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Review

The Multidimensional Impact of Exercise Timing on Health: A Systematic Review

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ABSTRACT

This systematic review aims to determine whether exercise timing influences different health indicators. The search, conducted until May 2025 across PubMed, Web of Science, EBSCO, China National Knowledge Infrastructure, and Wanfang databases, reviewed 2,937 articles. This review included randomized controlled trials in English that explored exercise timing for various populations, excluding unspecified exercise timing, animal studies, and low-quality articles. A total of 43 studies with 3,543 participants were included. The risk of bias was assessed using the Cochrane Risk of Bias 2 tool, and study characteristics and results were tabulated. Current evidence suggests that exercise timing may differentially impact health dimensions: afternoon exercise may improve metabolism in metabolic disorders; postdinner exercise might enhance blood glucose control for type 2 diabetes; premeal exercise could reduce appetite for overweight and obese individuals; evening exercise may improve sleep quality for sleep disorders but may negatively affect early chronotypes; morning exercise may enhance athlete performance, while afternoon exercise may promote the recovery of ordinary individuals; and morning exercise should be approached cautiously in cardiovascular risk groups. However, contradictions in some dimensions highlight the need for further rigorous research to solidify implications for exercise prescriptions. The study protocol was prospectively registered on PROSPERO (ID: CRD42024595984).

Keywords exercise timing, exercise prescription, chronic disease prevention and control, exercise intervention, proactive health

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Exercising at different times of the day can produce different physiological responses,[1,2] as the various physiological activities of the body, such as glucose and lipid metabolism and muscle oxidative capacity, are influenced by the biological clock and exhibit regular circadian rhythms.[3] Exercising at an appropriate time can serve as an external regulatory mechanism to improve the amplitude of circadian rhythms, influencing metabolic processes and health.[4–6] Therefore, selecting the optimal timing for exercise is one crucial factor among others, such as intensity and duration, that may enhance exercise intervention effectiveness[7] and contribute to precision in exercise prescriptions. However, compared to factors like "exercise type" and "exercise intensity," the factor of "exercise timing" is more likely to be overlooked in the process of formulating exercise prescriptions. This has not been sufficiently researched, and most published exercise guidelines lack precise recommendations on exercise timing,[2,6] which limits the scientific and precise formulation of exercise prescriptions.

The optimal exercise timing should be chosen based on specific goals of exercise interventions. However, there is a lack of comprehensive analysis of the multidimensional health effects of exercise timing. Although existing studies suggest that exercise timing may yield varying benefits, the recommended optimal exercise timing varies across studies depending on the specific goals and populations targeted.[8,9] Moreover, most studies to date have focused on acute interventions with short-term monitoring, limiting insights into the effects of exercise at different times of day across variables. To address these gaps, it is necessary to systematically summarize the multidimensional health effects of exercise timing to identify critical directions for future research and to integrate these findings with exercise intervention objectives. This will provide more comprehensive evidence for selecting optimal exercise timing in exercise prescriptions.

In summary, this study aims to determine whether the exercise timing influences different health indicators. To achieve this, this study systematically reviews the literature on the health effects of different exercise timing across five dimensions: glucose metabolism, body composition, sleep quality, hemorheology, and sports performance. The findings underscore the need for rigorous research to determine the effects and mechanisms of exercise timing in different populations, which is helpful to enhance the effectiveness of exercise interventions and personalize exercise prescriptions.

Methods

The study protocol was prospectively registered on PROSPERO (ID: CRD42024595984). This systematic review followed the PRISMA 2020 guidelines,[10] and the completed checklist is available in **Supplementary Files S1 and S2** (available in the online version only).

Search strategy

We conducted a systematic search in PubMed, Web of Science, EBSCO, China National Knowledge Infrastructure (CNKI), and Wanfang databases from inception to May 2025. The search terms were "Exercise," "Time," and their free words. The full search strategies for all databases are available in Supplementary File S3 (available in the online version only).

Selection criteria

We included (1) randomized controlled trials (RCTs) that (2) were written in English, and (3) explored the appropriate timing to exercise for different groups of people. To be considered, (4) subjects could be any population (including the general population, individuals with chronic diseases, athletes, and so on). We excluded studies that did not specify an exercise intervention timing or had a nonfixed intervention timing for the exercise group. Animal experiments were also excluded. Conference papers, dissertations, and articles of lower quality were excluded. Furthermore, literature from the same sample source was only taken from the largest sample size.

Data extraction

Title/abstract and full-text screening were conducted independently and in duplicate by two investigators, with disagreements resolved by discussion or adjudication by the third author. From each included study, we extracted basic information (authors, publication year) and characteristics of the study population (study population, sample size, age). We also extracted the characteristics of the intervention program (exercise type, intensity, timing, duration, frequency, and period) and the study results. All extracted information is presented in tabular form.

Risk of bias assessment for included studies

The risk of bias in the included studies was evaluated using the Cochrane Risk of Bias 2 (RoB2) tool.[11] The assessment was conducted independently and in duplicate by two investigators, with disagreements resolved by discussion or adjudication by the third author. The assessment covered biases related to the randomization process, deviations from intended interventions, missing outcome data, outcome measurement, and selection of the reported result. For randomized crossover trials, the supplementary RoB2 tool was used to assess the risk of bias specifically related to potential carryover effects.[12] Additionally, the risk of bias assessment figures will be generated using the Excel tool provided on the Cochrane Risk of Bias website.

Results

Article selection

A total of 2,937 articles were obtained through search strategies and deduplication. After screening, 43 articles were included, all of which were RCTs. The articles were excluded for the following reasons: not reporting exercise timing or having nonfixed exercise intervention timing, incorrect research topic, animal studies, incorrect language, and non-RCT designs. The flow and details of the literature screening process are shown in **Fig. 1**.

Characteristics of included studies

Of the 43 articles included, 28 employed a single acute exercise intervention, 4 conducted short-term interventions lasting less than 2 weeks, and 9 involved long-term exercise interventions exceeding 8 weeks. Each study clearly established different exercise intervention timing groups. The characteristics of the included studies are summarized in **Table 1**.

Risk of bias assessment

The study by Chtourou et al.[48] did not report the randomization process, so it had a higher risk of bias in randomization. The risk of bias in other studies was generally low. **Fig. 2** shows the risk of bias assessment results for the included studies.

Results of literature integration

After organizing the included literature, current studies related to the health effects of different exercise timing were summarized into the following five dimensions (**Fig. 3**).

Exercise timing and glucose metabolism

A total of 13 studies[1, 2, 6, 28–37] reported the effects of different exercise timing on glucose metabolism, including 2,591 participants. Among them, 2,544 were patients with metabolic disorders (type 1 diabetes, type 2 diabetes, overweight or obesity, nonalcoholic fatty liver), 24 were night shift workers, and 23 were healthy men.

Four studies[28, 29, 32, 34] investigated the effects of acute exercise performed before and after meals on diabetes patients using a randomized crossover design. Two studies suggested that exercising earlier after breakfast or dinner is more beneficial in reducing postprandial blood sugar levels in patients.[32, 34] Regarding lunch, for the same total amount of exercise, dividing exercise into sessions before and after lunch had a similar overall effect on 24-hour blood glucose levels as continuous exercise after lunch, but with lower glucose variability.[28] Additionally, exercising after dinner was more beneficial than exercising before dinner in reducing postprandial risk factors (such as lowering lipid peroxidation).[29]

Nine studies[1, 2, 6, 30, 31, 33, 35–37] explored the effects of exercising at different times of day on glucose metabolism in various populations. Four of these studies[1, 33, 35, 36] found that afternoon exercise was more effective in lowering blood glucose levels and promoting glucose adaptation in individuals with metabolic disorders. Two studies[30, 37] reported no statistically significant differences in blood glucose control or insulin sensitivity in type 2 diabetes patients based on different exercise timing. One study[31] found no statistically significant effect of low-intensity exercise before night shifts on glucose tolerance in healthy night shift workers. One

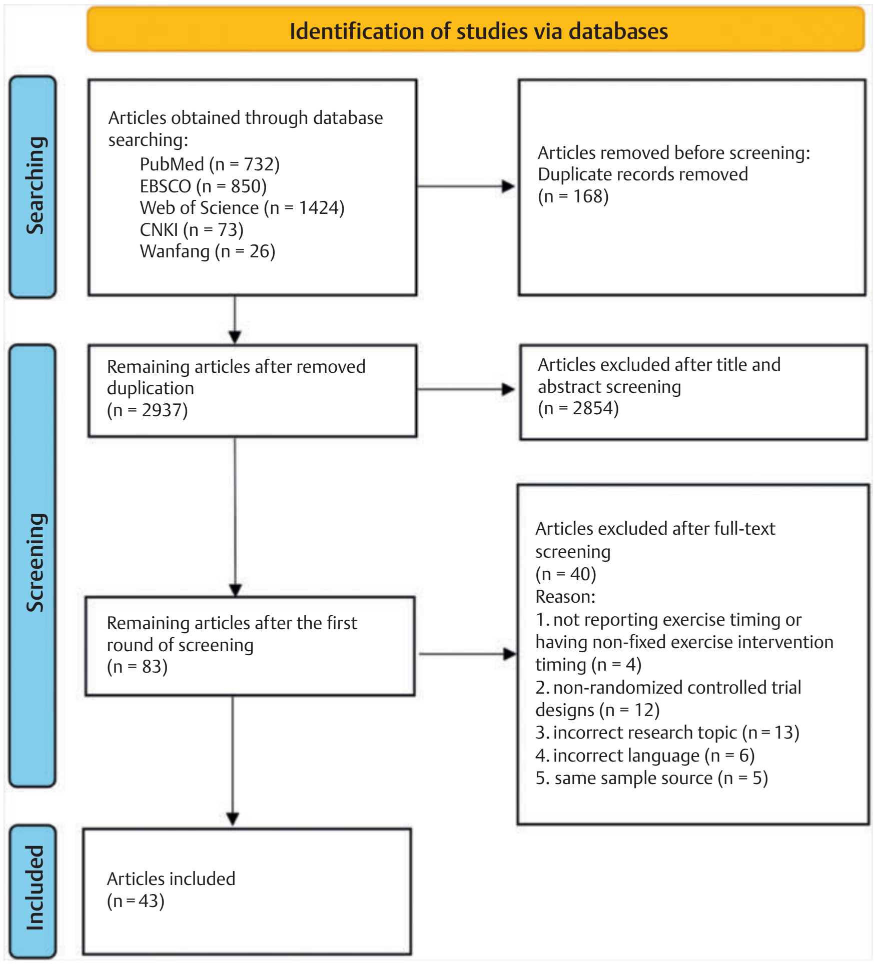

Fig. 1 Flowchart of the article selection process following the Preferred Reporting Items for Systematic Review.

study[6] suggested that afternoon exercise results in more unstable glucose levels and higher insulin levels in healthy men compared to morning exercise, while a different study[2] found that afternoon exercise more effectively improves glucose and lipid metabolism in healthy men.

Exercise timing and body composition

Eleven studies[5, 13–22] reported the effects of different exercise timing on body composition, including 413 participants, of whom 185 were overweight or obese patients, 14 were metabolic syndrome patients, and 214 were healthy individuals. Five studies[5, 14, 15, 18, 20] explored the impact of exercise timing on appetite, indicating that exercise before a meal increases postprandial satiety, and the closer the exercise time is to lunch, the lower the energy intake. In addition, moderate morning exercise seems to help reduce excessive attention to food. Three studies[13, 16, 17] found no statistically significant differences in fat loss effects based on different exercise timing. A study[19] on patients with metabolic syndrome showed that afternoon exercise significantly increases maximal fat oxidation during exercise, while another study[21] on healthy adults suggested that morning exercise might be more effective in mobilizing fat as an energy source compared to the afternoon. In addition, one study[22] suggests that morning and evening exercise have different beneficial effects on fat metabolism. Morning exercise is more conducive to acute fat oxidation than evening exercise, while evening exercise enhances fat metabolism the next morning.

Exercise timing and sleep quality

Six studies[13, 23–27] reported the effects of different exercise timing on sleep quality, including 181 participants: 33 overweight or obese individuals, 68 healthy young adults, 23 male runners or males with exercise habits, and 57 healthy elderly individuals. Four studies[13, 23–25] found that evening exercise can effectively improve sleep quality. One study[26] indicated that afternoon exercise might suppress melatonin secretion, recommending morning exercise for individuals with sleep disorders. Another study[27] noted that for individuals with an evening chronotype, both morning and evening exercise could have beneficial effects on sleep, whereas evening exercise could have negative effects for individuals with a morning chronotype.

Table 1 Characteristics of included studies: basic information, study population, intervention programs, and research outcomes

Author, year	Study population	Sample size (male/female)	Age	Timing	Intensity	Type	Duration (min)	Frequency	Period	Research conclusion
Creasy et al., 2022[13]	Overweight and obesity	10/21	25.6~49.2	②④	70~80 %HR_{max}	Free	NA	3 times/wk	15 wk	No statistical difference in weight loss effect across different exercise timing
Fillon et al., 2020[14]	Obesity	9/8	12.8 ± 1.4	⑧⑨⑫	65 %VO_{2max}	Cycling	30	One time	NA	Premeal exercise increases postprandial satiety
Fillon et al., 2020 (2)[15]	Obesity	6/9	12.0~15.0	⑧⑫	65 %VO_{2max}	Cycling	30	One time	NA	The closer the exercise is timed to lunch, the lower the energy intake
Mode et al., 2023[5]	Healthy adults	8/8	25.0 ± 3.0	②⑤	60 %VO_{2max}	Cycling	45	One time	NA	Evening exercise leads to higher free energy consumption
Teo et al., 2021[16]	Sedentary, overweight or obesity	17/23	51.0 ± 13.0	②⑤	70 %VO_{2max} 45~55 %1RM	Running, resistance	60	3 times/wk	12 wk	No statistical difference in weight loss effect across different exercise timing
Brooker et al., 2023[17]	Overweight or obese	20/62	28.0~53.0	②⑤⑫	Medium/high Intensity	Aerobic	50	2-5 times/wk	12 wk	No statistical difference in adult time use across different exercise timing
Albert et al., 2015[18]	Non obese boy	12/0	17.7 ± 1.6	⑧	70 %VO_{2max}	Running	30	One time	NA	The closer the exercise is timed to lunch, the lower the energy intake
Methnani et al., 2024[19]	Metabolic syndrome	7/7	43.1 ± 12.7	②④	Gradually increase to VO_{2max}	Cycling	NA	One time	NA	Afternoon exercise can significantly increase maximal fat oxidation
Carbine et al., 2024[20]	Healthy adults	63/75	25.7 ± 8.8	②⑤	3.8 miles per hour	Brisk walking	45	One time	NA	Moderate morning exercise cuts food attention
Kang et al., 2025[21]	Healthy adults	15/15	20.9 ± 1.5	②④	75 %VO_{2max}	Running	30	One time	NA	Morning aerobic exercise may more effectively mobilize fat for energy than afternoon exercise
Lan et al., 2025[22]	Male college students	18/0	23.5 ± 2.1	⑥⑦⑩⑪⑫	65 %VO_{2max}	Running	50	One time	NA	Morning exercise promotes acute fat oxidation better than evening exercise, while evening exercise enhances fat metabolism the next morning
Saidi et al., 2020[23]	Healthy adults	8/8	22.3 ± 1.4	④⑤⑫	60 %HR_{max}	Running	60	One time	NA	Acute nighttime exercise does not disrupt sleep and regular evening exercise improves sleep quality
Seol et al., 2021[24]	Healthy elderly people	14/43	71.0 ± 3.9	②⑤	2.0–2.9Met	Step	30	NA	8 wk	Nighttime walking can improve sleep quality
Aloulou et al., 2020[25]	Male runners	11/0	32.3 ± 5.2	⑤	60~100 %MAS	Running	48	One time	NA	High-intensity interval running at night can improve the sleep quality
Carlson et al., 2019[26]	Active men	12/0	20.8 ± 0.6	②④⑫	75 %VO_{2max}	Running	30	One time	NA	Morning exercise is more suitable for people with sleep disorders
Thomas et al., 2020[27]	Young people	16/36	22.8~26.0	②⑤	70 %VO_{2max}	Running	30	5 times	5 d	Exercising at night may exacerbate early onset circadian rhythm disorders

Table 1 Continued

Author, year	Study population	Sample size (male/female)	Age	Timing	Intensity	Type	Duration (min)	Frequency	Period	Research conclusion
Haxhi et al., 2016[28]	Type 2 diabetes	9/0	58.2 ± 6.6	⑧⑨⑫	50 %HRR	Brisk walking	40	One time	NA	Segmented exercise exhibits less glucose variability than continuous exercise
Heden et al., 2015[29]	Type 2 diabetes, obesity	5/8	48.5 ± 11.9	⑩⑪⑫	10RM	Resistance	46~47	One time	NA	Postmeal resistance exercise better reduces postprandial risk factors than premeal exercise
Savikj et al., 2019[1]	Type 2 diabetes	11/0	60.0 ± 2.0	②④	75 revolutions per minute	Cycling	18	3 times/wk	2 wk	Afternoon exercise better controls blood sugar than morning exercise
Tanaka et al., 2021[6]	Young people	11/0	24.5 ± 2.8	②④⑫	60 %VO_{2max}	Cycling	60	One time	NA	Afternoon exercise has less stable glucose and higher insulin than morning exercise
Munan et al., 2020[30]	Type 2 diabetes	8/6	65.0 ± 9.0	②④⑤⑫	5 kilometers per hour	Brisk walking	50	One time	NA	No statistical difference exists in 24-h blood glucose across exercise timing
Hannemann et al., 2020[31]	Night shift personnel	8/16	21.2~34.7	⑤⑫	65~75 %HR_{max} / 85 %~95 %HR_{max}	High-intensity interval training	35	Before each night shift	12 wk	Low-intensity exercise before night shift does not affect circadian rhythm, glucose
Kim et al., 2022[2]	Healthy adults	12/0	21.8 ± 0.2	②④	60 %VO_{2max}	Brisk walking	60	3 times	1 wk	Afternoon exercise can improve 24-h glucose and triglyceride levels more than morning exercise
Molveau et al., 2024[32]	Type 1 diabetes	24/16	44.1 ± 13.1	⑪	60 %VO_{2max}	Cycling	60	One time	NA	Exercising at 60 min postmeal reduces blood glucose fluctuation more than at 120 min
Niu et al., 2024[33]	Type 2 diabetes	24/8	43.5~56.6	②④	70~80 %HR_{max}	Running	30	3~4 times/wk	2 wk	Afternoon exercise may better improve blood glucose than morning exercise
Qi et al., 2025[34]	Type 2 diabetes	14/8	55.1 ± 12.5	⑦	50~60 %VO_{2max}	Cycling	30	One time	NA	Postprandial aerobic exercise at 45 min lowers blood glucose better than at 90 min
Mancilla et al., 2021[35]	Metabolic impaired patients	32/0	50.0~66.0	②④	70 % W_{max}	Aerobic, resistance	30	3 times/wk	12 wk	Afternoon exercise triggers more metabolic adaptation than morning exercise
Qian et al., 2023[36]	Overweight, obesity, type 2 diabetes	1002/1329	59.2 ± 6.8	②③④⑤⑫	NA	Free	NA	NA	4 years	Afternoon exercise can lower blood sugar levels more effectively
Teo et al., 2020[37]	Overweight, type 2 diabetes	17/23	51.0 ± 13.0	②⑤	60~70 %VO_{2max} / 45 %/50 %/55 %1RM	Walking, resistance	60	3 times/wk	12 wk	No statistical difference exists in blood glucose control and insulin sensitivity across
Ahmadizad et al., 2010[38]	Healthy adults	10/0	26.9 ± 5.5	②⑤	60 %VO_{2max}	Running	50	One time	NA	Morning and evening exercise cause no different reactions to the main determinants of blood rheology
Ballard et al., 2021[39]	Healthy adults	10/2	22.0 ± 4.0	②④	70 %W_{max}	Cycling	53	One time	NA	Morning exercise may increase adverse cardiovascular events more than afternoon exercise

Table 1 Continued

Author, year	Study population	Sample size (male/female)	Age	Timing	Intensity	Type	Duration (min)	Frequency	Period	Research conclusion
Brito et al., 2019[40]	Healthy adults	5/5	25.0 ± 5.0	②⑤	60 %P_{max}	Extend knees	60	One time	NA	No statistical difference exists in blood flow and vascular conductivity across different exercise timing
Edwards et al., 2005[41]	Bicycle athlete	8/0	24.0 ± 3.0	①③	60 %VO_{2max}	Cycling	40	One time	NA	Morning moderate exercise is more likely to boost performance than afternoon exercise
Bonato et al., 2017[42]	Active men	23/0	18.0~26.0	②⑤	90~95 %HR_{max} / 50~60 %HR_{max}	High-intensity interval training	38	One time	NA	Night exercise results in higher cortisol levels during morning workouts than morning
Brito et al., 2015[43]	Prehypertension	10/0	33.0 ± 6.0	②⑤	gradually increase to VO_{2max}	Cycling	22~23	One time	NA	Night exercise better reduces parasympathetic after-effects than morning exercise
Bommarito et al., 2025[44]	Healthy adults	11/15	23.0 ± 4.0	②⑤⑫	80 %P_{max} / 15 %P_{max}	High-intensity interval training	25	One time	NA	Morning exercise may raise female nighttime blood pressure responses
Palomo et al., 2024[45]	Metabolic syndrome	90/49	49.0~67.0	②④⑫	90 %HR_{max} / 70 %HR_{max}	High-intensity interval training	43	3 times/wk	16 wk	Afternoon exercise reduces systolic blood pressure and insulin resistance more than
Boettcher et al., 2024[46]	Healthy adults	16/15	23.0 ± 4.0	②④⑤	Gradually increasing to voluntary exhaust	Modified Bruce treadmill	NA	One time	NA	No statistical difference exists in systolic blood pressure, heart rate, and HRR across different exercise timing
Carmo et al., 2023[47]	Male undergraduate	11/0	25.5 ± 3.9	②④	P_{max} sprint	Cycling	6~16	One time	NA	Recovery after exercise was faster in the late afternoon
Chtourou et al., 2012[48]	Active men	31/0	23.1 ± 2.0	②⑤⑫	10RM	Resistance	NA	One time	NA	Conducting precompetition training and reducing workload during the competition time can enhance performance
Souissi et al., 2010[49]	Healthy Boys	20/0	10.7 ± 0.4	②④⑤	NA	Resistance	NA	One time	NA	Children perform better in afternoon exercise than in the morning
Yan et al., 2025[50]	Football player	30/0	20.1~26.3	②⑤⑫	All-out	High-intensity interval training	50	3 times/wk	7 wk	Morning training leads to more adaptive changes than evening training
Zhu et al., 2024[51]	Volleyball player	30/0	21.9 ± 2.1	②⑤⑫	NA	Plyometric training	60~70	2 times/wk	6 wk	Morning plyometric training enhances jumping and balance better than evening training

Abbreviations: HR_{max}, maximum heart rate; HRR, heart rate reserve; MAS, maximal aerobic speed; Met, metabolic equivalent; NA, not applicable or not reported; P_{max}, peak power; RM, maximum number of repetitions; VO_{2max}, maximum oxygen uptake; W_{max}, maximum power.

Note: ①, early morning; ②, in the morning; ③, at noon; ④, afternoon; ⑤, at night; ⑥, before breakfast; ⑦, after breakfast; ⑧, before lunch; ⑨, after lunch; ⑩, before dinner; ⑪, after dinner; ⑫, quiet comparison.

Fig. 2 Results of risk of bias assessment for included studies. Figure created with the Excel tool provided on the Cochrane Risk of Bias website.[11,12]

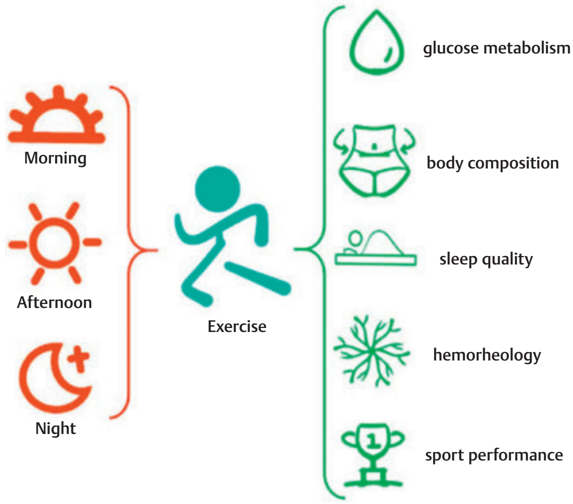

Fig. 3 The multidimensional impact of different exercise timings on health.

Exercise timing and hemorheology

Six studies[38–40, 44–46] reported the effects of different exercise timing on hemorheology, including 89 healthy adults and 139 metabolic syndrome patients. Three studies[38, 40, 46] found that while exercise significantly increased hematocrit and plasma viscosity, these measures returned to normal after rest, and there were no statistically significant differences in hemorheological indicators between exercise groups at different timing. One study[39] noted that morning exercise led to a greater reduction in flow-mediated vasodilation compared to afternoon exercise, which could potentially increase the incidence of adverse cardiovascular events. Additionally, one study[45] found that afternoon exercise has a greater effect than morning exercise in lowering systolic blood pressure and insulin resistance in patients with metabolic syndrome.

Exercise timing and sports performance

Eight studies[41–43, 47–49] reported the effects of different exercise timing on sports performance, including 163 participants: 8 cyclists, 54 males with exercise habits, 11 male undergraduates, 20 healthy adolescent boys, 10 individuals with prehypertension, 30 football players, and 30 volleyball players. One study[42] found that individuals accustomed to evening exercise had higher cortisol levels in the morning compared to those accustomed to morning exercise, but there were no statistically significant differences between the two groups during evening exercise. Two studies[41, 48] indicated that training at the same time as the competition period improved sports performance. Two studies[47, 49] found that afternoon exercise has better performance and recovery than morning exercise, while two others[50, 51] indicated morning training brings more adaptive changes and improves exercise performance than evening training. One study[43] noted that autonomic recovery speed after evening exercise was slower than after morning exercise in individuals with hypertension.

Discussion

This study categorizes the included literature into the effects of different exercise timing on five health dimensions: glucose metabolism, body composition, sleep quality, hemorheology, and sports performance. The optimal exercise timing varies across these dimensions based on intervention goals and population characteristics. Therefore, exercise timing should be carefully considered and recommended in line with specific objectives and the traits of the target population during prescription formulation.

Reducing fasting blood glucose levels and postprandial hyperglycemic fluctuations are key treatment targets in type 2 diabetes management.[28, 52] The circadian rhythm of insulin sensitivity and secretion influences blood glucose fluctuations,[2, 3] and since exercise enhances insulin sensitivity, its effect on blood glucose also varies over the day.[53, 54] This study synthesizes multiple findings, indicating that afternoon exercise may be more beneficial for enhancing fasting blood glucose control and lipid metabolism in patients with metabolic disorders such as type 2 diabetes.[1, 33, 35, 36] While Tanaka et al.[6] reported that afternoon exercise may not be advantageous for glucose stability in healthy males, this contrasts with Kim et al.[2] demonstrating improved glucose and lipid metabolism through afternoon interventions in the same population. The contradictory findings underscore the need for more in-depth verification.

For postprandial control, exercise is an important method for stabilizing postprandial blood glucose.[55] Although acute exercise around mealtimes generally lowers postprandial blood glucose in type 2 diabetes patients,[56, 57] this response also exhibits heterogeneity, with some patients showing no beneficial changes in glucose metabolism after premeal exercise.[58] Exercise timing differences may cause some patients to be “insensitive” or “nonresponsive” to acute exercise.[2, 30] Heden et al.[52] noted that acute postprandial exercise offers greater blood glucose control benefits than premeal exercise due to increased insulin levels and skeletal muscle glucose uptake, consistent with the results of this study. The included RCTs found that short-duration exercise after dinner was more effective in controlling blood glucose than predinner exercise.[29] Meanwhile, starting exercise earlier after breakfast or dinner may be more beneficial for stabilizing postprandial blood glucose metabolism.[32, 34] For patients exercising during the lunch period, exercising both before and after meals may be more beneficial in reducing postprandial glucose variability and stabilizing glucose fluctuations.[28] Additionally, although relevant studies[28, 29, 32] reported no nocturnal hypoglycemic events, Li Zheng et al.[55] indicated that prolonged or high-intensity postprandial exercise might increase hypoglycemia risk. Thus, future research should focus on determining the optimal postprandial exercise duration and intensity for diabetic patients to clarify the relationship between exercise timing and postprandial blood glucose response.

Exercise timing impacts on body composition primarily through appetite control and individual compensatory mechanisms.[5, 13, 16] Exercise not only increases energy expenditure but also influences subjective appetite level and energy intake.[59, 60] This study shows that exercise before meals reduces fat intake[14, 15] and increases postprandial satiety and that closer to mealtime more pronouncedly reduces daily energy intake.[18] Additionally, evening exercise is associated with greater spontaneous energy consumption despite comparable appetite scores.[5] Therefore, for clinical implementation, exercising before lunch may be an optimal time for overweight and obese patients. Notably, Methnani et al.[19] demonstrated enhanced maximal fat oxidation during afternoon exercise, contrasting with the finding of Kang et al.,[21] who discovered better fat mobilization during morning aerobic exercise. These conflicting temporal patterns in fat utilization require further mechanistic study. Moreover, while the included studies did not report differences in patient adherence or time reallocation across different exercise timing,[13, 17] these studies supervised and controlled the intervention process. Exercise prescription strategies should therefore prioritize individual preferences to avoid compensatory increases in intake or decreases in exercise volume.

Exercise can improve sleep quality across populations,[61, 62] but the circadian impact of nighttime exercise remains debated. Though evening exercise may disrupt circadian rhythms by delaying melatonin secretion and increasing nocturnal core temperature,[63] several included RCTs in this study demonstrate its superior sleep benefits compared to morning exercise, particularly in poor sleepers.[13, 23–25, 27] This contradiction may stem from variations in chronotypes. Early chronotypes might experience sleep deterioration with evening exercise.[27, 64] Therefore, morning exercise may be more suitable for them, potentially explaining some previous research discrepancies and requiring further in-depth study. Moreover, Saidi et al.[23] indicated that exercising within 2 hours of bedtime might reduce the benefits of exercise but does not affect sleep quality. Because of that, it may be more advisable for nonearly chronotype individuals to complete exercise at least 2 hours before bedtime. For those without exercise habits, choosing moderate-intensity exercise at night may avoid excessive activation of the sympathetic nervous system before sleep,[25] which is consistent with Alkhaldi et al.[65]

Acute exercise leads to various blood rheology changes, such as increased hematocrit and decreased plasma viscosity.[66] Both healthy individuals and those with chronic diseases exhibit circadian rhythm variations in the primary determinants of blood rheology.[38, 40] Since fluctuations in these determinants are linked to higher cardiovascular risk factors,[67] selecting appropriate exercise timing for individuals with chronic diseases or cardiovascular risk can lower the risk of adverse events during exercise. While multiple studies reported similar effects of different exercise timing on indicators such as plasma viscosity, hematocrit, and systolic blood pressure during exercise,[38, 40, 44, 46] Ballard et al.[39] found that morning exercise was more likely to reduce flow-mediated dilation of the brachial artery compared to afternoon exercise, Bommarito et al.[44] also noted that morning exercise in women may increase the nighttime blood pressure response. Therefore, caution must be exercised when prescribing morning exercise to patients with cardiovascular disease, though current recommendations remain provisional pending broader validation across exercise modalities and risk profiles.

Research on the impact of exercise timing on sports performance is divided into athletic performance and recovery speed for ordinary individuals. For competitive athletes, time-matched training (aligning practice with competition schedules) may enhance performance,[41, 48] though empirical evidence remains limited. In addition, there seems to be a contradiction in research between athletes and the general population regarding specific exercise timing. Yan et al.[50] and Zhu et al.[51] reported that morning exercise is more conducive to improving the athletic performance of football or volleyball players. These findings contrast with the benefits of afternoon exercise for healthy individuals, who can get higher recovery speed compared to the morning,[47, 49] consistent with the conclusions of Noone et al.[54] Moreover, prehypertension individuals exhibit slower autonomic recovery after evening exercise than morning exercise.[43] Considering their higher cardiovascular risk, afternoon training might suit them better, but this hypothesis lacks empirical evidence and requires further study to confirm.

This study indicates that optimal exercise timing varies across populations due to different training goals and precautions. A review published in *Cell Metabolism* highlighted that any physical activity requiring energy can have positive effects on the body through circadian rhythm amplitude, and personalized exercise timing can maximize physiological benefits, which is crucial for personalized exercise prescriptions.[54] Some scholars suggest extending the FITT-VP principle (frequency, intensity, time, type, volume, progression) by adding a third "T" to emphasize the significance of exercise timing.[58] This study synthesizes existing empirical evidence to help different populations choose suitable exercise timing: (1) afternoon exercise may optimize glucose and lipid metabolism in individuals with metabolic disorders. (2) People with type 2 diabetes may achieve better immediate blood glucose control with short-term exercise after dinner than before, and starting exercise early after the meal may be more beneficial for stabilizing postprandial blood glucose metabolism. For lunch, splitting exercise sessions before and after the meal may be more appropriate. (3) Premeal exercise appears to enhance appetite control for weight management. However, there is controversy over the exercise timing that leads to maximum fat oxidation. (4) Evening exercise might improve sleep quality in individuals with sleep disorders but could exacerbate sleep issues in early chronotypes. (5) Morning exercise may be associated with adverse cardiovascular responses in high cardiovascular risk groups. (6) Morning exercise seems to be more beneficial for athletes to improve their performance, while afternoon exercise appears more conducive to the recovery of ordinary individuals.

In conclusion, this study offers helpful information for selecting optimal exercise timing across populations and health dimensions. While conflicting data exist, future research should aim to resolve these inconsistencies and explore underlying mechanisms. Incorporating animal studies could enhance our understanding of potential human mechanisms, supporting the development of more precise exercise prescriptions.

Strengths and limitations

This study systematically evaluates the effects of exercise timing across five health dimensions: glucose metabolism, body composition, sleep quality, hemorheology, and sports performance, offering valuable information for individuals with various health conditions. The included articles demonstrate high methodological quality, which significantly strengthens the robustness of this systematic review. Moreover, contradictions persist in research findings across these dimensions, underscoring the need for further studies. In the discussion, we summarize these conflicting results to propose clear directions for future research on exercise timing.

This study has certain limitations. Although it systematically reviews the effects of different exercise timings on various health dimensions, the number of RCTs in each topic is limited, and the outcome measures and exercise timing categorizations are inconsistent. The research focus is scattered, and some studies are pioneering. As a result, this review can only offer a qualitative summary of the health benefits of exercise timing, without quantitative network meta-analysis or a more systematic recommendation system. Moreover, while exercise timing is gaining attention, most studies are still cross-sectional surveys, and the available evidence remains limited. Future research should refine study designs, conduct more prospective RCTs in diverse populations,[54] and emphasize exercise timing in program development. This will strengthen evidence for improving exercise intervention outcomes and developing precise exercise prescriptions.

Conclusion

Current evidence suggests that exercise timing may differentially impact health dimensions, including glucose metabolism, body composition, sleep quality, blood rheology, and sports performance. Optimal exercise timing may vary across different populations due to these diverse effects. However, most conclusions are based on studies with single acute exercise sessions, and conflicting results exist in some health dimensions, limiting our comprehension of how exercise timing affects health. More rigorous long-term and animal studies are needed to confirm the effects and mechanisms of exercise timing on health and to clarify its implications for exercise prescriptions.

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Statements and additional information

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