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REVIEW

Different Intensities of Evening Exercise on Sleep in Healthy Adults: A Systematic Review and Network Meta-Analysis

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Abstract: The effects of different intensities of evening exercise on subsequent sleep remain contradictory. Thus, this systematic review and network meta-analysis aimed to compare and rank the effects of different intensities of acute evening exercise on sleep in healthy adults with good sleep. Articles were systematically searched journals indexed in the PubMed, Web of Science, Cochrane Library, Embase, and Scopus databases from inception to the 5th of May, 2022. The basic search terms included exercise, sleep and timing, which were combined with AND. Of the 12,203 retrieved, twenty-eight studies with 325 participants met the inclusion criteria. Results revealed that there were no significant differences in terms of impacts on sleep caused by different intensities of acute evening exercise, except that when compared to no exercise, acute evening high-intensity exercise decreased rapid eye movement sleep (mean difference [MD] = −1.95%, 95% credible interval [CI] = −3.58 to −0.35). Compared to no exercise, acute evening moderate-intensity exercise was ranked as the most potential method to improve sleep, displaying a trend to improve wake time after sleep onset (MD = −2.50 min, 95% CI = −8.17 to 1.62), sleep efficiency (MD = +0.41%, 95% CI = −0.71 to 1.66), the proportion of stage N1 (MD = −0.72%, 95% CI = −2.08 to 0.71) and N3 sleep (slow-wave sleep) (MD = +0.84%, 95% CI = −1.17 to 2.78). Acute evening low-intensity exercise displayed the greatest tendency to shorten sleep onset latency (MD = −1.02 min, 95% CI = −4.39 to 2.50) compared to no exercise. Overall, regardless of intensity, acute evening exercise completed before bedtime does not disrupt subsequent sleep in healthy young and middle-aged adults.

Keywords: evening exercise, sleep quality, exercise intensity, systematic review, network meta-analysis

Introduction

Sleep and exercise play the vital role in maintaining human health. The prevalence of insomnia ranges from 10% to 30% in the general population,[1] increasing the risk of variable diseases and affecting life expectancy.[2–5] Exercise has been proven to be a low-cost and effective way to improve sleep.[6,7] A previous systematic review and meta-analysis showed regular exercise and daytime acute exercise had beneficial effects on sleep quality.[8] Time-use epidemiology showed that exercising and sleeping time competed with each other in daily life.[9] Lack of time has become an obstacle hindering people's exercise.[10] Exercise in the evening progressively becomes a good option for people burdened with day-to-day work. The appearance of 24-hour gym also provides the environment for evening exercise.[11] Nonetheless, the American Academy of Sleep Medicine (AASM) does not recommend exercising in the evening as it would cause arousal and disrupt subsequent sleep.[12] A cross-sectional study found that most people reported that evening exercise did not disrupt their sleep.[13] Some studies also showed that exercise in the evening did not disrupt sleep but rather had small to moderate beneficial effects on sleep.

Dworak et al found that compared to no exercise, only acute evening high-intensity exercise (HIE) made the positive modification to sleep efficiency (SE), sleep onset latency (SOL) and slow-wave sleep (SWS) while evening moderate-intensity exercise (MIE) had no significant effects on sleep in children.[14] Not inconsistent with Dworak et al, Oda and

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Shirakawa suggested acute evening HIE delayed sleep onset (+ 14 min), shortened total sleep time (TST) and decreased SE in active young adults, whereas evening MIE did not disrupt sleep.[15] The level of delayed sleep onset found by Oda and Shirakawa was greater than that previously reported in the study of Browman and Tepas (+6.5min).[16] Ramos-Campo et al recruited recreational ultra-endurance male runners to conduct acute morning MIE, morning HIE, evening MIE and evening HIE in a random sequence. A significantly higher average time of each awakening was observed in acute evening HIE than in the other three interventions.[17] The result of Ramos-Campo et al study suggested that exercise intensity was as important as training time in the evening or the morning.[17]

Actually, the effects of different evening exercise intensities on sleep are still a hot spot, leading to debates. Vlahoyiannis et al found that acute evening sprint interval training increased TST compared to MIE and no exercise. Moreover, compared to no exercise, sprint interval training also improved SE and shortened wake time after sleep onset (WASO).[18] A recent study by Thomas et al of endurance-trained runners showed that compared to no exercise, both acute evening HIE and low-intensity exercise (LIE) increased TST and shortened WASO despite the increase in cardiac autonomic activity.[19] Myllymäki et al also found that acute evening LIE, MIE and HIE did not disrupt sleep quality in young adults.[20] Conversely, Browman and Tepas found that even evening LIE ended 2 h before bedtime delayed sleep onset compared to no exercise in undergraduates.[16] It remains unclear whether acute evening exercise with different intensities disrupts sleep.

The controversies of previous studies might be attributed to the different times of evening exercise, the hours from the cessation of exercise to bedtime, the exercise modality, the physical activity level of participants, and the duration of evening exercise.[21,22] Furthermore, there might be an intensity threshold for the effects of evening exercise on sleep. Previous pairwise meta-analyses only focused on comparing high-intensity or moderate-intensity exercise with no-exercise controls, lacking comprehensive comparisons of different intensities of acute evening exercise.[21,22] It was necessary to conduct a comprehensive analysis of currently available data regarding acute evening exercise on sleep.

The current systematic review and network meta-analysis (NMA), which would combine direct and indirect evidence to potentially improve the precision of the effect estimates,[23,24] aimed to compare and rank different intensities of acute evening exercise on sleep in healthy adults. Owing to the larger magnitude of physiologic excitement that might be induced by HIE, we hypothesized that performing HIE before bedtime would disrupt sleep compared to no exercise, whereas performing MIE and LIE would not.

Materials and Methods

Search Strategy

The search was performed in the PubMed, Web of Science, Cochrane Library, Embase and Scopus databases from inception to the 5th of May, 2022. The basic search strategy consisted of the keywords and MeSH terms related to the intervention (exercise), the outcomes (sleep) and the timing (evening), which was combined with "AND". The detailed search strategy for Pubmed was: (exercise [mesh] OR sports [mesh] OR physical exertion [mesh] OR "interval training" [tiab] OR aerob* [tiab] OR endurance [tiab] OR strength* [tiab] OR sprint* [tiab] OR anaerob* [tiab] OR exercise [tiab] OR "physical activity" [tiab] OR "high intensity training" [tiab] OR run* [tiab] OR cycling [tiab] OR walk* [tiab] OR swim* [tiab] OR row* [tiab] OR "physical exertion" [tiab] or sport [tiab]) AND (sleep [mesh] OR sleep [tiab] OR "sleep architecture" [tiab] OR "sleep quality" [tiab] OR "sleep efficiency" [tiab] OR polysomnography [tiab] OR actigraphy [tiab]) AND (timing [tiab] OR evening [tiab] OR late-night [tiab] OR bedtime [tiab] OR afternoon [tiab] OR late [tiab] OR "time of day" [tiab] OR time-of-day [tiab] OR "pre sleep" [tiab] OR "before sleep"[tiab] OR pre-sleep [tiab] OR "going to sleep" [tiab] OR "going to bed" [tiab] OR "before bed"[tiab] OR nighttime [tiab] OR night-time [tiab] OR night [tiab]). In addition, we also searched the literature from references cited in the included articles and previous systematic reviews.

Eligibility Criteria

The population, intervention, comparison, outcome and study design (PICOS) framework was used to measure the eligibility criteria. Inclusion criteria for this systematic review and network meta-analysis included: 1) Population: healthy adults (18–65 years) with normal sleep. 2) Intervention: acute exercises in the evening (less than 4h before bedtime or if stated to be conducted in the evening) (high intensity: ≥77% maximal heart rate (HRmax), ≥60% heart rate reserve (HRR) or VO_2 reserve (VO_2R), ≥64% maximal oxygen consumption (VO_2max) or rating of perceived exertion (RPE) ≥14; moderate intensity: 64–76% HRmax, 40–59% HRR or VO_2R, 46–63% VO_2max or RPE 12–13; low intensity: ≤63% HRmax, ≤39% HRR or VO_2R, ≤45% VO_2max or RPE ≤11).[22,25] 3) Comparison: no exercise, LIE, MIE or HIE compared with each other 4) Outcomes: sleep quality and sleep quantity were objectively measured by polysomnography (PSG) and actigraphic sleep parameters and subjectively measured by questionnaires. 5) Study design: randomized controlled trials, randomized crossover trials and within-subject designs written in English were included.

Data Extractions and Risk of Bias Assessment

Two of the authors independently read the full text of included literature and extracted outcomes in an unblinded manner. Any disagreements were resolved by discussion with a third author to achieve consensus. The extracted information included (1) authorship and study design; (2) participant characteristics (sample size, age, gender, physical activity level); (3) intervention characteristics (exercise intervention type, duration, intensity and timing of exercise before bedtimes); (4) bedtimes; (5) sleep measurements; (6) sleep outcomes. The primary outcomes were: TST, SE, SOL, WASO, and sleep architecture including the proportion of stages N1, N2, N3, SWS, and rapid eye movement (REM) sleep. If a study reported the primary outcomes measured by actigraphy and PSG, the PSG data would be extracted for our network meta-analysis. Actigraphy is one-dimensional, while polysomnography includes at least three different types of data (electroencephalogram, electrooculogram, electromyogram) that together determine whether a person is asleep or awake.[26] Therefore, PSG is the "gold standard" for the sleep study.[26] The secondary outcome was subjective sleep quality (SSQ).

Risk of bias was measured by using the revised Cochrane risk of bias tool for crossover trials (RoB 2.0), which considered the crossover designs. ROB 2.0 consisted of 5 domains: (1) bias arising from the randomization process; (2) bias due to deviations from the intended intervention; (3) bias due to the missing outcome data; (4) bias in the measurement of the outcome; (5) bias in the selection of the reported result. Each domain had signaling questions, requiring the assessors to respond "probably yes", "yes", "probably no", "no" or "no information". According to an algorithm to the judgment of each domain, the included studies were rated as "low risk of bias", "some concerns" or "high risk bias". The assessment was conducted by two authors independently in an unblinded manner.

Statistical Analysis

Means and standard deviations (SDs) were extracted from included studies. If the study only reported standard errors (SEs), SDs were calculated by the following formula: $SD = SE * \sqrt{N}$.

Mean differences (MDs) and 95% credible intervals (CIs) were calculated for measuring the effect sizes of each objective sleep outcome, whereas standardized mean differences (SMDs) and 95% CIs were calculated for measuring the effect sizes of subjective sleep quality because of different evaluation methods in included studies. For this NMA, heterogeneity was assessed by I^2 static. Values of $I^2 \leq 25\%$, $25\% < I^2 \leq 50\%$, $50\% < I^2 \leq 75\%$, and $I^2 > 75\%$ indicated no significant heterogeneity, low heterogeneity, medium heterogeneity, and high heterogeneity, respectively.

Bayesian effects network meta-analysis (NMA) was performed by using the "gemtc" package in R (version 4.2.0). Four Markov chain Monte Carlo chains were used to assess convergence with 20,000 iterations. Posterior summaries were then obtained from 50,000 iterations in each of the four chains. Convergence was assessed by using potential scale reduction factors (PSRF). The value of PSRF approached 1, indicating the convergence of the model was satisfactory.

Network plots were created to describe different intensities of acute evening exercise on outcomes. Nodes in the geometry represented different intensities of acute evening exercise and no-exercise control and the lines represented direct comparisons for interventions. The size of each node and the thickness of each line were proportional to the number of participants.

Global inconsistency was assessed by comparing the difference values of differences in conditions (DIC) between the consistency and inconsistency models. A difference value of DIC >5 indicated an inconsistent model.[27] Local inconsistency was evaluated by using the node splitting method. In addition, probability ranking for each intervention was conducted by the surface under the cumulative ranking curve (SUCRA) values ranging from 0% to 100%, where 100% indicated the best intervention.

To test the robustness of the results and examine the effects of potential modifiers on primary outcomes, subgroup analyses were performed according to the following variables: time of evening exercise (early evening: 16:00 to 20:00, late evening: after 20:00), hours from cessation of exercise to bedtime (0.5–1.5 h, 2 or >2–4 h), exercise modality (cycling, running), physical activity level of participants (sedentary, physically fit), exercise duration (25–30 min, >30–60 min). Publication bias was subjectively assessed with comparison-adjusted funnel plots. In all the analyses, a statistical significance was set at $p < 0.05$.

This systematic review and network meta-analysis was carried out in conformance with the PRISMA Extension for Network Meta-analyses (PRISMA-NMA) checklist.[28] The protocol for this systematic review and NMA has been registered on PROSPERO (CRD42022327787).

Results

Study Selection

A PRISMA diagram of literature search and selection is presented in Figure 1. A total of 12,203 studies were initially identified from PubMed, Web of Science, Cochrane Library, Embase, and Scopus databases. After removing duplicates (n = 4131) and reading titles and abstracts (n = 8072), the remaining studies (n = 48) progressed to full-text review and 24 studies met the inclusion criteria. Twenty-four studies were excluded for the following reasons: (1) daytime exercise (n = 10), (2) poor sleep participants (n = 2), (3) adolescents (n = 1), (4) observational or cross-sectional designs (n = 5), (5) review (n = 2), (6) no sleep data (n = 3), (7) interrupted sleep (n = 1). In addition, four additional studies were found from the references of eligible studies. Overall, 28 studies were finally included in this systematic review and network meta-analysis.

Study Characteristics

The characteristics of the included studies are presented in Table 1. The SUCRA values were shown in Table 2. The network plot of eligible comparisons on objective and subjective sleep quality are shown in Figure 2. Four nodes were

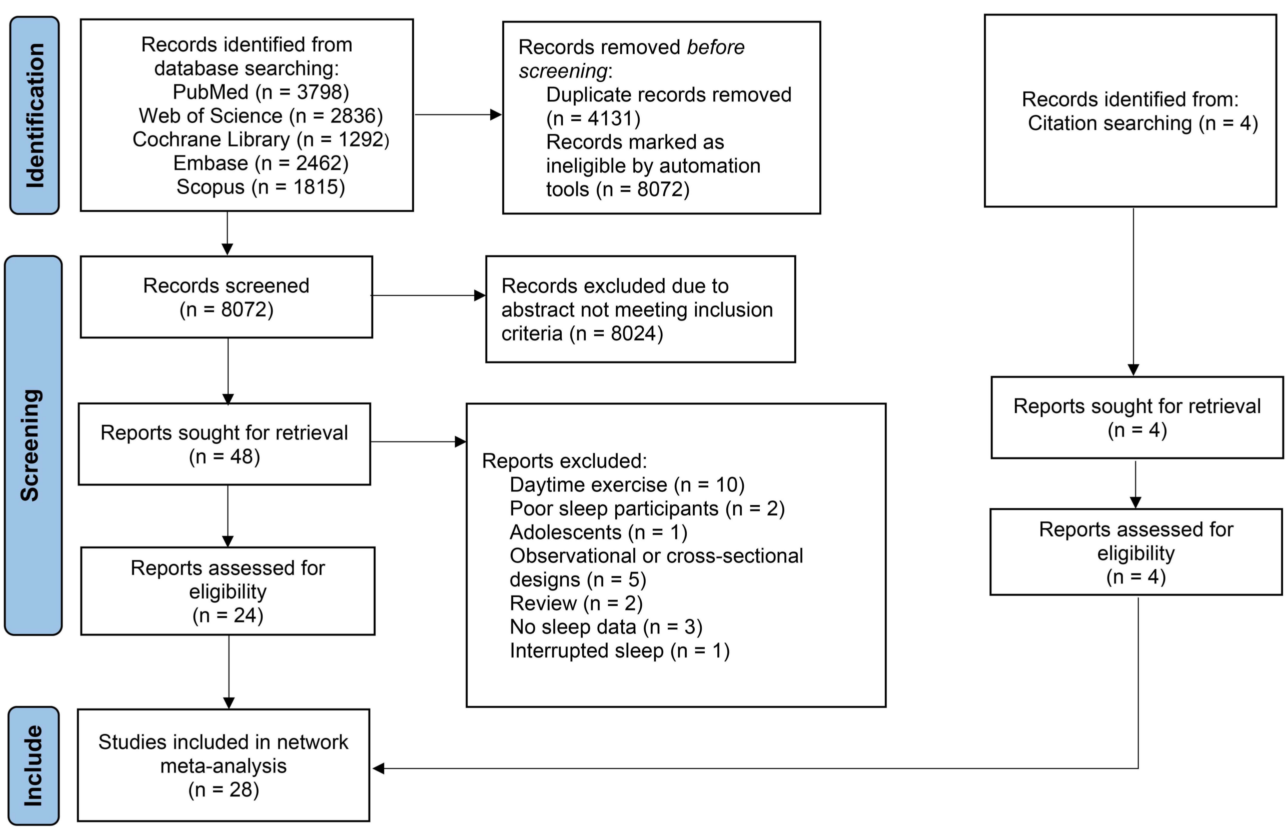

Figure 1 PRISMA flow diagram of systematic search and included trials.

Notes: PRISMA figure adapted from Liberati A, Altman D, Tetzlaff J, et al. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. Journal of clinical epidemiology. 2009;62(10). Creative Commons.[29]

Table 1 Descriptive Characteristics of the Included Studies

Study	Participants	Design	Arms	Outcomes	Timing of Exercise interventions (Start – end Time)	Sleep Time
Arias et al 2016[30]	**N** = 9 young non-professional sportsmen (performing exercise about 3 times per week) **M** = all males **Age** = 18–38 years	Crossover trial	**HIE**: 5 sets of 20m-SRT interspersed with 6 min breaks **CON**: no exercise	**Actigraphy**: SE, SOL, Movement and fragmentation index **Subjective sleep quality**: NSFSD	17:00 - NR / 21:00 - NR ended > 4 h before bedtime	Usual bedtime/ad libitum
Aloulou et al 2020[31]	**N** = 11 well-trained male runners **M**: all males **Age** (mean ± SD) = 32.3 ± 5.2 years **Chronotype**: neither-types	Crossover trial 1 week washout period	**HIE**: 45 min running at uphill (+10%) at 65% MAS; downhill (−12.5%) at 80% MAS & level treadmill (0%) at 60% MAS to maximal speed. Average HR was 83% HRmax **CON**: no exercise	**PSG**: TIB, TST, WASO, SE, SOL, REM-L, %N1, %N2, %N3, %REM **Actigraphy**: TST, WASO, SOL, SE **Subjective sleep quality**: SSI score	21:00–22:00 ended 2 h before bedtime	00:46–9:00
Browman & Tepas 1976[16]	**N** = 9 male undergraduates, average physical fitness **M**: all males **Mean age** = 18.89 years	Crossover trial	**LIE**: 45 min cycling alternating 5 min of cycling with a load of 0.5 kg and 3-min breaks **CON**: no exercise	**PSG**: TST, %N1, %N2, %SWS, % REM, REM-L	Started 2.5 h prior to bedtime; ended 2 h before bedtime	Usual bedtime/ad libitum, 7.5 h sleep duration
Bulckaert et al 2011[32]	**N** = 9 young adults with good physical health **M**: 4 males **Age** (mean ± SD) = 23 ± 3.4 years	Crossover trial	**MIE**: 60 min cycling at 65–75% HRmax **CON**: reference night	**PSG**: SOL, %N2, %SWS, %REM	Started 2 h before bedtime ended 1h before bedtime	22:30–23:00 to 7:00
Driver et al 1988[33]	**N** = 9 young sedentary women **M**: 0 male **Age** (mean ± SD) = 24 ± 3 years	Crossover trial 1 day washout period	**HIE**: 60 min cycling at 70% VO_{2peak} **CON**: no exercise	**PSG**: SOL, REM-L, N2, SWS **Subjective sleep quality**	16:00–19:00	NR
Flausino et al 2012[46]	**N** = 17 healthy young good sleepers with no regular exercise habits **M** = all males **Age** (mean ± SD) = 27.2 ± 3.6 years	Crossover trial ≥ 1 week washout period	**HIE**: 30 and 60min running at Delta 50 (50% above VT1) **MIE**: 30 and 60 min running at VT1 **CON**: no exercise	**PSG**: TST, WASO, SOL, SE, % N1, %N2, %SWS, % REM, REM-L	20:00–20:30 ended 2 h before bedtime	22:30–23:00 to 06:00–07:00
Hayashi et al 2014[50]	**N** = 9 sedentary college students **M** = all males **Age** (mean ± SD) = 22.8 ± 2.0 years	Crossover trial ≥ 3 days washout period	**HIE**: 60 min cycling at 80% HRmax **MIE**: 60 min cycling at 65% HRmax **LIE**: 60 min at 50% HRmax **CON**: no exercise	**PSG**: TIB, TST, SE, SOL, REM-L, WASO, %N1, %N2, %N3, %REM	Ended 2 h before bedtime	Go to bed 2 h after exercise

(*Continued*)

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Table 1 (Continued).

Study	Participants	Design	Arms	Outcomes	Timing of Exercise interventions (Start – end Time)	Sleep Time
Kern et al 1995[47]	**N** = 10 healthy non-professional male triathletes **M** = all males **Age** = 20–26 years	Crossover trial ≥1 week washout period	**MIE**: 120–150 km cycling at moderate intensity **LIE**: 40 km cycling at low intensity **CON**: no exercise	**PSG**: TST, SOL, %N1, %N2, SWS, %REM, REM-L	16:00–20:30 (LIE) 18:00–20:30 (MIE) ended 2.5 before bedtime	23:00–7:00
Larsen et al 2019[34]	**N** = 11 inactive men **M** = all males **Age** (mean ± SD) = 49 ± 5 years	Crossover trial ≥5 days washout period	**HIE**: 30 min HIIT (60s cycling at 100% VO_{2peak}, interspersed with 240s active recovery at 50% VO_{2peak}) **CON**: baseline or no exercise	**PSG**: TIB, TST, SE, SOL, REM-L, WASO, %N1, %N2, %N3, %REM **Actigraphy**: TIB, TST, SE, SOL, WASO, number of awakenings	19:00–20:00 3 h before bedtime	Ad libitum bedtimes and wake time
Miura et al 2016[35]	**N** = 10 young sedentary adults **M** = all males **Age** = 18–25 years	Crossover trial 1 week washout period	**MIE**: 60-min upright cycling at 60 rpm at an intensity of 50% HRR **CON**: no exercise	**Actigraphy**: TST, WASO, SE, SOL, REM, stage 1and2 sleep, stage 3 and 4 sleep	17:00–18:00 ended > 4 h before bedtime	23:00–00:00
Myllymäki et al 2011[36]	**N** = 11 physically fit young adults **M** = 7 males **Age** (mean ± SD) = 26 ± 3 years	Crossover trial 1 week washout period	**HIE**: 30 min incremental cycling until exhaustion at 100 W for men and 25 W for women **CON**: no exercise	**PSG**: TST, SOL, %N1, %N2, %N3, %REM **Actigraphy**: TST, SE, FI, total activity **Subjective sleep quality**: questionnaire	21:00 - ended 2 h before bedtime	NR
Myllymäki et al 2012[20]	**N** = 14 physically healthy young adults **M** = all males **Age** (mean ± SD) = 35.9 ± 4.3 years	Crossover trail ≥ 48h washout period	**HIE**: 30 min running at 75% VO_{2max} **MIE**: 30 min running at 60% VO_{2max} **LIE**: 30 min running at 45% VO_{2max} **CON**: no exercise	**Actigraphy**: TST, SE, FI, activity counts **Subjective sleep quality**: VAS	18:00–19:00, ended 4 h before bedtime	23:28–07:04
Miller et al 2020[11]	**N** = 12 healthy young males with regular exercise at least 3 times per week **M** = all males **Age** (mean ± SD) = 21.9 ± 2.7 years	Crossover trail 1 day washout period	**MIE**: 30 min cycling at 75% HRmax **CON**: no exercise	**PSG**: TST, SOL, N1, N2, N3, REM, SE **Subjective sleep quality**: Karolinska Sleep Scale	20:45–21:30 ended 1.5 h before bedtime	23:00–8:00
O'Connor et al 1998[48]	**N** = 8 physically active college students **M** = all males **Age** (mean ± SD) = 20.8 ± 2 years	Crossover trial	**MIE**: 60 min cycling at 60% VO_{2peak} **LIE**: 60 min cycling at 20% VO_{2peak} **CON**: no exercise	**Sleep Assessment Device**: SOL, TST, SE, awakenings	Late evening ended 1.5 h before bedtime	23:00–8:00
Oda & Shirakawa 2014[15]	**N** = 12 active young adults **M** = all males **Age** (mean ± SD) = 19.8 ± 0.9 years	Crossover trial 4–7 days washout period	**HIE**: 30 min running at 80% HRR **MIE**: 30 min running at 60% HRR **CON**: no exercise	**PSG**: TST, WASO, SOL, SE, N1, N2, SWS and REM, REM-L **Subjective sleep quality**: Sleep Inventory of Oguri-Shirakawa-Azumi	21:20–22:00 ended 1 h before bedtime	23:00–7:00

Park et al 2021[37]	**N** = 9 healthy young men with regular exercise no more than twice a week **M** = all males **Age** (mean ± SD) = 23.8 ± 2.7 years	Crossover trial 1 week washout period	**MIE**: 60 min running at 60% VO2max **CON**: no exercise	**PSG**: TIB, TST, SOL, SE, N1, N2, SWS, REM-L**Subjective sleep quality**: Sleep Inventory of Oguri-Shirakawa-Azumi	17:00–18:00 ended 6 h before bedtime	23:30–24:30 to 8:00
Robey et al 2013[38]	**N** = 11 athletes **M** = all males **Age** (mean ± SD) = 26 ± 4.4 years	Crossover trial 1 week washout period	**HIE**: 30 min cycling at 75% peak power + maximal time trial **CON**: no exercise	**PSG**: TIB, TST, SE, SOL, %WASO, %N1, %N2, %N3, %REM, REM-L, %NERM **Actigraphy**: TST, SOL, WASO, SE	19:00–20:00 ended 2.5 h before bed	22:30–6:00
Ramos-Campo et al 2019[17]	**N** = 14 recreational ultra-endurance male runners **M** = all males **Age** (mean ± SD) = 27.6 ± 7.4 years **Chronotype**: neither-types	Crossover trial ≥ 72h washout period	**HIE**: 7 x 3 min running at 100% VO_{2max}, interspersed with 3 min passive rest **MIE**: 60 min running at 60% VO_{2max}	**Actigraphy**: TIB, TST, SE, wake of time, number of awakenings, average time of each awakening **Subjective sleep quality**: Karolinska Sleep Diary	20:00–21:00 ended 2–4 h before bedtime	NR
Saidi et al 2020[39]	**N** = 16 healthy college students **M**: 8 males **Age** (mean ± SD) = 22.31 ± 1.44 years **Chronotype**: neither-types	Crossover trial	**MIE**: 50 min running at 60% HRmax **CON**: no exercise	**Actigraphy**: TIB, TST, SE, WASO, SOL	18:30–19: 30 ended 4h before bedtime 20:30–21:30 ended 2h before bedtime	22:00–8:00
Thomas et al 2020[19]	**N** = 8 endurance trained runners **M** = all males **Age** (mean ± SD) = 27.8 ± 6.9 years **Chronotype**: neither-types	Crossover trial ≥ 4 days washout period	**HIE**: 6×5 min running at 90% VO_{2peak}, interspersed with 5 min at 60% VO_{2peak} **LIE**: 60 min running at 45% VO_{2peak} **CON**: no exercise	**PSG**: TIB, TST, SOL, REM latency, WASO, %N1, %N2, SWS, %REM**Actigraphy**: TST, SOL, activity counts, FI**Subjective sleep quality**: Likert scale from the Consensus sleep diary	17:50 - ended 3.5h before bedtime	22:30–7:00
Ucar et al 2017[40]	**N** = 20 healthy male college students **M** = all males **Age** = 20–24 years	Crossover trial	**HIE**: 90 min hard football match **CON**: no exercise	**Subjective sleep quality**: Karolinska Sleep Diary, PSQI	21:30–23:00 ended 2.5 h before bedtime	1:39–8:08
Vitale et al 2017[42]	**N** = 23 college soccer players **M** = all males **Age** (mean ± SD) = 21.7 ± 2.72 years **Chronotype**: both morning-type and evening-type	Crossover trial 1 week washout period	**HIE**: 4×4 min running at 90–95% HRmax, interspersed with 3 min recovery at 70% HRmax **CON**: pre exercise	**Actigraphy**: SE, SOL, activity counts, MFI, moving time, immobility time	20:00 - NR	NR
Vincent et al 2020[41]	**N** = 12 healthy males with regular exercise at least 3 times per week **M** = all males **Age** (mean ± SD) = 27.3 ± 3.4 years	Crossover trial 4 days washout period	**MIE**: 30 min cycling at 75% HRmax **CON**: no exercise	**PSG**: TST **Subjective sleep quality**: Karolinska Sleep Diary	20:45–21:30 ended 1.5h before bedtime	23:00–8:00

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Table 1 (Continued).

Study	Participants	Design	Arms	Outcomes	Timing of Exercise interventions (Start – end Time)	Sleep Time
Vlahoyiannis et al 2021[18]	**N** = 10 recreationally trained young males **M** = all males **Age** (mean ± SD) = 23.9 ± 3.3 years **Chronotype**: neither-types	Crossover trial 1 week washout period	**HIE**: 10×1 min cycling at 90% Wmax interspersed with 1 min recovery at 20% Wmax / 6×20 s cycling at 140% Wmax, interspersed with 140s active recovery at 20% Wmax **MIE**: 45 min cycling at 70% Wmax **CON**: no exercise	**PSG**: TIB, TST, SE, SOL, WASO, METs	19:00–20:00 ended 3 h before bedtime	Ad libitum sleep duration
Wong et al 2013[49]	**N** = 12 healthy sedentary young adults **M** = 3 males **Age** (mean ± SD) = 25.2 ± 4.0 years	Crossover trial ≥ 2 days washout period	**HIE**: 40 min running at 65% VO2max / 75% VO2max **MIE**: 40 min running at 55% VO_{2max} **LIE**: 40 min running at 45% VO_{2max} **CON**: no exercise	**PSG**: TST, SOL, WASO, REM-L, SE, % SWS, %REM	Started 6 h prior to bedtime; ended 4–5 h before bedtime	Bedtime 22:30–01:30 (majority 23:30), ad libitum wake time
Yoshida et al 1998[43]	**N** = 5 healthy university male students with no exercise habits **M** = all males **Age** (mean ± SD) = 21.0 ± 0.7 years	Crossover trial 1–3 weeks washout period	**MIE**: 50 min aerobic exercise at AT **CON**: no exercise	**PSG**: SWS **Subjective sleep quality**: Sleep Inventory of Oguri-Shirakawa-Azumi	16:30–17:30 ended > 4 h before bedtime 20:30–21:30 ended 2 h before bedtime	23:30–7:30
Youngstedt et al 1999[44]	**N** = 16 highly fit cyclists **M** = all males **Age** (mean ± SD) = 27.3 ± 4.3 years	Crossover trial 2–4 weeks washout period	**HIE**: 3 h cycling at 65–75% of HRR under bright light (3000 lux) in a laboratory **CON**: no exercise or bright light alone	**Actigraphy**: TST, SOL, WASO **Subjective sleep quality**: SOL, WASO, subjective rating of insomnia	Ended 30 min before bedtime	30 min after exercise and were awakened at their usual time
Yamanaka et al 2015[45]	**N** = 8 healthy young males, paid volunteers, with a habit of light exercise once or twice a week **M**: all males	Crossover trial	**MIE**: 90 min cycling at 65–75% HRmax (2 x 45 min interspersed with a 10-min recovery) **CON**: no exercise	**PSG**: TST, SOL, SE, WASO	18:00–20:00 ended 4h before bedtime	24:00–8:00

Abbreviations: M, male; LIE, low-intensity exercise; MIE, moderate-intensity exercise; HIE, high-intensity exercise; TIB, time in bed; TST, total sleep time; SOL, sleep onset latency; WASO, wake time after sleep onset; SE, sleep efficiency; REM, rapid eye movement; REM-L, rapid eye movement latency; SWS, slow-wave sleep; NERM, non-rapid eye movement; N1, stage N1 sleep; N2, stage N2 sleep; N3, stage N3 sleep; SQ, sleep quality; SSQ, subjective sleep quality; PSG, polysomnography; SRT, Shuttle-Run-Test; NSFSD, National Sleep Foundation-Sleep Diary; SSI, Spiegel Sleep Inventory; KSS, Karolinska Sleep Scale; HR, heart rate; MAS, maximal aerobic speed; VT1, ventilatory threshold 1; PSQI, Pittsburgh Sleep Quality Index; VO_{2peak}, peak oxygen uptake; FI, fragmentation index; NR, not reported; METs, metabolic equivalent of tasks; Wmax, maximal power output; MAS, Maximal Aerobic Speed.

Table 2 SUCRA Values of Different Intensities of Acute Evening Exercise for Sleep Outcomes

	TST	SOL	WASO	SE	REM-L	N1	N2	N3	REM	SSQ
No exercise	71.5%	27.5%	26.4%	40.2%	12.8%	20.1%	9.3%	55.0%	17.9%	71.8%
LIE	37.0%	61.7%	59.4%	60.2%	69.3%	47.4%	55.2%	25.0%	23.1%	43.9%
MIE	47.3%	60.3%	74.8%	72.1%	46.9%	67.2%	66.6%	86.2%	73.6%	73.1%
HIE	44.2%	50.4%	39.4%	27.4%	71.0%	65.3%	68.9%	33.9%	85.4%	11.2%

Abbreviations: LIE, low-intensity exercise; MIE, moderate-intensity exercise; HIE, high-intensity exercise; TST, total sleep time; SOL, sleep onset latency; WASO, wake time after sleep onset; SE, sleep efficiency; REM, rapid eye movement; REM-L, rapid eye movement latency; N1, stage N1 sleep; N2, stage N2 sleep; N3, stage N3 sleep; SSQ, subjective sleep quality.

included in the NMA. Each node denoted different interventions: no-exercise control, evening low-intensity exercise (LIE), evening moderate-intensity exercise (MIE), and evening high-intensity exercise (HIE). Among the 28 crossover trials from 1976 to 2021 included in the analyses, 19 studies had two arms,[11,16,17,30–45] 6 had three arms[15,18,19,46–48] and 3 had four arms.[20,49,50] There were 325 participants (mean age: 25 years old, range: 18–49 years), of which 290 participants were male, and 35 participants were female. Twenty-three studies were men only,[11,15–20,30,31,34,35,37,38,40–48,50] one was women only[33] and the remaining four included both men and women.[32,36,39,49] In addition, most of the participants were physically active or trained populations, and the others were sedentary participants.

In terms of sleep outcomes, 22 of 28 studies reported on the results of the TST[11,15–20,31,34–39,41,44–50] and SOL.[11,15,18,19,30–39,42,44–50] 18 of 28 studies reported on the results of the SE.[11,15,17,18,20,30,31,34,35,37–39,42,45,46,48–50] Two studies did not report SE and calculations were conducted by TST and TIB.[19,36] Half of the studies (n = 14) reported on the results of the WASO[11,15,18,19,31,34,35,38,39,44–46,49,50] and SSQ (n = 14).[11,15,17,19,20,30,31,33,36,37,40,41,43,44] Less than half of the studies reported the latency of rapid eye movement (REM-L) (n = 12),[15,16,19,31,33,34,37,38,46,47,49,50] the proportion of REM sleep (n = 11),[16,19,31,32,34,36,38,46,47,49,50] the proportion of stage N3 sleep (SWS) (n = 11),[16,19,31,32,34,36,38,46,47,49,50] the proportion of stage N1 sleep (n = 9),[16,19,31,34,36,38,46,47,50] and the proportion of N2 sleep (n = 10).[16,19,31,32,34,36,38,46,47,50]

The evening exercises ranged from 25 min to 3 h and comprised cycling or running. Eleven of the included studies used early evening protocol (16:00–20:00),[18–20,33–35,37,38,45,47,49] and thirteen of the studies used late-evening protocol (after 20:00).[11,15–17,31,32,36,40–42,44,46,48] Three of the remaining studies used both early evening and late-evening protocols,[30,39,43] while one study did not mention the time to exercise in the evening.[50] Evening exercise ended 0.5 to 4 h before bedtime.

Quality Assessment

Details of RoB 2.0 in each included study were shown in Supplementary Table S1. The majority of included studies showed low risk bias, while eight studies had "some concerns" regarding the randomization process, wash-out period or missing outcome data.[11,16,20,33,35,40,48,49] Both "low risk bias" studies and "some concerns" studies were included in this network meta-analysis.

Network Meta-Analysis

TST

No significant difference was observed in regard to TST among these groups. In comparison with no exercise, the ranking probability based on the SUCRA values indicated that acute evening MIE had the lowest impact on TST (MD = −1.62 min, 95% CI = −9.17 to 6.00, SUCRA = 47.3%), followed by HIE (MD = −2.11 min, 95% CI = −10.01 to 6.24, SUCRA = 44.2%) and LIE (MD = −3.04 min, 95% CI = −10.19 to 7.34, SUCRA = 37.0%). Compared with LIE, acute evening MIE and HIE were comparable to each other in terms of the effects of increased TST, and no significant difference was found. Compared to MIE, though acute evening HIE reduced TST, no significant difference was observed (Figure 3).

SOL

No significant difference was observed in regard to SOL among these groups. In comparison with no exercise, according to the SUCRA values, acute evening LIE was ranked to be better for the shortening of SOL (MD = −1.02 min, 95% CI = −4.39

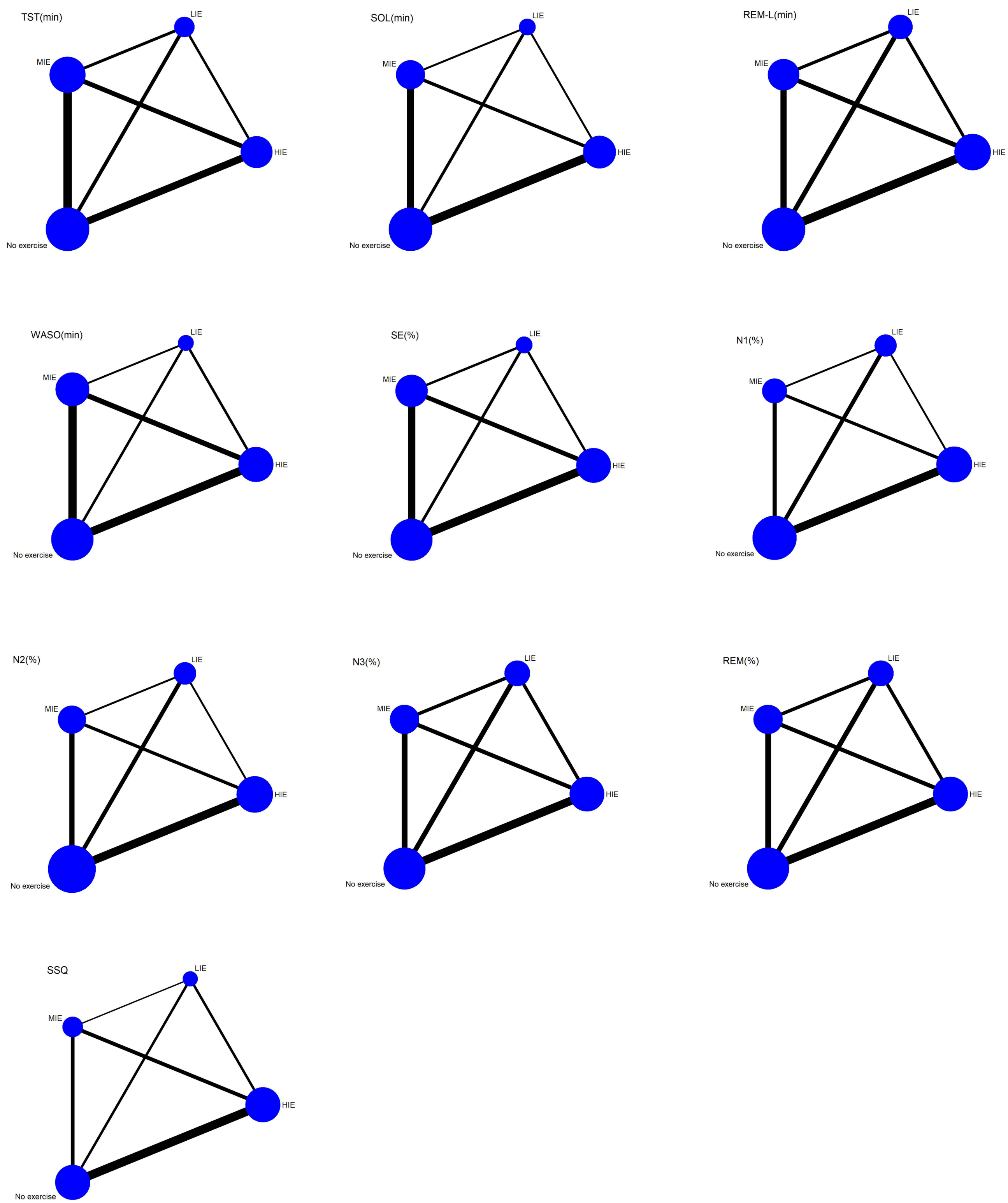

Figure 2 Network plots for comparisons of outcomes.

Abbreviations: LIE, low-intensity exercise; MIE, moderate-intensity exercise; HIE, high-intensity exercise; TST, total sleep time; SOL, sleep onset latency; WASO, wake time after sleep onset; SE, sleep efficiency; REM, rapid eye movement; REM-L, rapid eye movement latency; N1, stage N1 sleep; N2, stage N2 sleep; N3, stage N3 sleep; SSQ, subjective sleep quality.

to 2.50, SUCRA = 61.7%), followed by MIE (MD = −0.76 min, 95% CI = −2.87 to 1.28, SUCRA = 60.3%) and HIE (MD = −0.54 min, 95% CI = −2.31 to 1.31, SUCRA = 50.4%). Compared with LIE, acute evening MIE and HIE were comparable to each other in terms of the effects of increased SOL, and no significant difference was found. Compared to MIE, no significant difference was observed while acute evening HIE increased SOL (Figure 3).

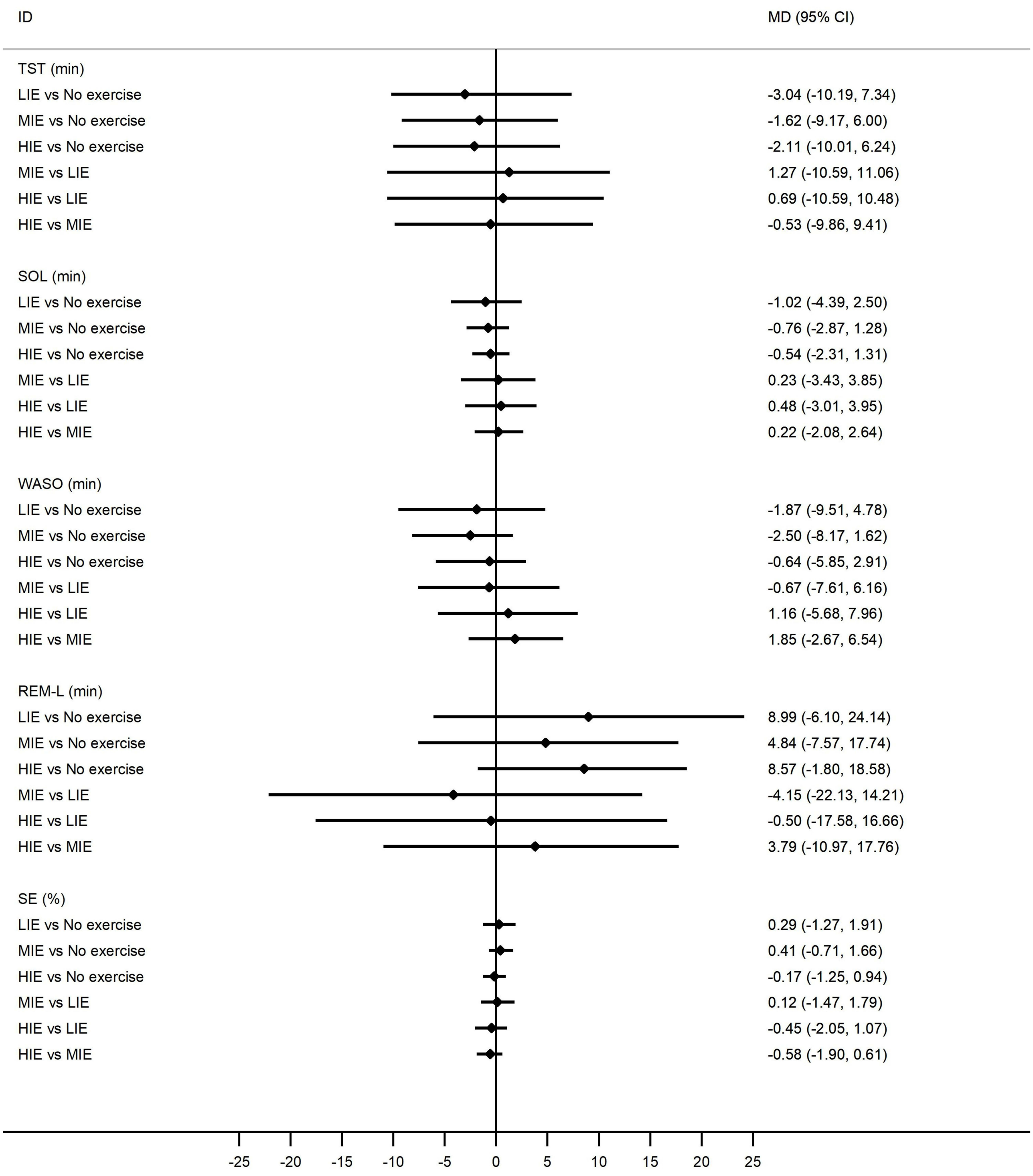

Figure 3 Forest plots of network meta-analysis of all comparisons for TST, SOL, WASO, REM-L, and SE.
Abbreviations: TST, total sleep time; SOL, sleep onset latency; WASO, wake time after sleep onset; REM-L, rapid eye movement latency; SE, sleep efficiency.

WASO

Regarding WASO, no statistically significant difference was observed among these groups. In comparison with no exercise, the SUCRA revealed that acute evening MIE was ranked the best method to shorten WASO (MD = −2.50 min, 95% CI = −8.17 to 1.62, SUCRA = 74.8%), followed by LIE (MD = −1.87 min, 95% CI = −9.51 to 4.78, SUCRA = 59.4%) and HIE (MD = −0.64 min, 95% CI = −5.85 to 2.91, SUCRA = 39.4%). Compared with LIE, acute evening MIE shortened WASO and HIE increased WASO, respectively, and no significant difference was found. Compared to MIE, no significant difference was observed while acute evening HIE increased WASO (Figure 3).

SE

Acute evening LIE, MIE and HIE yielded no significant effects on SE compared with no exercise. The MDs and 95% CIs of SE in the acute evening LIE, MIE, and HIE were +0.29% (95% CI = −1.27 to 1.91), +0.41% (95% CI = −0.71 to 1.66), and −0.17% (95% CI = −1.25 to 0.94), respectively. Acute evening MIE had the highest probability of being the best option to improve SE, based on the SUCRA values (72.1%). Compared with LIE, acute evening MIE improved SE, while HIE decreased SE, and no significant difference was found. Compared to MIE, no significant difference was observed while acute evening HIE decreased SE (Figure 3).

REM-L

In comparison with no exercise, although there were no significant effects, acute evening HIE was ranked the best intervention to increase REM-L (MD = +8.57 min, 95% CI = −1.80 to 18.58, SUCRA = 71.0%), followed by LIE (MD = +8.99 min, 95% CI = −6.10 to 24.14, SUCRA = 69.3%) and MIE (MD = +4.84 min, 95% CI = −7.57 to 17.74, SUCRA = 46.9%). Compared with LIE, acute evening MIE and HIE resulted in similar results, and no significant difference was found. Compared to MIE, no significant difference was observed while acute evening HIE increased REM-L (Figure 3).

The Proportion of Stage N1 Sleep

In comparison with no exercise, acute evening LIE, MIE, and HIE did not show significant reductions in the proportion of stage N1 sleep, showing MDs of −0.39% (95% CI = −2.49 to 1.59), −0.72% (95% CI = −2.08 to 0.71), and −0.66% (95% CI = −1.69 to 0.44), respectively. The ranking probability based on the SUCRA values indicated that acute evening MIE had the highest probability of being the best option to reduce the proportion of stage N1 sleep (SUCRA = 67.2%). Compared with LIE, both acute evening MIE and HIE resulted in a reduction of the proportion of stage N1 sleep, and no significant difference was found. Compared to MIE, no significant difference was observed while acute evening HIE increased stage N1 sleep (Figure 4).

The Proportion of Stage N2 Sleep

In comparison with no exercise, although there were no significant effects, acute evening HIE was regarded as the best method to increase the proportion of stage N2 sleep (MD = +2.09%, 95% CI = −0.12 to 4.34, SUCRA = 68.9%), followed by MIE (MD = +2.13%, 95% CI = −1.19 to 5.30, SUCRA = 66.6%) and LIE (MD = +1.62%, 95% CI = −1.45 to 4.68, SUCRA = 55.2%). Compared with LIE, both acute evening MIE and HIE resulted in increasing the proportion of N2 sleep, and no significant difference was found. Compared to MIE, no significant difference was observed while acute evening HIE decreased stage N2 sleep (Figure 4).

The Proportion of Stage N3 Sleep (SWS)

There was no significant difference observed in regard to the proportion of N3 sleep among these groups. In comparison with no exercise, the SUCRA revealed that acute evening MIE ranked the highest in terms of improving the proportion of N3 sleep (MD = +0.84%, 95% CI = −1.17 to 2.78, SUCRA = 86.2%), followed by HIE (MD = −0.41%, 95% CI = −2.04 to 1.24, SUCRA = 33.9%) and LIE (MD = −0.64%, 95% CI = −2.55 to 1.27, SUCRA = 25.0%). Compared with LIE, both acute evening MIE and HIE resulted in increasing the proportion of N3 sleep, and no significant difference was found. Compared to MIE, no significant difference was observed while acute evening HIE shortened stage N3 sleep (Figure 4).

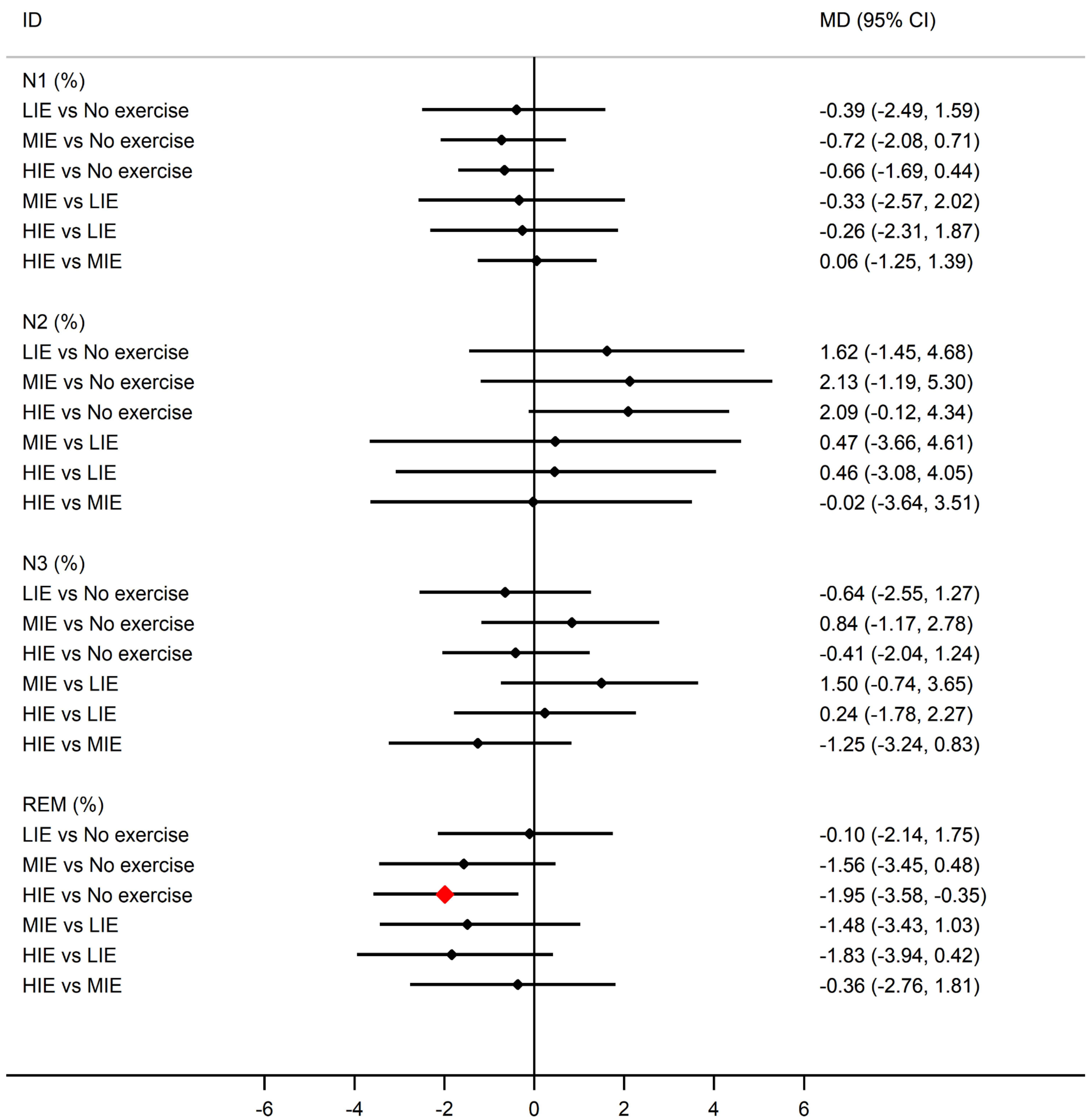

Figure 4 Forest plots of network meta-analysis of all comparisons for N1, N2, N3, and REM sleep.
Abbreviations: N1, stage N1 sleep; N2, stage N2 sleep; N3, stage N3 sleep (slow-wave sleep); REM, rapid eye movement.

The Proportion of REM Sleep

The NMA suggested that, in comparison with no exercise, acute evening HIE was ranked to be significantly better for the shortening of REM (MD = −1.95%, 95% CI = −3.58 to −0.35, SUCRA = 85.4%), followed by MIE (MD = −1.56%, 95% CI = −3.54 to 0.48, SUCRA = 73.6%) and LIE (MD = −0.10%, 95% CI = −2.14 to 1.75, SUCRA = 23.1%). Compared with LIE, both acute evening MIE and HIE resulted in shortening REM, and no significant difference was found. Compared to MIE, no significant difference was observed while acute evening HIE shortened REM (Figure 4).

SSQ

In comparison with no exercise, although there were no significant effects, the ranking probability based on the SUCRA values indicated that acute evening MIE had the lowest impact on SSQ (SMD = −0.01, 95% CI = −0.44 to 0.42, SUCRA = 73.1%), followed by LIE (SMD = −0.16, 95% CI = −0.67 to 0.37, SUCRA = 43.9%) and HIE (SMD = −0.34, −0.67 to 0.00, SUCRA = 11.2%). Compared with LIE, acute evening MIE improved SSQ, while HIE decreased SSQ, and no significant difference was found. Compared to MIE, no significant difference was observed while acute evening HIE decreased SSQ (Figure 5).

The test of global inconsistency did not show any significant difference between the consistency and inconsistency models for all outcomes (all difference values of DIC were <5). Similarly, the node splitting method, which tested local inconsistency, showed that all comparisons among direct and indirect estimates were consistent for all outcomes (all p values >0.5, Supplementary Table S12). In addition, no significant global heterogeneity of the NMA was found (I^2 = 0%). There was no significant local heterogeneity in most of the comparisons in this NMA (I^2 = 0% or 5.2%) except that only three comparisons showed low local heterogeneity (I^2 = 15.6%, 24.7% and 29.1%) (Supplementary Tables S2–S11). The comparison-adjusted funnel plots for the outcomes suggested publication bias was not evident (Supplementary Figures S1–S10).

The subgroup NMA explored the effects of time of evening exercise, hours from cessation of exercise to bedtime, exercise modality, physical activity level, and exercise duration of acute evening exercise on objective sleep quality. The results of NMA of all outcomes were not modified in most of the comparisons. Different intensities of exercise performed in early- and late-evening had no negatively impact on objective sleep quality. The timeslot between the end of exercise and bedtime (0.5–1.5 h, 2 h, >2–4 h) had no effects on objective sleep quality. In addition, regardless of sedentary or physically fit participants, different intensities of evening exercise had no effects on objective sleep quality. However, compared with no exercise, MIE with cycling significantly increased REM-L (MD = 38.78 min, 95% CI = 3.99 to 73.80) and a longer (>30–60 min) HIE decreased REM sleep (MD = −2.50%, 95% CI = −4.74 to −0.35) (Supplementary Table S13).

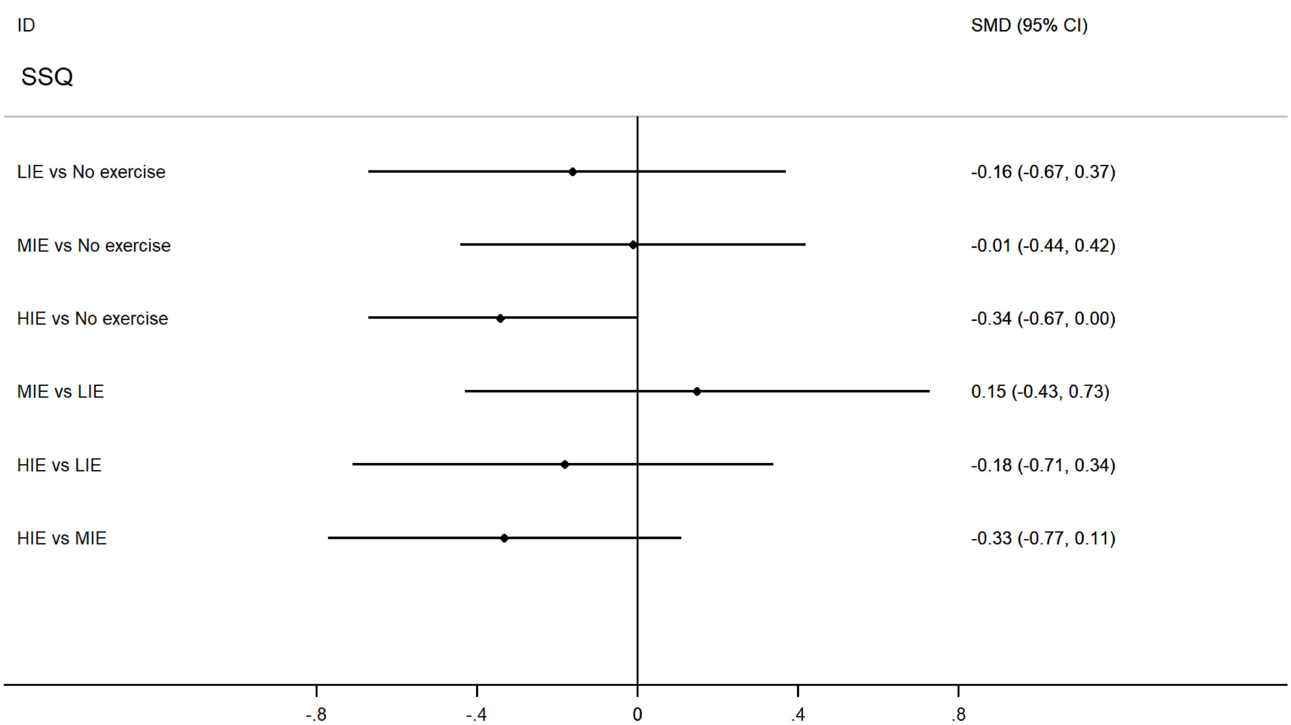

Figure 5 A forest plot of network meta-analysis of all comparisons for SSQ.
Abbreviation: SSQ, subjective sleep quality.

Discussion

This systematic review and network meta-analysis explored the effects of acute evening exercise with different intensities on sleep in healthy adults. In contrast to our hypothesis, no significant differences were observed in both objective and subjective sleep quality with different evening exercise intensities. The present findings were in line with a study showing that different intensities of acute evening exercises did not disrupt sleep in healthy young and middle-aged adults.[20] However, in line with our hypothesis and Frimpong et al's pairwise meta-analysis, 30–60 min duration with acute evening HIE resulted in a decrease in the REM sleep, which might worsen sleep quality.[21] In addition, acute MIE with cycling in the evening resulted in an improvement on REM-L.

Sufficient sleep plays an important role in restoring the consumption of the nervous system and metabolization in the waking stage,[51] and daytime exercise has been proven to be positive for sleep.[8] TST was associated with daytime sleepiness.[52] Furthermore, a previous study from the Asia Cohort Consortium suggested that TST was a behavioral risk factor in mortality in both men and women and TST of seven hours was recommended.[53] Oda and Shirakawa found a reduction in TST after acute HIE was completed one hour before bedtime compared with no exercise while TST in MIE did not change in twelve young males.[15] Not in line with Oda and Shirakawa, a recent study reported, compared with no exercise, acute evening HIE did not disrupt TST in 12 healthy males.[41] Thomas et al also found that acute evening HIE and LIE resulted in similar improvements in TST.[19] The crossover trial of Miller et al suggested that 30 min cycling at 75% HRmax ended 1.5 h before bedtime did not affect TST in 12 young males.[11] The results of the present NMA also supported the notion that acute evening exercise did not disrupt TST regardless of exercise intensities in healthy young and middle-aged adults. The results of Frimpong et al's pairwise meta-analysis were consistent with the current study that evening HIE did not significantly disrupt TST (+ 2.34 min).[21]

In addition to TST, knowledge about SOL, WASO, and SE was also important, because SOL, WASO, and SE could predict the perceived sleep quality in healthy subjects.[54] SOL could be recalled easily in the morning, which might result in increment in the perception of daytime dysfunction as well as perceived poor sleep quality.[55] The current study found there was a trend of shortening SOL after acute evening exercise compared to no exercise, and LIE might be the best method for the improvement of SOL (- 1.02 min). Oda and Shirakawa found a delay in SOL (+ 14 min) after HIE in the evening,[15] which was contrary to the current study that acute evening HIE did not delay sleep onset (−0.54 min). In line with our findings, Hayashi et al suggested relative to no exercise, acute evening HIE and MIE could significantly shorten SOL in nine sedentary college students.[50] In Myllymäki et al study, some indications of shortened SOL were also observed after acute evening HIE.[36] In addition, Ramos-Campo et al found average time of each awakening was significantly higher when 14 recreational male runners conducted acute evening HIE compared to MIE.[17] Conversely, a previous meta-analysis found that exercise conducted at any time of the day had a significantly positive result for WASO.[8] The current NMA revealed a decreased trend of WASO after acute evening exercise and the largest decrease in WASO was observed after acute evening MIE compared to no exercise (−2.50 min). In consistent with our findings, a recent crossover trial also found acute evening MIE did not affect WASO compared with no exercise in 16 healthy college students.[39] In regard to SE, although our study found acute evening exercise did not disrupt SE, different trends of SE after different intensities of acute evening exercise were observed. The current NMA resulted in improved trends of SE after acute evening LIE (+ 0.29%) and MIE (+ 0.41%), while the worsening trend of SE was observed after HIE (-0.17%) compared with no exercise. This was supported by a study conducted in eight physically active college students, which revealed that SE was not worsened after acute evening MIE and LIE.[48] In regard to acute evening HIE, compared to no exercise, a recent pairwise meta-analysis revealed similar trends of SE (−0.22%) with the findings in our study.[21] Disturbances of SOL and SE were associated with an increased risk of mortality.[56] The non-disruptive findings of SOL, WASO, and SE in the current NMA were of potential clinical significance.

In regard to sleep architecture, compared to no exercise, the current NMA did not find significant changes in the proportion of stages N1, N2, N3 sleep as well as REM-L after different intensities of acute evening exercise, while the proportion of REM sleep was significantly decreased after acute evening HIE. There was an indication of increased stage N1 sleep during the whole night in Aloulou et al study, and they also observed the proportion of stage N1 sleep was higher during the first 180 min of the night after acute evening HIE compared with no exercise.[31] Not inconsistent with the findings of Aloulou et al, Flausino et al found that the stage N1 sleep significantly decreased after acute evening HIE and MIE compared with no exercise.[46] The results of the current study showed a declining trend in stage N1 sleep after acute evening exercise compared to no exercise. As stage N1 sleep represented light sleep, acute evening MIE might be the best method to shorten the proportion of stage N1 sleep in our findings (−0.72%). A previous pairwise meta-analysis also supported our results that stage N1 sleep was not significantly changed after evening HIE compared to no exercise.[21] SWS, a component of non-rapid eye movement (NERM) sleep, was associated with increased growth hormone and decreased cortisol secretion.[47,57] Therefore, it has been proved to be the most restorative sleep stage. There were different trends in SWS after different intensities of acute evening exercise observed in the current findings. The positive modification of SWS was observed after acute evening MIE (+ 0.84%) while shortened SWS was observed after acute evening LIE (−0.64%) and HIE (−0.41%) compared to no exercise. In contrast to our findings, the randomized crossover trial of Dworak et al found that acute evening HIE completed 3–4 h before bedtime resulted in a significantly increased proportion of SWS, and this change was not found in acute evening MIE.[14] The discrepancy might be attributed to the population. The current study focused on young and middle-aged adults, whereas children (mean: 12.6 years old) were recruited in the study of Dworak et al. However, Hayashi et al study echoed the current results. Although Hayashi et al did not find significant difference, they found a tendency for an increase in the proportion of SWS after acute evening MIE compared to no exercise in nine sedentary college students (mean: 22.8 years old).[50] Considering that the sample size of included studies was small, the effects of evening MIE on SWS needed to be further researched.

Our study found REM sleep was significantly shortened after acute evening HIE compared to no exercise (−1.95%), which was consistent with Frimpong et al pairwise meta-analysis (−2.34%).[21] Previous studies found the similar effects of evening exercise on REM sleep. The meta-analysis of Stutz et al revealed that, after sensitivity analysis, the decrease of REM sleep became a trend or significant after acute evening exercise compared to no exercise (−0.69%).[22] Both Larsen et al and Aloulou et al observed a tendency for decreased REM sleep during the whole night after acute evening HIE compared to no exercise in healthy young adults.[31,34] Moreover, there was also a tendency for decreased REM sleep after acute evening LIE (−0.10%) and MIE (−1.56%) in the present study, which conformed to the result of Wong et al study.[49] Wong et al showed that there was a trend of a reduced proportion of REM sleep with increased evening exercise intensity.[49] The results of our study showed that acute evening HIE decreased REM sleep, whereas LIE and MIE did not. What is more, previous analyses found even if exercise during the day, REM sleep still decreased.[7,8,58] However, decreased REM sleep was not necessarily harmful. A previous study found that decreased REM sleep could reflect the consolidation of REM sleep and could also be the result of enhanced SWS.[59] The PSG data from Larsen et al showed decreased REM sleep predominantly within the initial 180 min of sleep after acute evening HIE, in keeping with the findings of Netzer et al and Robey et al[38,60] Furthermore, Netzer found that an increase in norepinephrine after intense exercise was associated with decreased REM sleep and increased REM-L.[60] Indeed, the results of the current NMA revealed a tendency for increased REM-L after acute evening exercise compared to no exercise, and acute evening HIE was regarded as the best intervention to increase REM-L (+ 8.57 min). After HIE, the release of norepinephrine was 14.5 higher than MIE,[61] which might result in delayed REM sleep.

In addition, most of the included studies assessed SSQ. There were disagreements about whether evening exercise was beneficial to SSQ among previous studies. Both Aloulou et al and Arias et al reported SSQ was impaired after acute evening HIE while good SSQ was observed without evening exercise.[30,31] Delayed onset muscle soreness after HIE might be the reason for poor SSQ the next morning.[62,63] In contrast to Aloulou et al and Arias et al, some studies revealed that SSQ was not affected after acute evening LIE, MIE and HIE compared to no exercise.[11,20,36] Compared with no exercise, acute evening MIE and HIE did not negatively affect subjective TST and WASO.[11,31,37] Oda & Shirakawa found that compared with no exercise, subjective SOL was negatively affected by acute evening HIE but not by acute evening MIE.[15] Conversely, some studies also supported the notion that neither acute evening MIE nor HIE would negatively affect subjective SOL compared to no exercise.[11,17,44] As we mentioned above, the SOL would be easily recalled in the next morning, which might affect the perceived SSQ of participants. The present NMA did not find distorted SOL after evening exercise, and the results supported the notion that evening exercise regardless of low-, moderate- and high intensity did not disrupt SSQ in young and middle-aged adults.

Previous pairwise meta-analyses suggested that the time of evening exercise, the hours from cessation of exercise to bedtime, the exercise modality, the physical activity level of participants, and the duration of evening exercise should be considered when analyzing the effects of acute evening exercise on objective sleep quality.[21,22] Subgroup analyses in the current study revealed a long duration (>30–60 min) of acute evening HIE significantly decreased the proportion of REM sleep compared to no exercise (−2.50%). Considering increased norepinephrine levels after HIE,[60] long duration might be a potential factor to facilitate this process. The results of Youngstedt et al study also showed acute evening HIE with 3 hours did not disrupt subsequent sleep in 16 cyclists.[44] Given that active participants might recover in a short period of time after exercise, the physical activity level of participants was considered in subgroup analysis. The present NMA subgroup analysis of physical activity level did not show any significant effects of acute evening exercise on objective sleep quality. In addition, cycling with acute evening MIE had significantly positive effects on REM-L compared to no exercise (+ 38.78 min), while there were no effects observed after running. Meanwhile, although a study had proven that running was more likely to induce higher levels of muscle damage and inflammation compared to cycling,[64] no sufficient evidence showed that muscle damage and inflammation affect sleep negatively.

Given that an acute psychophysiological response was induced by an acute exercise, exercise in the early evening might have sufficient recovery for a psychophysiological response that might not disrupt subsequent sleep, whereas exercise in the late evening might negatively affect sleep. However, the subgroup analysis of time of evening exercise in the present study found exercise in the early and late evening did not disrupt sleep regardless of exercise intensity. A previous meta-analysis found early evening HIE shortened SOL (−4.6 min), and late-evening exercise had no negative effects on sleep.[21] When considering the hours from cessation of exercise to bedtime, exercise performed close to bedtime might disrupt sleep especially HIE.[65] Oda and Shirakawa found that compared with no exercise, evening HIE end 1 h before bedtime delayed sleep onset (+14 min) and decreased TST and SE.[15] Conversely, the study of Youngstedt et al suggested that even acute evening HIE ended 0.5 h before bedtime did not disturb sleep.[44] Thus, the subgroup analysis was conducted to explore the effects of the hours from cessation of exercise to bedtime. The results of the present study showed that evening exercise regardless of intensity ended 0.5–1.5 h, 2 h and >2–4 h before bedtime did not disrupt sleep. In line with the present results, evening MIE ended 1h or 0.5 h before bedtime had no effects on sleep in previous studies.[15,48] The meta-analysis of Frimpong et al also showed that evening HIE ended 2 h before bedtime significantly decreased SOL and increased TST.[21] Although some studies found that compared with no exercise, evening HIE and MIE ended 2–4 h before bedtime decreased REM sleep,[21,45,47] the decreases in REM sleep were also found in daytime exercise[6–8] and, as we discussed above, the decreases in REM sleep did not necessarily indicate a negative effect on sleep. These results of subgroup analyses consolidated the main finding that evening exercise regardless of intensity did not disrupt subsequent sleep.

The chronotypes of participants might be a potential factor modulating the effects of evening exercise on sleep. Six of included studies reported the chronotypes of participants.[17–19,31,39,42] The study of Aloulou et al found that, compared with no exercise, late-evening HIE ended 2 h before bedtime had negative impacts on sleep in neither-type participants.[31] Not consistent with Aloulou et al, Thomas et al and Vlahoyiannis et al reported that evening HIE ended 3–3.5 h before bedtime improved sleep quality in neither-type participants.[18,19] Moreover, the positive changes of sleep quality induced by evening LIE ended 3.5 h before bedtime were comparable to those induced by evening HIE in neither-type participants.[19] Saidi et al also showed that early evening MIE ended 4 h before bedtime had positive effects on sleep quality in neither-type participants.[39] The study of Vitale et al, which involved both morning-type and evening-type participants, demonstrated that the sleep quality of morning-type participants was negatively affected by late evening HIE while that of evening-type participants was not affected.[42] However, morning HIE did not negatively affect the sleep quality of both morning-type and evening-type participants.[42] A recent cross-sectional study investigated 909 college students, and showed chronotype moderated the relationship between exercise timing and bedtime.[66] For every minute of delay in exercise timing, bedtime was delayed by 6.1 minutes for morning-type participants and only 3.6 minutes for evening-type participants.[66] Existing studies mainly focus on neither-type participants, while only one of included studies considered morning-type and evening-type participants. Few studies had taken chronotype into consideration when exploring the effects of evening exercise on sleep quality. Therefore, how chronotype modulates the relationship between different intensities of evening exercise and subsequent sleep needs to be further researched.

The potential complicated mechanisms between acute evening exercise and sleep were still unclear and were roughly clarified as the thermoregulation hypothesis, body recovery hypothesis, and energy storage hypothesis.[67–69] Some previous studies reported the rising body temperature induced by exercise made a positive effect on the proportion of SWS.[70,71] The study of Horne and Moore, who used extra clothes (hot) to elevate body temperature, found only exercise in hot conditions increased SWS.[70] Actually, during the period of high core body temperature (CBT), the human body was awake and active while during the period of low CBT, the body was inactive and asleep.[72] Based on this view and in consideration of previously mentioned studies which showed rising body temperature associated with the improvement of SWS were not conducted in the evening,[70,71] it seemed that high CBT close to bedtime was detrimental to subsequent sleep. However, some studies were in contrast with this notion. Youngstedt et al recruited 16 healthy cyclists, and the results showed that rising CBT caused by acute evening HIE with 3 hours completed 30 min before bedtime did not disrupt sleep.[44] The study of Aloulou et al showed that, although CBT significantly increased at the end of acute evening HIE (+1.40 ± 0.43°C) and remained high during the first 3 hours of sleep compared with no exercise, the objective sleep quality was not distorted by the elevated temperature.[31] Another notion that the decrease of CBT after exercise rather than absolute CBT was the inducement of sleep onset was worth mentioning to illustrate the influence of evening exercise on sleep.[73] Nevertheless, Miller et al found that CBT elevated during acute evening MIE and CBT returned to its pre-exercise level when going to bed, but no positive modification of SOL was observed.[11] Flausino et al did not find peripheral body temperature would increase with the increment of exercise intensity, nor did they find that the peripheral body temperature played a vital role in the delay of sleep latency and TST reduction.[46] CBT also declined rapidly after acute evening exercise, yet it did not make an improvement on SOL in Flausino et al study.[46] The present NMA subgroup analysis of hours from the cessation of exercise to bedtime (0.5–2 h, 2h, >2–4 h) did not show any significant difference between acute evening exercise on subsequent objective sleep quality regardless of exercise intensity, which disproved the thermoregulation hypothesis indirectly. However, complete clinical trials are also needed to directly verify whether the thermoregulation hypothesis can explain the effects of acute evening exercise with different intensities on sleep.

The body recovery and energy storage hypothesis suggested the quantity of TST and SWS would increase with the increased energy consumption.[68,69] High catabolic activity during awake was beneficial to anabolic activity during sleep.[46] As a previous study found, the growth hormone released during the SWS phase was beneficial to physical and mental health.[58] However, as existing studies did not measure energy consumption during different intensities of evening exercise, future studies could focus on this area. Moreover, hormone secretion after evening exercise might also affect subsequent sleep. As was mentioned in the study of Netzer et al, more norepinephrine released after HIE compared to MIE was associated with induced delayed REM sleep and the shortened proportion of REM sleep.[60] Buxton et al and Miyazaki et al found both the onset and peak phase of plasma melatonin were earlier after an acute exercise compared to no exercise.[74,75] How hormone secretion after different intensities of acute evening exercise affected subsequent sleep needed to be further researched.

To the best of our knowledge, this NMA represented the most comprehensive analysis of currently available data regarding different effects of intensities of acute evening exercise on subsequent sleep. The convergence of the current NMA was good (PSRF = 1 or 1.01) and the global heterogeneity was low (I^2 = 0%). However, some limitations should be noted in this study. The sample size of included studies was small (ranged 5 to 23) and most of the participants were males, which might cause bias in the results. In addition, this systematic review and network meta-analysis focused on acute evening exercise. Thus, the effects of different intensities of chronic evening exercise on sleep needed to be further researched. Our study did not find positive effects of acute evening exercise on subsequent sleep due to ceiling and floor effects, which meant that it would be more effective for participants who were already presented impaired sleep to exercise before sleep.[76] Also, only good sleepers were explored in our study, limiting the application of the findings to a broad population.

Conclusion

This systematic review and network meta-analysis found that acute evening exercise regardless of intensity completed before bedtime did not disrupt subsequent sleep in healthy young and middle-aged adults without sleep disorders. The modality and duration of evening exercise should be considered when developing sleep hygiene recommendations.

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