risk of bias summaries for all included RCTs.

Risk of Bias Within Studies

In terms of allocation concealment and blinding of outcome assessment, all studies were assessed to have a low risk of bias (Figures 2 and 3). Given the nature of the exercise interventions, the lack of blinding of patients and therapists was the most common cause of possible methodological bias. Only three of the 14 studies stated that participants and result assessors were blinded. Ten studies had incomplete outcome data but detailed reasons for withdrawal, so they were evaluated as moderate risk of bias. Thirteen studies' risk of selective reporting bias was considered low, with one study had risk of selective offset. Four studies had other risk of bias.

Compliance with the ACSM Recommendations

We used a specialized scoring system based on ACSM recommendations to evaluate adherence to ACSM in 14 studies (Table 2). Seven studies[20,23,25,28–31] had ACSM adherence rates of ≥80% while 7 studies[21,22,24,26,27,32,33] had a rate of <80%. The reasons for low adherence were on the one hand due to insufficient information of exercise prescription provided in the studies, which made it difficult to assess appropriately, on the other hand due to the design of exercise that fail to meet the recommendations of ACSM.

Major Outcome—Glycated Hemoglobin (HbA1c)

The American Diabetes Association has recommended that glycemic control in patients with T1DM is best assessed by HbA1c,[38] so we used HbA1c as the primary outcome indicator. A total of 12 studies involving 415 subjects were included (experimental group: 229, control group: 186). Carried by fixed effects model, the overall pooled WMD was −0.52 (95% CI: −0.74, −0.29; $p < 0.00001$), which indicated that the effect of exercise on HbA1c was significantly better than no exercise (Figure 4). Subgroup analyses showed that 6 studies had high adherence to ACSM recommendations, while 6 had low or uncertain adherence. In the subgroup with high adherence, the WMD was −0.74 (95% CI: −1.04, −0.44; $p < 0.00001$). In the subgroup with low or uncertain adherence, the WMD was −0.21 (95% CI: −0.56, 0.13; $p = 0.23$). The I^2 statistic revealed low heterogeneity in both the high adherence group (1%) and the low or uncertain

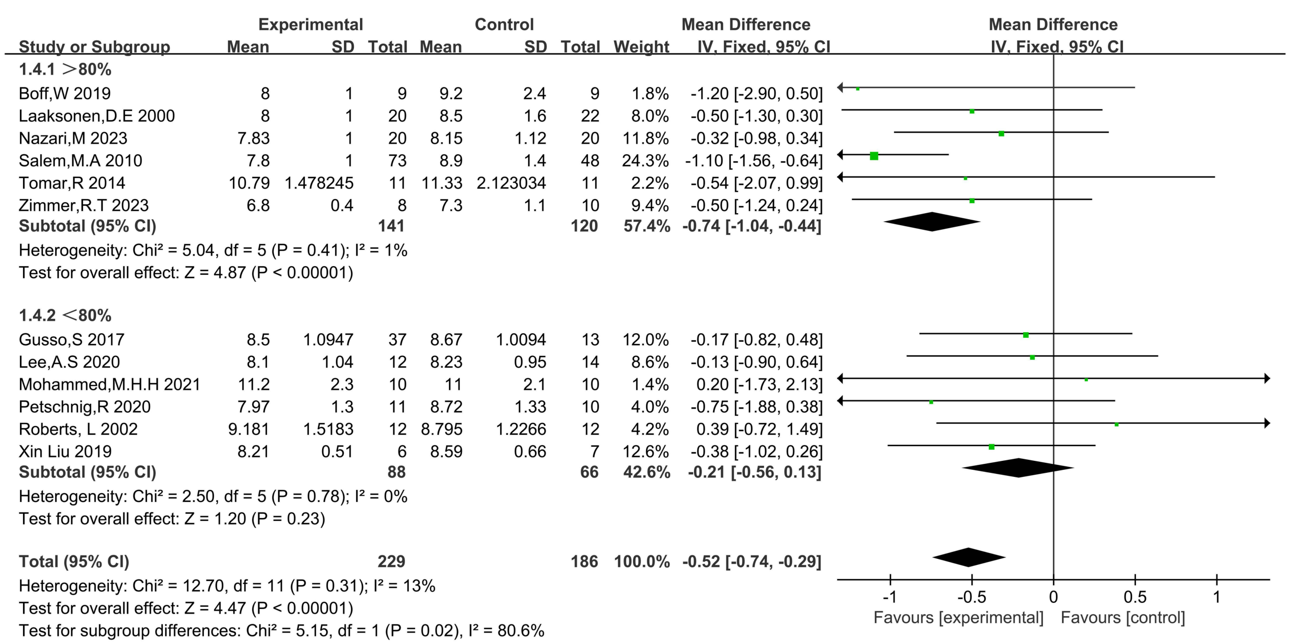

Figure 4 Forest plot of HbA1c.

Notes: Forest plot of HbA1c: High adherence to ACSM recommendations (>80%) vs low or uncertain adherence to ACSM recommendations (<80%). Due to non-significant heterogeneity (I^2 = 13%), a fixed-effects model was used. Data are presented as weighted mean difference because indicators and units of measurement are harmonized. Overall result: A total of 415 participants were included (186 in the control group and 229 in the experimental group). Exercise had a significant improvement in HbA1c in patients with T1DM (WMD: −0.52 [−0.74, −0.29], I^2= 13%, $p < 0.00001$). Subgroup analysis: The high adherence subgroup (WMD: −0.74 [−1.04, −0.44], I^2= 1%, $p < 0.00001$) had a significant effect on HbA1c improvement, while the low adherence subgroup (WMD: −0.21 [−0.56, 0.13], I^2= 0%, $p = 0.23$) had no significant effect on HbA1c.

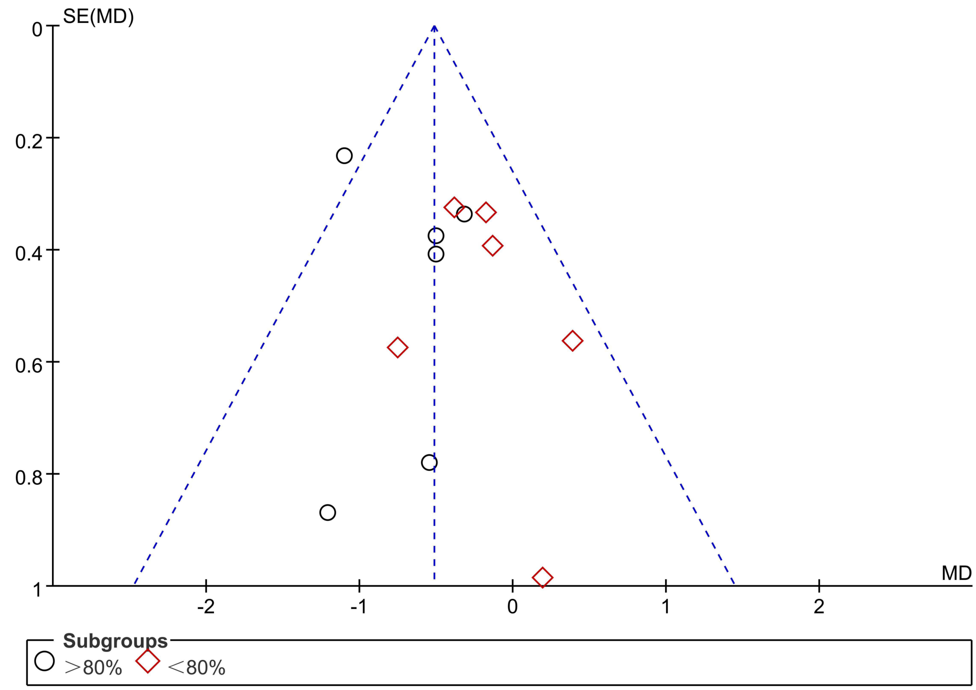

Figure 5 Funnel plot of HbA1c.
Notes: Symmetric funnel plots showed no publication bias. >80%, study with high adherence to ACSM recommendations. <80%, study with low or uncertain adherence to ACSM recommendations.
Abbreviations: SE, standard error; MD, mean difference.

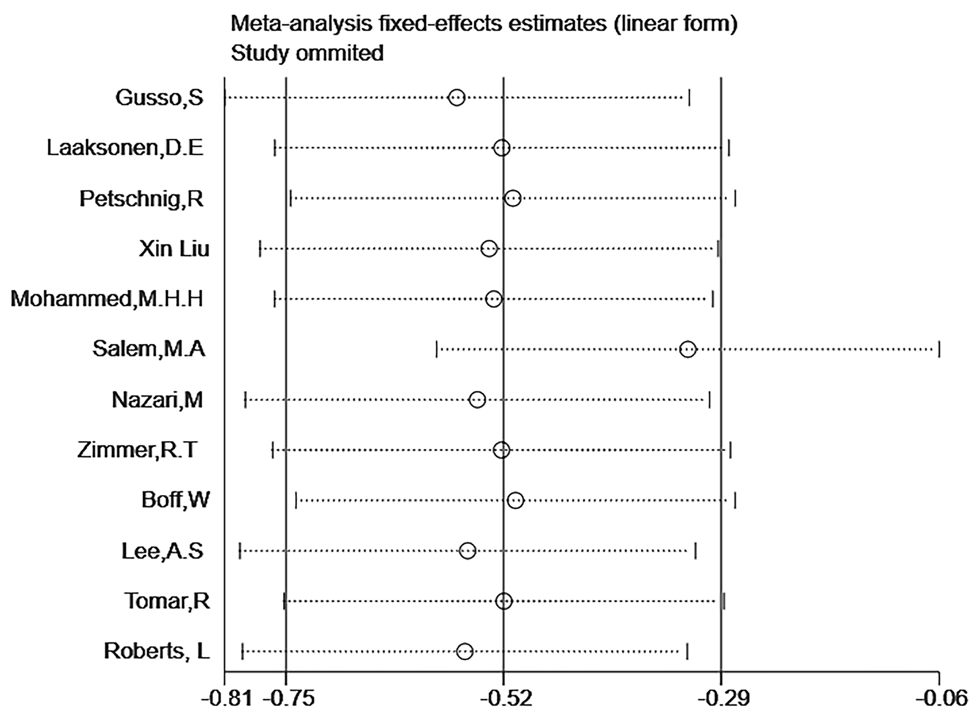

Figure 6 Sensitivity analyses of HbA1c.
Notes: The literature was eliminated one by one, and the results showed that none of the studies had a greater impact on the overall outcome.

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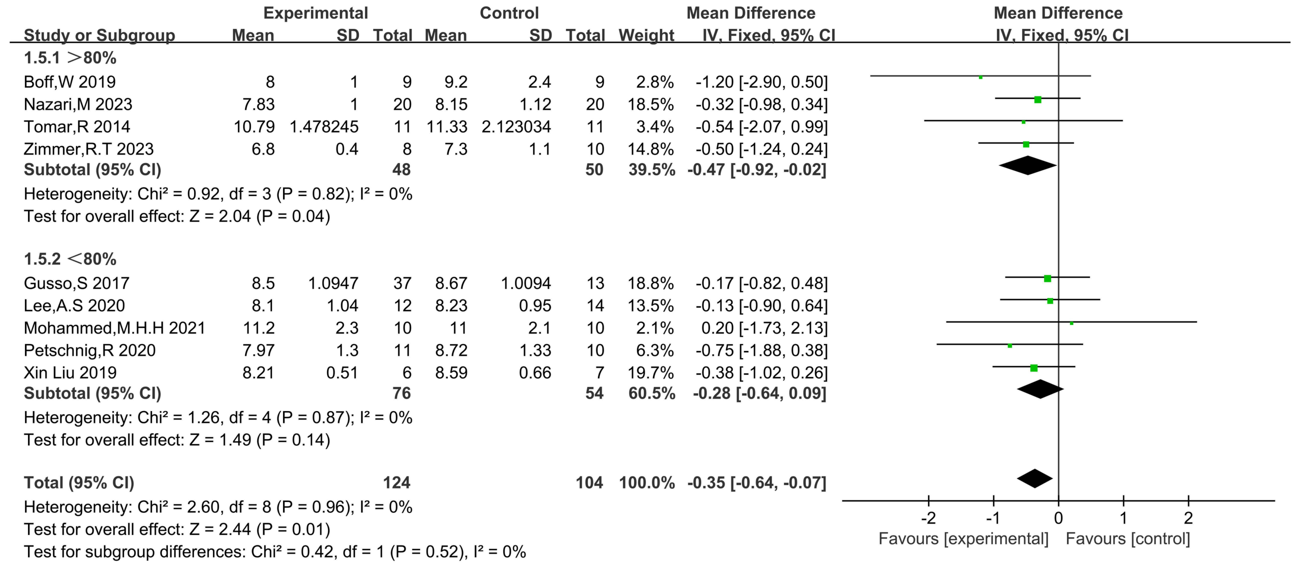

Figure 7 Forest plot of post-2010 study data: effect of exercise on HbA1c.

Notes: Forest plot of post-2010 study data: High adherence to ACSM recommendations (>80%) vs low or uncertain adherence to ACSM recommendations (<80%). Due to non-significant heterogeneity (I^2 = 0%), a fixed-effects model was used. Data are presented as weighted mean difference because indicators and units of measurement are harmonized. Overall result: A total of 228 participants were included (104 in the control group and 124 in the experimental group). Exercise had a significant improvement in HbA1c (WMD: −0.35 [95%CI: −0.64, −0.07], p = 0.01). Subgroup analysis: The high adherence subgroup (WMD: −0.47 [−0.92, −0.02], I^2 = 0%, p = 0.04) had a significant effect on HbA1c improvement, and the low adherence subgroup (WMD: −0.28 [−0.64, 0.09], I^2 = 0%, p = 0.14) had no significant effect on HbA1c.

adherence group (0%). The funnel plot of included studies was symmetric (Figure 5). The result of sensitivity analyses showed that the results were robust (Figure 6). The Egger's test (p = 0.216) also proved that there is no significant publication bias.

In summary, studies with high adherence played a better role on HbA1c than those with low or uncertain adherence (WMD: −0.74 < −0.21), even better than the overall pooled effect (WMD: −0.74 < −0.52). This further suggested the exercise dose prescribed by the ACSM tended to be more positively associated with HbA1c improvement.

In 2010, the diagnostic criteria for diabetes mellitus were significantly revised, taking HbA1c into the diagnostic criteria.[39] By browsing the articles published after 2010 (Figure 7), we find 9 studies that presented evidence regarding HbA1c alterations attributed to exercise, of which involved 228 participants. The results still revealed that exercise significantly improved HbA1c in T1DM (SMD: −0.35 [−0.64, −0.07], p = 0.01, I^2 = 0%). Compared with pooled data that included pre-2010 studies, post-2010 studies had less heterogeneity (post-2010 only, I^2 = 0% vs Including pre-2010, I^2 = 13%). In further subgroup analyses, studies with high adherence to ACSM (SMD: −0.47 [−0.92, −0.02], p = 0.04) showed that the improvement remained superior to those with low or uncertain adherence (SMD: −0.28 [95% CI: −0.64, 0.09], p = 0.14). Heterogeneity was lower in the high adherence studies after 2010 (including pre-2010 vs post-2010 only: I^2 = 1% vs I^2 = 0%), while no significant change was observed in the low adherence group (both were 0%). Following the exclusion of era-related confounding factors, the results of post-2010 studies not only indicated that the "period in which the study was conducted" (or "evolution of diagnostic criteria") was a major source of heterogeneity but also substantially strengthens the credibility of both the conclusion that "exercise is effective" and "differences in ACSM adherence were the main factor influencing the improvement in HbA1c".

Secondary Outcomes with Statistically Significant

Body Mass Index (BMI)

A total of 7 studies provided data proof for changes in BMI done by exercise, involving 295 participants (125 in the control group and 170 in the experimental group). Exercise showed significant beneficial effects in improving the BMI of patients with T1DM (SMD: −0.43 [95% CI: −0.67, −0.19], p = 0.0005, I^2 = 31%). On further subgroup analyses, studies with high adherence (SMD: −0.42 [95% CI: −0.72, −0.12], p = 0.006) showed no significant difference compared to those with low or uncertain adherence (SMD: −0.43 [95% CI: −0.83, −0.03], $p = 0.03$). Studies with high adherence had higher heterogeneity ($I^2 = 52\%$) than those with low adherence ($I^2 = 34\%$), which indicated more variation between studies with high adherence (Supplementary Figure S1). The funnel plot is roughly symmetrical on both sides (Supplementary Figure S2), suggesting no publication bias. Sensitivity analyses did not reveal any single factor that significantly affected the results (Supplementary Figure S3). Overall, exercise has a positive impact on BMI in individuals with type 1 diabetes. No superiority was observed with high-adherence ACSM recommendations. However, given the high heterogeneity across studies, the lack of significant effect with high adherence may be due to insufficient sample sizes, necessitating more research to validate these findings.

Triglyceride (TG)

When the outcomes were related to triglyceride, 6 studies involving 250 participants were included. In summary, exercise had a statistically significant effect on triglyceride (SMD: −0.37 [95% CI: −0.62, −0.11], $p = 0.005$, $I^2 = 4\%$). In the subgroup with high adherence to ACSM recommendations, the SMD was −0.47 (95% CI: −0.76, −0.19) ($p = 0.001$). In the subgroup with low adherence to ACSM recommendations, the SMD was 0.07 (95% CI: −0.50, 0.65) ($p = 0.81$). Heterogeneity was 0% in both subgroups, indicating a high degree of consistency (Supplementary Figure S4). The funnel plot is roughly symmetrical (Supplementary Figure S5), showing no publication bias. Furthermore, sensitivity analyses did not reveal any single article significantly influencing the overall results, suggesting the robustness of the study (Supplementary Figure S6).

VO_{2max}

A total of 5 studies about VO_{2max} were included, involving 156 participants. The pooled WDM was 3.93 (95% CI: 2.00, 5.86) ($p < 0.0001$), which suggested that exercise has a significant effect on improving VO_{2max} (Supplementary Figure S7). Although both studies demonstrated significant improvement, there was no apparent difference in treatment efficacy between the study with lower compliance (WMD: 4.25 [95% CI: 1.53, 6.97], $p = 0.002$) and the study with higher compliance (WMD: 3.60 [95% CI: 0.88, 6.33]). Both subgroups' heterogeneity was low. No publication bias was shown in the symmetrical funnel plot (Supplementary Figure S8). The result of the sensitivity analyses was robust (Supplementary Figure S9).

Secondary Outcomes with No Statistical Significance

Insulin Dose

When the results of the study were about insulin doses, no significant effects had been confirmed by the results (SMD: −0.62 [−1.30, 0.06], $p = 0.07$, $I^2 = 84\%$). Neither the subgroup with ≥80% adherence (SMD: −0.90 [−2.02, 0.21], $p = 0.11$, $I^2 = 90\%$) nor the subgroup with <80% adherence (SMD: −0.31 [−0.88, 0.26], $p = 0.29$, $I^2 = 42\%$) demonstrated a significant effect of exercise on insulin dose (Supplementary Figure S10). The symmetric funnel plot (Supplementary Figure S11) demonstrated no publication bias. Heterogeneity was higher in the group of high adherence. To investigate sources of heterogeneity, we employed sensitivity analysis (Supplementary Figure S12), and the results showed our data were robust. Overall, it suggests that the effect of exercise on the insulin dose in patients with T1DM is yet to be determined.

Serum Total Cholesterol (TC)

When it comes to the study of TC, 6 studies were included. Initially, the heterogeneity was 92%. Random effects model was applied. Regarding the overall effect, the SMD was −0.19 (95% CI: −1.20, 0.81) ($p = 0.71$, $I^2 = 92\%$). In the subgroup with high adherence to ACSM recommendations, the SMD was −0.72 (95% CI: −1.76, 0.33) ($p = 0.18$, $I^2 = 90\%$). In the subgroup with low or uncertain adherence to ACSM recommendations, the SMD was 0.88 (95% CI: −0.61, 2.36) ($p = 0.25$, $I^2 = 81\%$). All of their confidence intervals span 0, indicating that exercise did not have a significant improvement in TC (Supplementary Figure S13). High heterogeneity meant the results need to be treated with caution. Symmetry was showed in the funnel plot (Supplementary Figure S14), suggesting there were no publication bias. The sensitivity analysis displayed that our data were robust (Supplementary Figure S15).

High-Density Lipoprotein (HDL)

Six studies were included. Originally, the heterogeneity revealed I^2 value is high (86%). Therefore, a random-effects model was used for statistical analyses (Supplementary Figure S16). In the subgroup with high adherence to ACSM recommendations, the SMD was 0.36 (95% CI: −0.70, 1.42) (p = 0.50), with a heterogeneity of 90%. In the subgroup with low adherence to ACSM recommendations, the SMD was 0.59 (95% CI: −0.64, 1.82) (p = 0.35), with a heterogeneity of 75%. This indicated that exercise did not have an instructive effect on HDL. And the high degree of heterogeneity suggested that further studies need to be obtained. Symmetry of the funnel plot displayed no publication bias (Supplementary Figure S17). Sensitivity analysis demonstrated our data had robustness (Supplementary Figure S18).

Low-Density Lipoprotein (LDL)

A total of 6 studies were included. Using a random-effects model to statistical analyses (Supplementary Figure S19), the result showed exercise did not have a positive effect on LDL (SMD: 0.21 [−0.04, 0.47]; p = 0.10, I^2 = 31%). In the subgroup with high adherence to ACSM recommendations, the SMD was 0.13 (95% CI: −0.15, 0.41) (p = 0.38), with a heterogeneity of 0%. In the subgroup with low adherence to ACSM recommendations, the SMD was 0.61 (95% CI: 0.01, 1.21) (p = 0.05), with a heterogeneity of 66%. Neither the low-adherence nor the high-adherence studies demonstrated significant improvement in LDL. Symmetry was shown in the funnel plot (Supplementary Figure S20), indicating no publication bias. We carried out sensitivity analysis, showing our data had robustness (Supplementary Figure S21).

Weight

Six studies were included in total. Exercise did not play a positive role in weight management (SMD: −0.08 [−0.41, 0.25], p = 0.64, I^2 = 48%). Both studies with high adherence (SMD: −0.23 [−0.78, 0.32], p = 0.41, I^2 = 71%) and low adherence (SMD: 0.01 [−0.41, 0.42], p = 0.98, I^2 = 7%) failed to show a positive effect of exercise on weight (Supplementary Figure S22). The funnel plot is roughly symmetrical (Supplementary Figure S23), showing no publication bias. Sensitivity analyses demonstrated the results had robustness (Supplementary Figure S24).

Fat Free Mass (FFM)

Four studies were included in the follow-up data collection on FFM. The results demonstrated that exercise had no noticeable improvement in FFM (SMD: 0.27 [−0.43, 0.98], p = 0.45, I^2 = 64%). After subgroup analyses, the results hardly showed positive effect of exercise on FFM either for studies with high adherence (SMD: 0.64 [−1.20, 2.48], p = 0.50, I^2 = 84%) or study with low or uncertain adherence (SMD: 0.07 [−0.51, 0.65], p = 0.82, I^2 = 28%). Heterogeneity of the results were all more than 50% (Supplementary Figure S25), suggesting that the results need to be viewed with caution. Roughly symmetrical funnel plot showed no publication bias (Supplementary Figure S26). Sensitivity analyses showed the results had robustness (Supplementary Figure S27).

Systolic Blood Pressure & Diastolic Blood Pressure (SBP & DBP)

A total of six studies based on DBP and SBP were included, involving 249 participants.

Regarding DBP, the result showed exercise did not have a positive effect on DBP (SDM: −0.07 [−0.33, 0.19], p = 0.58, I^2 = 8%). On subgroup analysis, both studies of high (SMD: −0.01 [95% CI: −0.35, 0.33], p = 0.94, I^2 = 0%) and low adherence (SMD: −0.16 [95% CI: −0.56, 0.24], p = 0.44, I^2 = 39%) to ACSM have shown no positive effect of exercise on SBP. Heterogeneity was low in both subgroups, suggesting little difference between studies (Supplementary Figure S28). The funnel plot is roughly symmetrical (Supplementary Figure S29), showing publication bias did not exist. Sensitivity analyses showed the results were robust (Supplementary Figure S30).

The pooled effect (SMD: 0.01 [95% CI: −0.60, 0.61], p = 0.99, I^2 = 76%) of exercise on SBP showed no positive improvement (Supplementary Figure S31). Of the included studies, 2 were high adherence (SMD: 0.29 [95% CI: −1.14, 1.71], p = 0.69, I^2 = 87%) and 5 were low adherence (SMD: −0.14 [95% CI: −0.54, 0.26], p = 0.49, I^2 = 0%). Both with confidence intervals containing 0, which implied that the results were not statistically significant. Heterogeneity of subgroups with high adherence was high. Symmetry was visible in the funnel plot (Supplementary Figure S32), showing publication bias did not exist. To find the source of heterogeneity, we further performed sensitivity analyses, which showed robustness (Supplementary Figure S33).

Overall, none of the studies, whether high adherence or low, showed a positive effect of exercise on blood pressure. More studies are to be obtained in the future to explore the possible impacts.

Reporting of Hypoglycaemic Events

In the 14 studies, we found a total of 6 publications reporting cases of hypoglycemia. Three of these were in the high adherence subgroup[20,28,30], and 3 were in the low adherence subgroup.[27,32,33] Due to the variety of ways in which the included studies reported hypoglycemic events, a meta-analysis could not be achieved and therefore we summarized in narrative form.

In the high adherence subgroup, Salem et al[28] reported that the number of hypoglycemic episodes showed few distinctive differences from the non-exercise intervention group during 6 months of exercise training (4.7 ± 3.56 vs 4.82 ± 4). Alarcon-Gomez et al[20] concluded that exercise was generally safe for glycemic control, as there were only 3 cases of mild hypoglycemia in their 198 exercise sessions. In the study by Zimmer et al,[30] the TIR (time in range) was significantly elevated in the exercise group compared to the control week ($p = 0.049$), and there was no significant change in TBR (time below range) in the exercise group (TBR1:$p = 0.204$, TBR2:$p = 0.096$). This implied that exercise was productive in improving glycemic control without leading to an elevated risk of hypoglycemia. Overall, exercise revealed a very low risk of hypoglycemia in the high adherence subgroup.

In the low adherence subgroup, none of the three studies showed noticeable improvement in HbA1c. Mohammed et al[27] performed 90 minutes of soccer exercise twice a week at an intensity of 79%–84.6%. The number of nocturnal hypoglycemia reported by the football group (FG) was significantly higher than that of the control group (CG) without exercise (FG:4(2) vs CG:1(1)), which means that the ACSM low-adherence exercise program was not friendly to T1DM. Farrell et al[32] reported no significant differences in the number ($p = 0.32$) and duration ($p = 0.31$) of hypoglycemic exposures compared to controls. A case of severe hypoglycemia after exercise occurred in Lee's study.[33] In addition to this, no significant elevation of hypoglycemia occurrence was found in its blinded continuous glucose monitoring (CGM) measurements.

Overall, while there were several studies with hypoglycemic exposure, few demonstrated a marked increase compared to controls and were essentially without serious adverse events. Moreover, in the subgroup with high adherence, exercise resulted in an effective reduction in HbA1c with an overall lower frequency of hypoglycemic events. The frequency and severity of hypoglycemic events reported in the lower adherence subgroup were more apparent, and it was difficult to balance the reduction in hypoglycemic events with effective improvement in glycemic control.

The Effect of Exercise on Blood Glucose Using Continuous Glucose Monitoring (CGM)

Indicators monitored by CGM are another favorable tool to assess glycemic control.[40] CGM allows for the prevention of exercise-related dysglycemia problems and the risk of hypoglycemic unconsciousness through real-time glucose monitoring.[38] However, due to the late emergence of CGM, the number of experiments using CGM is small.

Of all included studies, only 3[30,32,33] used CGM and documented the time in range (TIR), time below range (TBR) and time above range (TAR). We therefore summarized it in narrative form without meta-analysis. Zimmer et al[30] compared blood glucose fluctuations at 4 weeks in the intensive glucose management group (the IT group) versus those in the intensive management combined with exercise group (the EX group). A significant improvement in TIR was observed for the EX group compared with the control week ($p = 0.049$). TBR and TAR remained stable in the EX group (TBR1: $p = 0.999$, TBR2: $p =1.0$; TAR1: $p = 0.204$; TAR2: $p = 0.305$). Lee et al[33] completed a 12-week HIIT exercise intervention. Compared to the control week, there were no significant differences in the HIIT group for any of the indicators tested using CGM ($p > 0.05$). Similarly, Farrell et al[32] observed no significant differences in mean (SEM) duration of all hypoglycaemia during a 4-week HIIT intervention.

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Overall, these studies using CGM failed to demonstrate an adverse effect of exercise on glycemic control.

Discussion

This meta-analysis exhibits several notable strengths. Initially, the subject matter of our meta-analysis was groundbreaking and held considerable clinical importance. The ACSM is a reputable organization in medicine, and its exercise guidelines, which are based on solid research, provide valuable guidance for many chronic conditions. To our knowledge, there has been no previous meta-analysis that has categorized trials according to ACSM adherence in order to evaluate the effects of high or low adherence exercise intervention in T1DM. The guidelines from the ACSM offer reliable information on many parts of exercise and prevent the results of meta-analyses from being confounded by a single aspect of the exercise dose, which also makes it more practical to apply in T1DM. Second, we excluded studies published before 2000 to mitigate the negative impacts caused by alterations in diabetes diagnosis and treatment protocols. Past meta-analyses have used both randomized and non-randomized studies.[11,41,42] In contrast, our meta-analysis only included randomized controlled trials, which made the results more rigorous. The meta-analysis demonstrated for the first time whether a complete exercise prescription is beneficial for patients with T1DM.

Summary of Results

The results of our meta-analysis showed that exercise significantly reduced HbA1c levels in patients with T1DM. Furthermore, the exercise intervention with high adherence to ACSM had a more positive effect on reducing HbA1c.

Other meaningful outcomes of this review are that exercise could decrease triglyceride and BMI levels, enhance VO_{2max} levels, leading to a multifaceted enhancement of physical fitness in patients with T1DM. At the same time, we subgrouped all these secondary outcomes, showing that the exercise intervention with high adherence to ACSM was more effective than those with low adherence intervention in lowering triglyceride levels in T1DM. Moreover, our analysis of hypoglycemia event statistics revealed that trials with high adherence exhibited generally lower frequency and severity of hypoglycemic events than those with low adherence subgroups.

Effect of Exercise on Glycemic Management in T1DM—Mechanisms and Challenges

HbA1c is a reflection of average glycemia over approximately 3 months.[38] Therefore, the long-term advantages of exercise on glycemic management, as indicated by the decrease in HbA1c, result from the cumulative effect of reducing average blood sugar levels with each exercise session.[14] The primary mechanism for reducing blood glucose concentrations by exercise is through the enhanced absorption of glucose by skeletal muscle. Exercise enhances the translocation of glucose transporter protein type 4 (GLUT4) to the plasma membrane of skeletal muscle cells. This, in turn, augments the rate at which glucose enters muscle cells through GLUT4, leading to a reduction in blood glucose levels.[43] Long-term exercise results in increased muscle mass and sustained improvement in insulin sensitivity, which may improve long-term chronic glycemic control, enabling a significant decrease in HbA1c.[11]

The reduction in HbA1c also elevates the risk of hypoglycemia for glycemic management in patients with type 1 diabetes. In healthy individuals, exercise-related glucose homeostasis is maintained through complex endocrine interactions (mainly insulin versus counter-regulatory hormones: glucagon, catecholamines, cortisol, and growth hormone).[44] Exercise upregulates gene expression of GLUT-4, leading to decreased glucose levels. In healthy people, insulin is downregulated to prevent excessive activation of GLUT-4.[45] Meanwhile, increased glucagon stimulates hepatic glycogenolysis and promotes gluconeogenesis. Elevated cortisol and growth hormone lead to increased glycolysis and fatty acid mobilization. Moreover, epinephrine and norepinephrine (catecholamines) enable an increase in the catabolism of glycogen and lipids.[12] The collective impact of the above hormones (also known as counterregulatory response) inhibits the excessive decrease in blood glucose concentration caused by physical activity.[12] In contrast, due to their impaired endogenous insulin production, patients with T1DM are chronically dependent on exogenous insulin supply, and insulin levels cannot be flexibly decreased during exercise.[46] High blood insulin level in T1DM patients inhibits endogenous glucose production and fatty acid mobilization mediated by counterregulatory response.[12] This results in the failure of glucose output to catch up with glucose consumption, leading to the potential danger of hypoglycemia. However, exercise, as a complex modulator, can reduce the incidence of hypoglycemia by adjusting the dose of intervention. As the intensity of exercise increases, the effects of the interaction between insulin and glucagon decrease. Catecholamines become a major influence, with a substantial increase in their circulating levels, promoting hepatic glucose release and inhibiting peripheral glucose uptake.[47] This results in glucose production exceeding demand, which increases blood glucose concentrations. Although this carries the risk of causing reactive hyperglycemia, it does effectively reduce the incidence of hypoglycemic events.

In summary, the processes by which exercise affects the body are intricate and vary depending on the exercise dosage. Therefore, achieving a balance between lowering HbA1c levels and minimizing hypoglycemia events in exercise prescriptions is challenging, no matter what type of exercise is being performed. Finding a more suitable exercise dose is the problem that our meta-analysis attempts to address.

Effects of Exercise Adherence According to ACSM on Glycemic Control

Based on our comprehensive meta-analysis, we found that randomized controlled trials in recent years have shown considerable variation in type, intensity, frequency, and duration of exercise, with different effects on glycemic control. First, there are conflictive evidence for each of the different types of exercise. Tonoli et al[11] argued that resistance exercise showed no improvement in glycaemic control, while Reddy et al[48] suggested that resistance exercise resulted in lower glycated hemoglobin and better glycemic control. Some studies regarding the effects of aerobic exercise on glycemic management also showed distinct differences.[49,50] Furthermore, the same exercise regimen can yield contradictory results depending on its frequency, intensity, and duration.[51,52] For example, while both involved resistance training twice weekly, Ramalho et al 's[49] 12-week program of 60-minute sessions showed no effect on improving HbA1c, whereas Petschning et al 's[24] 32-week regimen of 50-minute sessions demonstrated efficacy in improving glycemic control. The incongruous results of these studies mean that simply discussing the effect of exercise type on blood glucose in different exercise dose designs does not lead to compelling conclusions. Both the American Diabetes Association and the American College of Sports Medicine have provided evidence-based recommendations on the types of exercise to perform for people with type 1 diabetes.[17,53,54] However, the evidence of these recommendations is assessed as almost B or C grade for individuals with T1DM. Until yet, no research has reliably determined the most suitable exercise programs for individuals with T1DM, as existing studies mostly focus on analyzing a single element of exercise dosage and lack a holistic examination of exercise dose.[55] In contrast, our meta-analysis used the overall exercise guidelines recommended by the ACSM as the evaluation criteria. The results demonstrated that exercise interventions with high adherence to ACSM had a more positive effect on HbA1, with a decreased incidence and severity of hypoglycemic events. Moreover, we found that the overall heterogeneity was generally reduced in each subgroup, suggesting that the adherence rate to ACSM exercise dose is the main influential factor in glycemic control.

Cardiorespiratory Exercise

According to ACSM recommendations, the recommended exercise frequency for individuals with T1DM is 3–5 days per week, at an intensity of 55–90% of maximum heart rate, with each session lasting 20–60 minutes. Our meta-analysis revealed that in studies with high adherence, cardiorespiratory exercise predominantly focused on moderate-to-high intensity with moderate single-session duration, occurring 3–5 times weekly. This aligns with the "exercise dose" summarized in previous studies as effective for improving glycemic control.[13,56] Studies with low adherence commonly exhibit issues such as excessive intensity or inadequate frequency.[27,33] Moderate-to-high intensity exercise, on the one hand, enhances skeletal muscle uptake of glucose, thereby directly lowering blood sugar levels. On the other hand, when a certain intensity threshold is reached, it stimulates catecholamine secretion, suppresses insulin-mediated glucose utilization, and promotes hepatic gluconeogenesis.[57] This provides a safer blood glucose regulation model for individuals with type 1 diabetes mellitus (T1DM) compared to low-intensity aerobic exercise.[12] This also explains why high-intensity interval training (HIIT), characterized by "short duration and high intensity", is gaining attention among T1DM populations.[58] However, prolonged exercise at excessively high intensity (>90% maximum heart rate) still carries risks and can lead to a marked increase in the likelihood of delayed hypoglycemia, which rises significantly with both exercise intensity and duration.[59] Even when performing High-Intensity Interval Training (HIIT), maintaining an appropriate intensity and time window remains crucial.

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Exercise frequency is equally important for glycemic control. A 12-week intervention study by Huttunen et al,[60] which involved only one 45-minute exercise session per week, observed no improvement in HbA1c levels. In contrast, studies by Herbst et al[56] and Quirk et al[13] demonstrated that exercising three or more days per week was more effective in reducing HbA1c levels in patients with type 1 diabetes. This indicates that even prolonged exercise duration requires adequate frequency to achieve sustained HbA1c improvement. The differing outcomes between the high-adherence exercise program by Zimmer, R. T. et al[30] and the low-adherence program by Mohammed et al[27] stem from dividing the weekly 180 minutes of exercise into 3×60-minute sessions rather than 2×90-minute sessions. This approach increased frequency while shortening individual session duration. This distribution helps prevent the generalization of stimulus due to prolonged higher-intensity exercise, which could weaken counter-regulatory mechanisms and increase the risk of hypoglycemic events. It also enhanced the muscle's ability to adapt to changes in blood glucose levels. As demonstrated by a study, increased exercise frequency upregulates the expression and transport efficiency of GLUT4 in skeletal muscle, improves glucose metabolism, reduces glycation exposure of hemoglobin, and ultimately leads to sustained improvement in HbA1c.[61]

Resistance Exercise

Resistance exercise (RE) is a form of physical activity that utilizes non-oxidative glycolysis to supply energy. Its advantage lies in effectively improving body composition, including reducing fat mass and increasing muscle mass.[11,62] RE promotes increased production of catecholamines and lactate, thereby triggering a counter-regulatory response that elevates blood glucose levels. This mechanism can effectively reduce the occurrence of hypoglycemic events.[63] ACSM recommends that RE should ideally follow a strategy of 2–3 days per week, at 55–90% of maximal heart rate, with 8–12 repetitions or the number of repetitions required to induce muscle fatigue without reaching exhaustion, across 2–4 sets. Studies indicate that acute blood glucose and glucoregulatory responses vary with different doses of RE. For example, Turner et al[64] found that the first and second sets of resistance training led to an increase in blood glucose, whereas the third set showed a decrease in blood glucose. The increased exercise volume may enhance glucose uptake, thereby partially offsetting the hyperglycemic response. In terms of frequency, most resistance training protocols in studies with high adherence involved 3 sets. In contrast, studies with low adherence to ACSM[21,24] often featured lower training frequency or intensity below ACSM recommendations. It is speculated that this is due to the low frequency making it difficult to sustain the exercise-induced improvement in insulin sensitivity, while the insufficient intensity results in inadequate glucose uptake by skeletal muscle.[65,66] This explains why improvements in HbA1c levels are hard to detect in such studies.

Flexibility Exercise

ACSM's recommendations for flexibility and balance training are as follows: frequency: 2–3 times per week; intensity: stretching until a feeling of muscle tightness or slight discomfort is felt; duration: holding each stretch for 10–30 seconds, repeated 2–4 times. Studies have shown that flexibility training can improve joint mobility restricted by glycation in diabetic patients, particularly the elderly.[67] However, studies on its effects on blood glucose control and the optimal exercise dosage remain limited. Current evidence suggests that flexibility exercises hold potential for improving blood glucose control. Animal studies indicated that stretching can promote the transcription of glucose transporters.[68] Some clinical research also demonstrated that stretching alone provides immediate and long-term blood glucose control benefits for individuals with type 2 diabetes.[69] Notably, the exercise protocols adopted in several studies share a common pattern: each stretch is held for 30 seconds and repeated 4 times.[70–72] This pattern aligns with ACSM's exercise recommendations for patients with type 1 diabetes. Moreover, similar protocols and corresponding blood glucose improvements have been observed in studies with high adherence, which to some extent supports the rationality of ACSM's related recommendations. Nonetheless, further research is needed for validation.

For elderly patients with type 1 diabetes who are at higher risk of hypoglycemia, have a need for improved joint flexibility, and are suitable for gentle exercise, clarifying the effectiveness of flexibility training and its optimal dosage would be of significant clinical importance.

Combined Exercise

Some studies have employed combined interventions involving aerobic exercise, resistance training, or flexibility training for patients with T1DM. However, in trials with low adherence,[21,22] these combined exercise regimens failed to demonstrate significant improvements in glycemic control. Conversely, in studies with high adherence,[28,29] combined exercise exhibited stronger glycemic control effects. This suggests that regardless of whether a single or multiple exercise modalities are used, achieving optimal therapeutic effects is challenging if key dose parameters such as exercise frequency, intensity, and timing are neglected. Notably, combined exercise demonstrates unique advantages in reducing hypoglycemia risk. Research indicates that performing resistance training prior to aerobic exercise helps maintain glycemic stability and reduces the duration and severity of post-exercise hypoglycemia.[73] This implies that the combination of different exercise modalities may produce more complex and integrated effects on glycemic regulation through synergistic or complementary mechanisms, and its effective dosage is necessarily distinct from that of single exercise modes. Currently, although a preliminary evaluation of combined exercise has been conducted based on the dosage requirements for individual exercise modalities outlined by the ACSM prescriptions, it can be tentatively inferred that the recommendations for individual dosages may also be applicable to combined exercise. However, establishing a more precise dose range for combined exercise still requires further validation and refinement through future high-quality research.

Core Strategies for Glycemic Control

The core strategy for glycemic control is to improve blood glucose levels while simultaneously reducing the occurrence of hypoglycemic events. Based on our research, it is evident that the ACSM exercise prescription is an effective exercise program capable of consistently lowering glycated hemoglobin and improving glycemic control. Regarding the management of exercise-related hypoglycemia risk, the ACSM also demonstrates certain advantages. First, this meta-analysis showed that no significant difference was observed in the incidence of hypoglycemic events between the exercise groups (both high- and low-adherence) and the control group. This suggests exercise may not pose a significant hypoglycemic risk as feared by individuals with T1DM. Furthermore, studies with high adherence to ACSM prescriptions are associated with stable hypoglycemia risk, which underscores that structured exercise according to ACSM guidelines enhances both control and safety.

Nevertheless, psychological fear of hypoglycemia in T1DM patients still requires mitigation through systematic and continuous glucose monitoring. Therefore, implementing dynamic or regular glucose monitoring throughout exercise is a critical supportive measure for identifying trends in blood glucose fluctuations and enabling timely interventions (such as adjusting exercise intensity, taking breaks when needed, or supplementing with carbohydrates). And a continuous glucose monitor with alerts is an effective tool to achieve this.[74]

Risk Warning and Response

To comprehensively address patients' concerns regarding exercise, a structured system for risk warning and response must be established. First, prior to implementing an exercise prescription (including the ACSM guidelines discussed in this research), medical clearance should be obtained to assess an individual's cardiovascular risk and diabetes-related complications. During the pre-exercise phase, if blood glucose falls below the threshold, carbohydrate supplementation is recommended. If hyperglycemia occurs alongside ketosis, intense exercise should be avoided. Instead, supplement insulin, hydrate, and rest appropriately before considering exercise. For the post-exercise phase, if exercise ends late in the day or post-exercise blood glucose is in the low-normal range, a low-glycemic-index bedtime snack is suggested to maintain stable overnight glucose levels. As muscles are more insulin-sensitive after exercise and exercise-induced hyperglycemia may be temporary, injecting the usual insulin dose after exercise may lead to hypoglycemia. To prevent this, basal insulin should generally be reduced.[75] And it is recommended that when hyperglycemia occurs after exercise, delay reassessing glucose trends for 1–2 hours.

Throughout all phases, maintaining adequate hydration before, during, and after exercise is critical, as nearly 30% of T1DM patients already have blood glucose levels exceeding the renal glucose threshold at the start of exercise. This triggers osmotic diuresis. The combined effects of urine and sweat during exercise exacerbate fluid loss. Without replenishment, the risk of dehydration increases significantly.[76]

By establishing a comprehensive glucose alert and management system covering pre-exercise, during exercise, and post-exercise periods, patients can gradually build confidence in exercising. This structured approach enhances adherence to the ACSM exercise prescription and contributes to sustained improvements in long-term glucose management.

Other Outcomes

Regarding TG, our results showed that exercise is effective in reducing TG. This finding coincided with several previous studies.[10,13,77] Results of a further subgroup analysis revealed that studies with high adherence to ACSM were more favorable for lowering triglycerides. The included studies were mainly cardiorespiratory exercises. In the high adherence subgroup, we found that the frequency of exercise was within the prescribed range of 3–5 times, while the frequency of the low adherence subgroup was in the range of 2–3 times per week. Previous studies have found that increased exercise frequency is associated with a reduction in triglycerides,[28,77] suggesting that the ACSM-prescribed exercise frequency of 3–5 times per week is a beneficial dose for TG reduction in T1DM. Due to the few number of included studies, further studies are needed in the future to justify this conclusion.

In this systematic review and meta-analysis, exercise significantly reduced both BMI and maximal oxygen uptake (VO_{2max}) levels in patients with type 1 diabetes, consistent with the findings of multiple previous studies.[10,41,56,78] However, the degree of adherence did not result in significant differences in outcomes, which may be due to the limited number of studies included. In patients with T1DM, elevated BMI is a common occurrence and is associated with exacerbated insulin resistance and increased cardiovascular risk factors, such as hypertension and dyslipidemia.[79] VO_{2max} is related inversely to cardiovascular disease risk and all-cause mortality in T1DM.[80] Improvements in both BMI and VO2max demonstrated the importance of exercise for individuals with T1DM.

According to the results of our meta-analysis, exercise training (either high or low adherence to ACSM) did not lead to positive changes in insulin dose, blood pressure (SBP and DBP), weight, FFM, TC, HDL, or LDL. No significant effect of exercise on the improvement of blood pressure and some of the lipid indicators may be attributed to the fact that patients with T1DM are typically young and tend to be normotensive and have less tendency to have dyslipidemia, making it more difficult to demonstrate a benefit of exercise on T1DM. Based on our findings, we need more high-quality RCTs to validate the effects of exercise on these indicators.

Limitations of the Study

First, owing to the absence of standardized protocols for exercise intervention dosing in the past, the included studies were not consistent in the design and description of exercise frequency, intensity, and duration. In addition, some studies had relevant data that were not recorded (NR) or were simply described as individualized, which may have led to some of the studies with high/low adherence being incorrectly classified as indeterminate adherence, affecting the final pooled scores that determine the results of the subgroup classifications and potentially amplifying errors in subsequent analyses. To address this issue, we performed rigorous sensitivity analyses and publication bias measurements. At the same time, we chose a threshold of 80% adherence in order to balance methodological rigor and sufficient sample size. If the threshold had been set at 100%, most studies would not have been able to meet this point, and the disparity in numbers between subgroups would have been too large, leading to a decrease in the generalizability of the final results. If the threshold was set at 60%, it would result in some studies with less rigorous designs also being rated as highly adherent, thus weakening the value of the observed outcomes. By choosing an 80% adherence threshold, the numbers between the two subgroups were more balanced, and meanwhile, the 80% threshold minimized the impact of uncertain adherence, thus improving the statistical robustness and methodological rigor of the results.

Second, we were unable to ascertain if all the studies strictly adhered to the exercise protocols as intended, perhaps resulting in an overestimation of adherence. Moreover, the effect of exercise on glycemic control is also affected by a number of confounding factors (age, gender, body composition, dietary status, medicines, other lifestyles, etc). Unfortunately, our study failed to rigorously control these factors, which may affect the generalizability of the results.

Finally, readers should treat the results with caution due to the limited number of randomized controlled trials on the effect of exercise on glycemia in patients with type 1 diabetes mellitus.

Implications for practice/research

In terms of further improvement aspects for future exercise experiments, first, future studies demand larger samples, multicenter randomized controlled trials. Second, when scoring the current study, few experiments achieved a perfect score according to our scoring system. Moreover, most flexibility and resistance exercise programs lacked sufficient and detailed descriptions. Therefore, more clinical trials should be conducted using the ACSM as a guide to standardize experimental design for different types of exercise. In addition, research on resistance or flexibility exercises should be expanded. Fourthly, in order to prevent incomplete implementation from affecting glycemic control outcomes, future exercise trials should be rigorously monitored and the degree of implementation reported, and perhaps the ACSM should also incorporate patient compliance with the exercise regimen into the evaluation system when designing exercise prescriptions. Based on the standardized exercise protocols recommended by the ACSM, individual characteristics (eg age, gender, duration of diabetes, comorbidities, diet, medications, other lifestyles) should be taken into account in future studies to refine exercise prescriptions. In addition, we found a limited number of randomized controlled trials using the CGM devices system or examining the effects of combining two different types of exercise. The integration of emerging technologies and interventions, such as real-time glucose monitoring via CGM to reduce the risk of hypoglycemia, and the combination of novel exercise modalities such as HIIT with moderate-intensity aerobic exercise, may provide new opportunities to improve the effectiveness of exercise interventions in glycemic management in T1DM. Furthermore, to alleviate concerns about hypoglycemia among T1DM patients, future exercise prescriptions need to incorporate glucose monitoring protocols, standardized assessment of hypoglycemic events, risk warning mechanisms, and the effectiveness of countermeasures into a unified evaluation system.

Conclusion

Our meta-analysis demonstrated that adherence to the ACSM-recommended comprehensive exercise regimen (including aerobic activity, resistance training, and flexibility training) significantly improves glycemic control (HbA1c) in patients with T1DM without increasing the risk of hypoglycemia. Furthermore, higher adherence to this regimen was associated with a more pronounced reduction in triglyceride levels. These findings support the ACSM exercise prescription as a safe and effective management framework for T1DM patients.

To ensure the safe implementation of prescriptions, it is recommended that practical implementation be based on medical assessment and supported by rigorous blood glucose monitoring, hypoglycemia alerts, and response strategies.

The optimal dosages of exercise for beneficial changes in the health of T1DM remain to be tested. Since some studies did not provide detailed exercise intervention protocols, future research will require more experimental designs and larger samples for validation. In addition, the impact of the ACSM programme on other aspects of physical health in patients with T1DM needs to be further investigated.

Data Sharing Statement

The Original data generated and analyzed during this study are included in this published article or in the Supplementary Material.

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Author Contributions

RC: Conceptualization, Formal analysis, Investigation, Methodology, Writing-original draft. YYQ: Conceptualization, Formal analysis, Investigation, Writing-original draft. YYH: Investigation, Writing-original draft. XTL: Investigation, Writing-review & editing. FHZ: Conceptualization, Funding acquisition, Supervision, Project administration, Writing-review & editing. XXF: Conceptualization, Supervision, Writing-review & editing. All authors have acknowledged full responsibility for the analyses and interpretation of the report, have given final approval of the version to be published, have agreed on the journal to which the article has been submitted, and agree to be accountable for all aspects of the work.

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Disclosure

The authors report no conflicts of interest in this work.

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