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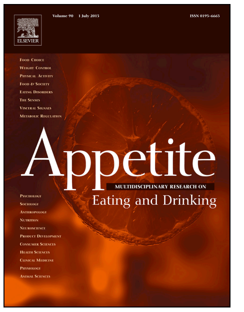

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The Impact of Exercise Timing on Energy Intake: A Systematic Review and Meta-Analysis of Diurnal and Meal Timing Effects

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Abstract

This systematic review and meta-analysis examine the literature (up to August 2nd 2024) on the influence of exercise timing on energy intake in both children and adults. A comprehensive search was conducted using MEDLINE, EMBASE, Cochrane Library, SPORTDiscus, and Web of Science Core Collection, following PRISMA guidelines. The review was registered in Prospero (CRD42024553381) and evaluated using QUADAS-2. From an initial 3,276 articles, a meta-analysis (six studies) revealed that daily energy intake was not significantly lower when exercise was performed in the morning versus the afternoon/evening: mean difference of 64±77 kcal (95% CI: -86 to 215 kcal; p=0.403). A meta-analysis (three studies, all with children) comparing lunch energy intake before versus after exercise showed a significant difference in energy intake when exercise was performed post-meal: (-39±13 kcal, 95% CI: -63 to -14 kcal; p = 0.002). For the meta-analysis of delayed lunch (five studies), where exercise ended 15 minutes to four hours before the meal, and the delay between the start of each exercise condition within the same study was typically around two hours, no significant difference in energy intake was found (-2±67 kcal; 95% CI: -134 to 130 kcal; p=0.977). Regarding chronic exercise, a decrease in energy intake was observed with evening exercise (one study), morning exercise (two studies) or independently of exercise timing (two studies). In conclusion, findings suggest acute exercise may reduce intake in children and adolescents, but this effect is dependent on the timing of exercise

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Keywords: Exercise timing – Energy Intake –Physical activity – Circadian rhythm

Introduction

Chronobiology refers to the mechanisms that regulate biological temporal structures, including the rhythmic manifestations of life (Haus et al. 1992). Initially explored by scientists interested in optimizing athletic performance, this field has yielded intriguing insights. For example, Conroy et al. showed that records were generally set in late afternoon races, coinciding with peak body temperature (Conroy et al. 1974). Further research has shown that the timing of physical activity has a profound effect on its outcomes. Studies by Racinais et al. and Wolf et al. suggest that strength, muscle contractility, and muscle mass increase more after resistance training when performed in the afternoon or evening, compared to the morning (Racinais et al. 2004; Wolff et al. 2019). In another study, Van Proeyen et al., found that morning fasting, compared to fed exercise, led to improved muscle adaptations and better glucose tolerance and insulin sensitivity during a hyper-caloric, high-fat diet (Van Proeyen et al. 2010). At the end of the 20th century, Atkinson et al. introduced the concept of exercise timing (Atkinson et al. 1996). Exercise timing, also known as chronoexercise, describes the time of day when the physical activity is performed in relation to other activities in the day. It depends not only on the time of day (morning, afternoon, or evening), but also on its position in relation to a meal (before or after) and the delay between the meal and the exercise (e.g., 30 min, 1h, 3h).

Our body operates on a circadian rhythm that is essential to maintaining metabolic balance (Hughes et al. 2012). This rhythm is regulated by our central clock, primarily synchronized by sunlight but also by diet and exercise (Hughes et al. 2012). Peripheral clocks, located in various organs, consist of circadian cells that function through a biological process involving a self-sustaining transcriptional-translational feedback loop originating in the hypothalamus (Egli et al. 2014). The hypothalamus serves as the primary regulator of time, integrating and then controlling stimuli via neural and endocrine pathways (Schibler et al. 2003). It should be noted that exercise also induces various physiological changes relevant to chronobiology, including increases in body temperature and the release or secretion of hormones that affect circadian rhythms, such as those governing wake/sleep, activity/rest, and eating/fasting cycles (Aoyama et al. 2017; Tahara et al. 2017).

A number of studies have highlighted the importance of exercise timing in improving cardiometabolic health (Chacko et al. 2016; Haxhi et al. 2013). However, the findings remains controversial. In individuals with type 2 diabetes, postprandial glucose control appears to be more effectively managed when exercise is performed after a meal rather than before it (Colberg et al. 2009; Heden et al. 2015). Other authors have shown that lipidemia improves when exercise is performed before a meal compared to after it (Petitt et al. 2003; Zhang et al. 1998). Arciero and colleagues observed a greater reduction in blood pressure, fat mass, and abdominal fat mass in women when exercise was performed in the morning compared to the afternoon (Arciero et al. 2022). Van Moorsel et al. found that evening exercise yields the highest fat oxidation compared to morning or early afternoon exercise (Van Moorsel et al. 2016).

Recently, Reid et al. proposed adding a third "T" for "Timing" to the FITT exercise prescription model [Frequency, Intensity, Time (duration), and Type of exercise] (Reid et al. 2019). The effects of exercise on energy intake in relation to its duration, intensity, and modality have been the subject of extensive research (Balaguera-Cortes et al. 2011; Laan et al. 2010; Masurier et al. 2018; Tamam et al. 2012; Thivel et al. 2012). Nevertheless, there remains a lack of information regarding the impact of exercise timing. Physical activity has been shown to increase satiety and reduce the sensation of appetite (Hellström et al. 2004). Additionnaly, the onset of exercise modulates the levels of appetite-regulating hormones (Schubert et al. 2013), and neurocognitive responses to food cues are diminished following exercise (Fearnbach et al. 2017). These physiological changes are commonly referred to as "exercise-induced anorexia", and may lead to a reduction in not only energy intake but also the consumption of fat, salty, or sweet foods after exercise (Wallis et al. 2019). However, many studies have reported that these benefits are observed only shortly after the activity (Broom et al. 2007; King et al. 2010, 2011; Martins et al. 2007), which highlights the importance of understanding the optimal timing of these effects.

The objective of this systematic review and meta-analysis is to provide an overview of the current literature on the acute and chronic impacts of three types of exercise timing on energy intake: 1) time of day; 2) before or after a meal, and 3) the delay between exercise and a meal. By demonstrating how adjusting the timing of exercise can lead to a greater change in energy balance for an equivalent amount of exercise (in terms of frequency, intensity, time, and type), we may contribute to better health outcomes and increased motivation in individuals who often struggle to maintain an active lifestyle.

2. Methods

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) guidelines (Liberati et al. 2009) and was registered with Prospero (registration number: CRD42024553381).

Literature search

Five databases were systematically searched from their inception to August 2nd 2024: MEDLINE (Ovid), EMBASE (Ovid), Cochrane Library (Ovid), SPORTDiscus with Full Text (Ebsco), and Web of Science Core Collection (Clarivate). The search was limited to publications in English and French. Additionally, the reference lists of all included papers were reviewed for relevant studies. The full search strategy is outlined below and can be requested from the corresponding author. It employed a combination of subject headings and keywords related to exercise timing, body weight, and energy balance:

(title(("chronoexercise" OR "chrono-exercise" followed by "exercise-meal" OR "meal-exercise" followed by "pre-exercise meal" OR "post-exercise meal" followed by "pre workout meal" OR "post workout meal")) OR title(("physical activity" followed by "exercise" OR "exercising" OR sport* OR exergam*) NEAR/3 (timing followed by morning OR afternoon OR evening OR night followed by "before meal" OR "after meal" followed by early OR "diurnal time" OR "circadian rhythms" followed by "time-restricted feeding" OR preprandial OR postprandial)) OR title((delay OR intermittent followed by resistance OR strength OR weight followed by endurance OR aerobic) NEAR/2 (exercise* followed by training OR program*) NEAR/2 (timing followed by morning OR afternoon OR evening OR night followed by "before meal" OR "after meal" followed by "early" OR "diurnal time" OR "circadian rhythms" followed by "time-restricted feeding" OR preprandial OR postprandial))). AND title("normal weight" followed by obesity OR "excess body weight" OR overweight followed by "body weight" OR "body weight changes" followed by "energy balance" OR "energy expenditure" OR "energy intake" followed by appetite OR overnutrition followed by "weight reduction" OR "weight loss" followed by "anthropometric indice" OR "body mass index"). Initially, time-restricted feeding studies, where food intake was limited to a specified window each day, were included to identify relevant studies. However, studies focused solely on time-restricted feeding protocols were subsequently excluded.

Following the search, all identified citations were compiled and uploaded into EndNote 20 (Clarivate Analytics, PA, USA), and any duplicates were removed. The remaining references were then uploaded to Covidence software (Melbourne, Victoria, Australia) for source selection. Authors were contacted to obtain full-text articles where they were not readily available. The articles were selected based on an independent review of the full texts, ensuring adherence to the inclusion and exclusion criteria.

Screening and data extraction

The studies were selected using a three-stage screening process: title, abstract, and full text reviews. Two independent reviewers (C.G. and A-C.G.) assessed each article at each stage based on the eligibility and exclusion criteria. Any discrepanices were resolved through consensus among the authors (C.G., A-C.G.). The flowchart below (*Figure 1*) shows the number of articles included and excluded at each stage of the selection process.

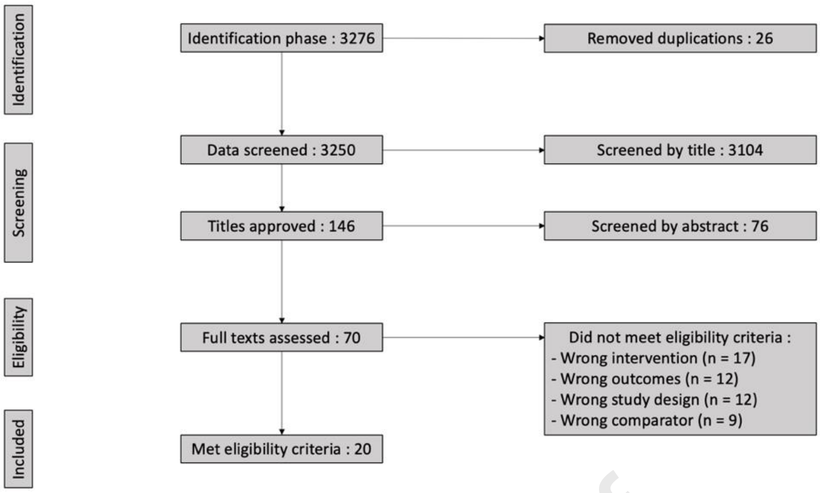

Figure 1. Systematic review flowchart

After the screening process, all eligible studies were analyzed by C.G. The following key information was extracted from each article: year of publication, author(s), study population, intervention details, exercise timing, type of measure, and primary outcomes. The results are presented in two separate tables: Table 1 outlines the acute effects of exercise timing, and Table 2 covers the chronic effects. To ensure the reliability and validity of our findings, a second reviewer (A-C. G.) independently verified the extracted data.

Inclusion and Exclusion criteria

To ensure the reliability and validity of our meta-analysis, explicit inclusion and exclusion criteria were established. Studies were included if they involved human participants of any age, with at least two exercise timings compared over an intervention period, with or without a control group. The review included participants of all body weight statuses and health conditions. However, trials involving dietary interventions, including time-restricted feeding protocols (e.g., Arciero et al. 2022; Morales-Palomo et al. 2023), were excluded. Exercise timing was defined either by the time of the day or the delay/position of exercise in relation to a meal or subsequent energy intake. Only studies reporting daily energy intake for exercise timing relative to the time of day were considered. Three studies were excluded from the review because they only reported post-exercise meal energy intake (Bilski et al. 2016; Dodd et al. 2008; Mode et al. 2023). Regarding exercise timing in relation to meal consumption (delay or position), only studies that compared lunch energy intake were included, as testing always took place in the morning. Consequently, the studies by Deighton et al. and Saidi et al. were excluded (Deighton et al. 2012; Saidi et al. 2020). Searches were restricted to published full-text articles. Conference abstracts, editorials, reviews, and unpublished studies were not included in the review.

Meta-analysis statistics

For the acute studies, meta-analyses were conducted on total energy intake or lunch energy intake depending on the time studied (i.e., total energy intake for time of day and lunch energy intake for the timing and delay relative to the meal). This included eight arms of studies for morning (AM) versus afternoon/evening (PM) exercise, three studies for exercise before versus after a meal, and six studies for exercise conducted near versus at a longer delay before a meal. In the AM vs. PM meta-analysis, data were included from two arms of the Ceylan et al. study, which separately analyzed ten overweight or obese subjects and ten normal-weight subjects, across two conditions (Ceylan et al. 2020). In the McIver et al. study, results from two diets (i.e., fed and fasting) were analyzed, and the sample size was divided in half to avoid duplication of participants (McIver et al. 2019). For Before vs. After Meal meta-analysis, only moderate-to-vigorous exercise conditions before and after lunch were considered from the Mathieu et al study (Mathieu et al. 2018), to reduce bias related to exercise intensity, as the effect of low-intensity exercise was only assessed before lunch. All meta-analyses followed the guidelines set by Sen et al. (2022). The data collected included sample size, mean daily or lunch energy intake (depending on the timing studied), and standard deviation for each study's two timing modalities (morning versus afternoon/evening, before versus after meal, and near versus at a longer delay before a meal). All data were analyzed using IBM SPSS Statistics version 29.0.1.0 software, with a significance level of p=0.05. Energy intake data reported in kilojoules were converted to kilocalories using a conversion factor of 1.000 kcal = 4.1868 kJ. The mean difference was calaculated, accounting for potential bias due to small sample sizes in the studies reviewed. The overall effect sizes were calculated using a random effects model to account for both variations in effects between studies and random error within a single study. A random-effects model was selected over a fixed-effects approach due to the variations observed in experimental parameters, such as energy intake measurements, which were better addressed by this approach. Cochrane's Q test and I^2 index were used to calculate heterogeneity, with thresholds of 25%, 50% and 75% respectivelyfor low, moderate and high heterogeneity according to I^2 analysis. A Cochrane's Q value greater than the degree of freedom (df) indicated significant heterogeneity. Given the overall number of studies (n=6), availability of required data (n=3 studies), and the heterogeneity of methods, the chronic exercise timing studies were included only in the systematic review section of this paper.

Risk of bias and quality assessment

The risk of bias and quality assessment were conducted using QUADAS-2, a widely accepted tool for evaluating the quality of diagnostic accuracy studies (Whiting et al. 2011). The assessment focuses on four key domains: 1) participant selection, 2) index tests, 3) reference standards, and 4) the flow of participants through the study, and the timing of the index test(s) and reference standards ("flow and timing") (Whiting et al. 2011). Each domain was evaluated in terms of their risk of bias and concerns regarding applicability. One reviewer (A.-C. G.) conducted the risk of bias assessment, and consensus was reached through discussion with two authors (C. G. and A.-C. G.).

3. Results

3.1 Study selection

Initially, 3,276 studies were identified through the database search. After removing 26 duplicate trials, 3,250 studies were screened. Based on the titles, 3,104 studies were excluded, followed by an additional 76 additional studies after abstract review. Subsequently, 49 studies were excluded after full-text analysis. Ultimately, 20 studies met the inclusion criteria (Figure 1) and were included in the present review. Among these, 15 were randomized control trials (Albert et al. 2015; Alizadeh et al. 2015, 2017; Brooker et al. 2023; Creasy et al. 2022; Damour et al. 2019; Farah et Gill 2013; Fillon et al. 2020 (a)(b)(c); Larsen et al. 2019; McIver et al. 2019; Willis et al. 2020), four were counterbalanced trials (Ceylan et al. 2020; Josaphat et al. 2020; Mathieu et al. 2018; O'Donoghue et al. 2010), one was a cross-sectional trial (McLoughlin et al. 2019), and Two studies were categorized as undefined (Maraki et al. 2005; Teo et al. 2021). The total number of participants across these studies ranged from 9 to 103, resulting in a cumulative total of 625 individuals.

3.2 Study characteristics

Twenty-three studies were included in this systematic review according to the inclusion criteria. These studies are organized in two separate tables: acute exercise (15 studies, Table 1) and chronic exercise (8 studies, Table 2).

Table 1 provides a comprehensive review of 15 acute trials, categorized into three groups based on the timing of exercise. The studies reported exercise intensity using various measures, including maximal aerobic capacity (VO2max, VO2peak), heart rate (%HRmax), and exercise intensity (light or moderate-to-vigorous physical activity). The volume of exercise was reported as energy expenditure (METs), number of repetitions of resistance exercise, or total minutes of exercise, reflecting the thoroughness of the research.

3.2.1 Acute exercise - Time of day

Our review included six studies with eight study arms that examined the effects of time of day for exercise. These studies compared the effects of exercising in the morning versus the afternoon/evening (Alizadeh et al. 2015; Ceylan et al. 2020; Larsen et al. 2019; Maraki et al. 2005; McIver et al. 2019; O'Donoghue et al. 2010). Depending on the study, the morning exercise condition was between 6:00am and 10:00am, while the afternoon/evening condition was between 2:00pm and 10:00pm. Specific details regarding the afternoon and evening exercise sessions are presented in Table 1, but are grouped as afternoon/evening thereafter. All participants in this meta-analysis were adults, with four studies focusing on men (Ceylan et al. 2020; Larsen et al. 2019; McIver et al. 2019; O'Donoghue et al. 2010) and two on women (Alizadeh et al. 2015; Maraki et al. 2005). The studies also considered body weight status, with two studies focusing individuals living with overweight or obesity (Alizadeh et al. 2015; Larsen et al. 2019), two on normal weight individuals (Ceylan et al. 2020; McIver et al. 2019), and two encompassing both statuses (Maraki et al. 2005; O'Donoghue et al. 2010). The type of exercise intervention varied, with two studies investigating the effects of exercise timing on light aerobic activity (Ceylan et al. 2020; McIver et al. 2019), two on moderate aerobic activity (Alizadeh et al. 2015; O'Donoghue et al. 2010), one on high-intensity exercise (Larsen et al. 2019), and one on a combination of aerobic and resistance training (Maraki et al. 2005). Energy intake was measured using food records in five studies (Alizadeh et al. 2015; Ceylan et al. 2020; Larsen et al. 2019; Maraki et al. 2005; McIver et al. 2019) and by an ad libitum buffet in one study (O'Donoghue et al. 2010).

3.2.2 Acute exercise – Before/After meal

Three studies examined the effects of exercise before and after meals (Fillon et al. 2020 (b); Mathieu et al. 2018; McLoughlin et al. 2019). In the studies by Fillon et al. and Mathieu et al., lunch was served between 11:15 AM and 1:30 PM (Fillon et al. 2020 (b); Mathieu et al. 2018). For the McLoughlin study, no specific data on meal timing are reported (McLoughlin et al. 2019). All included participants were children and adolescents of both gender, with one study focusing specifically on adolescents living with obesity (Fillon et al. 2020 (b)), while the other two addressed of varying weight statuses (Mathieu et al. 2018; McLoughlin et al. 2019). In terms of the type of exercise intervention, two studies assessed the impact of exercise timing with an acute intervention of moderate aerobic activity (Fillon et al. 2020 (b); Mathieu et al. 2018), while one study included physical activity during school recess (McLoughlin et al. 2019). Energy intake was assessed by an ad libitum buffet in two studies (Fillon et al. 2020 (b); Mathieu et al. 2018) and estimated through digital photography in one study (McLoughlin et al. 2019).

3.2.3 Acute exercise – Time between exercise and meal

The effect of the time between exercise and a meal was observed in five studies (Albert et al. 2015; Farah et al. 2013; Fillon et al. 2020 (a)(c); Josaphat et al. 2020). The conditions for exercising far from ameal ranged from four hours (Farah et al. 2013) to 1 hour 30 minutes (Fillon et al., 2020 (c)), while conditions for exercising close to a meal varied from two hours (Farah et al., 2013) to 15 minutes (Albert et al., 2015). In the Farah et al. study, participants consumed breakfast between the exercise and lunch periods in the far-from-meal condition. (Farah et al., 2013). Three studies focused on adults (Albert et al.

2015; Farah et al. 2013; Josaphat et al. 2020), and 2 on adolescents (Fillon et al. 2020 (a)(c)). With regard to body weight status, two included normal-weight or overweight individuals (Albert et al. 2015; Josaphat et al. 2020), while two studies focused exclusively on individuals living with obesity (Fillon et al. 2020 (a)(c)). The studies evaluated aerobic activity: one using light intensity trials (Farah et al. 2013) and four studies using moderate intensity trials (Albert et al. 2015; Fillon et al. 2020 (a)(c); Josaphat et al. 2020). Energy intake was only assessed using an ad libitum buffet.

3.2.4 Chronic exercise

Table 2 presents an overview of six chronic studies, all involving adults who are overweight or living with obesity (BMI > 25 kg/m^2) (Alizadeh et al. 2017; Brooker et al. 2023; Creasy et al. 2022; Damour et al. 2019; Teo et al. 2021; Willis et al. 2020). One study included only women (Alizadeh et al. 2017). Among these studies, five implemented an aerobic exercise program (Alizadeh et al. 2017; Brooker et al. 2023; Creasy et al. 2022; Damour et al. 2019; Willis et al. 2020), while one incorporated both aerobic and resistance exercises in each session (Teo et al. 2021).The frequency of exercise sessions and intervention duration varied across studies, ranging from two sessions per week (Alizadeh et al. 2017; Teo et al. 2021) to five sessions per week (Willis et al. 2020), and from six weeks (Alizadeh et al. 2017) to 40 weeks (Willis et al. 2020) weeks, respectively. Training intensity was described using measures such as maximal aerobic capacity (VO_{2peak}), heart rate ($\%HR_{reserve}$), energy expenditure (Cal), number of resistance exercise repetitions, or total minutes of training. Regarding exercise timing, seven studies evaluated the effects of morning exercise compared to afternoon/evening exercise (Alizadeh et al. 2017; Arciero et al. 2022; Brooker et al. 2023; Creasy et al. 2022; Morales-Palermo et al. 2023; Teo et al. 2021; Willis et al. 2020), while one study examined the impact of exercise timing in relation to a meal (Damour et al. 2019). Anthropometric measurements were taken using a body bioelectric impedance scale in six trials (Alizadeh et al. 2017; Brooker et al. 2023; Creasy et al. 2022; Damour et al. 2019; Teo et al. 2021; Willis et al. 2020) and dual-energy X-ray absorptiometry in four trials (Brooker et al. 2023b; Creasy et al. 2022; Teo et al. 2021; Willis et al. 2020). Energy intake was reported through various methods, including 24-hour recalls (Alizadeh et al. 2017; Brooker et al. 2023; Teo et al. 2021; Willis et al. 2020), 7-day food records (Willis et al. 2020), and food frequency questionnaires (Damour et al. 2019). One study reported energy intake using the calculated food intake method, which considers changes in body stores and total daily energy expenditure (Creasy et al. 2022).

Table 1: Characteristics and primary outcomes of studies - Acute exercise

AUTHORS, YEAR	STUDY POPULATION, N	INTERVENTION	TIMING OF EXERCISE	TYPE OF MEASURE	MAIN OUTCOMES
TIME OF DAY					
(MCIVER ET AL. 2019)	Active men (25 ± 3 years; BMI: 26 ± 4 kg/m^2), 12	45 min on treadmill at 55% $\dot{V}O2_{peak}$.	1) ME-FASTED: Fasting exercise at 09:15am 2) ME-FED: Exercise at 9:15am (meal at 8:00am) 3) EE-FASTED: Fasting exercise at 4:15pm 4) EE-FED: Exercise at 4:15pm (meal at 3:00pm)	• 24-hour food records	- No significant differences for 24 h EI ($p = 0.476$).
(MARAKI ET AL. 2005)	Female healthy (18-45 years; BMI: 19-25 kg/m^2), 12	10 min warm-up, 20 min aerobic exercise, 20 min muscle conditioning exercise and 10 min cool-down	1) Morning control 2) ME: exercise between 8:15-9:15am 3) Evening control 4) EE: exercise between 7:15-8:15pm	• 24-hour food records	- No significant differences in daily EI between trials. ($p>0.05$)
(O'DONOGHUE ET AL. 2010)	Healthy and physically active men (20 ± 3 years; BMI: 22.4 ± 1.6 kg/m^2), 9	45 min exercise on the treadmill at 75% VO_{2peak}	1) ME: Morning exercise session at 7:00am 2) EE: Evening exercise session at 5:00pm 3) Control	• Ad libitum buffet-type meal at 1:00pm •	- No significant differences in EI between trials at morning, mid-day or evening meal (all, $p > 0.1$).
(ALIZADEH ET AL. 2015)	Women (20-45 years; BMI: 25.0-30.0 Kg/m^2), 46	30-min moderate intensity exercise on the treadmill	1) ME: Exercise between 8:00-10:00am 2) AE: Exercise between 2:00-4:00pm	• 24-hour food records (+ interview)	- No significant differences in EI between ME and AE. ($p>0.05$)

(CEYLAN ET AL. 2020)	Men (30-45 years; normal weight or living with overweight and obesity), 20	30 min exercise at 55-59% $HR_{reserve}$	1) ME: Exercise between 8:00-10:00am 2) EE: exercise between 8:00-10:00pm	• 24-hour food records for 7 days	- No significant differences for EI between exercise conditions. (p>0.05) - Group of overweight or obese individuals consumed significantly less energy compared to the normal weight group in both conditions (p < 0.01).
(LARSEN ET AL. 2019)	Overweight inactive men (49± 5 years; BMI: 28 ± 3 kg/m^2), 11	30 min of HIIE (6x 60 seconds at 100% $VO2_{peak}$, 240 seconds at 50% ˙$VO2_{peak}$)	1) ME: exercise between 06.00-7.00am 2) AE : exercise between 2:00-4:00pm 3) EE: exercise between 7:00-8:00pm	• 24-hour food records	- No significant differences for EI (p = 0.57) between trials.
BEFORE/AFTER MEAL					
(MCLOUGHLIN ET AL. 2019)	Elementary children school [10.5 ± 0.5 years; underweight (2), healthy weight (62) or living with overweight (12) / obesity (27)], 103	15 or 30 mins of recess	1) Mid-day meal after recess 2) Mid-day meal before recess	• Weighed and calculated consumption of presented food items	- EI was greater than children eating mid-day meal after recess compared to children eating mid-day meal before (p<0.05).
(FILLON ET AL. 2020 (b))	Adolescents (12-16 years; BMI > 97th percentile), 17	30-min cycling exercise at 65% $VO2_{peak}$.	1) CON: Rest condition 2) EX-MEAL: Exercise at 12:00 and 12:30pm 3) MEAL-EX: Exercise between 1:30 and 2:00pm	• Ad libitum buffet-type meal between 12:30pm and 1:30pm	- No significant differences for EI between both conditions (p>0.05).

(MATHIEU ET AL. 2018)	Children (5.6 ± 0.5 years; underweight (1), normal weight (17) or living with overweight (2) / obesity (1), 21	40 min of Light Physical Activity (LPA) or 40-min Moderate to Vigorous Physical Activity (MVPA)	1) Meal_MVPA: 40 min of MVPA after mid-day meal 2) LPA_Meal: 40 min of LPA before mid-day meal 3) MVPA_Meal: 40 min of MVPA before mid-day meal	• Ad libitum lunchbox at 11:15am or 11:55am depending on conditions.	- EI was greater in the LPA_Meal condition than in Meal_MVPA and MVPA_Meal (all, p<0.05).
DELAY BEFORE THE MEAL					
(ALBERT ET AL. 2015)	Non-obese adult males (15-20 years; BMI: 19.9–29.0 kg/m^2), 12	30-min exercise on the treadmill at 70% VO_{2max}	1) ExMeal: Exercise at 11:15am (delay between the end of exercise and the beginning of the test-meal: 15min) 2) ExdelayMeal: Exercise at 9:00am (delay between the end of exercise and the beginning of the test-meal: 2h30min)	• Ad libitum buffet-type meal at 12:00pm	- EI is lower with ExMeal than ExdelayMeal at mid-day meal (- 154 kcal; p = 0.043).
(FARAH ET GILL. 2013)	Men (28.1 ± 10.7 years; BMI > 25.0 kg/m^2), 10	60 min exercise on the treadmill at 50 % $VO2_{max}$	1) Ex-meal: Exercise before morning meal at 9:00am (delay between the end of exercise and the beginning of the test-meal: 4h00) 2) Meal-Ex: Exercise after morning meal at 11:00am (delay between the end of exercise and the beginning of the test-meal: 2h00) 3) CONTROL: No exercise session	• Ad libitum buffet-type meal at 2:00pm	- No significant differences for EI in the ad libitum mid-day meal between trials.
(FILLON ET AL. 2020 (a))	Adolescents (12-15 years; BMI >	30 min exercise on ergocycle at 65% $VO2_{peak}$.	1) CON: Rest condition 2) EX-180: Exercise at 9:00am (delay between the end of exercise and	• Ad libitum buffet-type	- No significant differences in absolute EI at mid-day meal between conditions.

	97th percentile), 15		the beginning of the test-meal: 3h00) 3) EX-60: Exercise at 11:00am (delay between the end of exercise and the beginning of the test-meal: 1h00)	meal at 12:30pm	
(A. FILLON ET AL. 2020 (c))	Adolescents (12-15 years; BMI > 97th percentile), 18	30-min cycling exercise at 65% $VO2_{peak}$.	1) CON: Rest condition 2) MEAL-30: Exercise at 11:00am (between the end of exercise and the beginning of the test-meal: 30 min) 3) MEAL-90: Exercise at 11:00am (delay between the end of exercise and the beginning of the test-meal: 1h30min)	• Ad libitum buffet-type meal at 12:00pm or 1:00pm depending on conditions	- Mid-day meal and total daily EI was significantly lower in MEAL-90 than MEAL-30 (all, $p< 0.05$).
(JOSAPHAT ET AL. 2020)	Normal weight males (18-35 years; BMI: 22.4 ± 2.0 kg/m^2), 12	30-min exercise on the treadmill at 70% $VO2_{max}$	1) $EX_{9:40}$: exercise session at 9:40am (delay between the end of exercise and the beginning of the test-meal: 1h50 min) 2) Ex_{10h30}: exercise session at 10:30am (delay between the end of exercise and the beginning of the test-meal: 1h)	• Ad libitum buffet-type meal at 12:00pm	- No significant differences for EI between conditions.

The values and results displayed are reported exactly as stated by the authors of the original study.

Abbreviations: AE: afternoon exercise; BMI: body mass index; CHO: carbohydrate; DTE: desire to eat; EE: Evening exercise; EI: energy intake; HIIE: High intensity interval exercise; $HR_{max\ th}$: maximum heart rate theory; $HR_{reserve}$: reserve heart rate; ME: Morning exercise; PFC: prospective food consumption; REI: relative energy intake; VO_{2peak}: peak oxygen uptake; VO_{2max}: maximal oxygen uptake.

Table 2: Characteristics and main outcomes of studies - Chronic exercise

AUTHORS, YEAR	STUDY POPULATION, N	INTERVENTION	TIMING OF EXERCISE	TYPE OF MESURE	MAIN OUTCOMES
(ALIZADEH ET AL. 2017)	Women living with overweight (20-45 years, BMI: 25.0-29,9 kg/m^2), 48	3 exercise session (30 mins moderate intensity exercise on the treadmill) per week for 6 weeks	1) ME: exercise between 8:00 - 10:00am 2) EE: exercise between 2:00 - 4:00pm	• 24-hour food consumption record	- ↘ EI over the time in ME ($p = 0.06$).
(BROOKER ET AL. 2023A)	Overweight or obese adults (39 ± 11 years; BMI ≥ 25 kg/m^2), 100	250 min exercise on the treadmill per week for 12 weeks	1) ME: exercise between 6:00 - 9:00am 2) EE: exercise between 4:00 - 7:00pm 3) Control	• 24-hour dietary interview	- ↘ EI over the time in both exercise group : ME and EE, significantly different from CON (respectively, $p < 0.001$ and $p = 0.001$).
(CREASY ET AL. 2022)	Adults (18-56 years, BMI: 25.0-40.0 kg/m^2), 33	4 exercise sessions (aerobic exercise at 70-80% Hr_{max} – between 187.5 to 500 kcal per session) per week for 15 weeks	1) ME: exercise between 6:00-10:00am 2) EE : exercise between 3:00-7:00pm	• Energy intake calculated using the intake balance method.	- ↗ EI during the intervention for ME (+99 ± 198 kcal/day) and ↘ for EE (−21 ± 156 kcal/day).
(DAMOUR ET AL. 2019)	Overweight or obese adults (18-45 years, BMI ≥25 kg/m^2), 8	2 exercise sessions (15 mins) per day for one month	1) ExMeal: exercise one hour before 2 of the 3 daily meals: morning, mid-day and evening meal 2) MealEx: two 15-minute bouts of exercise each day outside the hour before the meal	• Food frequency questionnaire	- ↘ EI during the program with no difference between groups.

(TEO ET AL. 2021)	Overweight or obese adults (18-65 years / BMI ≥ 27 kg/m^2), 40	3 exercise sessions (30 min aerobic training at 70% $VO2_{peak}$ on the treadmill and 30 mins resistance training) per week for 12 weeks.	1) ME: Exercise between 8:00-10:00am 2) EE: Exercise between 5:00-7:00pm	• 24-hour dietary interview	- ↘ EI in response to the training program for both groups ($p<0.01$).
(WILLIS ET AL. 2020)	Adults (18-39 years / BMI: 25–40 kg/m^2), 79	5 exercise sessions on treadmill or stationary bike (achieving a target caloric expenditure of 400-600 cal on aerobic exercise) per week for 40 weeks.	1) "CON": Typical physical activity levels 2) ME: Completing ≥50% of their total sessions between 7:00-11:59am 3) EE: Completing ≥50% of their total sessions between 3:00-7:00pm 4) "Sporadic-EX": did not complete ≥50% of their total sessions in any time category	• 7-day food report: photographs taken before and after meal in cafeteria and multiple recalls for food consumed outside the cafeteria.	- No significant between-or within-group differences in EI. - ↗ Relative EI over the 10 months in ME, EE, Sporadic-EX and CON ($p = 0.003$).

The values and results displayed are reported exactly as stated by the authors of the original study.

Abbreviations: BMI: body mass index, EE: Evening exercise; EI: energy intake; ME: Morning exercise; PFC: prospective food consumption; HR_{max}: maximum heart rate; VO_{2peak}: peak oxygen uptake.

3.3 Study findings

3.3.1 Acute exercise

Ten studies reported no significant differences in energy intake based on exercise timing. McLoughlin et al. reported that the energy intake of children who ate mid-day meals after a regular recess was greater than that of children who ate mid-day meals before recess (McLoughlin et al. 2019). In contrast, Mathieu et al. found that energy intake was lower in children who exercised at moderate to vigorous intensity (active recess) before eating compared to those who delayed their meal following low-intensity exercise (Mathieu et al. 2018). Albert et al. reported that energy intake was lower when exercise was performed immediately before a meal compared to more than two hours prior (Albert et al. 2015). Conversely, Fillon et al. found that exercising 90 minutes before eating resulted in lower energy intake than exercising 20 minutes before the meal (A. Fillon et al. 2020 (c)).

A meta-analysis of six studies was conducted to compare daily energy intake when exercise was performed in the morning versus in the afternoon/evening (Figure 2). The mean difference was 265±329 kcal (95% CI: -380 to 910 kcal), with no significant difference observed (p=0.403). Heterogeneity among these studies was minimal: $I^2 = 2\%$; Q = 3.947; df = 6; p = 0.684. In contrast, the meta-analysis of three studies comparing energy intake at lunch when exercise was performed before versus after the meal (Figure 3) showed a significant difference, indicating that post-meal exercise may result in reduced energy intake (-161±52 kcal, 95% CI: -264 to -59 kcal; p = 0.002). This analysis revealed low heterogeneity ($I^2 = 0\%$; Q = 0.591; df = 2; p = 0.744). The meta-analysis of five trials examining delayed lunch revealed no significant difference in energy intake (53±236 kcal; 95% CI: -408 to 515 kcal; p=0.820), with moderate heterogeneity observed between studies ($I^2 = 39\%$; Q = 8.00; df = 5; p = 0.156). A sensitivity analysis was performed by excluding the Farah et al. study, as it was the only one to include a breakfast between one exercise condition and the test-meal. This analysis showed no significant difference : (mean difference : 7±82 kcal, 95% CI: -169 to 154 kcal; p=0.929).

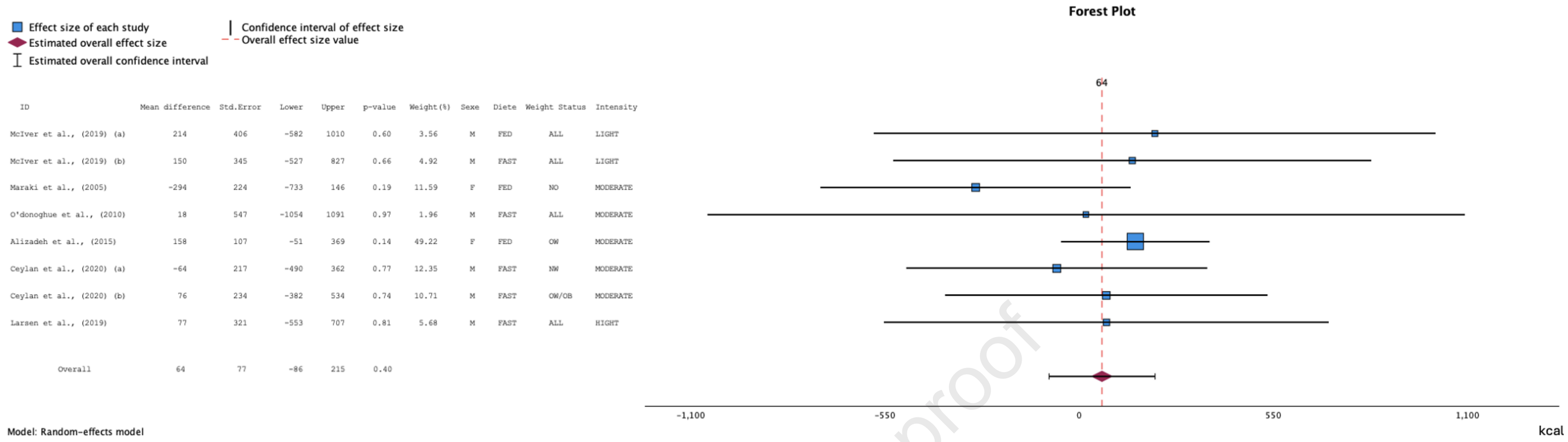

Figure 2. Forest plot of differences in daily energy intake between morning and afternoon/evening exercise sessions

The forest plot illustrates the effect estimates (blue blocks) and 95% confidence intervals (horizontal lines) for each study. Larger blue blocks indicate greater weight assigned to that study. Studies positioned to the left of the overall effect size line indicate lower energy intake with afternoon/evening exercise, while those to the right indicate lower energy intake with morning exercise. The diamond at the base of the plot shows the pooled mean difference effect and confidence intervals from all studies included in the meta-analysis

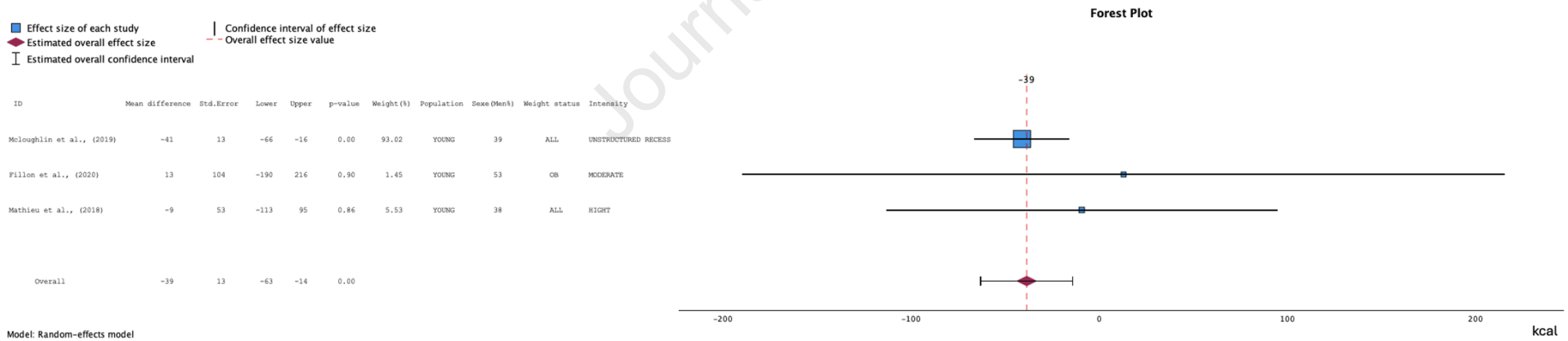

Figure 3. Forest plot of differences in lunch energy intake between before and after meal exercise sessions

The forest plot illustrates the effect estimates (blue blocks) and 95% confidence intervals (horizontal lines) for each study. Larger blue blocks indicate greater weight assigned to that study. Studies positioned to the left of the overall effect size line indicate lower energy intake with after-lunch exercise, while those to the right indicate lower energy intake with before-lunch exercise. The diamond at the base of the plot shows the pooled mean difference effect and confidence intervals from all studies included in the meta-analysis.

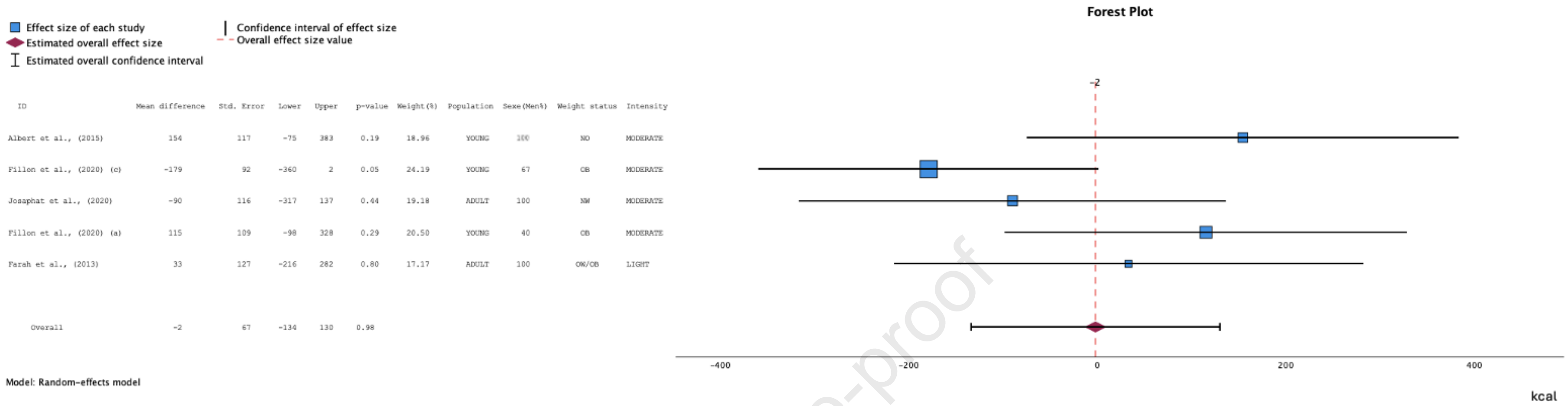

Figure 4. Forest plot of differences in lunch energy intake between near and delayed meal exercise sessions

The forest plot illustrates the effect estimates (blue blocks) and 95% confidence intervals (horizontal lines) for each study. Larger blue blocks indicate greater weight assigned to that study. Studies positioned to the left of the overall effect size line indicate lower energy intake with delayed meal exercise, while those to the right of the overall effect size line indicate lower energy intake with exercise near meals.The diamond at the base of the plot shows the pooled mean difference effect and confidence intervals from all studies included in the meta-analysis.

3.3.2 Chronic exercise

Two studies reported a significant decrease in energy intake throughout the intervention, regardless of exercise timing (Damour et al. 2019; Teo et al. 2021) (Table 2). In contrast, Willis et al. found an increase in energy intake during the intervention, independent of whether exercise was performed in the morning or the afternoon (Willis et al. 2020). Alizadeh et al. observed a decrease in energy intake following a morning exercise program (Alizadeh et al. 2017), while Creasy et al. reported an increase in energy intake over time for the morning exercise group and a decrease for the evening exercise group (Creasy et al. 2022). One study showed no change in energy intake (Brooker et al. 2023).

3.4 Risk of bias and quality assessment

In this review, most acute studies had a low risk of bias or applicability concerns. However, a few were classified as having an "unclear" risk of bias/applicability concerns, especially regarding participant selection and reference standards. Table 3 summarizes the results for the acute studies. Of the 15 studies listed in Table 3, five were categorized as unclear for their risk of bias and applicability concerns regarding the reference standard (Alizadeh et al. 2015; Ceylan et al. 2020; Larsen et al. 2019; Maraki et al. 2005; McIver et al. 2019). Typically, studies measuring the immediate effect of a specific intervention (e.g., exercise) on energy intake utilize an ad libitum buffet following the intervention. These five studies (Alizadeh et al. 2015; Ceylan et al. 2020; Larsen et al. 2019; Maraki et al. 2005; McIver et al. 2019) used 24-hour food records to assess overall energy intake following the exercise session. While 24-hour food records are effective for measuring energy intake throughout the day, they can introduce over- or underestimation, potentially compromising reliability compared to other energy intake measurements, such as ad libitum buffets or direct food consumption. Additionally, this method introduces potential bias related to flow and timing, as simultaneous data collection on the same participant is needed to accurately attribute changes to the intervention (Whiting et al. 2011).

Furthermore, applicability concerns regarding participant selection were noted for two studies (Mathieu et al. 2018; McLoughlin et al. 2019), which involved children aged under 12 years old. While this review aims to describe the effects of exercise timing on energy intake, variations in participant characteristics, such as demographics, can raise concerns about the applicability of findings to the population of interest (Whiting et al. 2011). Despite differences in participant demographics, athletic backgrounds, or weight status, comparisons were made between different exercise timings rather than against a control group, suggesting no significant participant selection bias. None of the studies analyzed in this review compared test performance to an index test. Apart from the five studies mentioned earlier, which had risk of bias and applicability concerns over reference standards, and flow and timing (Alizadeh et al. 2015; Ceylan et al. 2020; Larsen et al. 2019; Maraki et al. 2005; McIver et al. 2019), uniform post-exercise energy measurements and consistent study designs regarding flow and timing, minimized risks associated with intervention variability. Overall, the risk of bias and applicability concerns in the acute studies included in this systematic review are considered low, given the high quality and detailed methods employed. No studies were excluded from the review based on the risk of bias or quality assessment.

Table 3: **Risk of Bias Assessment for acute studies**

Author, year	Risk of bias				Applicability concerns		
	Participant selection	Index test	Reference standard	Flow and timing	Participant selection	Index test	Reference standard
Albert et al., 2015	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Alizadeh et al., 2015	(+)	(+)	(?)	(?)	(+)	(+)	(?)
Ceylan et al., 2020	(+)	(+)	(?)	(?)	(+)	(+)	(?)
Farah et al., 2013	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Fillon et al., 2020	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Fillon et al., 2020	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Fillon et al., 2020	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Josaphat et al., 2020	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Larsen et al., 2019	(+)	(+)	(?)	(?)	(+)	(+)	(?)
Maraki et al., 2005	(+)	(+)	(?)	(?)	(+)	(+)	(?)
Mathieu et al., 2018	(+)	(+)	(+)	(+)	(?)	(+)	(+)
McIver et al., 2019	(+)	(+)	(?)	(?)	(+)	(+)	(?)
McLoughlin et al., 2019	(+)	(+)	(+)	(+)	(?)	(+)	(+)
O'Donoghue et al., 2010	(+)	(+)	(+)	(+)	(+)	(+)	(+)

(+): Low Risk; (-): High Risk; (?): Unclear Risk.

Table 4 presents the evaluation of the overall risk of bias and applicability concerns for the chronic studies included in this systematic review and meta-analysis, revealing a consistently low risk. No studies were excluded based on the risk of bias or quality assessment. While five studies enrolled participants living with overweight or obese (Alizadeh et al. 2017; Brooker et al. 2023; Creasy et al. 2022; Damour et al. 2019; Teo et al. 2021), this characteristic was not indicative of participant selection bias since within-study results were compared across different exercise timings rather than against a control group. Given that the primary aim of this review was to present an overview of the current literature regarding the impact of varied exercise timing on energy intake, no concerns regarding participant selection were identified. The studies did not compare results to a reference standard or specific test performance. Additionally, each study protocol included various forms of monitored exercise at different intensities. Potential confounding factors related to variation in the interventions were minimized by the consistent measurement of energy intake after exercise across all studies, which followed similar designs concerning study flow and timing.

Table 4: Risk of Bias Assessment for Chronic Studies

Author, year	Risk of bias				Applicability concerns		
	Participant selection	Index test	Reference standard	Flow and timing	Participant selection	Index test	Reference standard
Alizadeh et al., 2017	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Brooker et al., 2023	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Creasy et al., 2022	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Damour et al., 2019	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Teo et al., 2021	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Willis et al., 2020	(+)	(+)	(+)	(+)	(+)	(+)	(+)

(+): Low Risk; (-): High Risk; (?): Unclear Risk.

4. Discussion

The objective of this systematic review was to provide a comprehensive overview of the current body of literature on the impact of three exercise timings on energy intake. A meta-analysis was conducted for each distinct timing (acute): time of day (n=8 studies), position relative to a meal (n=3 studies), and the delay between exercise and meal (n=6 studies). No significant differences were found regarding time of day or the delay between exercise and eating. In contrast, exercise after lunch appears to reduce lunch energy intake as shown by studies involving children and adolescents. However, it is important to note that this finding is primarily driven by a single study where exercise was limited to recess, with no structured intervention to ensure active engagement. A systematic review was also conducted of six studies on energy intake following a chronic exercise program. Two studies demonstrated a reduction in daily energy intake with morning exercise, while one observed an increase with a morning exercise program and another a decrease with evening exercise.

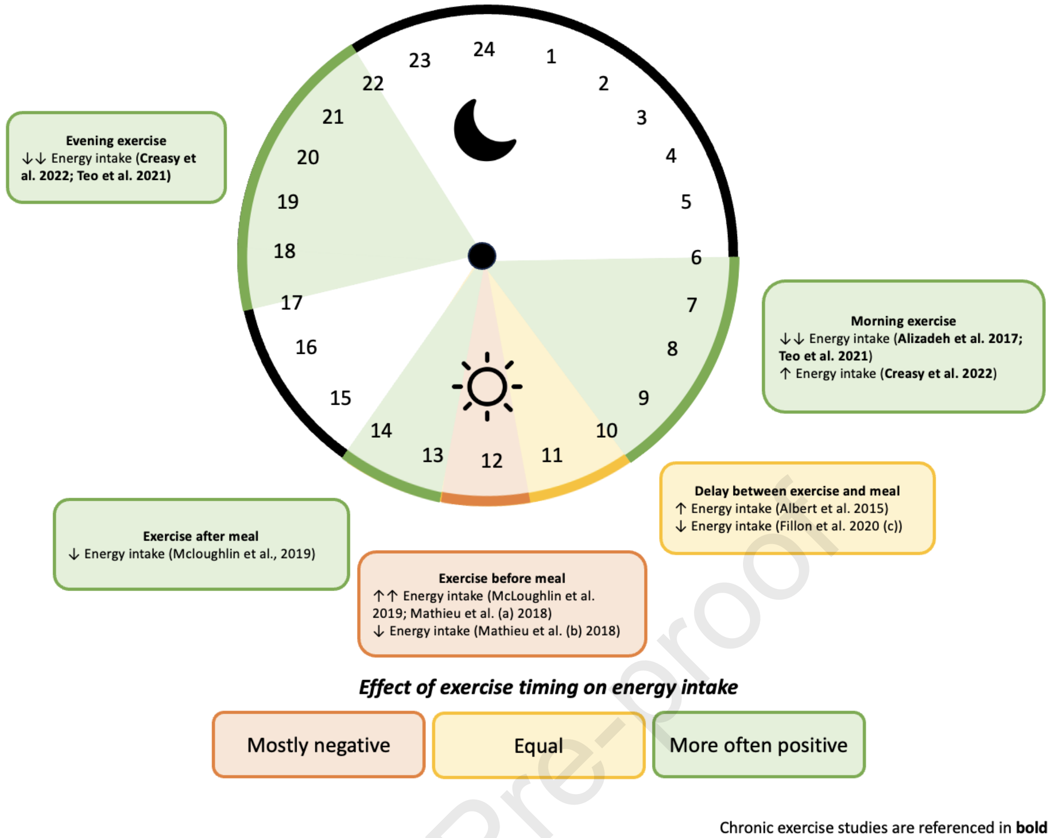

Figure 2. Impact of exercise timing on energy intake

4.1 - Impact of different exercise timing

4.1.1 Time of day

The meta-analysis found no significant difference in energy intake between morning and afternoon/evening exercise. Notably, none of the eight studies included in this analysis individually showed a significant difference in energy intake.

For chronic studies, some showed a similar reduction in energy intake following a morning or evening exercise program. For example, Brooker et al. found an average significant decrease of 611 kcal for the morning exercise program and 533 kcal for the afternoon exercise program, with both reductions observed compared to the non-exercise condition. However, the difference between morning or evening exercise training was not signifiant (Brooker et al. 2023). Interestingly, Alizadeh et al. observed a decrease of 361 kcal only in the morning exercise group compared to the evening group (Alizadeh et al. 2017). Conversely, Teo et al. reported a decrease of 280 kcal for the AM exercise group and 437 kcal for the PM group, both compared to baseline (Teo et al. 2021). The study by Willis et al. was an exception, showing an increase in energy intake (Willis et al. 2020). It should be noted that these chronic studies primarily focused on individuals with excess body weight. This raises the possibility that the optimal timing of exercise for reducing energy intake may vary according to body weight status. Individuals with lower adiposity might compensate for the energy expended during exercise to a greater extent. This hypothesis aligns with findings that untrained individuals with excess adiposity generally do not adjust their energy intake in response to an exercise regimen (Durrant et al. 1982), while more active individuals tend to exhibit better appetite regulation, matching energy intake with expenditure (homeostatic appetite control) (Beaulieu et al. 2018). Overall, the intensity of exercise did not appear to play a significant role in influencing subsequent energy intake. Studies conducted at light, moderate, and high intensities yielded similar results. The timing of morning exercise is unique since it can be performed in either a fasted or fed state. Although most studies examined fasted exercise, both morning and afternoon/evening sessions were shown to have advantages in certain conditions. Unfortunately, fitness or physical activity levels were not systematically measured and reported in these studies. Moreover, the study by Willis et al. is an exception, showing an increase in energy intake (Willis et al. 2020). Paradoxically, prolonged exercise can sometimes lead to compensatory increases in energy intake, as previously reported by several authors (Bagdade et al. 1967; Beaulieu et al. 2016; Considine et al. 1996; Coutinho et al. 2018; Jokisch et al. 2012; Karra et al. 2010; King et al. 2013). Regular exercise may heighten the drive to eat and trigger strong satiety signals (Hagobian et al. 2009; Hickey et al. 1997), potentially increasing energy intake without necessarily affecting body weight, considering that exercise contributes to an energy deficit. The study by Willis et al. is also the longest, lasting 40 weeks compared to 15 weeks or less for other studies. This longer timeframe may suggest a long-term adaptation to training. Also, after 40 weeks of exercising five times per week, participants could be considered “active” and thus have an improved alignment between energy intake and expenditure.

Additionnaly, most studies have shown a reduction in body weight with morning exercise (Alizadeh et al. 2017; Brooker et al. 2023; Creasy et al. 2022; Teo et al. 2021; Willis et al. 2020). Alizadeh et al. observed a 2.2% reduction in body weight in the morning exercise group, while no significant difference was found in the afternoon/evening group (Alizadeh et al. 2017). Similarly, Willis et al. reported a larger decrease in body weight for the morning exercise group (-6.2 kg) compared to the afternoon/evening exercise group (-1.6 kg) (Willis et al. 2020). Finally, beyond the physiological benefits of regular morning exercise, Schumacher et al. found that exercising in the morning improves adherence by facilitating planning, establishing exercise routines, and enhancing self-regulation (Schumacher et al. 2020). These factors are crucial for sustaining long-term exercise habits and achieving weight loss.

4.1.2 –Before/After meal

Three studies investigated the effects of exercising before and after meals (Fillon et al. 2020 (b); Mathieu et al. 2018; McLoughlin et al. 2019). The meta-analysis revealed a lower energy intake when exercise is performed after lunch in children and adolescents. However, these results should be interpreted with caution, as they rely heavily on McLoughlin et al.'s study, which contributed 93% of the weight of the meta-analysis. Interestingly, when recess and meals were simply switched in schools, as seen in McLoughlin et al. (2019), energy intake increased when recess took place before lunch. In this case, the delayed meal may have heightened appetite, leading to higher energy intake. Furthermore, the typical recess exercise intensity may not have been sufficient to influence appetite control optimally. Prado et al. found that children's energy intake decreased more with higher intensity exercise, regardless of the timing of exercise (Prado et al. 2015). Other studies have observed greater and more sustained increases in PYY, a satiety hormone, following vigorous exercise compared to lower intensity exercise (King et al. 2012; Ueda et al. 2009). Fillon et al. found no significant differences in energy intake when moderate-intensity exercise was performed before or aftera meal (Fillon et al. 2020 (b)), as the meal was taken at the same time in both conditions (i.e., 12:30 pm), and exercise performed immediately before or after. Similarly, our group tested two intensities of recess (light and moderate-to-vigorous) before a mid-day meal and a control condition (mid-day meal first followed by moderate-to-vigorous recess) in a school-based scenarion (Mathieu et al. 2018). This study showed that delaying the mid-day meal did not increase energy intake when higher-intensity exercice was performed. In contrast, introducing low-intensity recess before the meal led to a significant increase in energy intake, echoing McLoughlin et al.'s findings (McLoughlin et al. 2019).

To our knowledge, this timing has only been studied by our group in the context of chronic exercise. Significant decreases of 1,291 kcal/day and 1,013 kcal/day compared to baseline assessments were observed when exercising before and after meals, respectively (Damour et al. 2019). While the difference of over 239 kcal favors exercise before meals and is clinically relevant, the limited sample size (n=8) contributed to the non-significant differences. In addition, the short duration of the study (1 month per timing) resulted in similar anthropometric changes across both conditions.

4.1.3 - Interval before the meal

This work considers the delay between the end of exercise and the beginning of the test-meal as the third timing factor, specifically when the test-meal was taken at midday. The meta-analysis revealed no significant effect of delays in eating. Only two studies in this review showed different effects depending on when the exercise was performed. Albert et al. found that energy intake was lower (-154 kcal) when exercise occured closer to the midday meal (Albert et al. 2015). Conversely, Fillon et al. reported that energy intake was lower (-179 kcal) when exercise was performed farther in advanceof the midday meal (Fillon et al. 2020 (c)). Although these results appear contradictory, they may be explained by significant methodological differencesthat could influence metabolic and energy load, even when the duration, modality, and intensity of exercise are similar (Aucouturier 2011). In the study by Fillon et al., the test-meal at midday differed between trials (noon vs. 01:00 pm) (Fillon et al. 2020(c)), which may cause variation in energy intake and appetite sensations, particularly due to hormonal diurnal variations that regulate appetite (Miguet et al. 2018; Nemet et al. 2010). Additionally, Albert et al. compared exercise that ended 15 minutes versus 150 minutes before the test-meal (Albert et al. 2015), while Fillon et al. compared exercise that ended 30 minutes versus 90 minutes prior (Fillon et al. 2020 (c)). The shorter delay in the Fillon et al. study may not have been sufficient to capture the effects of exercise, particularly as the nearer condition was further from the test-meal. Several authors have reported that the anorexigenic effect of exercise decreases during the recovery period (Broom et al. 2007; King et al. 2010; Martins et al. 2007; Ueda et al. 2009), yet the specific timing of exercise has yet to be studied. Finally, participants in the study by Josaphat et al. performed sensory tests involving the presence of solutions in the mouth between exercise and the meal (Josaphat et al. 2020). In the context of exercise, the mere presence of solutions in the mouth can enhance performance (Best et al. 2021), suggesting that such procedures could interfere with the subsequent energy intake. Finally, it should be noted that including or excluding the study by Farah et al., which involved a small meal (i.e. breakfast) between exercise and the test meal, did not yield different results, suggesting a limited impact of small energy intakes on the outcomes of the test-meal (Farah et al. 2013). However, in this study, exercice ended two hours and four hours before the test-meal, potentially extending the duration beyond what is necessary to maintain the anorexigenic effect of exercise.

In the context of chronic exercise, Damour et al. is among the few studies to have considred the timing of exercise in relation to meals (Damour et al. 2019). This study was mentioned in the previous section since, over a chronic period, individuals typically have more than one meal, making it essential to examine exercise timing relative to meal times - specifically, whether the exercise occurs before or after a meal and how close it is to the meal. The study compared the effects of fifteen minutes of exercise one hour before two daily meals every day for one month with fifteen minutes of sporadic exercise outside that timeframe performed twice a day. Both groups showed reductions in energy intake, body weight, and fat percentage.

4.2 Potential impact of population characteristics

The studies included in this meta-analysis exhibited considerable heterogeneity in population characteristics, particularly in terms of age, gender, and weight status, which explains the diversity of results. Aging, for instance, can reduce the ability to manage energy balance effectively (Roberts et al. 2006). Notably, in this meta-analysis the studies involving younger participants appeared to yield more pronounced results regarding energy intake: two-thirds (4/6) of findings were significant for children and adolescents *versus* only one-third (5/15) for adults. Ansdell et al. have also documented that physiological responses to acute and chronic exercise vary between males and females (Ansdell et al. 2020). Current literature indicates that men generally exhibit a stronger anoretic response to exercise compared to women, regardless of exercise timing (George et Morganstein 2003; Kissileff et al. 1990; Moore et al. 2004; Pomerleau et al. 2004). For instance, fasting women tend to have higher levels of the appetite-stimulating hormone ghrelin than men (Alajmi et al. 2016; Douglas et al. 2017). In addition, exercise appears to decrease blood levels of leptin and insulin in women participants (Hickey et al. 1997), while appetite suppression is more apparent in men following exercise (Hagobian et al. 2009). However, some studies report unchanged leptin and ghrelin concentrations (Alajmi et al. 2016; Hagobian et al. 2009; Hagobian et Evero 2013; Panissa et al. 2016), alongside suppressed appetite (Hazell et al. 2016) and comparable energy intake between men and women after exercise (Caudwell et al. 2013; Ebrahimi et al. 2013; Shamlan et al. 2017). Among the studies in this review, only Alizadeh et al. reported significant differences in women, noting lower energy intake with morning exercise (Alizadeh et al. 2017). Albert et al. observed lower energy intake in men exercising close to a meal (45 minutes before) compared to three hours before the meal (Albert et al. 2015). Miguet et al. found that vigorous exercise reduced energy intake in adolescents living with obesity, suggesting the anorexigenic effect correlates with the participant's BMI or fat mass (Miguet et al. 2018). In contrast, Nemet et al. found that only normal-weight children had reduced energy intake after exercise compared to sedentary conditions (Nemet et al. 2010). Douglas et al. reported transiently suppressed appetite and increased PYY and GLP-1 levels after 60 minutes of treadmill exercise, regardless of weight status (Douglas et al. 2017). Only one study has examined how exercise timing affects weight status, reporting no significant differences in energy intake (Ceylan et al. 2020; Dodd et al. 2008). Nonetheless, Ceylan et al. (2020) noted greater decreases in asproxin, insulin, and lipocalin-2 levels in individuals living with obesity compared to those of normal weight. These peptides, secreted by adipose tissue, play a key role in regulating appetite, satiety, and inflammation, suggesting a greater reduction in orexigenic signals in individuals living with obesity (Walewski et al. 2014; Zheng et al. 2017). Moreover, the same study observed that the group of individuals living with overweight consumed less energy in the evening than their normal-weight counterparts, which may reflect this phenomenon (Ceylan et al. 2020). At this stage, it therefore seems important to standardize research on these three parameters (age, gender and body weight status) alongside exercise intensity and timing, to draw clear conclusions and propose semi-individualized solutions.

4.3 Limitations

While we conducted an extensive search in an attempt to include all studies reporting on energy intake and exercise timing, this subsequently led us to sort the studies into three levels (title, abstract, text) instead of the two recommended by PRISMA (title and abstract, text). Despite our best efforts, it is possible that some studies were overlooked. Additionally, the sample sizes in many studies were relatively small, typically around 15 participants. In contrast, school-based studies, such as the one conducted by McLoughlin et al. (2019), involved larger samples (>100) and significantly influenced the meta-analysis. Future work should aim to include more participants to strengthen the conclusions drawn from these studies. It is also essential to incorporate control groups for chronic interventions to account for potentail confounding factors, such as seasonal changes in lifestyle habits, and to document participants' chronotype and baseline fitness/physical activity levels. The examination of time delay presents specific challenges. First, two key factors need consideration;: 1) the variation in delay between the end of the exercise session and the start of the test-meal, and 2) each study does not assess the same time delay. For instance, in Albert et al. (2015), the delay tested were 145 minutes apart, while they were 60 minutes in Fillion et al. (2020 c). Lastly, there is a notable gap between acute and chronic findings that warrants further investigation. Most acute studies focus solely on the immediate subsequent meal, rather than monitoring the 24- to 48-hour responses.

5. Conclusion

This study aimed to address an important question: when is the optimal time to exercise to optimize its impact on energy intake? Our analysis revealed no significant differences in energy intake based on the time of day or delay between exercise and meals. However, exercising after lunch appears to reduce energy intake at that meal. A key limitation of the current studies is the small number of acute and chronic investigations, coupled with methodological diversity (including variations in exercise regimens, and energy intake assessments, which often focus on a single meal and individual factors). To gain a deeper understanding of how different exercise timings impacts energy intake, future research should involve a wider range of subgroups to improve the effectiveness of the findings.

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PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	p.1
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	p.1
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	p.2-3
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	p.3
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	p.5
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	p.3-4
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	p.3-4
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	p.4-5
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	p.4-5
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	p.4-5
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	p.4-5
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	p.6-7
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	p.6
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	p.5
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	p.6
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	p.6
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	p.6
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	p.6
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	p.6
Reporting bias	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	p.6-7

PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
assessment			
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	p.5-6
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	p.4-5
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	p.4-5
Study characteristics	17	Cite each included study and present its characteristics.	p.7-15
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	p.19-21
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	p.7-15
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	p.16-19
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	p. 16-19
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	p. 16-19
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	p. 16-19
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	p.16
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	p.16-19
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	p.21-26
	23b	Discuss any limitations of the evidence included in the review.	p.27
	23c	Discuss any limitations of the review processes used.	p.27
	23d	Discuss implications of the results for practice, policy, and future research.	p.27
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	p.3
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	p.3-4
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	NA
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	p.28
Competing interests	26	Declare any competing interests of review authors.	p.28

PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	p.4-5

From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71.

PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Reported (Yes/No)
TITLE			
Title	1	Identify the report as a systematic review.	Yes
BACKGROUND			
Objectives	2	Provide an explicit statement of the main objective(s) or question(s) the review addresses.	Yes
METHODS			
Eligibility criteria	3	Specify the inclusion and exclusion criteria for the review.	Yes
Information sources	4	Specify the information sources (e.g. databases, registers) used to identify studies and the date when each was last searched.	Yes
Risk of bias	5	Specify the methods used to assess risk of bias in the included studies.	Yes
Synthesis of results	6	Specify the methods used to present and synthesise results.	Yes
RESULTS			
Included studies	7	Give the total number of included studies and participants and summarise relevant characteristics of studies.	Yes
Synthesis of results	8	Present results for main outcomes, preferably indicating the number of included studies and participants for each. If meta-analysis was done, report the summary estimate and confidence/credible interval. If comparing groups, indicate the direction of the effect (i.e. which group is favoured).	Yes
DISCUSSION			
Limitations of evidence	9	Provide a brief summary of the limitations of the evidence included in the review (e.g. study risk of bias, inconsistency and imprecision).	Yes
Interpretation	10	Provide a general interpretation of the results and important implications.	Yes
OTHER			
Funding	11	Specify the primary source of funding for the review.	Yes
Registration	12	Provide the register name and registration number.	Yes

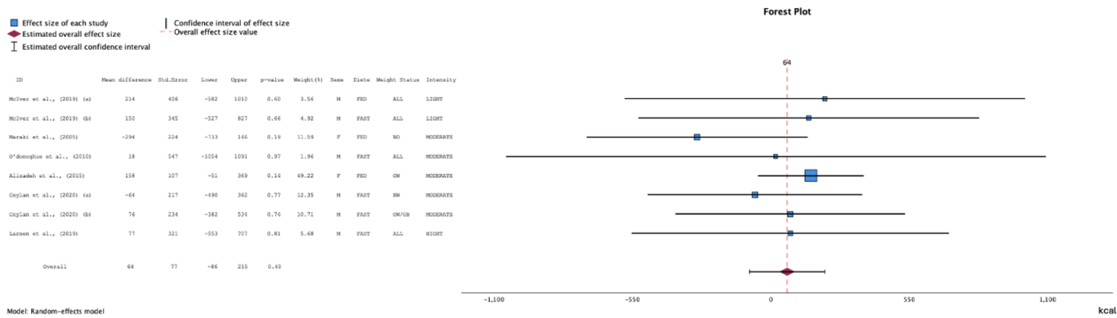

Figure 2. Forest plot of differences in daily energy intake between morning and afternoon/evening exercise sessions

The forest plot illustrates the effect estimates (blue blocks) and 95% confidence intervals (horizontal lines) for each study. Larger blue blocks indicate greater weight assigned to that study. Studies positioned to the left of the overall effect size line indicate lower energy intake with afternoon/evening exercise, while those to the right indicate lower energy intake with morning exercise. The diamond at the base of the plot shows the pooled mean difference effect and confidence intervals from all studies included in the meta-analysis

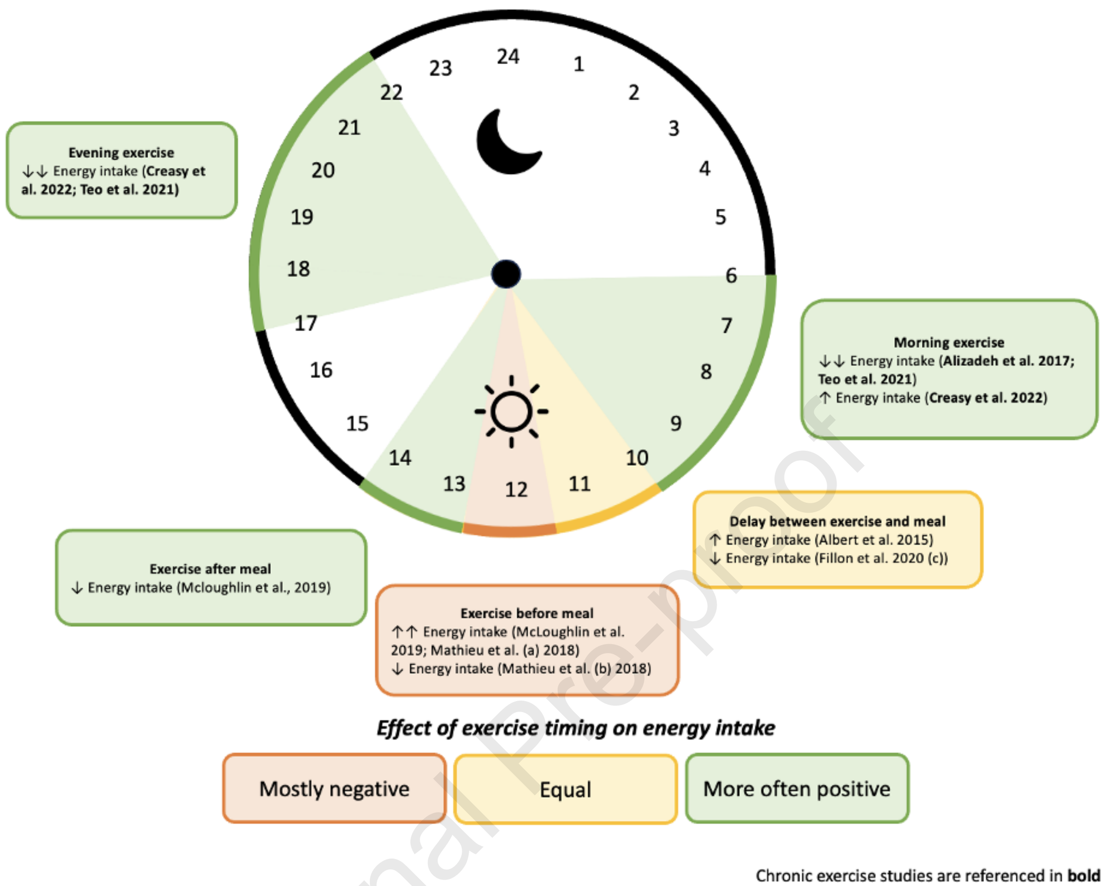

Figure 2. Impact of exercise timing on energy intake

Ethical Statement

Thus, it did not require any ethics board approval. For further information concerning the ethical statement of this paper, feel free to contact the corresponding author listed below.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: