

## Review

## Exercise training for executive function in type 2 diabetes: A systematic review and practice implications

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## ABSTRACT

Type 2 diabetes (T2DM) is associated with cognitive decline, particularly impairing executive function. Although exercise is recognized as a potential strategy to mitigate cognitive deficits, the most effective exercise characteristics for improving executive function in individuals with T2DM remain unclear. This systematic review evaluated the effects of exercise interventions lasting at least four weeks on executive function. A comprehensive search of five English-language databases identified 7,641 records, of which 16 studies met the inclusion criteria, including 11 randomized controlled trials (RCTs). Aerobic training was the most commonly investigated modality, followed by combined aerobic and resistance training. Overall, 63% of studies and 82% of RCTs reported directional findings favoring exercise on executive-function outcomes. Combined training showed the most consistent directional findings; certainty remains limited. Higher exercise intensity and the inclusion of cognitively engaging motor tasks were more frequently associated with directional findings favoring exercise on executive-function outcomes. Evidence suggests that structured, multi-component exercise programs incorporating aerobic, resistance, balance, and flexibility training at moderate-to-high intensity may represent promising approaches for improving executive function and may be reasonable candidates for future trials and cautious clinical consideration. Regular participation and the integration of cognitive challenges during exercise may further enhance benefits. These findings suggest that tailored exercise interventions may contribute to cognitive health management in individuals with T2DM, although confidence in these findings remains limited by methodological heterogeneity and the absence of pooled effect estimates.

## 1. Introduction

Type 2 diabetes mellitus (T2DM) is a common chronic disease characterized by elevated blood glucose levels, which can arise from insufficient insulin secretion or impaired insulin receptor response to insulin signaling [1]. T2DM leads to multiple complications, including cardiovascular diseases, neuropathy, nephropathy, retinopathy, and central nervous system-related impairments, including cognitive dysfunction [1]. Due to ongoing shifts in lifestyle-related factors, including reduced physical activity, energy-dense dietary patterns, and increasing rates of overweight and obesity, the global burden of type 2 diabetes continues to rise. These changes, together with population

aging and urbanization, have contributed to a steady increase in prevalence and to substantial health and economic consequences through diabetes-related complications and long-term care needs [2].

In addition to classic complications, growing evidence indicates that T2DM is associated with reduced cognitive function, with executive function being particularly vulnerable [3]. Cognitive function encompasses abilities such as planning, decision-making, behavior control, problem-solving, reasoning, memory, attention, language, and information processing, all of which are essential for daily tasks [4]. Executive function, a higher-order cognitive domain largely mediated by the prefrontal cortex, plays a critical role in goal-directed behavior and self-regulation, and impairment in this domain can result in reduced

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personal independence, challenges in disease management, and lower quality of life for patients with T2DM [5]. Beyond its neuropsychological relevance, executive function has direct clinical implications for individuals with T2DM. Effective diabetes management requires complex self-regulatory behaviors, including medication adherence, dietary control, glucose monitoring, and engagement in regular physical activity [6,7]. These behaviors rely heavily on executive function domains such as inhibitory control (the ability to suppress automatic or inappropriate responses), cognitive flexibility or set-shifting (the capacity to switch between tasks or mental sets), and working memory (the ability to temporarily store and manipulate information). Impairments in executive function may therefore contribute to poor treatment adherence, suboptimal glycemic control, and increased risk of disease-related complications [8].

The literature suggests that regular physical activity may protect individuals from age-related atrophy of brain structures involved in executive control and enhance prefrontal cortex metabolism [9]. While objective declines in cognitive function accelerate around age 50, except for certain cognitive skills, research has shown that a regular exercise program can slow or prevent this functional decline [9,10]. Studies using animal models have demonstrated that increased physical fitness boosts cerebral blood flow, oxygen uptake, and glucose utilization at the tissue level, while also activating growth factors that mediate structural changes, such as increased capillary density [11]. Although much of this mechanistic evidence originates from animal models or non-diabetic populations, regular physical activity appears to strengthen executive function, and exercises requiring greater cognitive engagement may have a stronger impact than simpler ones with limited cognitive demands [12]. Scientists posit that physical activity induces non-specific neural activation, which, when combined with an engaging context, promotes robust and sustained neurogenesis in the brain's learning and memory centers [13]. Thus, exercise may positively influence brain function, in part, by improving insulin sensitivity, enhancing cerebral blood flow, and stimulating the release of neurotrophic factors such as brain-derived neurotrophic factor (BDNF) [14]. However, these proposed mechanisms remain largely inferential in the context of T2DM-related executive function outcomes, as much of the supporting evidence derives from animal studies, healthy populations, or broader cognitive outcomes rather than executive function-specific intervention trials in individuals with T2DM. Therefore, although these mechanisms are biologically plausible, they should not be considered established explanations for exercise-induced improvements in executive function in this population. Nevertheless, evidence on the optimal type, intensity, and duration of exercise for improving cognitive function in individuals with T2DM remains scattered and inconsistent [15].

Given the marked methodological differences and heterogeneity in existing studies [15], drawing firm conclusions about the impact of regular exercise on executive function in people with T2DM is challenging. While prior reviews have examined broader cognitive effects of exercise in T2DM [8,16], to our knowledge, none have systematically focused on executive function-specific outcomes or synthesized training characteristics relevant to this cognitive domain. The present study aims to fill this scientific gap through a systematic review of research examining the effects of various types of regular physical activity on executive function-related cognitive test scores in individuals with T2DM. As physical activity is a key element of non-pharmacological diabetes treatment [17,18], developing an evidence-informed exercise framework may assist physicians, exercise specialists, and patients in selecting and implementing effective programs. Therefore, the secondary objective of this systematic review is to propose a preliminary, practice-oriented exercise framework to support executive function in individuals with T2DM.

## 2. Methods

### 2.1. Study Registration

The current systematic review adhered to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [19] and followed the recommendations outlined in the Cochrane Handbook for Systematic Reviews of Interventions [20]. Moreover, the protocol for this study was prospectively registered with the International Prospective Register of Systematic Reviews (CRD420251160349).

### 2.2. Search strategy

A comprehensive electronic database search was conducted using MEDLINE, Cochrane Library, Scopus, Web of Science, and Embase up to 6 September 2025 by two independent researchers. Additional sources and the reference lists of relevant review articles were screened to identify studies that may not have been captured through the primary database search. Dissertations and conference proceedings were not searched. We used a combination of Medical Subject Headings (MeSH) and free-text terms related to the key concepts to identify studies assessing executive function in individuals with T2DM who participated in physical activity or exercise interventions. The search strategy consisted of three main concepts: T2DM ("type 2 diabetes" OR "type II diabetes" OR "diabetes mellitus type 2" OR "T2DM"), exercise-related terms ("exercise" OR "physical activity" OR "aerobic training" OR "resistance training" OR "training"), and executive function terms ("executive function" OR "cognitive function" OR "executive control" OR "cognitive performance" OR "cognition") (Supplementary Table S1). There were no constraints on the year of publication during the search.

### 2.3. Study selection and eligibility criteria

Fig. 1 illustrates the study selection process. After duplicates were removed, the titles and abstracts of the remaining articles underwent an initial screening, followed by a full-text review of studies deemed potentially relevant during the secondary screening. Both screening stages were conducted independently by two reviewers (A.J. and R.N.), and any disagreements were resolved through discussion with a third author (R.B.).

The PICOS framework was used to define the eligibility criteria for studies included in this systematic review [21].

**Participants:** Eligible studies included individuals diagnosed with T2DM. Studies that included participants with cognitive impairments were also considered eligible. There were no age restrictions. Participants were generally sedentary or not engaged in structured exercise.

**Intervention:** Studies were included if they involved regular physical activity, structured exercise training, or any activity that could be classified as exercise. The intervention was required to last for a minimum of four weeks. Studies combining physical activity with additional tasks, such as cognitive training, were also considered for inclusion.

**Comparator:** Executive function outcomes were compared between exercise intervention groups and comparator groups receiving usual care, education or counseling, stretching or other light-intensity physical activity, or no structured exercise during the intervention period. For synthesis, RCTs comparing exercise interventions with usual-care T2DM control groups were treated as primary evidence. Five additional studies either included lifestyle intervention comparators or compared participants with healthy control groups and were therefore categorized as contextual evidence.

**Outcomes:** The review included studies that either independently evaluated executive function or reported specific domains of executive function based on cognitive performance assessment tools.

**Study design:** Controlled intervention studies evaluating the effects of exercise training on executive function in individuals with T2DM were eligible. RCTs comparing exercise interventions with usual-care T2DM

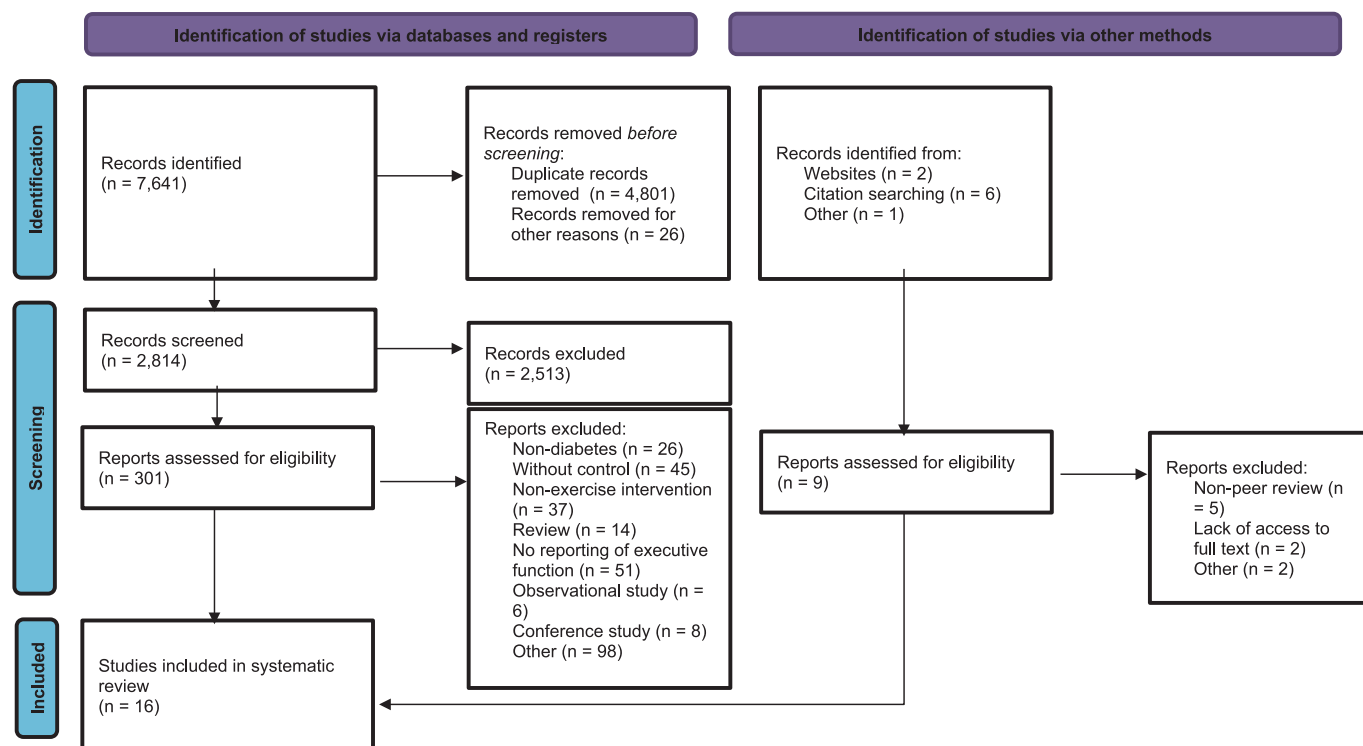


Fig. 1. Study selection PRISMA flow diagram.

control groups were designated a priori as the primary evidence base for evaluating exercise-specific effects. Controlled studies incorporating lifestyle or dietary co-interventions, active comparators, or healthy control groups were also eligible and were included as contextual evidence to inform interpretation of findings and sources of heterogeneity.

#### 2.4. Data extraction

The following information was extracted from each study: (A) participant characteristics, including sex, age, body mass index (BMI), and sample size; (B) details of the exercise intervention, such as type, intensity, number of weekly sessions, and duration in weeks; and (C) executive function outcomes and the specific assessment tools used to measure them. When available, priority was given to between-group differences in pre-post changes for executive function outcomes, as these comparisons best reflect intervention effects. Data extraction was conducted independently by two reviewers (A.J. and R.N.), and any disagreements were resolved through discussion with a third author (R. B).

#### 2.5. Quality assessment

To assess the potential risk of bias, the Physiotherapy Evidence Database (PEDro) scale was utilized [22]. The scale includes 11 original items: (1) clear criteria for participant eligibility; (2) random allocation of participants; (3) concealed allocation of participants; (4) baseline similarity of group characteristics; (5) blinding of all outcome assessors/researchers; (6) blinding of exercise therapists/trainers; (7) blinding of participants; (8) outcomes assessed in at least 85% of participants; (9) use of intention-to-treat analysis; (10) reporting of statistical comparisons between groups; and (11) provision of point estimates and measures of variability. Studies scoring 0–5 were considered low quality, scores of 6–7 indicated moderate quality, and scores of 8–10 reflected high methodological quality.

#### 2.6. Data synthesis

Due to substantial heterogeneity across studies in executive function domains assessed, outcome measures, exercise modalities, and comparator conditions, a quantitative meta-analysis was not deemed appropriate. Therefore, a narrative synthesis was conducted. A structured vote-counting approach based on the direction of effects was used to summarize findings across studies. Specifically, results were categorized according to whether outcomes favored exercise, were directionally null/inconsistent, or favored the comparator on executive function outcomes. The limitations of vote-counting were acknowledged, as this approach does not account for effect sizes, study precision, or sample size and may oversimplify complex intervention effects. Accordingly, vote-counting results were interpreted cautiously and were complemented by a qualitative comparison of intervention characteristics (e.g., exercise type, intensity, and duration) to identify consistent patterns associated with executive function outcomes in people with T2DM. Importantly, because vote-counting does not weight studies by sample size, precision, or effect size magnitude, our findings cannot provide quantitative estimates of the magnitude of executive-function benefits. This limitation directly affects the strength of the preliminary practical recommendations presented, which should therefore be interpreted as directionally consistent patterns rather than precision-based prescriptions.

### 3. Results

#### 3.1. Study selection

In the present systematic review, a total of 7,641 records were initially identified through searches of electronic databases. After duplicate removal and title/abstract screening, the remaining studies underwent full-text eligibility assessment. Ultimately, full-text evaluation confirmed that 16 studies [16,23–37] met the predefined inclusion criteria for the present systematic review; however, only 11 were RCTs that used a T2DM control group without any lifestyle or dietary

intervention. These 11 RCTs were treated as primary evidence, whereas the remaining 5 studies (lifestyle comparators and/or healthy control comparisons) were summarized as contextual evidence (1).

### 3.2. Characteristics of the included studies

The included studies comprised a total of 2,899 individuals diagnosed with T2DM, who were predominantly allocated to exercise intervention and control groups. A summary of the extracted data from the included studies is presented in Table 1 & 2. In addition to executive function-related cognitive outcomes, which constituted the primary outcome of the present review, several related variables were also reported as secondary outcomes (e.g., body composition).

Among the 13 studies reporting sex distribution, 63% of participants were women with T2DM. Moreover, while most studies focused on middle-aged and older adults (aged > 50 years), several investigations also included younger adult participants.

Baseline metabolic status varied considerably across the included studies. Mean T2DM duration ranged from 1 to 29 years, with most studies reporting durations between 10 and 15 years. In the majority of studies, mean baseline HbA1c was above 6.5%, consistent with suboptimal glycemic control. The overall range of baseline HbA1c across studies was 5.0% to 11.0%, with most values falling between 6.5% and 9.0%. It is important to note that a substantial number of included studies did not report baseline T2DM duration or baseline HbA1c values. Specifically, approximately 62% of studies (10 out of 16) did not report diabetes duration, and approximately 44% of studies (7 out of 16) did not report baseline HbA1c.

### 3.3. Methodological quality

According to the PEDro scale, the methodological quality scores of the included studies ranged from a minimum of 6 [25,27,38] to a maximum of 9 [16,24,30]. The primary contributors to lower quality scores were the absence of blinding of participants, intervention providers, and outcome assessors, as well as the lack of intention-to-treat analyses. While some limitations (e.g., participant blinding) were inherent to exercise-based interventions, others (e.g., intention-to-treat analysis) were methodological shortcomings that could be addressed (Table 4). Overall, the mean methodological quality score was  $7.75 \pm 1$ , indicating moderate methodological quality (median = 7). Although all studies met the threshold for at least moderate quality, seven studies were classified as high quality [16,23,24,28–30,39].

### 3.4. Exercise training programs

Aerobic exercise accounted for the largest proportion of the reviewed studies (56%, 9/16 studies), followed by combined exercise training (most commonly a combination of aerobic and resistance training) (31%, 5/16 studies). In addition, other exercise modalities were employed, including Tai Chi [30], strength training [16], exercise activity simulation [31], and functional training [32]. In two studies, weight loss was considered a primary training objective [25,27]; therefore, in addition to exercise training, nutritional recommendations and lifestyle counseling were also implemented. The duration of exercise interventions ranged from 6 weeks [24] to 8 years [25], although most studies focused on intervention periods  $\geq 24$  weeks. Based on the reviewed training protocols, the duration of each exercise session was generally scheduled to last 45 to 60 min. The exercise intensity used in most interventions could be classified as moderate to vigorous, and various methods were applied to prescribe or monitor intensity, including heart rate reserve (HRR), one-repetition maximum (1RM), and the Borg rating of perceived exertion.

Although most studies defined the control condition as no change in lifestyle and no structured physical activity, some investigations used light physical activity [16,28], diabetes self-management counseling

[30], workshops [39], or stretching exercises [28,29,39] as control conditions. An important methodological consideration across the included studies is the heterogeneity of comparator conditions. Some trials employed active control groups rather than true non-exercise controls, which may independently confer cognitive or psychosocial benefits, thereby reducing the contrast between intervention and control groups and potentially diluting the observed effects of exercise on executive function.

### 3.5. Outcomes

For analyses presented in Table 3, classifications were conducted at the intervention/comparison level rather than the study level because some studies contributed multiple intervention arms and exercise-characteristic categories were not mutually exclusive. Overall, the effects of exercise training on executive function were relatively evenly distributed, with 63% (10/16) showing directional findings favoring exercise on at least one executive function outcome, while 37% (6/16) were directionally null/inconsistent findings. When considering only the 11 studies with usual-care T2DM controls, 9 of 11 studies (82%) reported directional findings favoring exercise. Notably, directional findings favoring exercise were observed in all combined exercise interventions/comparisons (5/5; 100%), compared with 4 of 9 aerobic interventions/comparisons (44%) and 1 of 4 interventions/comparisons involving other exercise modalities (25%) (Table 3). Findings were predominantly directionally null/inconsistent in studies that combined structured exercise with lifestyle interventions.

In Ghahfarahi et al. (2024), outcomes favored high-intensity, low-volume exercise relative to low-intensity, high-volume training on executive function measures [24]. Consistent with this observation, fewer than 50% of interventions/comparisons classified as low-to-moderate intensity showed directional findings favoring exercise on executive-function outcomes, whereas all high-intensity interventions/comparisons (e.g., Borg > 15 or HRR > 75%) reported directional findings favoring exercise on executive-function outcomes. Conversely, complex exercise interventions, such as those reported by Jamali et al. (2025), showed directional findings favoring exercise despite low-to-moderate exercise intensity [23]. Furthermore, intervention duration beyond six months was not consistently associated with more favorable executive-function outcomes, as medium-term (> 6 months) studies yielded heterogeneous results. In contrast, shorter-term interventions (<6 months), which more frequently incorporated complex training protocols due to feasibility constraints, more consistently favored exercise on executive function outcomes (Table 3). Cumulatively, the overall direction of findings favored structured exercise for executive function in T2DM, whereas lifestyle-focused interventions were mostly directionally null/inconsistent in this dataset.

Based on executive function domains, directional findings favoring exercise were observed for inhibitory control in 64% (7/11 interventions/comparisons), cognitive flexibility in 55% (6/11 interventions/comparisons), and working memory in 67% (2/3 interventions/comparisons). Additionally, a relative advantage was observed for combined and complex exercise training with higher intensity, although the number of studies addressing the working memory domain was limited (Table 3).

## 4. Discussion

This systematic review suggests that structured exercise, particularly combined and higher-intensity programs is more consistently associated with directional findings favoring exercise on executive function outcomes in individuals with T2DM. However, this benefit is contingent upon exercise modality, intensity, and comparator type, and is not uniformly observed across all studies.

Of the 16 included studies, 11 were RCTs comparing exercise to usual-care T2DM controls (primary evidence), and 5 used active or

**Table 1**

Summary of Studies on the Effects of Different Types of Physical Activity on Executive Function-Related Cognitive Test Scores in people with Type 2 Diabetes.

| First Author & Year | Sample Size (Intervention/Control) | Gender (Male/Female) | Age (Years)                                                                                       | Time of T2DM diagnosis (Years)                                                                | HbA1c (%)                                                                                    | Intervention Group                                                                                                                                                                                                                                                                                                                                    | Control Group                                                                                                                                          | Dependent Variable & Measurement Tools                                                 | Outcome                                                                                                                                                                                                    |
|---------------------|------------------------------------|----------------------|---------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Yanagawa (2010)     | 16 (7/9)                           | 11/5                 | Intervention: 71.56 ± 3.84<br>Control: 70.14 ± 3.72                                               | NR                                                                                            | 7.23 ± 0.57                                                                                  | Exercise with a horse-riding simulator for 12 months, 4 sessions per week and at least 45 min per day.                                                                                                                                                                                                                                                | Continuing normal exercise activities such as walking                                                                                                  | Digit symbol test<br>Stroop Color-Word<br>Trail Making Test<br>HbA1c                   | No significant between-group differences were observed in cognitive test performance, fasting blood glucose, HbA1c, body fat percentage, or body mass index.                                               |
| Callisaya (2017)    | 50 (24/26)                         | 26/24                | Intervention: 65.3 ± 5<br>Control: 67.1 ± 4.8                                                     | 12.6 ± 7.1                                                                                    | 6.8 ± 1.1                                                                                    | Incremental combined exercise for 6 months (3 × 60-min sessions/week: 2 supervised, 1 unsupervised), comprising 30 min of resistance training (3 sets of 8–12 repetitions at Borg 14–17 using body weight, machines, and free weights) and 30 min of aerobic training (Borg 12–16 using a stationary bike, elliptical, rowing machine, or treadmill). | Stretching and light exercises for the upper and lower extremities: 2 supervised sessions and one unsupervised session for 1 h each week for 6 months. | Digit symbol test<br>Stroop Task<br>Trail Making Test<br>Rey–Osterrieth complex figure | Improvement in Stroop scores, A and B sequence construction, symbol digit, and Rey–Osterrieth complex figure during 6 months of exercise intervention in the exercise group compared to the control group. |
| Baker (2010)        | 28 (9/19)                          | 10/18                | Intervention: 71 ± 7.5<br>Control: 66 ± 6                                                         | NR                                                                                            | NR                                                                                           | 4 sessions per week of 45–60 min for 6 months of aerobic activity using a treadmill, stationary bike, or elliptical at an intensity of 75%–85% of your heart rate reserve.                                                                                                                                                                            | Perform stretching and balance exercises at an intensity of 50% of your heart rate reserve or less.                                                    | Trail Making Test<br>Task Switching<br>Stroop<br>Self-ordered pointing test            | Significant improvement in TMT-B, Stroop, self-ordered pointing test and Task Switching scores in the training group.                                                                                      |
| Kour (2015)         | 60 (30/30) + 30 *                  | 24/36                | Intervention: 36.4 ± 3.89<br>Control: 35.6 ± 3.72                                                 | NR                                                                                            | Intervention: 5.6 ± 4.1<br>Control: 5.9 ± 4.5                                                | Eight weeks of combined training: aerobic exercise 5 × 30 min/week at 70–80% heart rate reserve, and resistance training 3 × week for all major muscles (3 sets of 8–10 reps at Borg 8–10).                                                                                                                                                           | –Diabetic control group: Adherence to medication and diet<br>–Healthy control group: Maintaining normal life routine                                   | Stroop Test<br>HbA1c                                                                   | The exercise group showed significant improvements in Stroop, HbA1c, and body mass index.                                                                                                                  |
| Chen (2023)         | 328 (111/110/107) #                | 161/167              | Tai Chi Intervention: 67.56 ± 4.99<br>Walking Intervention: 67.46 ± 4.73<br>Control: 67.62 ± 5.35 | Tai Chi Intervention: 9.87 ± 5.58<br>Walking Intervention: 10.7 ± 7.49<br>Control: 10.9 ± 7.2 | Tai Chi Intervention: 7.14 ± 1.48<br>Walking Intervention: 6.8 ± 6.1<br>Control: 6.72 ± 5.35 | Both intervention groups: 24 weeks, 3 sessions of 60 min per week of Tai Chi or walking exercise.                                                                                                                                                                                                                                                     | Not receiving any exercise intervention and maintaining the previous lifestyle. Once every 4 weeks for 24 weeks,                                       | Digit symbol test<br>Trail Making Test<br>Rey-Osterrieth complex figure<br>HbA1c       | The Tai Chi group showed significant improvements in TMT-B at week 36 and digit symbol scores at week 24 compared to controls, as well                                                                     |

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Table 1 (continued)

| First Author & Year | Sample Size (Intervention/Control) | Gender (Male/Female) | Age (Years)                                                                      | Time of T2DM diagnosis (Years)                              | HbA1c (%)             | Intervention Group                                                                                                                                                                                                                                                                                        | Control Group                                                                                                                                                                                                                             | Dependent Variable & Measurement Tools              | Outcome                                                                                                                                                                                                                                                                                   |
|---------------------|------------------------------------|----------------------|----------------------------------------------------------------------------------|-------------------------------------------------------------|-----------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                     |                                    |                      |                                                                                  |                                                             |                       |                                                                                                                                                                                                                                                                                                           | participating in a 30-minute diabetes self-management education session like the other two groups                                                                                                                                         |                                                     | as a significant reduction in fasting blood glucose at week 36. No significant between-group differences were observed in Rey–Osterrieth complex figure scores or HbA1c.                                                                                                                  |
| Espeland (2017)     | 415 (216/199) 1061 *               | 155/260              | Intervention: 58.47 ± 6.79<br>Control: 58.17 ± 6.61                              | NR                                                          | NR                    | 24 months of walking, resistance training, flexibility and balance. 2 supervised training sessions per week and 3–4 home training sessions per week for 30 min of moderate to vigorous intensity walking, 10 min of lower body resistance training with wrist weights, 10 min of balance and flexibility. | Participate in health education workshops (travel safety, age-appropriate preventive services, nutrition, and 5–10 min of upper extremity stretching and flexibility exercises) weekly for the first 26 weeks and then monthly thereafter | Digit symbol test<br>Task Switching<br>Flanker Task | Improved cognitive function in people with diabetes in the exercise group compared to the control group.                                                                                                                                                                                  |
| Shellingn (2018)    | 24 (12/12)                         | 16/8                 | Intervention: 65.9 ± 5.2<br>Control: 71.2 ± 6.9                                  | Intervention: 10 ± 6<br>Control: 10 ± 5<br>Control: 6.9 ± 1 | Intervention: 7.2 ± 1 | 24 weeks of square stepping training with increasing pattern complexity, 2 sessions per week for 1 h                                                                                                                                                                                                      | No physical activity (waiting list)                                                                                                                                                                                                       | CANTAB (planning and inhibitory Control)            | Significant improvement in planning domain scores in the exercise group compared to the control group between weeks 12 and 24                                                                                                                                                             |
| Ghahfarokhi (2024)  | 48 (16/16/16) &                    | 17/31                | High-intensity: 66.4 ± 6.6 /<br>Low-intensity: 68.3 ± 5.4<br>Control: 67.7 ± 5.4 | NR                                                          | ≥ 6.5                 | 6 weeks of functional training<br>High-intensity, low-volume training group: three sessions per week at an intensity of 120%–125% lactate threshold<br>Low-intensity, high-volume training group: five sessions per week at an intensity of 70%–75% lactate threshold                                     | No physical activity                                                                                                                                                                                                                      | Stroop Task<br>Digit symbol test<br>HbA1c           | Significant improvement in cognitive tests related to executive function in the high-intensity, low-volume exercise group compared to the control group. Significant improvement in fasting blood sugar in both exercise groups. Significant improvement in HbA1c in both exercise groups |
| Zhao (2022)         | 103 (54/49)                        | 51/52                | Intervention: 66.9 ± 4.7<br>Control: 68.8 ± 6.1                                  | 1–29                                                        | 7.1 ± 1.1             | Strength training group: 12 months, three sessions per week, three sets of 8 repetitions with an intensity of 15–18 on the Borg scale                                                                                                                                                                     | Similar light exercise, without increasing heart rate, Vo2peak or power or other factors related to physiological outcomes                                                                                                                | Trail Making Test                                   | No significant difference in cognitive performance between groups. Reduction in body fat percentage in the exercise group                                                                                                                                                                 |

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Table 1 (continued)

| First Author & Year       | Sample Size (Intervention/Control) | Gender (Male/Female) | Age (Years)                                        | Time of T2DM diagnosis (Years)                 | HbA1c (%) | Intervention Group                                                                                                                                                                                                                                    | Control Group                       | Dependent Variable & Measurement Tools                                                                           | Outcome                                                                                                                                                                                                       |
|---------------------------|------------------------------------|----------------------|----------------------------------------------------|------------------------------------------------|-----------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------|------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Silveira-Rodrigues (2023) | 35 (18/17)                         | 9/24                 | Intervention: 63.9 ± 7.7<br>Control: 63.3 ± 7.8    | Intervention: 14 ± 10.1<br>Control: 11.3 ± 7.7 | NR        | 8 weeks of combined aerobic (on treadmill) and resistance training (6 movements), three times a week                                                                                                                                                  | Not specified                       | brain-derived neurotrophic factor<br>Trail Making Test<br>Stroop color task<br>Digit Span                        | Significant increase in function related to inhibitory control interference, working memory interference, and overall executive function score in the exercise group.<br>No significant change in BDNF levels |
| Jamali (2025)             | 100 (50/50)                        | 0/100                | Intervention: 60.1 ± 6.2 /<br>Control: 60.97 ± 5.8 | Intervention: 10.2 ± 7<br>Control: 11.8 ± 7.1  | 6.5–10    | 12 weeks of stretching (6 to 10 types of movements), resistance (4 to 8 types of movements), balance (4 types of movements), and dual training (30 min of walking combined with mental exercises, at an intensity of 40 to 60% of heart rate reserve) | No physical activity (waiting list) | 6 Minutes walking test<br>Hand-grip strength<br>Sitting and standing test<br>IL-10<br>TNF-α<br>Trail Making Test | Improved executive function in the exercise group.<br>Improved physical performance in the exercise group.<br>Significant reduction in IL-10 and TNF-α levels in the exercise group.                          |

NR: Not reported.  
TUG: Timed up and go.  
HbA1c: Hemoglobin A1C.  
BDNF: Brain-derived neurotrophic factor.  
IL-10: Interleukin 10.  
TNF-α: Tumor necrosis factor.  
\* Normal control participation  
# Control group/fitness walking group/Tai chi chuan group.

healthy comparators (contextual evidence). When limited to primary evidence, the proportion of studies reporting directional findings favoring exercise on executive-function outcomes increased from 63% to 82%, suggesting that the true effect of structured exercise may be underestimated when including studies with active control groups that independently confer cognitive benefits.

One of the key findings of the present review was the role of combined training (aerobic and resistance) in being more consistently associated with directional findings favoring executive function outcomes. The results indicated that all combined training interventions/comparisons (100%, 5/5) showed directional findings favoring exercise on executive function outcomes, compared to 44% (4/9 interventions/comparisons) for aerobic training alone and 25% (1/4 interventions/comparisons) for other exercise modalities. This finding aligns with previous evidence [40,41], suggesting that combined training may enhance cognitive-related neural networks by simultaneously activating metabolic and neuromuscular pathways, increasing glucose utilization, reducing insulin resistance, and stimulating the release of neurotrophic factors such as BDNF and IGF-1 [8,38,41].

Exercise variety, which can be interpreted as one component of exercise complexity, increases the cognitive demands during training. As a result, individuals engage more actively with the designed intervention, potentially promoting the development of central nervous system neural networks and, subsequently, improving cognitive function [8]. Evidence

indicates that aerobic exercise enhances cerebral blood flow, oxygen delivery, and the release of neurotrophic factors such as BDNF and VEGF, whereas resistance training increases the secretion of several hormones, including IGF-1, testosterone, and growth hormone, which respectively stimulate neurogenesis, synaptogenesis, and strengthen anabolic neural pathways while maintaining neuronal structure [8,15]. Therefore, employing both exercise modalities simultaneously may engage both neurotrophic and anabolic pathways, a pattern that is compatible with the more consistent directional findings observed for combined training in this review.

Combined training, particularly when accompanied by balance and flexibility exercises, often involves motor coordination, decision-making, divided attention, and motor working memory. Such exercises compel the central nervous system (CNS) to process motor and cognitive information simultaneously [38]. This feature activates neural networks associated with executive function, and therefore, combined and complex training can be considered a cognitive-motor exercise, providing both physical and cognitive stimulation to the CNS. Furthermore, it is well established that insulin resistance is not solely a peripheral phenomenon but also occurs in the brain [14], where it can disrupt or impair cognitive functions. The pathogenic mechanisms by which hyperglycemia adversely affects executive function include neuronal apoptosis [42], impaired synaptic plasticity [43], excessive nutrient accumulation in neurons leading to abnormal AMPK/PGC-1α

**Table 2**

Summary of Studies on the Effect of Lifestyle with an Emphasis on Physical Activity in People with Type 2 Diabetes or Comparison with a Healthy Control.

| First Author & Year    | Sample Size (Intervention/Control) | Gender (Male/Female) | Age (Years)                                     | Time of T2DM diagnosis (Years) | HbA1c (%) | Intervention Group                                                                                                                                                                                                                                                                                                                                                                                      | Control Group                                                                                                                             | Dependent Variable & Measurement Tools                | Outcome                                                                                                                                                                   |
|------------------------|------------------------------------|----------------------|-------------------------------------------------|--------------------------------|-----------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Coelho Junior (2018)   | 144 (72/72)                        | NR                   | Intervention: 66 ± 3.2<br>Control: 64.4 ± 5.7   | NR                             | NR        | Stationary exercise activity (12 different stations) for 26 weeks, 2 sessions per week including 12 min of functional activity, 24 min of walking, and 12 min of rest.                                                                                                                                                                                                                                  | Same as the experimental group, doing the exercise program                                                                                | TUG Cognitive Test                                    | Improved executive function in the healthy control group (indicating the negative effect of type 2 diabetes on adaptive response to physical stimuli)                     |
| Anderson-Hanley (2012) | 20 (10/10)                         | NR                   | Intervention: 72.8 ± 8.6<br>Control: 73.7 ± 9.1 | NR                             | NR        | Exercise with a stationary and virtual bike for 3 months, 5 sessions of 45 min per week.                                                                                                                                                                                                                                                                                                                | Same as the experimental group, doing the exercise program                                                                                | Color Trails Stroop test<br>Digit Span                | Significant improvement in type 2 diabetes patients compared to healthy individuals in scores Color Trails                                                                |
| Watson (2006)          | 28 (13/15)                         | NR                   | Intervention: 58 ± 9.7<br>Control: 60.6 ± 9     | NR                             | NR        | Treadmill walking or jogging for 12 months (3 × 60-min sessions/week at 50–70% heart rate reserve) combined with a diet providing < 7% saturated fat, <30% fat, <55% carbohydrates, and 15% protein.                                                                                                                                                                                                    | Stretching for 12 months (3 × 60-min sessions/week) combined with a diet providing 30% fat, 50% carbohydrates, and 20% protein.           | Trail Making Test<br>Stroop Task                      | No change in cognitive outcomes at 6 and 12 months. Significant improvement in body mass index in the exercise group                                                      |
| Lehtisalo (2016)       | 522 (158/364)                      | 172/350              | Intervention: 55.1 ± 6.8<br>Control: 55.3 ± 7.8 | NR                             | NR        | Participants received nutritional counseling, physical activity guidance, and individualized weight-loss support during the first year (7 in-person sessions) and then quarterly until the study's end, aiming to lose ≥ 5% of body weight, reduce total fat intake by 30%, saturated fat by 10%, consume > 15 g fiber per 1000 kcal, and engage in 30 min/day of moderate-intensity physical activity. | Get public health advice early.                                                                                                           | Trail Making Test                                     | No correlation between TMT results and weight changes. No significant difference in body mass index between groups                                                        |
| Espeland (2014)        | 978 (479/499)                      | 425/553              | Intervention: 50<br>Control: 50                 | NR                             | < 11      | Lose 10% of your weight in the first year and maintain it for the next 8 years. Do at least 175 min of physical activity, similar to brisk walking, per week.                                                                                                                                                                                                                                           | Attend three annual group diabetes education and support sessions and receive advice on physical activity, nutrition, and social support. | Trail Making Test<br>Stroop test<br>Digit symbol test | No change in cognitive function in obese adults with type 2 diabetes during a lifestyle intervention, despite evidence of benefit in overweight but not obese individuals |

NR: Not reported.

TUG: Timed up and go.

signaling and ATP depletion [44], micro- and macrovascular complications [45,46], oxidative stress, activation of aldose reductase, protein kinase C, poly(ADP-ribose) polymerase, and cyclooxygenase, dyslipidemia, disturbances in calcium homeostasis, and altered cytokine secretion [47].

Aerobic exercise increases insulin sensitivity and enhances glucose uptake by neurons [48,49], whereas resistance training increases muscle mass, thereby elevating peripheral glucose utilization [48,50]. Together, these mechanisms may improve overall metabolic efficiency,

including in the brain, which in turn may be associated with better cognitive function. However, aerobic exercise appears to have a relative advantage in managing insulin resistance and blood glucose, and may therefore be associated with more favorable executive-function outcomes than resistance training alone. This pattern is reflected in the present review, where directional findings favoring exercise were observed in 44% of aerobic interventions/comparisons (4/9), compared with resistance training alone, for which directional findings favoring exercise were observed in 33% of interventions/comparisons (1/3).

**Table 3**  
Effect of Intervention Based on Type, Intensity, and Duration of Exercise and Executive Function Domains.

| Feature                                     | Interventions/<br>comparisons (S/<br>LH) | Effect on Executive<br>Function                                                        | Description                                                                                                                                                   |
|---------------------------------------------|------------------------------------------|----------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Combined<br>Exercise                        | 5 (5/0)                                  | Directional findings<br>favoring exercise in 5<br>interventions/<br>comparisons (100%) | Most promising effect<br>in complex and high-<br>intensity training<br>protocols                                                                              |
| Aerobic<br>Exercise                         | 9 (6*/3)                                 | Directional findings<br>favoring exercise in 4<br>interventions/<br>comparisons (44%)  | Most promising effect<br>in high-intensity<br>training protocols;<br>Minimal or no impact<br>when combined with<br>lifestyle<br>interventions                 |
| Other<br>Exercise<br>Methods                | 4 (2/2)                                  | Directional findings<br>favoring exercise in 1<br>intervention/<br>comparison (25%)    | Positive impact from<br>Tai Chi                                                                                                                               |
| High-<br>Intensity<br>Exercise              | 3 (3*/0)                                 | Directional findings<br>favoring exercise in 3<br>interventions/<br>comparisons (100%) | Most promising effect<br>in combined exercise<br>training                                                                                                     |
| Low to<br>Moderate<br>Intensity<br>Exercise | 15 (10*/5)                               | Directional findings<br>favoring exercise in 7<br>interventions/<br>comparisons (47%)  | Most promising effect<br>in complex and<br>structured training<br>protocols; Minimal or<br>no impact when<br>combined with<br>lifestyle<br>interventions      |
| Exercise < 6<br>Months                      | 7 (6*/1)                                 | Directional findings<br>favoring exercise in 5<br>interventions/<br>comparisons (67%)  | Most promising effect<br>in high-intensity<br>training protocols                                                                                              |
| Exercise ≥ 6<br>Months                      | 11 (6*/4)                                | Directional findings<br>favoring exercise in 5<br>interventions/<br>comparisons (45%)  | Most promising effect<br>in complex training<br>protocols; Minimal or<br>no impact when<br>combined with<br>lifestyle<br>interventions                        |
| Inhibitory<br>Control                       | 11 (7/4)                                 | Directional findings<br>favoring exercise in 7<br>interventions/<br>comparisons (64%)  | Most promising effect<br>in complex training<br>protocols; Minimal or<br>no impact when<br>combined with<br>lifestyle<br>interventions                        |
| Cognitive<br>Flexibility                    | 11 (8/3)                                 | Directional findings<br>favoring exercise in 6<br>interventions/<br>comparisons (55%)  | Most promising effect<br>in complex and high-<br>intensity training<br>protocols; Minimal or<br>no impact when<br>combined with<br>lifestyle<br>interventions |
| Working<br>Memory                           | 3 (2/1)                                  | Directional findings<br>favoring exercise in 2<br>interventions/<br>comparisons (67%)  | Minimal or no impact<br>when combined with<br>lifestyle<br>interventions                                                                                      |

S: Studies that evaluated structured exercise interventions compared with a control group consisting of participants with T2DM receiving usual care or no structured exercise (primary evidence).

LH: Studies that included lifestyle interventions (e.g., dietary counseling, weight-loss programs, or multi-component lifestyle modification) and/or comparisons with healthy control groups (contextual evidence).

# The study by Chen et al. (2023) included two exercise intervention groups (Tai Chi Chuan and fitness walking); therefore, each intervention/comparison was classified separately for modality-specific analyses.

\* The study by Ghahfarokhi et al. (2024) included two exercise intervention groups (high-intensity and low-intensity training); therefore, each intervention/comparison was classified separately for intensity-specific analyses.

Note: Category totals may exceed the total number of included studies because

classifications were performed at the intervention/comparison level rather than the study level. In addition, exercise modality, intensity, duration, and executive-function domain classifications were not mutually exclusive; a single study or intervention could contribute to more than one category. Therefore, denominators reflect the number of analyzable interventions/comparisons within each classification rather than the total number of included studies.

Finally, combined training is particularly notable for reducing systemic inflammation, as it lowers pro-inflammatory cytokines such as IL-6 and TNF- $\alpha$ , as reported by Jamali et al. (2025), thereby providing a safer biochemical environment for the brain [23]. It should be acknowledged, however, that the Jamali et al. study is part of the present review, and its findings, while consistent with the broader evidence base should not be weighted disproportionately.

The review of studies indicated that exercise intensity may be an important factor associated with executive-function outcomes. While only 40% (4/10 interventions/comparisons) classified as low-to-moderate intensity showed directional findings favoring exercise on executive-function outcomes, 100% (3/3) of high-intensity interventions/comparisons reported directional findings favoring exercise. Notably, this finding aligns with Ghahfarahi et al. (2024), who reported more favorable executive-function outcomes with high-intensity, low-volume exercise than with low-intensity, high-volume exercise [24]. The candidate mechanisms mediating the effects of exercise intensity on executive function are not yet fully understood. Following a single session of high-intensity exercise, sympathetic network activity is stimulated, and levels of norepinephrine and dopamine in the brain rise [51]. These neurochemical changes appear to enhance attention processing, response selection, and executive functions such as decision-making and filtering of distracting stimuli. Accumulation of high-intensity exercise sessions over time may be associated with favorable changes in cognitive function, particularly executive function. High-intensity exercise also increases cerebral blood flow and oxygen delivery to prefrontal cortical regions, thereby enhancing information processing and the execution of cognitive tasks [52,53].

Another debated mediating mechanism is lactate produced during high-intensity exercise. It has been proposed that lactate not only serves as a fuel source for the CNS but can also stimulate the production of neurotrophic factors, including BDNF, leading to enhanced synaptic plasticity, memory consolidation, and neuronal rehabilitation [54]. Cumulative evidence indicates that physical activity, particularly high-intensity exercise that elicits greater lactate and hormonal responses, is associated with more favorable executive-function outcomes, cognitive flexibility, and working memory outcomes compared with moderate-intensity exercise, although factors such as exercise protocol, duration, and population can influence the outcomes [54,55].

An examination of the intervention durations across studies revealed that the effect of exercise on executive function was largely independent of, or at least not clearly dependent on, the length of the intervention. Indeed, contradictory findings were reported in both short-term studies (<6 months) and long-term studies (>1 year). However, most short-term studies employing high-intensity exercise showed the most consistent directional findings favoring exercise on executive-function outcomes, supporting a possible association between exercise intensity and more favorable executive-function outcomes. Moreover, due to the rapid physiological and motivational responses elicited by high-intensity exercise, it is reasonable that, in the short term, high-intensity exercise demonstrates a relative advantage in improving executive function.

From a biological mechanism perspective, the results of the present review align with neurobiological models that consider exercise as a protective intervention for the CNS. Exercise has been shown in previous research to enhance insulin sensitivity, improve glucose metabolism, reduce systemic inflammation, increase cerebral blood flow, and stimulate the release of neurotrophic factors, thereby strengthening synaptic connections in key brain regions, including the prefrontal cortex

**Table 4**

Quality assessment of the included studies.

| First Author and Year of Publication | #1 | #2 | #3 | #4 | #5 | #6 | #7 | #8 | #9 | #10 | #11 | Total |
|--------------------------------------|----|----|----|----|----|----|----|----|----|-----|-----|-------|
| Yanagawa (2010)                      | 1  | 1  | 1  | 1  | 0  | 0  | 0  | 1  | 0  | 1   | 1   | 7     |
| Callisaya (2017)                     | 1  | 1  | 1  | 1  | 0  | 0  | 1  | 1  | 0  | 1   | 1   | 8     |
| Baker (2010)                         | 1  | 1  | 1  | 1  | 0  | 0  | 1  | 1  | 0  | 1   | 1   | 8     |
| Kour (2015)                          | 1  | 1  | 1  | 1  | 0  | 0  | 0  | 1  | 0  | 1   | 1   | 7     |
| Chen (2023)                          | 1  | 1  | 1  | 1  | 0  | 0  | 1  | 1  | 1  | 1   | 1   | 9     |
| Espeland (2017)                      | 1  | 1  | 1  | 1  | 0  | 0  | 1  | 1  | 0  | 1   | 1   | 8     |
| Shellington (2018)                   | 1  | 1  | 1  | 1  | 0  | 0  | 0  | 1  | 0  | 1   | 1   | 7     |
| Ghahfarokhi (2024)                   | 1  | 1  | 1  | 1  | 0  | 0  | 1  | 1  | 1  | 1   | 1   | 9     |
| Zhao (2022)                          | 1  | 1  | 1  | 1  | 0  | 0  | 1  | 1  | 1  | 1   | 1   | 9     |
| Silveira-Rodrigues (2023)            | 1  | 1  | 1  | 1  | 0  | 0  | 0  | 1  | 0  | 1   | 1   | 7     |
| Jamali (2025)                        | 1  | 1  | 1  | 1  | 0  | 0  | 1  | 1  | 0  | 1   | 1   | 8     |
| Coelho Junior (2018)                 | 1  | 1  | 1  | 1  | 0  | 0  | 0  | 1  | 0  | 1   | 1   | 7     |
| Anderson-Hanley (2012)               | 1  | 1  | 1  | 1  | 0  | 0  | 0  | 1  | 0  | 1   | 1   | 7     |
| Watson (2006)                        | 1  | 1  | 0  | 1  | 0  | 0  | 1  | 1  | 0  | 1   | 1   | 7     |
| Lehtisalo (2015)                     | 1  | 1  | 0  | 1  | 0  | 0  | 0  | 1  | 0  | 1   | 1   | 6     |
| Espeland (2014)                      | 1  | 1  | 0  | 1  | 0  | 0  | 0  | 1  | 0  | 1   | 1   | 6     |

1 Eligibility criteria.

2 Random allocation

3 Allocation concealment.

4 Baseline similarity of key outcome measures.

5 Blinding of participants.

6 Blinding of intervention providers.

7 Blinding of outcome assessors.

8 Outcome measures obtained from more than 85% of participants.

9 Intention-to-treat analysis.

10 Between-group statistical comparisons of key outcomes.

11 Reporting of point measures and measures of variability.

[24,40,41,49]. However, it should be noted that some of the benefits of exercise may be indirect, stemming from improvements in general health and psychological well-being in individuals with T2DM. Enhancements in mood, reductions in anxiety, and increased self-confidence resulting from exercise [56] may also contribute to improved cognitive function.

It is important to contextualize the overall findings with precision. Across all 16 studies, 63% (10/16) reported directional findings favoring exercise on executive-function outcomes, while 37% (6/16) reported null or inconsistent findings. However, when analysis was restricted to the 11 RCTs that employed true usual-care T2DM control groups (primary evidence), the proportion of studies with directional findings favoring exercise rose to 82% (9/11). Notably, all five studies that did not show directional findings favoring exercise either used active control conditions (e.g., stretching, education, counseling) or combined exercise with lifestyle interventions that may have obscured the independent effect of structured exercise. This pattern is compatible with the possibility that the effects of exercise on executive function in T2DM may be underestimated in studies employing active comparators.

It is important to acknowledge that the majority of the included studies did not systematically control for or report detailed baseline dietary habits, such as total caloric intake, macronutrient composition, fiber consumption, or glycemic index of foods. In some included studies [25,27,33], structured exercise was combined with nutritional modifications and weight loss goals, making it impossible to isolate the independent contribution of exercise. Energy-dense dietary patterns and shifts in macronutrient distribution have direct metabolic consequences that influence cognitive outcomes through pathways overlapping with those of exercise. For example, high intake of saturated fats and refined carbohydrates can exacerbate brain insulin resistance, impair synaptic plasticity, and promote neuroinflammation as mechanisms that are also targeted by exercise. Conversely, dietary patterns rich in omega-3 fatty acids, polyphenols, and fiber may enhance neurotrophic signaling (e.g., BDNF) and reduce oxidative stress, potentially amplifying the cognitive benefits of exercise [57]. Thus, depending on the direction of dietary change, nutritional co-interventions could either obscure (mask) true exercise effects or create spurious synergistic effects. Therefore, a

conceptual distinction for future research: (1) 'pure exercise' studies with no dietary modification and usual-care controls, which provide the clearest estimate of exercise-specific effects; (2) exercise with diet studies where dietary changes are controlled or statistically adjusted, allowing assessment of additive or interactive effects; and (3) lifestyle interventions where exercise is one of several components, from which independent exercise effects cannot be reliably extracted. In the current review, the directional null/inconsistent findings observed specifically in studies combining exercise with lifestyle or dietary modifications (100% of such studies showed null/inconsistent results for executive function) raise the possibility that dietary co-interventions may have diluted or interacted with exercise-specific effects, rather than indicating that exercise itself is ineffective. Future trials should systematically collect dietary intake data and, where possible, employ appropriate designs to disentangle these interactions.

It should be emphasized that the synthesis method employed in this review was vote-counting based on the direction of effects, as prospectively registered (CRD420251160349) and detailed in Section 2.6. Accordingly, all references to "improvements," "beneficial effects," "positive effects," or "favorable outcomes" throughout this discussion reflect whether the original study authors reported directional outcomes favoring exercise compared to the comparator condition. This approach does not imply *meta*-analytic pooling of effect sizes, statistical significance testing, or p-value-based inference across studies. The terminology used in this discussion has been carefully aligned with the vote-counting methodology to ensure consistency between the stated analytical approach and the language used to interpret findings. Consequently, our preliminary recommendations are based solely on the direction and consistency of findings across studies (i.e., whether exercise 'favorably' affected executive function relative to a comparator), not on the magnitude of those effects. This means that while we can state with moderate confidence that combined, higher-intensity exercise is consistently associated with directional benefits, we cannot specify how large those benefits are likely to be. We should therefore interpret these recommendations as hypothesis-generating and clinically directional, rather than as precision-based prescriptions. Future *meta*-analyses with sufficient statistical power and homogeneous outcome measures are

needed to provide effect size estimates that can guide clinical decision-making with greater precision.

The present study has some limitations. The review was restricted to English-language studies, so relevant studies published in other languages may have been missed. After data collection, it became evident that the diversity of exercise protocols and heterogeneity in executive function assessment tools precluded *meta-analysis*, limiting direct comparability and making definitive conclusions difficult. Several studies had small sample sizes, reducing statistical power, and incomplete reporting of potential confounders (e.g., dietary habits and medication use) may have affected reliability. In addition, exercise intensity was not always precisely controlled, and training program characteristics were sometimes insufficiently reported, compromising reproducibility. A key methodological issue across included trials was heterogeneity in comparator conditions: many studies used “active” controls (e.g., stretching, light-intensity physical activity, health education, or counseling) rather than true non-exercise controls, which may independently improve cognitive or psychosocial outcomes and thereby reduce between-group contrast, potentially underestimating exercise-specific effects and contributing to variability in findings. Moreover, some interventions combined structured exercise with lifestyle modifications, counseling, or dietary changes [25–27], which increases real-world relevance but complicates isolation of exercise effects; future trials should use designs that disentangle these components (e.g., clearly defined comparator groups or stratification by comparator type). The current review did not perform a critical analysis of baseline dietary habits or nutritional intake of participants across the included studies. Given the well-established influence of nutrition on glycemic control, insulin resistance, and brain health (including neurotrophic factor expression), the absence of dietary data precludes the ability to determine whether the observed directional findings favoring exercise were solely attributable to exercise or partly confounded by dietary factors. This limitation is particularly salient because studies that combined exercise with lifestyle interventions (including dietary counseling) frequently showed null or inconsistent executive function outcomes, whereas pure exercise interventions with usual-care controls more consistently favored exercise. Future primary studies should systematically collect and report dietary intake data, and future systematic reviews in this area should consider including nutritional assessment as a moderating variable when data permit. A substantial proportion of the included studies did not systematically report baseline metabolic status, particularly T2DM duration (approximately 62% of studies) and baseline HbA1c (approximately 44% of studies). This incomplete reporting limits the ability to examine whether baseline metabolic factors moderate exercise-induced improvements in executive function. Future primary studies should consistently report these clinical characteristics as a minimum reporting standard. An additional limitation is that no formal certainty-of-evidence assessment (e.g., GRADE) was conducted. Consequently, the overall confidence in the observed patterns of findings cannot be quantified and should be interpreted cautiously. Furthermore, the vote-counting approach used in this review summarizes the direction of effects but does not account for effect size magnitude, study precision, or sample size, which may oversimplify complex intervention effects and limit the strength of inferences. Another important consideration is the heterogeneity of executive function assessment methods. Although outcomes were classified into executive function domains such as inhibitory control, cognitive flexibility, and working memory, the included studies used a wide range of neuropsychological tests that may differ in construct validity, sensitivity, and domain specificity. Consequently, some degree of outcome-classification uncertainty cannot be excluded, which may have contributed to variability across findings. Taken together, these limitations reduce the certainty of the evidence and suggest that the practical recommendations proposed in this review should be interpreted as preliminary and hypothesis-generating rather than definitive clinical guidance. Finally, future research should prioritize well-defined

cognitive–motor exercise protocols, improved characterization of dose/intensity (including biological markers such as BDNF), and mechanistic studies clarifying how different exercise modalities influence executive function.

#### 4.1. Preliminary practical recommendations for enhancing executive function

The following recommendations are derived from directional patterns observed across the included studies using vote-counting synthesis. Because no *meta-analysis* was performed, these recommendations indicate the direction and consistency of benefits (i.e., whether exercise is ‘favorable’ compared to control) but do not provide quantitative effect size estimates or confidence intervals for expected cognitive improvements.

##### 4.1.1. Based on established diabetes and exercise guidelines

Most existing guidelines for individuals with T2DM, such as those from the American College of Sports Medicine (ACSM) [58] and the American Diabetes Association (ADA) [17], primarily focus on blood glucose control, cardiovascular health, and prevention of diabetes related complications. Generally, these guidelines recommend aerobic exercise for at least 150 min per week, resistance training 2 to 3 sessions per week, and balance and flexibility exercises. Notably, cognitive outcomes, including executive function, are not presently a primary consideration in these consensus-based recommendations.

##### 4.1.2. Based on the findings of the present systematic review

Recent evidence, including the 16 studies synthesized in this review, indicates that multi-component combined training including aerobic, resistance, balance, and flexibility exercises was most consistently associated with directional findings favoring executive-function outcomes in individuals with T2DM. This approach has received less attention in existing guidelines. Accordingly, combined exercise modalities may be considered, and may be prioritized in future research and clinical judgment when executive function is a target outcome, ideally performed with simultaneous cognitive challenges such as dual-task exercises [23], which may confer additional benefits. Furthermore, while a variety of intensities may be used, higher-intensity exercise sessions (e.g., Borg perceived exertion > 15) may be considered where feasible, clinically appropriate, and consistent with individual patient characteristics, as these approaches were more frequently associated with directional findings favoring executive-function outcomes in the included studies. Each high-intensity session may last less than one hour; however, achieving the recommended weekly volume of 150 min (see section 4.1.3) typically requires more than two sessions per week. These considerations should be interpreted as preliminary and hypothesis-generating rather than definitive clinical guidance.

##### 4.1.3. Integration with existing guidelines and clinical considerations

Consistent with previous guidelines [17,58], at least 150 min of weekly exercise is recommended. It is important to emphasize that this volume recommendation is derived from ACSM/ADA guidelines for general health and glycemic control, not from the studies included in this review. The present review does not provide direct evidence regarding optimal exercise volume for cognitive outcomes; therefore, the weekly volume target is extrapolated from existing diabetes management guidelines. This distinction is made explicitly to separate evidence derived from our review versus recommendations adapted from external sources.

From a clinical safety perspective, considering the pathological status of the target population, glucose monitoring before, during, and after exercise is advised. In patients with peripheral neuropathy, balance exercises and foot protection should be mandatory. Additionally, attention to hydration, pre-exercise nutrition, and avoidance of hypoglycemia is essential. These safety recommendations are derived from

standard clinical practice guidelines for exercise in T2DM and were not systematically examined in the studies included in this review.

## 5. Conclusion

This systematic review suggests that structured exercise, particularly combined and higher-intensity training, was most often associated with directional findings favoring executive-function outcomes in individuals with T2DM. However, findings should be interpreted cautiously due to heterogeneity across studies and the absence of *meta-analysis*. The evidence provides preliminary support for incorporating combined exercise performed regularly (often  $\geq 2$  sessions per week), with overall weekly volume tailored as appropriate, into management plans. These considerations should be interpreted as provisional, hypothesis-generating, and not as definitive clinical guidance. This recommendation requires confirmation through future well-controlled trials, formal certainty-of-evidence assessment, and standardized executive-function outcome measures.

## CRedit authorship contribution statement

**Afsaneh Jamali:** Writing – original draft, Methodology, Data curation. **Shahnaz Shahrbanian:** Writing – original draft, Data curation, Conceptualization. **Raouf Negaresh:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Fatemeh Kazeminasab:** Writing – review & editing, Writing – original draft, Methodology. **Zohreh Karimi:** Writing – review & editing, Writing – original draft, Methodology. **Reza Bagheri:** Writing – review & editing, Writing – original draft, Supervision, Methodology.

## Declaration of competing interest

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

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Not applicable

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.diabres.2026.113423>.

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