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Review

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The impact of exercise on sleep and sleep disorders

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Regular exercise provides a variety of health benefits, including enhanced sleep quality and reduced symptoms of sleep disorders. The complex interaction between sleep and physical activity involves various physiological and psychological processes. Exercise has a positive effect on sleep, but factors such as age, sex, and fitness level, and specific exercise aspects such as intensity, duration, and timing play crucial roles. Understanding these dynamic interactions is essential to gaining insight into how exercise benefits sleep in both healthy individuals and those with sleep disorders. Given the positive effects of moderate exercise on sleep and its potential as a therapeutic option, this narrative review highlights the extensive benefits of exercise on sleep and underscores its important role in overall health and wellness.

Exercise, structured physical activity, is essential for maintaining physical fitness, health, and wellness[1]. Encompassing aerobic, anaerobic, resistance training, high-intensity interval training, and stretching, exercise improves cardiovascular health, muscle strength, and injury prevention[2]. The benefits of exercise extend beyond physical fitness, positively influencing weight management, mental health, and overall quality of life[3,4]. Additionally, exercise has an important role in sleep regulation, with research consistently demonstrating its positive effects on sleep quality, duration, and disorders like insomnia and sleep apnea[5–7].

Sleep quality is a primary indicator of overall sleep health, with disturbances often manifested through troubles initiating sleep, maintaining sleep, or experiencing frequent awakenings[8,9]. Insomnia, the most common sleep disorder, is marked by persistent dissatisfaction with sleep duration or quality, including challenges in falling asleep, multiple awakenings, and premature awakenings[10]. Prevalence rates of insomnia generally range from 10% to 30% but can reach 50% to 60% in certain populations[11–13]. This condition is notably more widespread among older adults, women, and those with physical or mental health issues. The consequences of inadequate sleep quality extend beyond diminished cognitive functions, including attention and memory, and adversely impact physical health, social interactions, and psychological well-being[14,15].

Engaging in exercise enhances sleep quality through multiple mechanisms. It boosts melatonin production, which is essential for regulating sleep cycles, facilitates faster sleep onset, and improves sleep quality[16]. Research indeed suggests that while exercise can influence melatonin rhythms, its effects are highly dependent on factors such as exercise timing, intensity, and the presence of other zeitgebers, like light exposure and food intake. For instance, evening exercise has been shown to delay or suppress melatonin release, which may affect sleep onset and quality[17,18]. Exercise also plays a crucial role in reducing stress, which is a common barrier to initiating and maintaining sleep. Enhanced mood from regular exercise generates a positive cycle, encouraging continued exercise due to elevated feelings of well-being and reduced negative emotions[19,20]. Finally, exercise contributes to regulating body temperature, which is also crucial for sleep initiation. The post-exercise body temperature reduction promotes sleepiness, making it easier to fall asleep[21].

Extensive research emphasizes a positive association between exercise and better sleep, with consistent exercise not only enhancing sleep quality but also increasing sleep duration[22–25]. Female adults with insomnia (<6.5 h habitual sleep duration) who commit to at least half an hour of daily exercise gain ~15 additional minutes of sleep compared with those who do not exercise[26]. Exercise is particularly beneficial for addressing sleep challenges such as insomnia, excessive daytime sleepiness, and sleep apnea[24,26,27]. Insomnia patients engaged in moderate-intensity aerobic exercise for 30 min 3 times weekly for 8 weeks exhibit improved sleep quality[26,28].

This review focuses on the various benefits of exercise, its impact on sleep, and its relevance to sleep-related issues, highlighting the importance of exercise for promoting holistic health and well-being.

Exercise and its benefits

Exercise is a distinct subset of physical activity. Unlike other activities that expend energy, exercise is well-planned and structured, and incorporates frequency, intensity, and duration to achieve specific health benefits[29]. The main objective of exercise is to improve physical fitness, overall health, and well-being[30]. Exercise is beneficial for ameliorating the effects of aging, promoting muscle and cardiovascular development, enhancing weight loss

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or maintenance, boosting athletic skills, and encouraging recreation[31]. In general, there are 2 main types of exercise: aerobic exercise induces oxygen utilization by large muscle groups and strengthens cardiovascular function[32,33], whereas anaerobic exercise, such as weight training and sprinting, primarily promotes muscle mass and strength[33]. Stretching exercises primarily focus on maintaining or improving the range of motion. While they can contribute to overall mobility, the evidence of their role in injury prevention is mixed and varies depending on the context, such as the type of activity and individual differences[33].

Exercise may be classified as dynamic or static. Dynamic exercise, which involves joint movement, can have long-term benefits, such as lowering diastolic blood pressure and improving blood flow. In contrast, static exercise, which involves muscle activation without movement, can acutely increase systolic blood pressure during the exercise but may also offer long-term strength benefits[34].

Weight and health regulation

The benefits of exercise have been recognized since ancient times and are broadly acknowledged. (Fig. 1). Exercise helps prevent excessive weight gain and aids in maintaining weight loss[35]. Engaging in physical activity burns calories, whereas weight gain occurs when calorie expenditure is lower than calorie intake[36]. Surplus energy is stored as fat and may lead to obesity due to excessive fat accumulation. Exercise enhances levels of high-density lipoprotein, or 'good' cholesterol, and lowers levels of harmful triglycerides[37]. This improvement in health markers significantly reduces the risk of developing cardiovascular diseases, depression, hypertension, diabetes, and other health issues[38–40].

Enhancing energy, mood, and heart health

Regular exercise enhances muscle strength and boosts endurance[41]. It improves cardiovascular efficiency by facilitating the delivery of oxygen and nutrients to tissues, which provides more energy for daily tasks. Exercise and physical activity can also provide enjoyment, offering opportunities to relax, enjoy the outdoors, or engage in activities that bring joy, thereby promoting relaxation and reducing stress and tension[42,43]. Regular exercise and physical activity support growth and development, providing numerous benefits for physical, mental, and psychosocial well-being, and significantly enhancing overall health[44]. Furthermore, regular exercise decreases the resting heart rate and speeds up recovery after exertion, leading to a reduced risk of cardiovascular diseases. It increases capillary density in the heart, blood volume, and red blood cell count, and enhances both cardiac output and stroke volume[45].

Key to muscle growth and overall health

Muscle hypertrophy improves ATP and enzyme efficiency and is characterized by increased muscle cell size and volume, often involves growth in type II (fast-twitch) fibers, which generally have lower mitochondrial function and oxidative capacity compared to type I (slow-twitch) fibers. While hypertrophy may improve strength and power, its effects on oxygen utilization and mitochondrial function are context-dependent and may not always result in enhanced oxidative capacity. It also increases myoglobin storage, which is crucial for oxygen transport in muscles[46]. Exercise also leads to enhanced synovial fluid production, improving joint mobility, bone density, ligament strength, and cartilage health[47]. It elevates hormone levels and increases the number of hormone receptors in cells, which enhances the metabolic rate, regulates blood sugar levels, and improves insulin sensitivity with weight training[48]. Additionally, exercise plays a crucial role in mental health by enhancing neural efficiency, promoting new brain cell growth, and improving brain oxygenation and waste removal[49]. Insufficient physical activity is inextricably linked to chronic illnesses such as heart disease, cancer, and diabetes, which are leading causes of mortality worldwide, highlighting the crucial role of exercise in promoting global health and preventing diseases[50].

Exercise and sleep

A growing body of research suggests that increasing exercise is beneficial for improving mood, preventing pain, reducing weight, and boosting the quality of sleep in insomnia patients[5,36,49,51]. Although evidence shows that exercise affects sleep (Table 1), many aspects of these effects remain unclear. Notably, sleep loss is clearly well-correlated with exercise-induced injuries[52]. This suggests that moderate exercise habits and good sleep hygiene could be mutually beneficial. The impact of exercise on sleep is influenced by various elements, including personal attributes and the specifics of the exercise regimen. Personal attributes include factors such as age, sex, level of fitness, body mass index (BMI), and sleep patterns, while the exercise regimen details include such factors as acute or consistent exercise, aerobic or anaerobic, as well as intensity, duration, setting (indoors or outdoors, in warm or cool conditions), and timing of the exercise. These factors can have various effects on sleep[53–56].

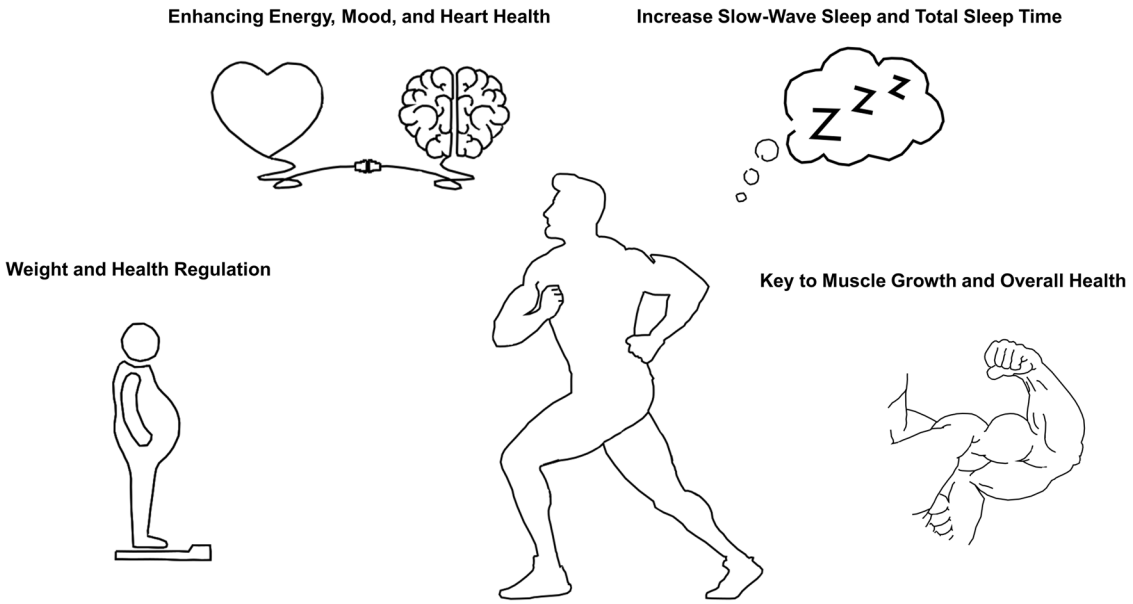

Fig. 1 | Benefits of exercise. Exercise is widely recognized to regulate weight and health, enhance energy and mood, and improve sleep and heart health. It is key to muscle growth and overall well-being.

Table 1 | Exercise effects on the body and sleep

Exercise	Body Effects	Sleep Effects
Regular (moderate-intensity aerobic)	• Increase GH, decrease IR[91,170] • Increase T_c[171] • Decrease vagal activity[171] • Decrease PGE_2, TNFα[172] • Potentially increase melatonin[171] • Increase level of BDNF[171]	Increase SWS Increase total sleep time[173]
Acute (moderate-intensity aerobic)	• Increase GH, decrease IR[174,175] • Increase T_c[171] • Inhibit vagal activity[176]	Increase SWS Increase total sleep time[173,177]

BDNF brain-derived neurotrophic factor, *GH* growth hormone, *IR* insulin resistance, *PGE_2* prostaglandin E2, *SWS* slow wave sleep, *T_c* body core temperature, *TNFα* tumor necrosis factor-alpha.

Impact of acute, regular exercise on sleep

Acute exercise marginally affects sleep architecture by increasing slow wave sleep (SWS), delaying the onset of rapid eye movement (REM) sleep, and reducing the total amount of REM sleep[53,54,56]. Exercising 4–8 h before bedtime reduces the sleep onset latency and wakefulness after sleep onset. Exercising more than 8 h before or less than 4 hours before bedtime, however, may have negative effects[53,55,56]. The negative findings, particularly regarding evening exercise, may not be entirely reliable, however, as the studies often involved sedentary women or were measured after extreme physical exertion, such as long-distance races, where exercise-induced stress may have significantly contributed to the disturbed sleep[57,58]. Contrary to common beliefs, evidence suggests that moderate and low-intensity exercising near bedtime is less likely to disrupt sleep in children and young adults who typically sleep well[59,60]. Objective measurements like polysomnography have demonstrated an increase in NREM sleep percentage after vigorous or moderate late-night exercise[61,62].

Regular exercise offers a viable non-pharmacological approach to enhance sleep quality[63]. Consistent exercise is associated with deeper SWS, longer total sleep time, and reductions in REM sleep, sleep onset latency, and wakefulness after sleep onset among good sleepers[53]. These findings are supported by the results of a 3-week study involving 51 adolescents with a balanced sex distribution who engaged in 30 minutes of moderate-intensity exercise every weekday morning and exhibited enhanced sleep duration and efficiency, reduced sleep onset latency, and extended REM sleep latency compared with a non-exercising control group[64]. Furthermore, participants noted enhancements in their perceived quality of sleep, mood, and focus during the day. Additional research suggests that adolescents who are more physically active experience longer durations of sleep, less wakefulness after sleep onset, and greater sleep efficiency[65,66]. Over the last decade, researchers have explored the impact of regular exercise on older adults and individuals with sleep issues, revealing moderate improvements in sleep quality, latency, and reduced dependency on sleep medications[67–71]. Among the behavioral intervention trials for insomnia examined, only a few utilized objective measurements like polysomnography. In one such study, older adults with sleep issues following a 12-month exercise program experienced notable enhancements in sleep quality; a briefer 16-week regimen, however, only boosted subjective measures of sleep quality without affecting objective sleep metrics[68,70]. Research validates the dose-dependent effect of physical activity on the subjective quality of sleep among postmenopausal women[72]. Moreover, basic animal research suggests that chronic aerobic exercise significantly reduces fragmented sleep and enhances slow-wave activity during sleep, with effects lasting beyond the exercise period, indicating lasting benefits of exercise on the central nervous system. There remains a growing demand for in-depth research to better understand how exercise specifically affects sleep, taking into account both its direct effects and indirect factors such as the impact of environmental lighting, changes in diet, emotional state, influence of medications, and circadian rhythms. Stress also affects sleep[73]; exercise can reduce stress, which may in turn improve sleep. A comprehensive approach to studying the effects of exercise on sleep is essential due to the wide-ranging effects of exercise on various health aspects, including body composition, metabolic rate, heart health, blood sugar control, emotional well-being, and immune system function[54,74].

Exercise, circadian rhythms, and sleep

The influence of exercise on human circadian rhythms is complex, affecting key physiological processes, sleep quality, and overall health. Consistent physical activity functions as a strong non-photic zeitgeber, assisting in the stabilization and alignment of circadian rhythms, thereby alleviating negative impacts from circadian disruptions. Exercise is a critical non-photic signal that modulates circadian rhythms, particularly through its interaction with the suprachiasmatic nucleus (SCN), the brain's central circadian regulator[75]. It enhances the amplitude of circadian rhythms, improving the synchronization of physiological functions to external environmental cues[75]. Short-term evening exercise may delay the release of melatonin and raise core body temperature, but it has minimal effect on sleep quality[17]. In contrast, regular morning exercise has been linked to lower cortisol levels and better sleep quality over time[17].

Exercise, body temperature, and sleep

Numerous studies have established a strong association between sleep and body temperature[76,77], revealing that a 0.5–1 °C reduction in body temperature facilitates sleep onset, whereas a ~1.5–2.5 °C increase in body temperature can delay sleep onset[78–80]. Specifically, a decrease in temperature within the brain's pre-optic area is thought to initiate sleep[81]. Exercise influences body temperature both during and after exercise, another pathway by which exercise could impact sleep. Exercise increases core, skin, and brain temperatures, which fluctuate based on the intensity and duration of the exercise and on environmental factors such as ambient temperature and humidity[82,83]. Cessation of exercise may thus dysregulate body temperature[80], affecting sleep similarly to passive temperature changes. Acute exposure to heat just before sleep reportedly reduces total sleep time and SWS, often with a concurrent reduction in REM sleep[82]. On the other hand, warm water immersion, leading to a temperature increase of 1.5–2.5 °C, reduces sleep onset latency and boosts SWS the following night[78,79]. Running in warm conditions by wearing extra clothing as opposed to cool conditions specifically increased SWS through body cooling post-exercise[84]. Following the initial hyperthermia, the body activates thermoregulatory mechanisms like peripheral vasodilation to dissipate heat. The resulting temperature gradient between the core and skin surfaces plays a key role in sleep initiation[85,86]. A swift drop in the core body temperature after heat exposure facilitates sleep onset and promotes deeper sleep stages[76,87]. Consistent exercise, 1 h 3 times a week, promotes a steadier decline in body temperature, further improving sleep quality[87].

Exercise, endocrine function, and sleep

Physical activity also impacts key hormonal systems, including the hypothalamic-pituitary-adrenal axis, the gonadal and somatotropic axes, and the sympathetic nervous system (SNS) axis. Changes in metabolism and hormone levels due to exercise significantly alter central neurotransmitters and immune system functions. While asleep, hypothalamic–pituitary–adrenal and SNS activities diminish, resulting

in lower plasma cortisol, epinephrine, and norepinephrine levels, and a significant rise in growth hormone, prolactin, and melatonin levels[88,89]. Additionally, there is a notable rise in plasma thyroid-stimulating hormone in the evening and upon falling asleep, with levels declining towards the end of the sleep period[90]. Daytime exercise is reported to increase[91,92], decrease[93,94], or have no effect on nocturnal growth hormone levels[92,93]. Kern and colleagues[92] reported that long-duration, moderate-intensity exercise during the day led to decreased growth hormone secretion and increased cortisol secretion during the first half of the night, and increased growth hormone levels and a smaller increase in cortisol secretion during the second half of the night. Although the total growth hormone levels remain unchanged, resistance exercise alters the secretion patterns by decreasing the burst mass and amplitude while increasing the frequency of bursts[95]. The effect of exercise on melatonin levels varies and is influenced by factors such as light exposure, timing of exercise, intensity, sex, and age, subsequently affecting sleep indirectly[96,97].

Exercise, cardiac and autonomic functions, and sleep

Sleep is characterized by significant circadian fluctuations in heart rate and blood pressure due to reduced sympathetic activity and enhanced parasympathetic activity, particularly in SWS[98]. Heart rate variability provides a noninvasive window into autonomic nervous system function. This measurement is widely used to assess changes across sleep stages and to explore how sleep disorders such as insomnia and sleep-disordered breathing affect sleep and daytime functioning[99]. Chronic sleep deprivation disrupts these rhythms, leading to persistent SNS dominance, which results in a higher heart rate, elevated blood pressure, and an increased risk of cardiovascular and metabolic diseases[99–101]. Individuals with chronic insomnia exhibit an increased heart rate and decreased heart rate variability before sleep onset and in stage-2 SWS compared with controls, with minimal differences observed in stage-3 SWS. These findings indicate a key role of autonomic hyperarousal in primary insomnia[102]. Exercise activates the SNS[103], and studies performed immediately after exercise demonstrate an increased heart rate due to reduced parasympathetic activity and heightened sympathetic activity[104,105]. This sympathovagal balance gradually normalizes within 24 hours post-exercise[104]. Based on meta-analyses, regular exercise enhances vagal modulation, leading to a reduced heart rate[106].

Daytime exercise is associated with a higher heart rate during sleep[57,61,107,108], while moderate to intense exercise, such as running a marathon, results in lower nocturnal heart rate variability, reflecting reduced parasympathetic activity[108]. Late-day exercise, on the other hand, has varied effects on heart rate variability during sleep, with some studies noting no change or changes only at the start of the night[109,110], suggesting that early sleep heart rate increases may be due to minimal decreases in vagal activity and a rise in sympathetic activity[61]. Remarkably, 2 months of intensive training increases vagal activity and decreases sympathetic activity during sleep among sedentary individuals[103], thereby enhancing vagal modulation, which is linked to a lower risk of cardiovascular events[111]. Conversely, overtraining leads to diminished parasympathetic activity and heightened sympathetic activity during sleep. This is accompanied by reduced heart rate variability, which, in patients with chronic fatigue syndrome, leads to poor sleep quality[103,112,113]. Definitive proof that alterations in heart rate and autonomic activity directly enhance sleep quality and quantity, however, is lacking. Research suggests that cardiac sympathetic activity remains relatively constant throughout SWS-REM cycles[114] and that sleep quality is not adversely affected by increased exercise intensity or duration despite significant heart rate and heart rate variability changes[110].

Exercise, immune-inflammatory response, and sleep

Sleep and the circadian rhythm are crucial in regulating immune functions, with evidence of a bidirectional relationship between sleep and the immune system[96,115]. Studies indicate that in the early stages of nighttime sleep, there is an increase in undifferentiated naive T cells and pro-inflammatory cytokines, including interleukin (IL)-6, tumor necrosis factor-alpha, and IL-12. During the day, natural killer cell activity and the secretion of anti-inflammatory cytokines, like IL-10, are increased. Sleep deprivation is associated with elevated cortisol levels and reduced levels of testosterone and growth hormone[116], suggesting the potential protective role of exercise for those lacking sleep. There is growing evidence that exercise can mitigate some of the negative effects of sleep deprivation, particularly in relation to metabolic health, although it may not fully offset other detrimental impacts, such as mood disturbances[117–119]. Further studies are needed to examine this possibility as well as how the anti-inflammatory effects of exercise may counteract immunoinflammatory responses triggered by sleep deprivation or restriction.

Exercise, metabolic functions, and sleep

Over the past 4 decades, considerable attention has been focused on how sleep affects endocrine and metabolic functions, particularly the relationship between sleep deprivation, diabetes, and obesity[120,121]. How exercise influences metabolic functions during sleep, however, is still unclear[116]. Exercise may induce alterations in growth hormone and cortisol secretion, as mentioned above, potentially affecting glucose regulation. These alterations could result in increased glucose use during REM sleep and elevated glucose levels in the evening, potentially aligning with a reduction in insulin sensitivity[122]. There is a clear need for further research into the specific effects of exercise on metabolic functions and hormone secretion patterns during sleep.

Exercise, mood, and sleep

Beyond physiological adjustments, it is widely recognized that exercise enhances mood, significantly contributing to improved sleep quality[123–125]. Furthermore, sleep disorders often correlate with a higher risk of anxiety and depression[126]. Engaging in regular exercise is linked to reduced anxiety and its physiological manifestations, as well as a lower incidence of depression, thereby boosting the mental health of broad populations[127]. Additionally, consistent exercise decreases REM sleep, exerting a considerable antidepressant effect over time[128]. The antidepressant properties of exercise are attributed to increased levels of brain-derived neurotrophic factor and, indirectly, to better sleep quality[116,123,124,127]. The connections between immediate and long-term exercise effects and changes in sleep patterns require further investigation. In summary, various interlinked mechanisms may underlie the effects of exercise on sleep quality. Future studies are needed to investigate the impact of exercise on sleep duration and examine how the interactions influence SWS and REM sleep.

Exercise and sleep disorders

Sleep disorders, including insomnia, sleep apnea, restless leg syndrome (RLS), and hypersomnia, can significantly impact sleep quality and, consequently, athletic performance. RLS, characterized by an irresistible urge to move the limbs accompanied by discomfort, tends to worsen during rest and improve with activity, particularly in the evening or at night[129]. This condition is also associated with periodic leg movements during sleep[129]. A higher prevalence of RLS is observed among marathon runners compared to the general population[130]. Aerobic exercise effectively improves symptoms and sleep quality in patients with RLS and uremic RLS[131–133], suggesting that exercise may offer potential benefits for a variety of sleep disorders (Table 2).

Exercise and insomnia

In many countries, 1 in 4 adults is affected by insomnia, 10% of whom suffer from severe symptoms[134]. Emotional stress from exercise competition and performance can potentially disrupt sleep, possibly leading to insomnia. This condition could then negatively affect an individual's ability to exercise and perform well. For individuals struggling with insomnia, however, engaging in regular exercise is often recommended as a strategy to improve sleep quality[5,26]. Sleep quality more significantly influences aerobic exercise the following day than exercise affects sleep, especially among those with initially shorter total sleep durations[26,135]. This suggests that improving sleep

Table 2 | Exercise effects on sleep disorders

Sleep Disorders	Exercise effects
Insomnia	• Exercise is recommended to improve sleep in individuals with insomnia[26]. • Sleep quality influences aerobic exercise more than exercise affects sleep[26]. • An intensive lifestyle modification program reduced insomnia symptoms by 64%[138]. • Exercise training improved sleep quality in middle-aged and older adults[70]. • Moderate-intensity aerobic exercise combined with sleep hygiene therapy increased total sleep time[139]. • Acute physical exercise improved sleep parameters in patients with chronic primary insomnia[28]. • Regular exercise and enhancement of adenosine $A_{2A}R$ signaling could be beneficial[26,145].
Sleep apnea	• The direct relationship between sleep apnea and exercise is unclear, but exercise is crucial for weight loss, which improves sleep apnea symptoms[149]. • Exercise has positive effects on sleep apnea, suggesting the potential efficacy of a combined approach with weight loss and CPAP treatment •[151,152]. • Exercise is linked to a lower occurrence of sleep-disordered breathing, independent of BMI[153]. • Exercise can reduce OSA severity based on the Apnea-Hypopnea Index by up to 50%, independent of weight loss[72]. • Exercise benefits include decreased sleepiness and enhanced daytime function for OSA patients[156].
Restless leg syndrome (RLS)	• Aerobic exercise improves symptoms and sleep quality in patients with RLS and uremic RLS[132].

BMI body mass index, *OSA* obstructive sleep apnea, *RLS* restless-leg syndrome.

could enhance exercise engagement, presenting a topic that warrants further exploration.

Common recommendations for treating insomnia include exercise and cognitive behavioral therapy, yet cognitive behavioral therapy for insomnia (CBT-I) is considered to be the first-line treatment for insomnia[136,137]. One study investigating the epidemiological impact of an intensive lifestyle modification program, including sports and stress management for 10 h weekly over 4 weeks in 2624 adults with insomnia reported a 64% reduction in insomnia symptoms[138]. Participants who maintained their coffee/tea consumption over the 4 weeks were more prone to sleep disorders and demonstrated increased emotionality. Another study assessing the effects of exercise training on sleep quality in middle-aged and older adults with sleep problems based on the Pittsburgh Sleep Quality Index found improved sleep quality scores, reduced sleep latency, and lower medication use in the exercise group compared with the control group[70].

Several studies have defined the relationship between exercise and insomnia. An investigation into the combined effects of moderate-intensity aerobic exercise and sleep hygiene therapy on 22 insomnia patients noted improvements, including longer total sleep times and shorter periods of wakefulness[139]. Another study examining the effects of acute physical exercise in 48 patients with chronic primary insomnia found significant enhancements in sleep parameters only within the group that participated in moderate-intensity aerobic exercise[28]. The exercise program included different exercises, conducted in 3 sets of 10 repetitions each at 50% of the 1-repetition maximum, with each session lasting approximately 50 min[140].

Significant improvements in sleep onset latency, wake time after sleep onset, and sleep efficiency are observed following moderate aerobic exercise, independent of when the exercise is performed. In a study involving 17 sedentary adults over 55 with insomnia, combining aerobic exercise with sleep hygiene improved various aspects of sleep quality compared with a control group[141]. The use of sedative drugs, especially hypnotics, should be approached with caution, however, especially before competition due to the potential side effects, including daytime sleepiness and confusion. Research in mice demonstrated that allosteric modulation of adenosine A_{2A} receptors can induce sleep without affecting body temperature or cardiovascular function[142–144]. This suggests that regular exercise and the enhancement of adenosine $A_{2A}R$ signaling could be beneficial for individuals with insomnia[145,146].

Exercise and sleep apnea

Sleep apnea affects 5–10% of adults, with a greater frequency and severity observed in males and overweight or obese individuals[134]. Sleep apnea is defined by symptoms such as non-restorative sleep, sleepiness, and intermittent hypoxemia, which can affect exercise capacity[147] Conversely, the direct effect of exercise on sleep apnea symptoms is not clear. While exercise has a significant role in promoting weight loss[148] and the benefits of weight loss for improving sleep apnea symptoms are well known[149,150], disentangling the direct relationship between sleep apnea and exercise aside from weight considerations is challenging.

The complex relationships among obesity, cardiovascular health, inflammation, and sleepiness make it challenging to understand how exercise can prevent or mitigate sleep apnea syndrome. Studies revealing the positive effects of exercise on sleep apnea suggest that a combined approach of exercise, weight loss, and continuous positive airway pressure (CPAP) treatment could offer the most effective solution for many patients with obstructive sleep apnea (OSA)[151,152]. An epidemiological study of 1521 adults from the Wisconsin sleep cohort indicated that exercise is linked to a lower occurrence of sleep-disordered breathing[153]. The findings showed that not all exercise-sleep-disordered breathing associations could be explained by BMI adjustments, hinting at exercise's potential to influence sleep-disordered breathing through mechanisms beyond weight loss.

Clinical studies demonstrated that exercise could reduce OSA severity based on the apnea–hypopnea index by up to 50%, independent of weight loss effects[72,154], though not all studies found this improvement significant[155]. Chronic exercise demonstrated a significant weight-independent effect on the apnea–hypopnea index in a study of 42 subjects, with varying degrees of reduction in apnea–hypopnea index scores, demonstrating that while exercise training's efficacy as a sole treatment for OSA may not match that of CPAP or surgery, its impact is comparable to other surgical treatments and similar to a 10% body weight reduction[72]. Exercise's benefits include decreased sleepiness and enhanced daytime function for OSA patients[156], although these improvements weren't statistically significant. Further research is needed, especially on inflammatory pathways, to elucidate how exercise benefits OSA beyond weight loss.

Exercise for patients with sleep-related disorders

While exercise is a well-established non-pharmacological treatment for insomnia[28,70,138–140] or sleep-disordered breathing[153], caution is advised for patients with other sleep disorders due to their higher risk for sudden cardiac events[157], coronary heart disease, and other cardiovascular problems[158,159]. Short periods of sleep can exacerbate these risks by inducing increased blood pressure[160], systemic inflammation[161,162], and endothelial dysfunction[163,164], which is an early indicator of cardiovascular disease and is associated with exercise-induced myocardial ischemia[165,166]. Therefore, pre-exercise medical screening is essential for patients with poor sleep or sleep disorders[167]. For patients with coronary spastic angina, a graded program starting with moderate-intensity aerobic exercise is recommended and is more effective than resistance exercise in enhancing endothelial function and lowering the risk of a heart attack[168–170]. Regular moderate-intensity aerobic exercise training can further benefit these patients by reducing oxidative stress,

inflammation, and insulin resistance, ultimately lowering the risk of heart attacks[170].

Recommendations for future research, clinical practice, and public policy

Comprehensive longitudinal studies. There is a need for long-term studies to investigate how different types, intensities, and durations of physical exercise influence sleep patterns across diverse populations, including those with underlying health conditions. This will aid in identifying the most effective exercise interventions tailored to specific demographic groups.

Mechanistic exploration. Future foundational research should focus on elucidating the physiological mechanisms through which physical activity influences circadian rhythms and sleep quality. This could improve our understanding of how exercise affects sleep at the molecular and systemic levels, particularly in populations with chronic sleep disorders.

Guidelines for athletes. Clinical guidelines should emphasize sleep management in athletes, as sleep deprivation can impair cognitive function, increase perceived exertion, and elevate the risk of injury. Personalized sleep protocols and monitoring systems should be integrated into athlete training programs to optimize performance and recovery.

Public health campaigns. Policymakers should promote physical activity as a key non-pharmacological intervention for sleep improvement in public health initiatives. These campaigns should provide clear recommendations on the timing, frequency, and intensity of exercise that can best support sleep health across various age groups.

Individualized exercise prescriptions. Clinical practice should consider personalized exercise prescriptions that take into account factors such as age, sex, existing sleep disturbances, and overall health status. By tailoring exercise routines to individuals, healthcare providers can better support patients in managing sleep disorders and improving general well-being.

Concluding remarks

Sleep and exercise are interconnected through intricate and bidirectional relationships involving various physiological and psychological processes. Complying with practical guidelines, moderate aerobic exercise can be recommended as an effective non-pharmacological intervention for sleep disturbances. There is an urgent need for novel foundational studies to deepen our understanding of the sophisticated physiological effects and to elucidate the advantages of physical activity for enhancing sleep quality among both healthy individuals and those with medical conditions. Additionally, sleep management is frequently overlooked in athletes, leading to negative effects on cognitive abilities, perceived exertion, and the risk of exercise-related ailments. A more comprehensive understanding of the physiological effects of sleep deprivation is essential for improving athletic performance. Engaging in consistent physical exercise can lead to better sleep quality, shorter sleep onset times, and improved overall sleep. It is also beneficial in addressing insomnia. Activities of moderate intensity are typically the most beneficial, while engaging in vigorous exercises close to bedtime might interfere with sleep. The effectiveness of physical exercise on sleep can depend on various factors, including age, sex, the specific type of exercise, as well as its timing, duration, and frequency. Although more research is required to identify the best exercise routines and understand how physical activity contributes to better sleep, encouraging regular exercise remains an effective method for improving sleep health and enhancing overall well-being.

Data Availability

No datasets were generated or analysed during the current study.

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A.K. and M.K. were responsible for the literature survey and the initial drafting of the paper, while M.L. helped with the literature survey and paper writing. All authors significantly contributed to the paper's discussion, content, and editing. The graphical illustrations within the paper were prepared by A.K. and M.K. All authors have reviewed and consented to the final version of the paper for publication.

Competing interests

The authors declare no competing interests.

Additional information

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