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SYSTEMATIC REVIEW

The best approaches and doses of exercise for improving sleep quality: a network meta-analysis and dose-response relationship study

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Abstract

Background Poor sleep quality not only diminishes people's quality of life and work efficiency but is also closely associated with various diseases. A reasonable exercise regimen can improve sleep quality to some extent, but there is a lack of comparative studies on the effects of different types of exercise, especially varying exercise doses, on sleep quality.

Objective To systematically evaluate the effects of different exercise modalities and doses on sleep quality.

Methods A search was conducted in PubMed, Web of Science, EBSCO, Cochrane Library, and China National Knowledge Infrastructure (CNKI) databases for randomized controlled trials (RCTs) on the effects of different exercise modalities on sleep quality, from database inception to November 2024. Two researchers independently screened the literature, extracted data, and assessed the risk of bias in the included studies. Network meta-analysis and dose-response analysis were performed using Stata 16.0 and R software with a random-effects model.

Results A total of 86 RCTs involving 7,276 participants were included. Six types of interventions were assessed: Aerobic Exercise (AE), Resistance Training (RT), Combined Aerobic and Resistance training (AE + RT), Yoga, Pilates, and Traditional Chinese Sports (TCS). The network meta-analysis results showed that compared to the control group, AE (SMD = -1.21, 95% CI: -1.50, -0.91, $P < 0.01$), RT (SMD = -1.12, 95% CI: -1.80, -0.44, $P < 0.01$), AE + RT (SMD = -1.11, 95% CI: -1.56, -0.66, $P < 0.01$), YOGA (SMD = -0.82, 95% CI: -1.22, -0.42, $P < 0.01$), Pilates (SMD = -1.65, 95% CI: -2.42, -0.88, $P < 0.01$), and TCS (SMD = -0.94, 95% CI: -1.28, -0.60, $P < 0.01$) all significantly improved sleep quality. The cumulative ranking probability (SUCRA) ranking showed that Pilates (91.7%) was the most effective, followed by AE (69.7%), AE + RT (59.4%), RT (58.6%), TCS (40.5%), and YOGA (30.1%). Additionally, the relationship between exercise dose and sleep quality was nonlinear, following a U-shaped curve. The overall optimal exercise dose for improving sleep quality was 920 MET-min/week. The optimal doses varied across exercise types, ranging from 390 MET-min/week for Pilates to 1,100 MET-min/week for aerobic exercise.

Conclusion This study provides strong support for non-pharmacological interventions to improve sleep quality. For individuals aiming to improve their sleep through exercise, Pilates and aerobic exercise are recommended as the

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preferred options. Additionally, controlling the exercise dose within the optimal range (e.g., 920 MET-min/week) can significantly enhance the intervention effect.

Clinical trial number Not applicable.

Keywords Exercise, Sleep quality, Dose, Meta-analysis, Systematic review

Introduction

Sleep quality serves as a crucial indicator of an individual's overall physical health and quality of life, exerting substantial influences on psychological well-being and cognitive function. Global epidemiological data indicate that sleep disturbances have emerged as a prevalent issue in adult populations, particularly among the elderly, pregnant women, and other vulnerable groups [1–3]. Moreover, extensive research has demonstrated that poor sleep quality is closely associated with a range of adverse health outcomes, including cardiovascular diseases, endocrine disorders, depression, and anxiety [4, 5]. Consequently, improving sleep quality has become a major public health priority.

Numerous studies have demonstrated that exercise exerts beneficial effects on sleep quality. Physical activity appears to enhance sleep through a variety of physiological mechanisms, such as regulating body temperature, modulating neurotransmitter levels, adjusting hormone secretion, and bolstering immune system function [6]. For instance, both aerobic exercise and mind-body practices (e.g., Yoga and Tai Chi) have been shown to significantly improve sleep quality in adult and elderly populations [7–9]. Nevertheless, variations in exercise modality, dosage (including intensity, frequency, and duration), and individual response remain subjects of ongoing debate in current research.

In recent years, network meta-analysis (NMA) has provided a novel framework for comparing the effects of different exercise modalities on sleep quality. Several studies employing NMA have systematically evaluated the efficacy of various exercise types among adults and the elderly, ranking interventions and demonstrating that aerobic exercise, Pilates, and Tai Chi are particularly effective [10–12]. Although these investigations offer valuable insights into optimal exercise regimens for enhancing sleep, most have focused on singular intervention strategies, with only limited exploration of the dose-response relationships among exercise intensity, frequency, and duration.

This study introduces an innovative approach by utilizing a Bayesian network meta-analysis based on metabolic equivalents (MET) to systematically assess the dose-response relationship between diverse exercise modalities and sleep quality. MET, as a standardized measure of exercise intensity, enables a unified quantification of exercise dosage across various activities, thereby facilitating a more precise evaluation of how exercise influences sleep quality. By integrating both direct comparisons and indirect evidence from multiple studies through Bayesian analysis, this research provides a robust and scientifically grounded evaluation of optimal exercise interventions. Ultimately, quantifying the dose-response relationship between exercise and sleep quality will offer compelling evidence to support the development of targeted, evidence-based exercise strategies for enhancing sleep.

Methods

Registration

This systematic review and NMA were conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [13]. The study protocol has been prospectively registered in the International Prospective Register of Systematic Reviews, ID: CRD42024622727.

Literature search strategy

Computerized searches were conducted in databases such as CNKI, PubMed, Cochrane Library, Web of Science, and Embase, with the search period ranging from database inception to October 2024. The search strategy combined both subject headings and free text terms. For Chinese literature, only Chinese core journals were included. Additionally, the references of some articles were traced and integrated to further obtain relevant literature. The data retrieval strategy is exemplified by the PubMed database(See Table 1 for details).

Inclusion criteria

The design follows the PICOS framework, specifically: (P) Population: Adults aged 18–75 years; (I) Intervention: Various interventions including aerobic exercise, resistance training, combined aerobic and resistance training, ball sports, yoga, Pilates, and traditional Chinese exercises, as detailed in Table 2; (C) Comparison: Daily activities or no intervention; (O) Outcome measures: PSQI (Pittsburgh Sleep Quality Index), ESS (Epworth Sleepiness Scale), and ISI (Insomnia Severity Index); (S) Study type: Randomized controlled trials.

Exclusion criteria

(1) Studies that did not use a single exercise intervention (e.g., exercise combined with moxibustion or other pharmacological treatments); (2) Theses, conference

Table 1 Search strategies of pubmed database

Serial number	Search formula
#1	("Exercise"[Mesh]) OR ((((((((((((((((((((((((((Exercises[Title/Abstract]) OR (Walking[Title/Abstract])) OR (endurance training[Title/Abstract])) OR (strength training[Title/Abstract])) OR (Exercise, Physical[Title/Abstract])) OR (Exercises, Physical[Title/Abstract])) OR (Physical Exercise[Title/Abstract])) OR (Physical Exercises[Title/Abstract])) OR (Physical Activity[Title/Abstract])) OR (Activities, Physical[Title/Abstract])) OR (Activity, Physical[Title/Abstract])) OR (Physical Activities[Title/Abstract])) OR (Exercise, Aerobic[Title/Abstract])) OR (Aerobic Exercise[Title/Abstract])) OR (Aerobic Exercises[Title/Abstract])) OR (Exercises, Aerobic[Title/Abstract])) OR (Training, Exercise[Title/Abstract])) OR (Trainings, Exercise[Title/Abstract])) OR (sport[Title/Abstract])) OR (aerobic[Title/Abstract])) OR (yoga[Title/Abstract])) OR (tai chi[Title/Abstract])) OR (qigong[Title/Abstract])) OR (Pilates[Title/Abstract])) OR (Baduanjin[Title/Abstract])) OR (resistance[Title/Abstract])) OR (resistance training[Title/Abstract]))
#2	("Sleep Quality"[Mesh]) OR ((((((((((Qualities, Sleep[Title/Abstract]) OR (Quality, Sleep[Title/Abstract])) OR (Sleep Qualities[Title/Abstract])) OR (Insomnia[Title/Abstract])) OR (insomnias[Title/Abstract])) OR (sleep disorder[Title/Abstract])) OR (sleep disturbance[Title/Abstract])) OR (sleep insufficiency[Title/Abstract])) OR (sleep problem[Title/Abstract])) OR (sleep complaint[Title/Abstract])) OR (sleep wake disorders[Title/Abstract]))
#3	#1 AND #2

Table 2 Definitions of exercise training interventions

Modality	Definition
Aerobic Exercise(AE)	The continuous exercises aimed at improving cardiovascular efficiency and capacity, such as walking, cycling, and jogging [18].
Resistance Training (RT)	Exercises designed to improve muscular strength, endurance and muscle hypertrophy[18]
Combined Aerobic and resistance Training(AE+RT)	Combined aerobic and resistance training for an integrated approach to exercise
YOGA	A systematic fitness exercise of ancient Indian origin that improves strength, flexibility, coordination and endurance through postures (yoga asanas, asanas) and enhances breath control and concentration through breathing exercises (pranayama, pranayama)[19]
Traditional Chinese Sports(TCS)	Systematic fitness methods originating from traditional Chinese culture and philosophy, including taijiquan, qigong, and baduanjin, which promote the flow of qi and blood, balance yin and yang, and enhance the flexibility and strength of the body through the combination of slow and coordinated movements, breath control, and intention, in order to achieve physical and mental harmony and health[20]
Pilates	A modern systematic approach to fitness that improves strength, stability and flexibility through precise movement control and core strengthening exercises, while improving posture, coordination and body awareness

proceedings, or abstracts for which the full text was not accessible; (3) Studies from which valid outcome data could not be extracted, and where contact with the authors was unsuccessful; (4) Duplicate publications.

Literature screening and data extraction

Two researchers independently screened the literature, extracted data, and cross-checked their findings. In case of discrepancies, a third-party expert was consulted for assistance in making a judgment. Missing data were supplemented by contacting the authors whenever possible. During the literature screening process, the title and abstract were first reviewed, and obviously unrelated studies were excluded. The full text of the remaining studies was then examined to determine whether they should be included. The data extraction included the following information: first author, country, publication year, intervention subjects (sample size, gender, age of each group), intervention details (type of exercise intervention, duration, frequency, and time), and outcome measures.

Data coding and management

Exercise intensity in this study is quantified using MET-minutes per week (MET-min/week). A metabolic equivalent of task (MET) represents the energy cost of physical activities expressed as multiples of the resting metabolic rate. By multiplying the MET value of an activity by its duration (in minutes) and its frequency per week, MET-min/week offers a comprehensive measure of the total energy expenditure associated with a given exercise regimen.

MET-min/week is widely recognized in exercise science as a standardized unit that integrates both exercise intensity and duration. This unified metric enables direct comparisons across diverse exercise modalities—even when the types, durations, or frequencies vary. Numerous studies have validated the use of MET-min as a reliable indicator of physical activity dose in relation to various health outcomes. For instance, the 2011 Compendium of Physical Activities provides extensive evidence supporting the use of MET values to quantify energy expenditure [14]. Moreover, international guidelines—such as the World Health Organization's "WHO Guidelines on Physical Activity and Sedentary Behaviour" [15] and recommendations from the American College of Sports Medicine [16]—advocate expressing physical activity in MET-min/week. This endorsement underlines its clinical relevance and enhances the generalizability of our findings. Employing MET-min/week in our study facilitates a more precise quantification of exercise dose and improves the interpretability of the dose-response relationship between exercise and sleep quality.

In practical application, the intensity of specific exercises was coded according to the 2011 Compendium of Physical Activities [14], which contains 821 specific activity codes covering nearly all forms of physical activity. Exercise frequency was represented by the total number of exercise sessions per week, including instances of multiple sessions in one day. If the duration of an exercise session was not specified, the average duration from all studies on that specific exercise intervention was used; and if the exercise duration gradually increased over several weeks, the average total exercise time was taken. Finally, for the purposes of network connectivity and dose-response network analysis, weekly MET-min values were categorized into six groups: 0 (control group), 300, 600, 900, 1200, and 1500 MET-min/week[17].

Risk of bias evaluation of included studies

Two researchers independently assessed the risk of bias in the included studies using the Cochrane Handbook for RCTs risk of bias assessment tool [21]. This tool includes seven domains: (a) random sequence generation; (b) allocation concealment; (c) blinding of participants and personnel; (d) blinding of outcome assessment; (e) incomplete outcome data; (f) selective reporting of results; (g) other sources of bias. According to the following criteria, the overall risk of bias for each study was classified: if none of the seven domains were rated as high risk of bias, and three or fewer domains were rated as unclear risk, the study was rated as low risk of bias. If one domain was rated as high risk or four or more domains were rated as unclear risk, it was rated as moderate risk of bias. In all other cases, it was rated as high risk of bias.

Quality of evidence evaluation

Two independent reviewers assessed the quality of evidence using the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) approach. The GRADE framework evaluates evidence based on five key factors: study limitations, consistency, directness, precision, and publication bias. Based on these factors, the quality of evidence is classified as "high," "moderate," "low," or "very low."

Statistical analysis

Network meta-analysis (NMA)

To minimize the impact of baseline differences, this study used the change in mean values and standard deviations before and after the intervention to combine effect sizes. The calculation method for the standard deviation of the change was performed using the formula provided in the Cochrane Handbook (version 6.3) [21]. Following the PRISMA guidelines for network meta-analysis [13], a random-effects model was used within a frequentist framework to combine effect sizes and calculate 95% confidence intervals (CI) in Stata 16.0 software [22], to assess the impact of various exercise interventions on sleep quality. Due to the diversity of sleep quality assessment scales, the standardized mean difference (SMD) was used as the effect size for merging. A network evidence plot was generated to describe the relationships between exercise interventions, where the lines connecting nodes represent direct comparisons between interventions, with line thickness proportional to the number of studies, and node size proportional to sample size. The consistency of each loop was evaluated by calculating the inconsistency factor and its 95% CI[23]. The inconsistency model was used to test for inconsistency, and when $P > 0.05$, the consistency model was applied for analysis [24]. Cumulative ranking probability plots (surface under the cumulative ranking, SUCRA) were used to rank and compare the effectiveness of different exercise interventions [25]. SUCRA values range from 0 to 100%, with 100% indicating the best intervention effect and 0 indicating the worst [26]. Funnel plots were used to check for publication bias or small sample effects.

Bayesian dose-response meta-analysis

This study employed a Bayesian network meta-analysis (MBNMA) model based on random effects to explore the dose-response relationship between exercise and sleep quality [27]. The analysis results indicated no abnormalities in the key assumptions of MBNMA, including network transitivity [17], data consistency [28], and network connectivity [29] (see Appendix 8 for details). Due to the diversity of scales used to assess sleep quality, the standardized mean difference (SMD) was used as the effect size, and a 95% credible interval (CrI) was applied to evaluate confidence.

Several recommended dose-response functions (e.g., Emax, restricted cubic splines, quadratic functions, and nonparametric functions) were referenced in the study [30], and the fitting indicators of different functions (including DIC, standard deviation across studies, model parameters, and residual deviation) were compared [31]. The results showed that the quadratic function model consistently provided the best fit under various conditions and was therefore used to evaluate the nonlinear dose-response relationship (see Appendix 9).

The quadratic function random-effects model performed exceptionally well in handling nonlinear relationships, particularly in time-dependent and dose-dependent models, often providing a more accurate reflection of phenomena compared to linear models [32]. In this model, beta coefficients were used to estimate the minimum exercise dose required to achieve significant changes in sleep quality. The effectiveness of exercise modalities was ranked based on the likelihood of these changes [27]. In the dose-response analysis, results were considered statistically significant when the 95% CrI of the effect size did not include 0.

Finally, a 95% "prediction interval" was used to describe the variation range of future study outcomes, predicting the potential effects of future exercise interventions [33]. This analysis was conducted using the "MBNMAdose" package in R software (version 4.3.1), with dose-response curves and visualizations generated using the "ggplot2" package.

Other analyses

To ensure the reliability of the study results, a sensitivity analysis was conducted on the network meta-analysis to explore the impact of high risk of bias, small sample sizes ($N < 30$), and short intervention durations (≤ 4 weeks) on the intervention effects.

Results

Literature search results

A total of 2,037 relevant articles were retrieved through database searches, including CNKI ($n = 15$), PubMed ($n = 404$), Embase ($n = 646$), Cochrane Library ($n = 600$), and Web of Science ($n = 357$). After reviewing the titles and citation information, 1,780 unrelated articles were excluded. A further 162 articles were excluded after full-text review for being irrelevant to the study objectives, and 7 articles were excluded as interference studies. Ultimately, 86 RCT studies were included (see Fig. 1 for the literature screening flowchart).

Basic characteristics of included studies

A total of 86 randomized controlled trials (RCTs) involving 7,276 participants were included, with an average age

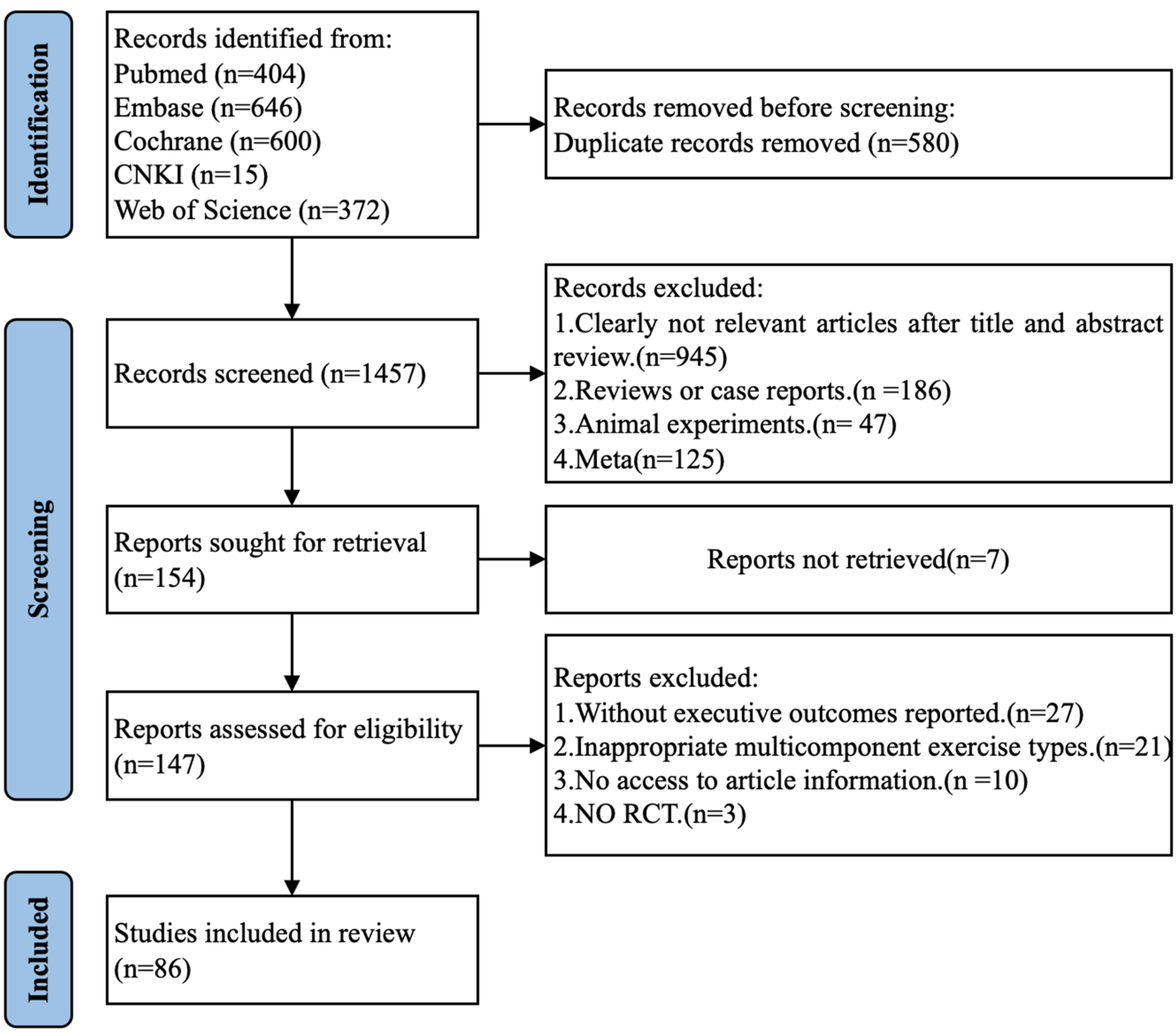

Fig. 1 Literature screening process and results

range of 18 to 75 years. The most common intervention was aerobic exercise (AE), covered in 37 studies, followed by traditional Chinese sports (TCS) in 25 studies. Yoga was evaluated in 18 studies, combined aerobic and resistance training (AE + RT) in 14 studies, resistance training (RT) in 7 studies, and Pilates in 5 studies. The frequency of exercise interventions ranged from once to seven times per week, with an average session duration of 57 min. (For the basic characteristics of the included studies, see Appendix 1).

Evaluation results of risk of bias in included studies

A total of 86 articles explicitly described their group allocation methods, and 72 articles reported allocation concealment. Due to the inherent difficulty of implementing blinding for exercise interventions, most studies in this review were rated as high risk or unclear risk for participant and personnel blinding. Thirty-two studies reported blinding in data analysis. For the evaluation of data completeness, studies with a loss-to-follow-up rate exceeding 20% and without the use of intention-to-treat analysis were rated as high risk. Among the included studies, 3 had a loss-to-follow-up rate greater than 20%, and 50 studies reported loss-to-follow-up rates with similar numbers and reasons for loss in both the intervention and control groups.

Regarding other biases, studies were rated as high risk due to small sample sizes (fewer than 10 participants in any group), lack of supervision, or significant measurement errors in outcome assessments. Overall, 52 articles were classified as having low risk of bias (Low ROB), 28 as moderate risk of bias (Moderate ROB), and 6 as high risk of bias (High ROB). (Detailed information on the ROB assessment for each study is provided in Appendix 2).

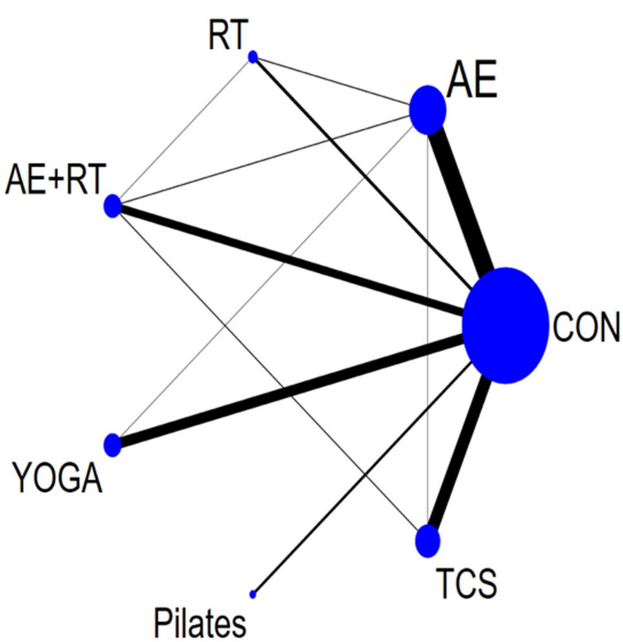

Fig. 2 Network evidence map of the effects of different exercise interventions on sleep quality. AE: Aerobic Exercise; RT: Resistance Training; AE + RT: Combined Aerobic and Resistance Training; TCS: Traditional Chinese Sports; CON: Control Group

Network meta-analysis results

Network evidence diagram

In the network evidence plot (Fig. 2), the size of the nodes is positively correlated with the sample size of each intervention, and the thickness of the lines between the nodes represents the number of studies comparing the connected exercise modalities.

Inconsistency test

Inconsistency across outcome measures was assessed using loop inconsistency tests, inconsistency models, and node-splitting methods. The loop inconsistency test results showed that only the "AE-RT-AE + RT" loop exhibited inconsistency, while other loops demonstrated good consistency. Inconsistency model tests revealed that the P-values for all outcome measures were > 0.05, indicating no significant inconsistency; thus, a consistency model could be applied for analysis. The node-splitting method showed that only the direct comparisons between CON-AE and RT-AE + RT had poor consistency ($P < 0.05$), while the direct and indirect evidence for other outcome measures demonstrated good consistency ($P > 0.05$), indicating high reliability of the results (see Appendix 4 for details).

Combining effect size analysis and ranking results

Compared to the non-exercise group, AE (SMD = -1.21, 95% CI: -1.50 to -0.91, $P < 0.01$), RT (SMD = -1.12, 95% CI: -1.80 to -0.44, $P < 0.01$), AE + RT (SMD = -1.11, 95% CI: -1.56 to -0.66, $P < 0.01$), YOGA (SMD = -0.82, 95% CI: -1.22 to -0.42, $P < 0.01$), Pilates (SMD = -1.65, 95% CI: -2.42 to -0.88, $P < 0.01$), and TCS (SMD = -0.94, 95% CI: -1.28 to -0.60, $P < 0.01$) all significantly improved sleep quality (Fig. 3).

The SUCRA probability ranking results indicated that Pilates had the highest probability of being the most effective intervention (SUCRA = 91.7%), followed by AE (SUCRA = 69.7%), AE + RT (SUCRA = 59.4%), RT (SUCRA = 58.6%), and TCS (SUCRA = 40.5%). YOGA had the lowest probability (SUCRA = 30.1%) (Fig. 4).

Publication bias test

Publication bias was analyzed using a funnel plot, which revealed a certain degree of asymmetry, suggesting the potential risk of publication bias or insufficient sample sizes in studies related to certain outcomes. This may have impacted the results (see Fig. 5).

AE						
-0.08 (-0.80,0.63)	**RT**					
-0.09 (-0.62,0.43)	-0.01 (-0.80,0.78)	**AE+RT**				
-0.39 (-0.88,0.10)	-0.30 (-1.09,0.49)	-0.29 (-0.89,0.31)	**YOGA**			
0.45 (-0.38,1.27)	0.53 (-0.50,1.56)	0.54 (-0.35,1.43)	0.83 (-0.04,1.70)	**Pilates**		
-0.27 (-0.71,0.18)	-0.18 (-0.94,0.58)	-0.17 (-0.71,0.37)	0.12 (-0.40,0.65)	-0.71 (-1.55,0.13)	**TCS**	
-1.21 (-1.50,-0.91)	**-1.12 (-1.80,-0.44)**	**-1.11 (-1.56,-0.66)**	**-0.82 (-1.22,-0.42)**	**-1.65 (-2.42,-0.88)**	**-0.94 (-1.28,-0.60)**	**CON**

Fig. 3 Results of reticulated Meta-analysis. AE: Aerobic Exercise; RT: Resistance Training; AE + RT: Combined Aerobic and Resistance Training; TCS: Traditional Chinese Sports; CON: Control Group

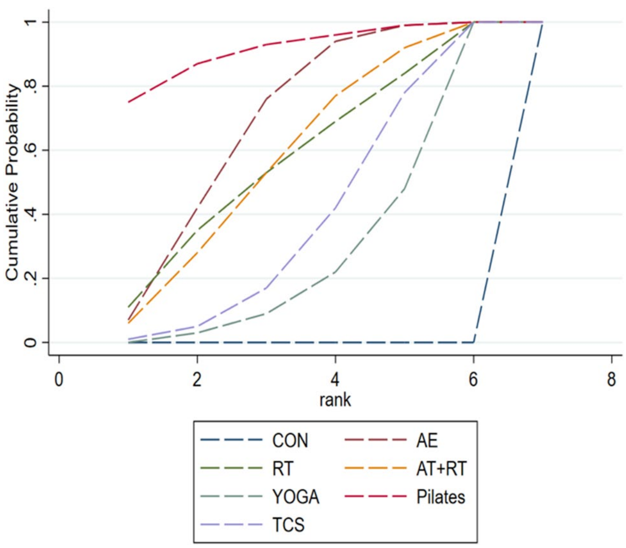

Fig. 4 Area under the cumulative probability ranking curve. AE: Aerobic Exercise; RT: Resistance Training; AE + RT: Combined Aerobic and Resistance Training; TCS: Traditional Chinese Sports; CON: Control Group

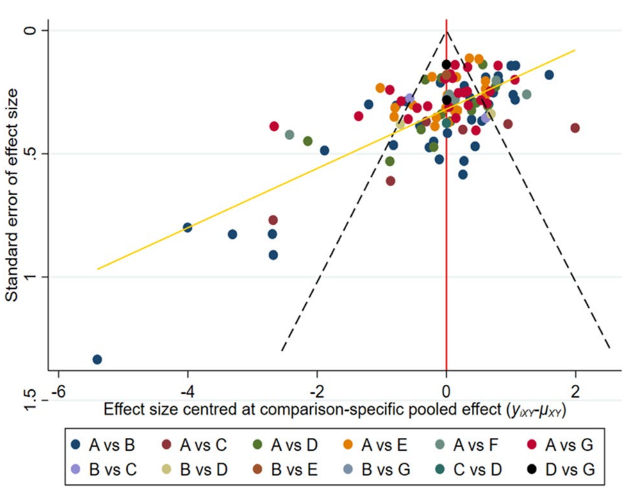

Fig. 5 Publication bias analysis of the included literature

Bayesian dose-response meta-analysis results

Overall dose-response relationship of exercise

The overall dose-response relationship between exercise dosage and sleep quality exhibited a nonlinear dose-dependent U-shaped curve (Fig. 6). Sleep quality showed significant improvement at 180 MET-min/week and reached a plateau of improvement at 1500 MET-min/week. At 600 MET-min/week (the lower limit of physical activity recommended by the World Health Organization for energy expenditure [15]), the predicted effect was moderate (SMD = -1.13; 95% CrI: -1.48, -0.75; SD = 0.19). Similarly, at 1200 MET-min/week (the upper limit of physical activity recommended by the World Health Organization for energy expenditure [15]), the predicted effect was also moderate (SMD = -1.16; 95% CrI: -1.55, -0.74; SD = 0.21), but with a larger SD value. The optimal intervention effect was achieved at 920 MET-min/week (SMD = -1.30; 95% CrI: -1.64, -0.93; SD = 0.18).

Dose-response relationships of the six exercise modalities

Figure 7 shows the dose-response relationships of the six exercise modalities. The dose-response relationships of aerobic exercise (AE) combined aerobic and resistance training (AE + RT), traditional Chinese sports (TCS), and yoga (YOGA) exhibited U-shaped patterns and demonstrated significant effects (Fig. 7). The predicted maximum significant response for aerobic exercise occurred at 1100 MET-min/week (SMD = -1.54; 95% CrI: -2.01, -1.03; SD = 0.25), for combined aerobic and resistance training at 1000 MET-min/week (SMD = -1.06; 95% CrI: -1.86, -0.28; SD = 0.4), for traditional Chinese sports at 730 MET-min/week (SMD = -1.17; 95% CrI: -1.84, -0.49; SD = 0.34), and for yoga at 510 MET-min/week (SMD = -0.84; 95% CrI: -1.54, -0.15; SD = 0.35).

Pilates showed a nonlinear negative correlation with sleep quality, with the minimum significant response occurring at 390 MET-min/week (SMD = -1.29; 95% CrI: -2.54, -0.04; SD = 0.67). Additionally, a U-shaped dose-response relationship was observed between resistance training (RT) and sleep quality; however, this relationship was not statistically significant. The study also showed that Pilates had the highest likelihood of producing the optimal effect on pain relief (Appendix 10, Table 8 for predicted rankings).

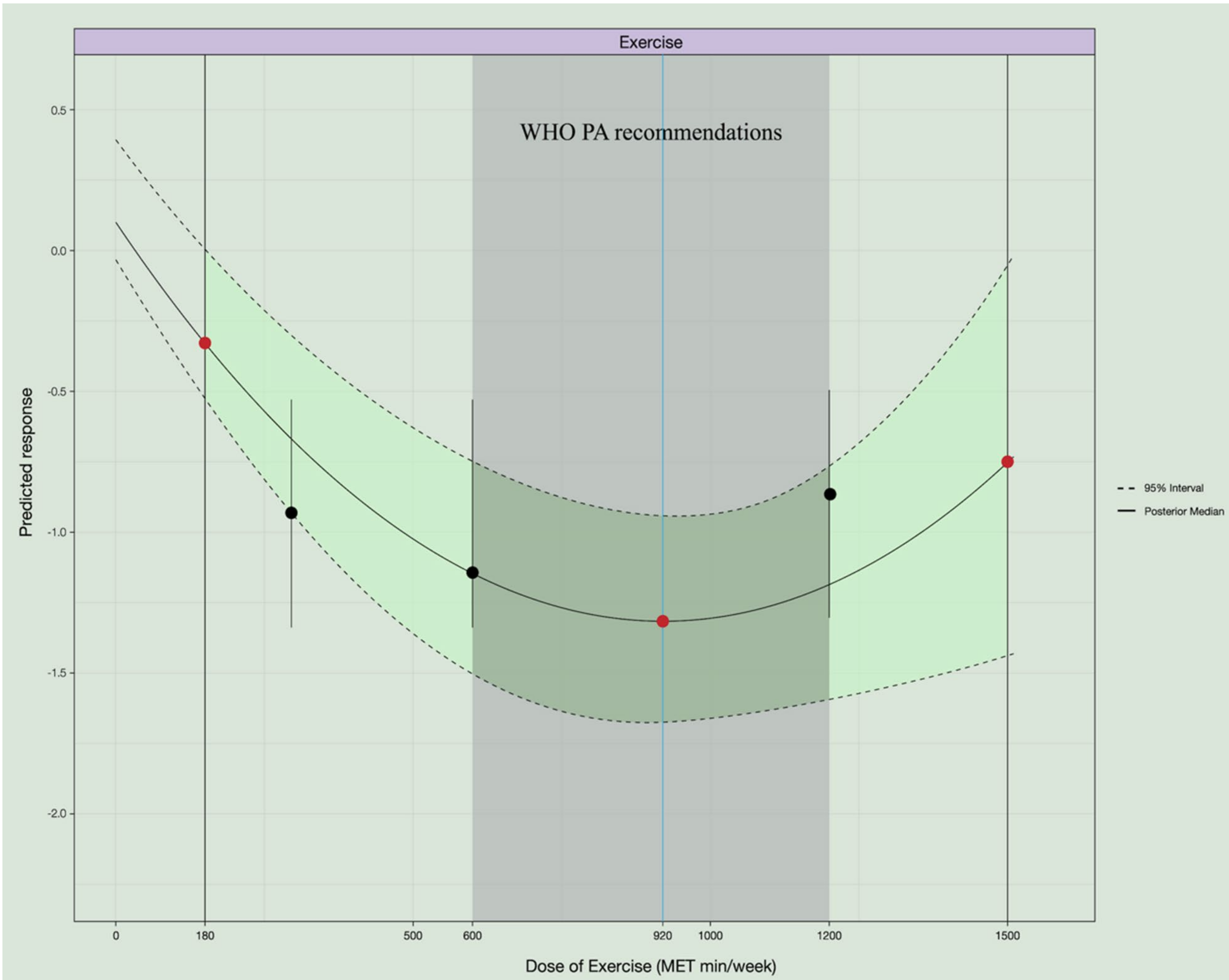

Fig. 6 Dose-response relationship of exercise to improve sleep quality. The dark green area denotes the region of statistical significance ($p < 0.05$), where the confidence intervals do not cross the null effect, indicating a reliable improvement in sleep quality. The blue solid line marks the dose at which the optimal effect is achieved, while the short black solid line represents the original dataset. Abbreviations: MET, Metabolic Equivalent of Task; PA, Physical Activity; SMD, Standardized Mean Difference; WHO, World Health Organization

Sensitivity analysis of the network meta-analysis

To investigate the impact of articles wi0074h high risk of bias, small sample sizes ($N < 30$), and short intervention durations on the intervention effects, the study conducted a meta-analysis after sequentially excluding these articles. The results showed that neither the significance nor the SUCRA rankings were affected, indicating that the findings of this study are robust and reliable (see Appendix 6 for details).

GRADE evidence quality assessment

Appendix 7 presents the GRADE evidence quality assessment results for each comparison as well as for the SUCRA rankings of treatment methods. Overall, most comparisons were rated as moderate to low quality in the GRADE assessment. The GRADE evidence level for SUCRA rankings was rated as moderate. This indicates that the results of this study have a relatively high level of credibility.

Discussion

This network meta-analysis investigated the effects of different exercise interventions on sleep quality and ranked their efficacy using SUCRA. The results showed that all exercise modalities significantly improved sleep quality in the network meta-analysis comparisons. There were no statistically significant differences in efficacy between aerobic exercise (AE), resistance training (RT), Yoga, Pilates, and traditional Chinese sports (TCS). SUCRA rankings indicated that Pilates had the highest probability of being the most effective intervention (SUCRA = 91.7%), followed by AE (SUCRA = 69.7%), while YOGA had the lowest probability (SUCRA = 30.1%).

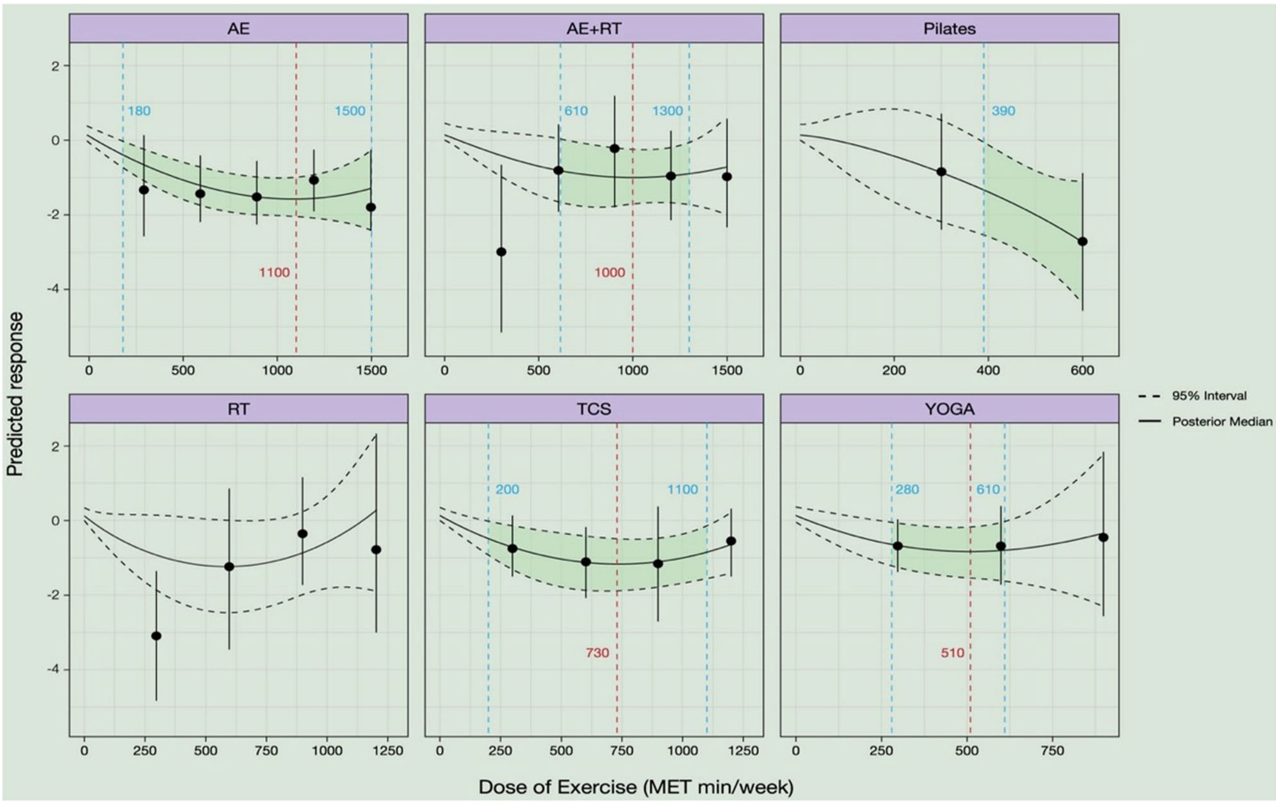

Fig. 7 Dose-effect relationship between different exercise interventions and sleep quality. The dark green area denotes the region of statistical significance ($p < 0.05$), where the confidence intervals do not cross the null effect, indicating a reliable improvement in sleep quality. The red numbers indicate the dose values at which the optimal dose-response relationship is observed, while the short black solid lines represent the original dataset. The blue numbers specify the range of doses where the dose-response relationship remains statistically significant. Abbreviations: MET, Metabolic Equivalent of Task; SMD, Standardized Mean Difference. AE: Aerobic Exercise; RT: Resistance Training; AE + RT: Combined Aerobic and Resistance Training; TCS: Traditional Chinese Sports

This study also found a nonlinear dose-response relationship between overall exercise and sleep quality—a U-shaped relationship. The optimal effective dose was estimated at 920 MET-min/week, equivalent to 263 min of walking (3.5 MET-min), 230 min of cycling (4 MET-min), 184 min of resistance training (5 MET-min), 230 min of yoga (4 MET-min), 310 min of Tai Chi (3 MET-min), or 330 min of Pilates (2.8 MET-min) per week. When the exercise dose reached 1500 MET-min/week, the improvement in sleep quality plateaued. These findings suggest that engaging in physical activity within the World Health Organization's (WHO) recommended range of 600–1200 MET-min/week can provide substantial benefits for improving sleep quality. Additionally, we observed distinct dose-response relationships for different exercise modalities. Among them, only Pilates exhibited a nonlinear negative correlation, while other exercise modalities showed a U-shaped relationship.

Finally, sensitivity analyses revealed that factors such as high risk of bias, small sample sizes ($N < 30$), and short intervention durations did not significantly affect the efficacy of exercise interventions.

Comparison of the effects of different exercise modalities and mechanistic explanations

The study results indicate that Pilates has a significantly superior effect on improving sleep quality compared to other exercise modalities (SMD = – 1.65, 95% CI: –2.42, – 0.88, $P < 0.01$; SUCRA = 91.7%). This enhanced efficacy appears to stem from the comprehensive action of Pilates on both the musculoskeletal and neuroendocrine systems, involving precise modulation of the musculoskeletal system and profound regulation of the central nervous system [34].

From a physiological standpoint, Pilates emphasizes core muscle training, increased flexibility, and optimized postural alignment. These factors work synergistically to effectively relieve muscle tension and chronic pain, thereby reducing nocturnal discomfort and improving sleep architecture [11]. Previous studies have demonstrated that targeted muscle training can enhance heart rate variability—a marker for autonomic balance—which facilitates entry into a more restorative sleep state [35]. Moreover, the low-impact nature of Pilates avoids the excessive sympathetic activation that may result from high-intensity exercise, maintaining a relatively stable internal environment and promoting a smooth transition into sleep [36].

From a neuroendocrine perspective, Pilates utilizes controlled breathing and meditation practices to directly regulate the autonomic nervous system by promoting parasympathetic activity and suppressing sympathetic arousal [37]. This dual modulation not only lowers cortisol levels but may also increase the secretion of sleep-promoting hormones such as melatonin [38]. Recent neuroscientific studies have shown that mindfulness and meditation training can induce neuroplastic changes in brain regions such as the prefrontal cortex and hippocampus, thereby improving emotional regulation and reducing symptoms of anxiety and depression—key psychological factors that adversely affect sleep quality [36, 39]. For example, Amzajerdi et al. found that both four-week and eight-week Pilates interventions significantly improved sleep quality in female college students [40], and long-term interventions (12–24 weeks) have shown sustained benefits [36, 41, 42]. In addition, Xie et al.'s network meta-analysis further confirmed that, among all exercise modalities, Pilates produced the most pronounced improvements in sleep quality [11].

In contrast, aerobic exercise (AE) has also been widely demonstrated to improve sleep quality, though its mechanisms differ. In our study, AE achieved a SUCRA ranking of 69.7%, second only to Pilates. AE primarily enhances sleep by regulating cardiopulmonary function, promoting endocrine balance (e.g., by increasing melatonin secretion) [43], and stabilizing circadian rhythms [44, 45]. Furthermore, long-term aerobic exercise has been shown to improve the balance between sympathetic and parasympathetic activities, thereby reducing stress levels and alleviating sleep disturbances related to anxiety and stress [46–50]. The sustained workload and consistent intensity of AE make it particularly effective in overall sleep quality improvement, especially for older adults and individuals with insomnia [51].

Combined aerobic and resistance training (AE + RT) integrates the benefits of both aerobic and resistance exercises. Its aerobic component improves cardiopulmonary function and metabolic rate [51], while the resistance training component enhances muscle strength and joint stability [52], thereby reducing discomfort due to muscle weakness and increasing sleep efficiency43. However, although AE + RT yields multiple health benefits, its capacity to modulate the neuroendocrine system is not as direct or pronounced as that of Pilates, resulting in a slightly less pronounced overall improvement in sleep quality.

Traditional Chinese sports (e.g., Tai Chi and Baduanjin) and yoga also play a positive role in improving sleep quality. These mind–body exercises utilize slow, coordinated movements combined with deep, controlled breathing and meditation to effectively reduce stress hormone secretion, regulate the autonomic nervous system, and lower inflammatory markers, thereby alleviating psychological stress and promoting relaxation [3, 7, 53, 54]. Although these modalities perform well in reducing anxiety and enhancing balance and proprioception, their targeted impact on relieving musculoskeletal discomfort is generally less pronounced than that of Pilates [55], leading to a somewhat lower overall effect on sleep quality.

These findings not only reveal the intrinsic differences in the mechanisms by which various exercise modalities improve sleep quality but also have significant implications for public health and clinical practice. Sleep disturbances are closely associated with cardiovascular diseases, metabolic syndrome, and mental health issues [56]. By simultaneously alleviating musculoskeletal discomfort and regulating the neuroendocrine system, Pilates offers a comprehensive intervention strategy for these problems [56–58]. For populations such as chronic pain patients, older adults, and individuals under high stress, Pilates—a low-impact, low-risk exercise modality with dual physical and psychological benefits—holds considerable application potential. Incorporating Pilates into community health promotion programs, rehabilitation clinics, and chronic disease management strategies may provide an economical and feasible approach to improving sleep quality and reducing the risk of related chronic diseases.

In summary, although aerobic exercise, AE + RT, traditional Chinese sports, and yoga each improve sleep quality through distinct mechanisms, Pilates, with its unique ability to concurrently regulate both physiological and neuroendocrine functions, exhibits a more pronounced therapeutic effect. These results are consistent with previous research, which indicates that interventions addressing both physical and psychological aspects are more effective in mitigating sleep disturbances [11, 39, 40], and they offer profound guidance for public health policy and clinical practice.

Dose-response relationship analysis

This study found a U-shaped relationship between overall exercise and sleep quality, with the optimal overall exercise dose identified as 920 MET-min/week. This suggests that excessive exercise may reduce the intervention effect. For instance, Passos et al. [9] found that, in patients with primary insomnia, a single session of moderate-intensity exercise resulted in significantly better outcomes in sleep latency (SL), total sleep time (TST), and sleep efficiency (SE) compared to high-intensity exercise. This may be due to excessive exercise causing fatigue and overtraining syndrome, affecting stress levels and circadian rhythms [9]. Similarly, Chin LM et al. reported that after 12 weeks of intense aerobic exercise, cognitive function improved significantly, but changes in total PSQI scores were not significant [59]. Based on these findings, a total exercise dose of 920 MET-min/week is recommended.

Additionally, the differences in the optimal doses of various exercise modalities reflect their specific physiological effects and exercise intensities. For example, the optimal dose for aerobic exercise was 1100 MET-min/week, primarily improving sleep through enhanced cardiopulmonary function and thermogenic effects [45]. In contrast, Pilates achieved significant effects at a much lower dose (390 MET-min/week), likely due to its low-intensity exercise model and its direct impact on the nervous system and psychological state [11, 60]. Traditional Chinese sports (730 MET-min/week) and yoga (510 MET-min/week) further confirmed the unique advantages of mind-body exercises. These exercises combine moderate intensity with psychological relaxation, avoiding the negative effects of high-intensity exercise while gradually adjusting the psychological state to promote sleep [7, 61, 62].

In comparison, resistance training (RT) demonstrated a U-shaped dose-response relationship with sleep quality; however, this relationship was not statistically significant. Nevertheless, the results of this study indicate that resistance training, when combined with aerobic exercise (AE + RT), has a more pronounced effect, with the maximum significant response observed at 1000 MET-min/week. This suggests that combined exercise modalities may be more effective in improving sleep.

Practical implications of the U-shaped dose-response relationship for exercise recommendations

The dose-response analysis of this study revealed a clear U-shaped relationship between exercise and improvements in sleep quality, indicating the existence of an optimal exercise dose (e.g., approximately 920 MET-min/week for overall exercise) at which the enhancement in sleep quality is most pronounced. This finding holds significant practical implications, as it suggests that both insufficient and excessive exercise may lead to suboptimal improvements in sleep quality.

On one hand, insufficient exercise may fail to provide adequate physiological and neuroendocrine stimulation, thereby not activating the mechanisms that facilitate sleep regulation [63]. Conversely, excessive exercise may induce an overactive physiological stress response, such as heightened sympathetic nervous system activity, increased cortisol levels, or even overtraining, all of which can adversely affect sleep quality [64]. Therefore, moderate exercise emerges as a key factor in enhancing sleep.

On the other hand, this U-shaped relationship provides a scientific basis for personalized exercise prescriptions. By quantifying exercise dose using a unified metric, such as MET-min, clinicians and public health experts can more accurately recommend the appropriate intensity and duration of exercise needed to achieve optimal improvements in sleep quality. For instance, for populations such as individuals with chronic pain, older adults, or those under high stress, adhering to this optimal exercise dose can effectively activate sleep-promoting mechanisms while avoiding the detrimental effects associated with excessive exercise.

Furthermore, this finding is consistent with the moderate-intensity exercise guidelines recommended by organizations such as the World Health Organization [65], which further underscores the importance of maintaining an appropriate level of physical activity in practical applications. Incorporating this optimal exercise dose into community health promotion, rehabilitation programs, and chronic disease management plans may not only improve sleep quality but also reduce the risk of cardiovascular disease and metabolic syndrome associated with sleep disturbances, thereby promoting public health on a broader scale.

In summary, the U-shaped dose-response relationship revealed in this study indicates that careful consideration of exercise dosage is crucial when developing exercise interventions aimed at improving sleep quality. By appropriately regulating exercise intensity and duration to reach the optimal dose, sleep quality can be maximized. This finding provides clear guidance for the optimization of exercise prescriptions and has far-reaching implications for both public health policy and clinical practice. (Table 3 lists exercise recommendations for improving sleep quality).

Comparison with existing studies

The findings of this study are highly consistent with existing literature. For instance, previous research has confirmed the significant effects of low-intensity mind-body exercises such as Pilates and yoga on improving sleep quality [10, 60]. Studies by Fleming and Lim demonstrated the positive impact of Pilates on mental health, including reducing anxiety and improving mood, which provides theoretical support for its prominent effects on sleep quality [39, 60]. Additionally, consistent with the studies by Alexandra and Zhou, aerobic exercise significantly promotes sleep by regulating circadian rhythms and core body temperature [45, 47].

However, unlike traditional meta-analyses, this study employed a network meta-analysis method, which not only provided a comprehensive comparison of various exercise modalities but also determined the most effective intervention using SUCRA rankings. Furthermore, this study is the first to utilize Bayesian dose-response analysis to quantify the optimal doses for different

Table 3 Exercise recommendations to improve sleep quality

Type of exercise	Minimum significant dose[a] (METs-min/week)	Intensity	Energy expenditure[b] (METs-min)	Minimum recommended accumulation[c] (min/week)	Minimum recommendations for exercise prescription[d] (sessions × min/per week)
AE	1100	Moderate	4.3(code 17200)	~255	5 ×~ 50 6 ×~ 45
		Vigorous	7.5(code 03016)	~146	3 ×~ 50 4 ×~ 40
AE + RT	1000	Moderate	4.3(code 02035)	~233	5 ×~ 50 6 ×~ 40
		Vigorous	7.5(mean of codes 01030, 02050)	~133	3 ×~ 45 4 ×~ 35
YOGA	510	Moderate	4.0(code 02160)	~128	3 ×~ 40 4 ×~ 30
Pilates	390	Moderate	2.8(code 02105)	~140	3 ×~ 45 4 ×~ 35
TCS	730	Moderate	3.3(code 15670)	~222	5 ×~ 45 6×~ 35

AE: Aerobic Exercise; RT: Resistance Training; AE + RT: Combined Aerobic and Resistance Training; TCS: Traditional Chinese Sports; CON: Control Group

[a] Determined based on dose–response relationships for specific exercise types

[b] Intensity coding was extracted from the 《Compendium of Physical Activities》 [14]: Code 17,200: walking, 3.5 mph, level, brisk, firm surface, walking for exercise; Code 03016: aerobic, step, with 6–8-inch step; Code 02035: circuit training, moderate effort; Code 01030: bicycling, 12–13.9 mph, leisure, moderate effort; Code 02050: resistance training (weight lifting, free weight, nautilus or universal), power lifting or body building, vigorous effort; Code 02160: yoga, power; Code 02105: Pilates, general; Code 15,670: Tai chi, qi gong, general

[c] Minimum weekly time of exercise

[d] Frequency and duration of each exercise, not counting warm-up and cool-down

exercise modalities, offering scientific evidence for personalized interventions.

Practical and applied significance

The findings of this study provide strong support for non-pharmacological intervention strategies to improve sleep quality. For individuals aiming to enhance sleep through exercise, Pilates and aerobic exercise are recommended as the preferred modalities. Additionally, controlling exercise dosage within the optimal range (e.g., 920 MET-min/week) can significantly enhance intervention effectiveness. This study offers scientific evidence for policymakers and healthcare practitioners, supporting the integration of exercise interventions into public health programs to promote better sleep quality at the population level.

Future research directions

Future research should investigate how different populations respond to varying exercise doses and modalities, particularly among high-risk groups such as older adults and individuals with chronic diseases. The unique physiological and endocrine characteristics of these groups may influence their optimal exercise dose. Employing rigorous study designs, stratified analyses, and objective sleep measurements (e.g., actigraphy or polysomnography) will facilitate the development of personalized exercise prescriptions, thereby more effectively improving sleep quality and enhancing the impact of clinical and public health interventions.

Methodological strengths and limitations

The primary strength of this study lies in the integration of network meta-analysis and Bayesian analysis, which systematically compared the intervention effects of various exercise modalities and quantified the optimal dose. This approach allows for the synthesis of both direct and indirect evidence, providing a more comprehensive and reliable evaluation of intervention effectiveness.

Despite the robust findings, several limitations warrant consideration. First, there is substantial heterogeneity in study quality among the included randomized controlled trials. Variations in randomization methods, allocation concealment, blinding procedures, and outcome reporting were observed. Some studies exhibited high or unclear risk of bias, which may have affected the pooled effect estimates and limits the generalizability of the findings.

Second, most studies relied on self-reported sleep measures, such as the Pittsburgh Sleep Quality Index (PSQI), Epworth Sleepiness Scale (ESS), and Insomnia Severity Index (ISI). Self-reported data are inherently susceptible to recall bias and social desirability bias, potentially compromising the accuracy of the reported sleep outcomes. Moreover, differences in the interpretation of questionnaire items across studies may have introduced additional variability in the assessment of sleep quality.

Third, the potential for publication bias and selective reporting cannot be overlooked. Studies with null or negative findings might be underrepresented in the literature, thereby possibly exaggerating the observed effects of the exercise interventions.

Collectively, these limitations suggest that while the current findings are promising, caution should be exercised in their interpretation. Future research should prioritize the use of objective sleep measurement tools (e.g., polysomnography or actigraphy) and adhere to more rigorous study designs to mitigate these issues and confirm the dose-response relationships observed.

Conclusion

This study systematically evaluated the effects of different exercise modalities and their doses on sleep quality using network meta-analysis and Bayesian dose-response analysis. The results showed that all exercise modalities significantly improved sleep quality, with Pilates being the most effective, followed by aerobic exercise and combined aerobic and resistance training. The relationship between exercise dosage and sleep quality followed a nonlinear U-shaped pattern, with an overall optimal dose of 920 MET-min/week. The optimal dose varied among exercise modalities, ranging from 390 MET-min/week for Pilates to 1100 MET-min/week for aerobic exercise. The study further emphasizes that moderate exercise is key to improving sleep, while excessive exercise may diminish the intervention effects due to fatigue and physiological stress. Mind-body exercises, such as Pilates and yoga, demonstrated unique advantages, making them ideal options for personalized interventions. This study provides an important reference for developing evidence-based exercise intervention strategies, while also laying a foundation for optimizing exercise modalities and doses and exploring the mechanisms by which exercise improves sleep in future research.

Supplementary Information

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Supplementary Material 1

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Author contributions

Hai wang: Data curation, Formal Analysis, Methodology, Supervision, Writing–original draft, Writing–review and editing. Yingxu Pan: Data curation, Formal Analysis, Writing–review and editing. Xianyang Xin: Data curation, Formal Analysis, Methodology, Writing–review and editing. Yingxu Pan: Formal Analysis, Supervision, Validation, Writing–review and editing.

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Data availability

All data and material reported in this review and meta-analysis were from peer-reviewed publications. The datasets supporting the conclusions of this article are included within the article and its additional files.

Declarations

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