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Effects of Aerobic Exercise on Inhibitory Control in Methamphetamine Addicts: A Systematic Review and Meta-Analysis

This systematic review and meta-analysis aimed to evaluate the effects of aerobic exercise (AE) on inhibitory control among individuals with methamphetamine (MA) addiction and to examine potential dose–response relationships influenced by gender and intervention parameters. Randomized controlled trials (RCTs) investigating AE interventions targeting inhibitory control in individuals with MA addiction published before July 2024 were systematically retrieved from six databases (PubMed, Web of Science, Embase, Cochrane Library, CNKI, and Wanfang). Methodological quality was assessed using the Cochrane Risk of Bias Tool. Meta-analyses were conducted with RevMan 5.3, and publication bias was examined using funnel plots and Egger's test via Stata MP 18.0. The certainty of evidence was graded using the GRADE approach. Nine papers comprising 11 studies with a total of 587 participants were included. Although most studies showed a moderate risk of bias due to incomplete reporting of blinding, the pooled analysis demonstrated significant benefits of AE on inhibitory control. Specifically, AE significantly improved behavioral accuracy ($n = 455$, $SMD = 0.77$, 95 % CI: 0.14–1.40, $p = 0.02$) and reduced reaction time ($n = 498$, $SMD = -0.51$, 95 % CI: -0.84 to -0.18 , $p = 0.002$). Subgroup analyses indicated that the magnitude of improvement was associated with gender and varied according to intervention duration, frequency, and exercise modality. Aerobic exercise exerts a significant positive effect on inhibitory control in individuals with methamphetamine addiction. The outcomes suggest a potential dose–response pattern moderated by gender and specific intervention parameters. These findings provide empirical support for integrating structured aerobic programs into rehabilitation protocols for MA addicts. Future research should refine exercise prescriptions and elucidate the underlying neurobiological mechanisms driving these cognitive benefits.

Keywords: aerobic exercise; methamphetamine; inhibitory control; meta-analysis; reaction time

Introduction

Methylamphetamine (MA) addiction is a chronic substance use disorder in which continued use of MA impairs brain functioning, resulting in a reduced ability to control impulses to use MA and ultimately leading to addiction [1]. A total of 64 million people worldwide will have a substance use disorder by 2022, a growth rate of more than 80 % in the last five years, with the drug-using population growing by nearly 20 %, but only 1 in 11 will be able to receive treatment, instead of a downward trend [2]. Long-term drug use requires financial support, and most drug users do not have a stable financial source, which leads to an increase in the crime rate [3]. Drug abuse places are mostly in public areas, which can also lead to negative impacts on the enjoyment of recreational and public spaces, as well as local children who may be exposed to these places [3]. Therefore, curbing drug abuse can be effective in improving social stability and the well-being of the population.

Drug use can cause serious physical and psychological harm, and one of the core symptoms of MA addiction is impairment of inhibitory control [4]. Inhibitory control is an important component of executive functioning, a conscious ability to control behavior. Impairment of inhibitory control is recognized as an important cause of craving and relapse after withdrawal [5]. Therefore, how to increase control over drugs or drug cues by improving inhibitory control in MA addicts becomes critical in helping to accomplish detoxification.

Aerobic Exercise (AE) can regulate the internal environment and enhance the immunity of the body [6], as an effective therapeutic means, AE is not only low-cost, but also has the advantages of ease of operation, which is widely used in the field of rehabilitation and health care [7]. In recent years, more and more studies have focused on the potential of AE in improving inhibitory control. It has been shown that open-ended skill activities can improve inhibitory control well [8], and a large number of studies have confirmed that inhibitory control can be improved to a certain extent in MA addicts after exercise intervention [9, 10]. However, it has also been suggested that the ameliorative effects of AE are not significant in smoking addicts [11] and this area remains highly controversial. Although studies have examined the effects of AE on inhibitory control in MA addicts, the current findings are inconsistent and systematic Meta-analysis is lacking.

Therefore, by searching domestic and international databases, conducting a comprehensive assessment of relevant literature, systematically analyzing the effects of AE on inhibitory control in MA addicts, and exploring its possible influencing factors, the present study aims to provide a scientific basis for MA abstinence and an effective exercise intervention program for drug addicts.

Methods and materials

Literature search strategy

In this study, searches were conducted in English databases (PubMed, Web of Science, Embase, Cochrane library) and Chinese databases (China Knowledge Network, Wanfang) to collect randomized controlled trials (RCTs) on the effects of AE on inhibitory control in MA addicts, and the search timeframe was from the construction of each database to July 2024. The search strategy combined subject and free terms, as well as tracking citations of included literature and reading relevant Meta-analysis literature to ensure a comprehensive collection of relevant studies. Chinese search formula: (aerobic exercise OR exercise) AND (drug OR methamphetamine OR substance addiction OR drug addiction) AND (inhibition control OR inhibition OR control) AND randomized controlled trial. English search terms: (aerobic exercise OR exercise) AND (drug OR methamphetamine OR substance addiction OR drug addiction) AND (inhibition control OR inhibition OR control) AND (randomized controlled trials OR RCTs) control) AND (randomized controlled trials OR RCT). This study is registered with the International Prospective Registry for Systematic Evaluation (PROSPERO) (No. CRD42024573123).

Inclusion and exclusion criteria

This study used the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA), and based on strict adherence to the study methodology and requirements of the PRISMA, the inclusion and exclusion criteria were developed based on the characteristics of PICOS included in each study. Specifically: Study subjects included MA-addicted individuals with no history of mental illness, infectious diseases, or contraindications to exercise, who voluntarily participated (no restrictions on gender, ethnicity, or age), excluding non-MA-addicted populations; Interventions included effective non-acute exercise-based AE interventions for MA addicts, excluding acute exercise and non-AE interventions; control measures comprised routine rehabilitation (including drug abstinence education, legal education, occupational health, daily activities, routine nursing, etc.), excluding groups receiving intervention measures; Outcome measures included behavioral paradigms assessing inhibitory control using Go/No-go, Stroop, or Stop-signal tests (primary: higher accuracy indicates stronger inhibitory control; secondary: lower reaction time indicates stronger responsiveness), excluding measures unrelated to inhibitory control; Study types included RCTs (randomized controlled trials), excluding experimental designs and non-RCT studies.

Literature screening and data extraction

Literature was imported into EndNote to eliminate duplicates, and two researchers independently screened the literature according to the inclusion and exclusion criteria, extracted data, and reviewed each other after the statistics were completed, and discussed the main points or referred to third-party opinions in case of disagreement. Extracted data: first author, year of publication, country, sample size, gender, age, years of drug use, intervention, frequency of intervention, duration of intervention, and outcome indicators. If the description of the original study data was unclear or information was lacking, the data were collected

through other channels, or attempts were made to contact the authors by email, and the literature was excluded if there was no information from other sources or no response from the authors.

Quality assessment

In this study, the methodological quality assessment of each RCT was conducted using the RCT risk of bias evaluation criteria provided by the Cochrane Collaboration, which included: (i) randomized sequence generation; (ii) allocation scheme concealment; (iii) blinding applied to subjects and staff; (iv) blinding applied to outcome data assessment; (v) completeness of outcome data; (vi) selective reporting bias; and (vii) other potential sources of bias. Quality assessment was conducted independently by two investigators and reviewed with each other, and in case of disagreement, discussion or reference to a third investigator's opinion was made until agreement was reached. Meanwhile, the quality of evidence for each outcome indicator was evaluated using the GRADE evidence grading system, which was categorized into four grades: high, intermediate, low, and very low. If there were differences in ratings, a third researcher was involved in the discussion and agreement was reached.

Statistical analysis

Meta-analysis was performed using RevMan 5.3 software provided by the Cochrane Collaboration. I^2 was used to measure the degree of heterogeneity between studies. If $I^2 \geq 50\%$ and $P < 0.1$, the effect sizes were combined using a random effect model (RE); conversely, a fixed effect model (FE) was used. RE was used if the source of heterogeneity could not be explained by clinical or methodological differences. For data that could not be combined, descriptive analyses were performed. Continuous variables were expressed using mean difference (MD) and 95% confidence interval (CI) when the effect measures or units of the interventions were consistent; otherwise, standardized mean difference (SMD) and 95% CI were used. CI. The significance level was set at $P < 0.05$. To assess the effect of heterogeneity on the results, this study conducted sensitivity analyses using a case-by-case exclusion method and comparison of models with different effects to minimize the impact of high heterogeneity and small sample effects on the reliability of Meta-analyses. Stata MP 18 was used to draw funnel plots to assess publication bias. If the information is biased, the funnel plot will show asymmetry, and the degree of asymmetry is proportional to the degree of bias.

Results of the literature search

A total of 1,382 documents were obtained through database searches and other sources. After reading the titles and abstracts to screen and exclude non-RCTs and clinical trials with inconclusive data, 9 documents were finally included, with a total of 11 studies, of which 1 study was published in Chinese and 10 in English, with a total of 587 patients, and the flowchart of the literature search is shown in Figure 1.

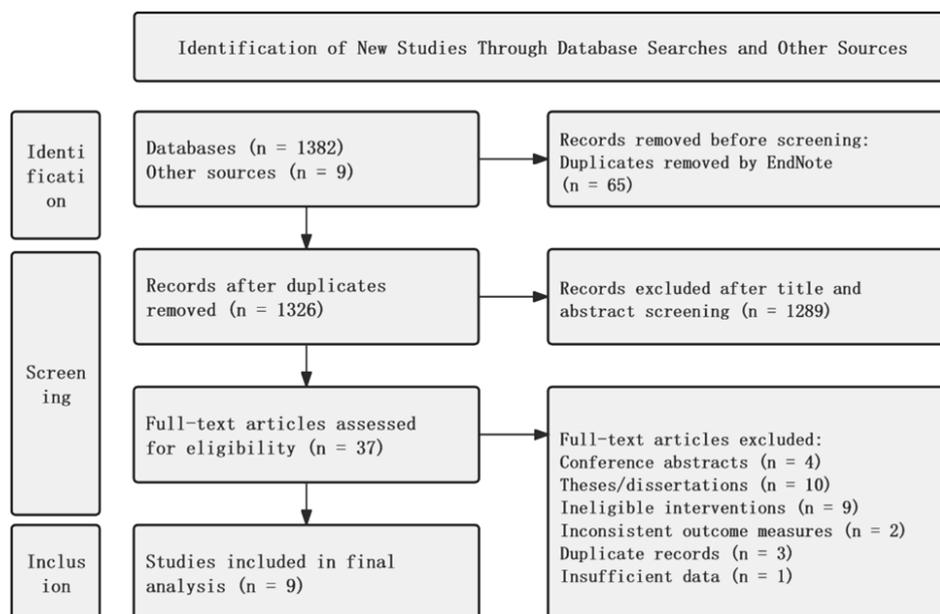


Figure 1. Flowchart of Literature Retrieval

Basic information and data extraction for included studies

Basic information on included studies (Table 1)

Basic information on included studies

Inclusion of studies	nations	sample size	(a person's) age	distinguishing between the sexes	Years of drug use	Type of intervention		intervention period	outcome indicator
						T/C	Age (T/C)		
Chen 2021A ^[12]	sino	19/21	29.58±1.01/ 33.24±1.73	male	5.53±0.75/ 6.62±0.84	Aerobic exercise, 30 minutes three times a week	read	12 weeks	①
Chen 2021B ^[12]	sino	17/21	32.53±1.16/ 33.24±1.73	male	6.82±0.56/ 6.62±0.84	High-intensity aerobic exercise, 30 minutes three times a week	read	12 weeks	①
He 2021A ^[13]	sino	16/16	41.88±13.44/ 42.81±11.54	male	11 from 0–5 years, 2 from 5–10 years, 3 from 10+ years / 9 from 0–5 years, 2 from 5–10 years, 5 from 10+ years	Tai chi, three times a week, 25 minutes each time	routine	4 weeks	①③
He 2021B ^[13]	sino	16/16	41.88±13.44/ 42.81±11.54	male	11 from 0–5 years, 2 from 5–10 years, 3 from 10+ years / 9 from 0–5 years, 2 from 5–10 years, 5 from 10+ years	Tai chi, three times a week, 25 minutes each time	routine	4 weeks	①③
Liu 2021 ^[14]	sino	43/46	29.93±7.91/ 28.96±8.27	women	8.05±3.84/ 7.82±3.57	Aerobic exercise, 40 minutes five times a week	routine care	12 weeks	①③
Liu 2023 ^[15]	sino	23/23	28.48±3.30/ 27.66±3.66	male	8.16±3.81/ 8.44±3.62	Treadmill exercise, 40 minutes five times a week	health education	8 weeks	①③
Shen 2021 ^[16]	sino	35/37	39.31±10.33/ 39.37±9.28	daughter	unreported	Tai chi, three times a week, 60 minutes each time	Regular activities	12 weeks	①
Wang 2017 ^[17]	sino	25/25	32.20±6.97/ 34.76±7.96	hybrid	6.94±4.48/ 6.99±4.86	Aerobic exercise (cycling, jogging, jumping rope), 30 minutes three times per week	routine care	12 weeks	②
Zhu 2022 ^[18]	sino	40/37	34.61±5.12/ 34.94±6.58	male	8.57±7.14/ 8.92±5.31	Group aerobics, 36 minutes five times a week	routine care	12 weeks	②

Continuation of Table 1

Inclusion of studies	nations	sample size	(a person's age)	distinguishing between the sexes	Years of drug use	Type of intervention		intervention period	outcome indicator	
						T/C	Age (T/C)			M/F
Zhu 2023 ^[19]	sino	32/32	30.30±5.28/ 29.80±5.51	male	5.20±1.65/ 5.65±1.54		Cycling, running exercise, 40 minutes three times a week	conventional treatment	8 weeks	②
Zhang Yanhui 2024 ^[20]	sino	25/22	28.13±1.81/ 27.28±1.62	women	unreported		Rehabilitation exercises, 30 minutes twice a week	read	10 weeks	④

Note. T stands for experimental group; C stands for control group. ① Stroop; ② Go/No-go; ③ 2Back; ④ Stop-signal.

Data extraction

Exercise prescription variables included exercise modality, exercise frequency, exercise duration, and intervention period. Specifically, exercise modalities were programmed as regular AE and Tai Chi or rehabilitation exercises. Exercise frequency was categorized as: ≤ 2 times/week, 3-4 times/week, or 5-7 times/week [21]; exercise duration was categorized as: less than 45 minutes, 45-60 minutes [21]; and intervention period was categorized as: ≤ 8 weeks or >8 weeks. Patient characteristics included gender (male; female).

Bias Risk and Evidence Quality Assessment

The risk of bias of the included studies was assessed independently by two researchers using the Cochrane Collaboration's risk of bias assessment tool, with a third researcher involved to resolve any discrepancies through discussion. The results of the assessment showed that there was a low risk of bias for randomized sequence generation, allocation concealment, data completeness, selective reporting, and other biases; there was a high risk of bias for participant blinding; and the majority of the literature did not report the blinding of the outcome assessment in full, so the risk of bias for this component was unclear (Fig. 2).

The GRADE software assessment showed that the quality of evidence was intermediate for paradigm correctness and low for response time. This may be due to the fact that some of the literature did not use allocation concealment or did not implement blinding in its entirety, thus leading to some limitations in the study.

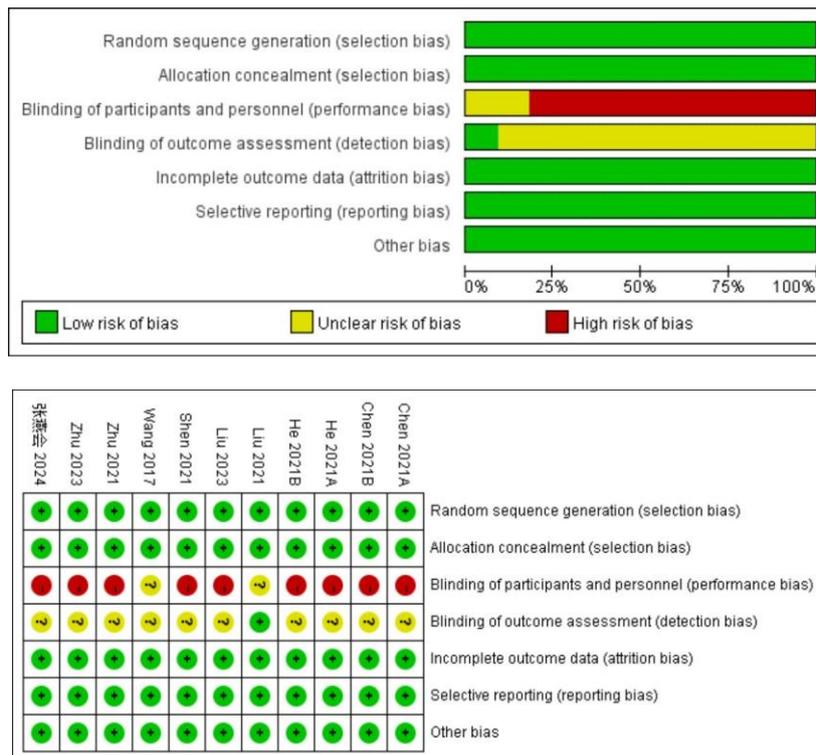


Figure 2. Overall risk of bias evaluation

Results

Meta-analysis and subgroup analysis

Meta-analysis

AE was able to significantly improve the correctness of the behavioral paradigm in MA addicts [SMD = 0.77, 95 % CI (0.14, 1.40), p = 0.020] and significantly improve response time [SMD = -0.51, 95 % CI (-0.84, -0.18), p = 0.002], as shown in Table 2. In analyzing the between-study heterogeneity, the use of the single study-by-study exclusion method found that Wang 2017 [17] had a large impact on inter-study heterogeneity of results, and after their exclusion, the combined results of the remaining RCTs showed a significant decrease in study-by-study heterogeneity between correct rates of behavioral paradigms (I2=63 %, P=0.030), and the SMD range after further exclusion of the single studies was -0.58~ -0.42, I2ranging from 63 %~ 72 %, suggesting more robust results.

Table 2

Intervention effects of AE on inhibitory control in MA addicts

Outcome indicator	Inclusion of studies	I2/%	Meta-analysis results	
			SMD (95 % CI)	P-value
Paradigm correctness	7 (455) ^[14-20]	90	0.77 (0.14,1.40)	0.02
response time	10 (498) ^[12,12,13,13,15-20]	63	-0.51 (-0.84,-0.18)	0.03

Subgroup analysis

Subgroup Analysis of Paradigm Correctness

In this study, subgroup analyses of paradigm correctness were conducted for gender, exercise mode, exercise frequency, exercise duration, and intervention period. The results showed that the subgroups of males, exercise frequency of 5–7 times/week, single intervention time of 36–60 minutes, and exercise cycle of 4–8 weeks had better efficacy than the control group. However, the small number of studies in the Tai Chi and Rehabilitation Exercise subgroups and the high heterogeneity among the remaining subgroups need to be interpreted with caution (Table 3).

Table 3

Subgroup analysis of paradigm correctness rates

Subcomponent group		Number of studies included	I ² /%	Subgroup analysis results	
				SMD (95 % CI)	P-value
distinguishing between the sexes	male	3 ^[15,18,19]	49	0.30 [0.18,1.02]	0.005
	female	3 ^[14,16,20]	68	0.15[-0.34,0.64]	0.550
sports	Regular Aerobic Exercise	5 ^[14,15,17-19]	91	1.14 [0.34,1.94]	0.005
	Tai Chi, Rehabilitation Exercise	2 ^[16,20]	0	-0.09[-0.45,0.27]	0.630
exercise frequency	≤2 times/week	1 ^[20]	-	-0.23 [-0.80,0.35]	0.440
	3-4 times/week	3 ^[16,17,19]	96	0.82 [0.49,1.14]	<0.001
	5-7 times/week	3 ^[14,15,18]	0	0.48 [0.21,0.76]	<0.001
exercise duration	25-35 minutes	3 ^[17,18,20]	96	1.20[-0.62,3.01]	0.200
	36-60 minutes	4 ^[14-16,19]	62	0.53[0.13,0.94]	0.010
intervention period	4-8 weeks	2 ^[15,19]	0	0.81 [0.42,1.20]	<0.001
	9-12 weeks	5 ^[14,16-18,20]	93	0.79[-0.09,1.66]	0.080

Subgroup analysis at the time of reaction

In this study, gender, exercise mode, exercise frequency, exercise duration, and exercise cycle subgroups were analyzed at the time of response, and the results showed that the efficacy of an exercise cycle of 4-8 weeks was better than that of the control group, and the heterogeneity between the remaining subgroups was high (Table 4).

Table 4

Subgroup analysis at the time of reaction

Subcomponent group		Number of studies included	I ² /%	Subgroup analysis results	
				SMD (95 % CI)	P-value
distinguishing between the sexes	male	7 ^[12,12,13,13,15,18,19]	58	-0.56[-0.91,-0.21]	0.002
	women	2 ^[16,20]	90	-0.68 [-1.93,0.57]	0.280
sports	Regular Aerobic Exercise	6 ^[12,12,15,17,19]	73	-0.47 [-0.92, -0.03]	0.040
	Tai Chi, Rehabilitation Exercise	4 ^[13,13,16,20]	79	-0.39[-1.06,0.28]	0.260
exercise frequency	≤2 times/week	1 ^[20]	-	-1.34[-1.98,-0.70]	<0.001
	3-4 times/week	7 ^[12,12,13,13,16,17,19]	53	-0.40[-0.73,-0.08]	0.020
	5-7 times/week	2 ^[15,18]	88	-0.44 [-1.50,0.63]	0.420
exercise duration	25-35 minutes	7 ^[12,12,13,13,17,18,20]	68	-0.67[-1.09,-0.25]	0.002
	36-60 minutes	3 ^[15,16,19]	46	-0.19 [-0.59,0.22]	0.360
intervention period	4-8 weeks	4 ^[13,13,15,19]	16	-0.35[-0.68,-0.02]	0.040
	9-12 weeks	6 ^[12,12,16-18,20]	79	-0.62[-1.13,-0.11]	0.020

Sensitivity analysis

In this study, we sensitized studies with high heterogeneity in paradigm correctness and response time by excluding individual studies one by one. After excluding the studies of Wang 2017 et al. [17] the combined effect of paradigm correctness was SMD = 0.37, 95 % CI (0.04, 0.71), P = 0.03; I² decreased from 90 % to 63 %, which was a significant decrease in heterogeneity and significantly different from the control group (P < 0.05); after excluding the other individual studies, the combined effect SMD ranged from 0.74~0.94 for I² and 90 %~92 % for I², which were significantly different from the control group except for Zhu2023 [19] (P < 0.05); the combined effect at response was SMD = -0.51, 95 % CI (-0.84, -0.18),

$P = 0.002$; The range of SMD after excluding single studies was 0.58~ 0.42, I² of 63 %~ 72 %, suggesting a more robust result, all of which were significant compared with the control group ($P < 0.05$).

The study by Wang 2017 et al. [17] included patients whose subjects' sex was mixed braided, and whose intervention was a combination of exercises, which may be a source of heterogeneity. Excluding this study, the combined effects of SMD and I² for paradigm correctness were within a relatively robust range, further supporting the robustness of the results.

Publication bias

Since only seven studies were included in the paradigm correctness, this study only tested for publication bias in the literature about the time of reaction, and there was asymmetry in the lower part of the funnel plot, which may have publication bias, but the method relies on subjective judgment and the results may be uncertain. For further validation, the Egger regression method was used to test for publication bias, and the results showed that there was no significant publication bias in the Egger regression test ($|t| = 0.76$, $P = 0.470$) at the time of reaction.

Discussion

The aim of this Meta-analysis was to investigate the effect of AE on inhibitory control in MA addicts. Relevant studies were screened through a systematic literature search, applying standardized inclusion and exclusion criteria, and effect sizes were calculated.

Findings suggest that AE significantly improves inhibitory control in MA addicts. Exercise significantly improves depressive symptoms and physical health in substance addicted patients [22], and as an adjunctive treatment, it also alleviates psychiatric disorders induced by substance addiction [23], which enhances inhibitory control, which may be related to dopamine conversion rate. It has been shown that structured exercise improves the dopamine conversion rate, increases dopamine release, synthesis and secretion, and suppresses its concentration for a period of time after exercise [24], improves the D2/D3 receptor deficits in dopamine in MA addicts [25], repairs the midbrain-limbic dopamine system, attenuates euphoria triggered by MA, and reduces MA craving, thus facilitating inhibitory control. In addition, AE enhances inhibitory control by promoting synaptic plasticity [26] and increases brain-derived neurotrophic factor (BDNF) [27], which not only affects inhibitory control and neuroplasticity [28] but is also associated with the survival and function of dopaminergic neurons [29]. Endogenous dopamine also plays an important role in the improvement of response time, which only occurs when movement is coordinated with signals from higher brain centers [30].

Subgroup analyses revealed significant differences in the role of gender in the AE intervention. AE significantly improved inhibitory control in male addicts and had little effect on female addicts, which is consistent with the findings of a Meta-analysis on drug addiction [31]. The relatively high heterogeneity in the female subgroup may affect the statistics of the effect sizes and therefore needs to be interpreted with caution. Interestingly, a study conducted in older adults with subcortical ischemic vascular cognitive impairment found that AE significantly increased inhibitory control in females and had a negative effect in males [32]. This may be due to a common functional single nucleotide polymorphism in the prepeptide domain of the BDNF gene, which causes an amino acid substitution at position 66 from valine (Val) to methionine (Met), known as the Val66Met substitution. In carriers of the BDNF Met allele, this is associated with reduced activation of attentional targets in the dorsolateral and dorsomedial prefrontal cortex [33]. The Val66Met polymorphism has been associated with susceptibility to neuropsychiatric disorders, especially schizophrenia, and with depression, anxiety, and other disorders with gender-specific dimorphisms [32, 34]. MA addicts may be due to the substitution of Val for Met in the BDNF, which leads to dimorphisms in inhibitory control. In a study on subcutaneous white adipose tissue and dimorphism, it was shown that male subcutaneous white adipose tissue was more enriched in aspects related to aerobic metabolism and also showed strong dimorphism [35]. Thus, AE may play a greater role in the improvement of inhibitory control in MA addicts in males. Currently, the mechanisms underlying the gender differences in the effects of AE on inhibitory control in MA addicts are unclear, and the influence of gender on the effects of exercise interventions needs to be further explored in future studies. However, the present study mainly investigated RCTs of 4–12 weeks, so whether AE below 4 weeks or above 12 weeks has the same results for MA addicts still needs to be analyzed by including a large number of gender-controlled RCTs at a later stage. Exercise mode: conventional AE significantly improved correct rates, but heterogeneity between studies was high. Heterogeneity decreased significantly after excluding the study of Wang 2017 [17], which may be related to the combined exercise intervention used in this study. Both AE and combined training significantly improved functional motor ability, and the improvement effect of combined training was better [36], so combined exercise may

have a more significant improvement effect on inhibitory control in MA addicts. The results supporting AE are consistent with previous studies that have demonstrated the ability of AE to significantly improve inhibitory control in MA addicts [37, 38]. Although the subgroup analysis showed that Tai Chi and Rehabilitation Exercise were not significant compared to the control group, the heterogeneity shown in their subgroup analysis was high and has been confirmed by other studies [39], so the role of Tai Chi and Rehabilitation Exercise could not be denied in this study, and it needs to be further verified by high quality studies in the future. In addition, this Meta-analysis included only two studies on correct rate of Tai Chi and rehabilitation exercise intervention modalities, and the between-group heterogeneity of group performance at response time according to exercise modalities was high, and subgroup analyses according to exercise modalities may have resulted in less reliable findings because of the limited number of studies and high heterogeneity. More RCTs should be conducted to investigate the effects of different forms of exercise on inhibitory control in MA addicts. Exercise frequency: the results of subgroup analyses showed that the frequency of engaging in AE training had a significant effect on the intervention effect, and the intervention effect of AE was most significant in 3–4 sessions/week compared with 5–7 sessions/week of AE. Unfortunately, there were not a sufficient number of studies testing the effect of exercise interventions ≤ 2 sessions/week on inhibitory control. Importantly we found a more significant effect of interventions at moderate frequencies compared to high frequencies. Previous reviews have described the effects of exercise at low and moderate frequencies and similarly demonstrated that moderate frequency exercise had the best intervention effect [40, 41]. However, this result needs to be interpreted with caution as the heterogeneity of the exercise frequency subgroups was all relatively high. There was no significant difference between the AE intervention group, which was 5–7 times per week at the time of response, and the control group. This may be related to the fact that exercise induces mental fatigue and a decrease in perceptual ability, and that the speed and accuracy of decision-making decreases with increasing fatigue [42], and that too many interventions per week may cause increased fatigue in patients, leading to a decrease in responsiveness. Duration of exercise: results obtained in the subgroup of 25–35 minutes need to be interpreted with caution due to high heterogeneity, but previous studies have shown that ≤ 45 minutes of exercise per session had the most significant effect in improving executive function [40]. However, in the subgroup of 36–60 minutes, the AE intervention group was significantly different from the control group, and although heterogeneity was high, taking a study-by-study approach to exclusion revealed a significant decrease in heterogeneity after excluding the Shen 2021 [16] study ($I^2 = 0\%$, $p < 0.001$), and since only Shen 2021 [16] one study had an intervention duration of 60 minutes, exercise time may be the source of heterogeneity. The excluded studies all had an intervention time of 40 minutes, so the present study hypothesized that an AE intervention at 40 minutes per session could significantly improve inhibitory control in MA addicts. Again, this is consistent with previous studies that have concluded [43]. Since the present study included only a single 60-minute intervention, it is not yet possible to determine whether a 60-minute exercise session has a beneficial effect on inhibitory control in MA addicts. Further RCTs are needed to investigate the effects of varying intervention durations on inhibitory control in this population. Subgroup analyses of response times revealed high heterogeneity in both groups, and the results obtained need to be interpreted with caution. Exercise period: in the subgroup of 4–8 weeks of exercise intervention, both the rate of paradigm correctness and response time were better than the control group, which could significantly improve inhibitory control [44], while the difference between the subgroup of 9–12 weeks of exercise intervention compared with the control group was not significant but the heterogeneity between the groups was higher, therefore, we do not speculate that the 9–12 weeks of exercise intervention did not have an effect on inhibitory control of MA addicts, and, the previous studies have shown that 12 weeks of AE can significantly improve inhibitory control and cognitive ability in MA addicts, and more high-quality studies are needed in the future to further validate the effect of exercise cycles on inhibitory control in MA addicts. Considering the influence of exercise dose effect, exercise intervention cycles should not be less than 4–8 weeks.

Limitations of this study

The overall quality of the literature included in this study was moderate, with some limitations. Most of the literature did not fully report on blinding, which may have had an impact on the posttest results. A publication bias test at the time of response showed no significant publication bias. In addition, only Chinese and English literature were included in this study, which may be deficient in the comprehensiveness of the included literature; the patients included in the study were all Chinese, which may be less valuable as a reference for other countries or regions; and there was a large amount of heterogeneity among studies, and the included literature was carefully read, but no direct evidence of the source of heterogeneity was found. More

randomized controlled trials should be conducted in follow-up to explore the effects of AE on inhibitory control in MA addicts.

Conclusions

This meta-analysis provides robust evidence that aerobic exercise (AE) significantly enhances inhibitory control in individuals with methamphetamine (MA) addiction. The magnitude of improvement was influenced by gender and exercise modality, and a dose–response relationship was evident across exercise duration, frequency, and intervention period. Specifically, male participants achieved greater improvements in inhibitory control when engaging in AE three to seven times per week, approximately 40 minutes per session, for a minimum of four weeks.

These findings underscore the potential of structured AE as a complementary strategy in cognitive rehabilitation programs for MA addicts. Future studies should further explore the optimal exercise prescriptions and elucidate the neurobiological mechanisms underlying these improvements to guide evidence-based clinical practice.

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