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Quality in Sport. eISSN 2450-3118.

Journal Home Page

<https://apcz.umk.pl/QS/index>

WOŹNIAK, Weronika Maria, WINIARSKA, Zuzanna, WITCZAK, Katarzyna Wiktoria, WIELEBA, Marcin, MALEC, Julia Anna, WIERCIOCH, Eliza, WŁODARCZYK, Franciszek, KRUPSKA, Barbara Izabela, ZAPALSKA, Magdalena and KULIG, Lidia. Meal timing and metabolic regulation: the emerging role of chrononutrition. Quality in Sport. 2026;53:70180. eISSN 2450-3118. <https://doi.org/10.12775/QS.2026.53.70180>

The journal has been awarded 20 points in the parametric evaluation by the Ministry of Higher Education and Science of Poland. This is according to the Annex to the announcement of the Minister of Higher Education and Science dated 05.01.2024, No. 32553. The journal has a Unique Identifier: 201398. Scientific disciplines assigned: Economics and Finance (Field of Social Sciences); Management and Quality Sciences (Field of Social Sciences).

Punkty Ministerialne z 2019 - aktualny rok 20 punktów. Załącznik do komunikatu Ministra Szkolnictwa Wyższego i Nauki z dnia 05.01.2024 Lp. 32553. Posiada Unikatowy Identyfikator Czasopisma: 201398. Przypisane dyscypliny naukowe: Ekonomia i finanse (Dziedzina nauk społecznych); Nauki o zarządzaniu i jakości (Dziedzina nauk społecznych). © The Authors 2026.

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The authors declare that there is no conflict of interest regarding the publication of this paper.

Received: 23.03.2026. Revised: 30.03.2026. Accepted: 30.03.2026. Published: 04.04.2026.

Meal timing and metabolic regulation: the emerging role of chrononutrition

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Abstract

Background. In recent years, in the context of the growing burden of metabolic diseases, increasing attention has been paid to novel dietary approaches, among which the concept of chrononutrition has gained considerable interest. It focuses on the relationships between meal timing and circadian rhythms, as well as their potential impact on metabolic regulation.

Aim. The aim of this study was to present the current state of knowledge regarding the influence of meal timing and circadian rhythms on metabolic processes and metabolic health.

Material and methods. A narrative literature review was conducted using the PubMed and Scopus databases, including publications from 2020 to 2026. Original studies and review articles, including systematic reviews and meta-analyses addressing chrononutrition and its potential health implications, were included.

Results. Available evidence suggests that synchronization of food intake with circadian rhythms may promote more favorable regulation of glucose and lipid metabolism. Strategies such as time-restricted eating (TRE) may support weight reduction and improve selected metabolic parameters. However, their effectiveness appears to depend, among other factors, on the timing of the eating window. Unfavorable patterns, such as skipping breakfast or late-night eating, have been associated with impaired metabolic control and an increased risk of metabolic disorders. Overall, the findings across studies remain heterogeneous.

Conclusions. Meal timing may represent an important component of metabolic regulation and complement traditional dietary approaches. However, due to limitations of the current evidence, further well-designed studies are required to clarify its role in clinical practice.

Key words: chrononutrition, meal timing, circadian rhythm, time-restricted eating, metabolic health, obesity.

1. Introduction

In recent decades, a steady increase in the prevalence of obesity and its associated metabolic disorders, such as type 2 diabetes, cardiovascular diseases, and lipid abnormalities, has been observed. These conditions represent a significant public health challenge, and their rising incidence has prompted the search for more effective preventive and therapeutic

strategies (Boutari & Mantzoros, 2022). Traditionally, dietary approaches aimed at preventing and managing these disorders have primarily focused on total caloric intake and macronutrient composition (Contreras et al., 2024). However, increasing attention is being paid to the fact that not only the quality and quantity of food, but also the timing of food intake, may play an important role (Fuad et al., 2025; Peters et al., 2024).

In this context, the concept of chrononutrition has gained increasing interest in recent years. It examines the relationships between meal timing and the functioning of biological rhythms. Chrononutrition is based on the premise that metabolic processes are closely linked to the activity of the biological clock, regulated by circadian rhythms. Circadian rhythms influence, among others, hormone secretion, glucose and lipid metabolism, as well as appetite regulation and energy homeostasis (Fuad et al., 2025; Katsi et al., 2022).

The growing interest in chrononutrition stems from observations that modern lifestyles often contribute to misalignment between eating behaviors and circadian rhythms. Behaviors that may affect metabolic regulation include irregular meal patterns, skipping breakfast, late-night eating, and prolonged eating windows. At the same time, potential benefits of dietary strategies better aligned with biological rhythms, such as limiting the eating window or consuming a greater proportion of daily energy earlier in the day, are increasingly being explored (Katsi et al., 2022; Peters et al., 2024; Raji et al., 2024).

Despite the growing body of evidence, the relationships between meal timing and metabolic health remain complex and not fully understood. The aim of this study is to present the current state of knowledge regarding the relationship between meal timing, circadian rhythms, and metabolic health, with particular emphasis on physiological mechanisms and potential implications for the prevention of metabolic diseases.

2. Research materials and methods

A narrative literature review was conducted using the PubMed and Scopus databases to identify relevant studies examining the relationship between chrononutrition, meal timing, circadian rhythms, and metabolic health. The search included publications from January 2020 to March 2026. The following keywords and their combinations were used: “chrononutrition,” “meal timing,” “circadian rhythm,” “time-restricted eating,” “metabolic health,” “obesity,” “insulin resistance,” and “metabolic syndrome”.

The inclusion criteria comprised original research articles, systematic reviews, review articles, and meta-analyses published in English that addressed the influence of meal timing or circadian rhythms on metabolic processes and health outcomes. Both clinical and experimental

studies were considered. Articles not written in English, opinion pieces, conference abstracts, and studies with insufficient methodological information or without available full text were excluded from the analysis.

3. Research results

3.1. Biological basis of circadian rhythms

The circadian rhythm is one of the fundamental mechanisms regulating the functioning of the human body. It is an endogenous, approximately 24-hour biological cycle that coordinates numerous physiological processes, including the sleep-wake cycle, hormone secretion, nutrient metabolism, and body temperature regulation. This mechanism enables the adaptation of biological processes to regular environmental changes, primarily related to the light-dark cycle (Fagiani et al., 2022; Fuad et al., 2025).

The central component of the system regulating circadian rhythms is the master biological clock located in the suprachiasmatic nucleus (SCN) of the hypothalamus in mammals. This structure receives light signals from the retina and, based on this input, synchronizes internal biological processes with the day-night cycle. The SCN coordinates the function of numerous peripheral clocks present in various tissues, including the liver, adipose tissue, skeletal muscles, and pancreas. This coordination allows for the maintenance of coherent regulation of processes occurring in individual organs (Fagiani et al., 2022; Flanagan et al., 2021).

At the cellular level, the functioning of the biological clock is based on the cyclical expression of so-called clock genes. A key role in this mechanism is played by the transcription factors Circadian Locomotor Output Cycles Kaput (CLOCK) and Brain and Muscle ARNT-Like 1 (BMAL1), which form a heterodimer that initiates the transcription of Period (Per) and Cryptochrome (Cry) genes. The protein products of these genes, PER and CRY, gradually accumulate in the cell and subsequently translocate to the nucleus, where they inhibit the activity of the CLOCK-BMAL1 complex. This mechanism forms a negative feedback loop responsible for generating the approximately 24-hour cycle of biological clock activity (Fagiani et al., 2022). This regulation is further modulated by additional molecular components, including the nuclear receptors Reverse-strand of ERBA (REV-ERB) and Retinoic acid receptor-related Orphan Receptor (ROR), which participate in the regulation of Bmal1 gene expression and stabilize the molecular mechanism of the biological clock. The interplay of these mechanisms leads to rhythmic changes in the expression of numerous genes involved in cellular

function. As a result, many physiological processes, including metabolic pathways, can be temporally aligned with the day-night cycle (Flanagan et al., 2021; Fuad et al., 2025).

The synchronization of peripheral clocks occurs not only through signals originating from the central clock in the SCN but also through various environmental cues known as zeitgebers. The most important of these is light. However, behavioral factors such as the sleep-wake cycle, physical activity, and food intake also play a significant role. These cues enable the adjustment of tissue-specific functions to current environmental conditions and the organism's activity patterns (Peters et al., 2024; Raji et al., 2024; Schrader et al., 2024).

Understanding the mechanisms regulating circadian rhythms provides a basis for analyzing the influence of the biological clock on metabolic regulation and the body's adaptation to changing environmental conditions (Fagiani et al., 2022).

3.2. Circadian regulation of metabolic processes

Circadian rhythms play a crucial role in regulating numerous metabolic processes in the human body. A growing body of evidence suggests that metabolic activity exhibits pronounced diurnal variation, which allows for the adaptation of nutrient utilization to the time of day and the level of physical activity. These mechanisms include, among others, the regulation of glucose and lipid metabolism, energy homeostasis, and the secretion of hormones involved in appetite control and energy balance (Flanagan et al., 2021) (Meléndez-Fernández et al., 2023).

One of the best-documented examples of circadian regulation is the variation in glucose tolerance and insulin sensitivity throughout the day. Numerous studies have demonstrated that the body's ability to metabolize glucose efficiently is higher in the morning and gradually declines in the evening. This phenomenon is partly explained by rhythmic changes in the activity of metabolic enzymes as well as diurnal fluctuations in the secretion of hormones that regulate carbohydrate metabolism (Leung et al., 2020). Changes in the activity of metabolic pathways involved in glucose transport and utilization in peripheral tissues, such as skeletal muscle and the liver, are also of significant importance. It has been shown that gene expression related to glucose transport, glycolysis, and glycogen storage exhibits circadian variation. During the first part of the day, increased activity of processes related to glucose uptake by tissues and its utilization for energy production, including glycolysis and glycogen synthesis, is observed. In contrast, during the evening hours, there is a relative decrease in tissue sensitivity to insulin and a reduction in the efficiency of carbohydrate metabolism. As a result, the body demonstrates a greater capacity for glucose utilization earlier in the day (Mentzelou et al., 2024; Zhang et al., 2025; Zhao et al., 2021).

Circadian rhythms also influence lipid metabolism and processes related to energy storage and utilization. The expression of numerous genes involved in fatty acid synthesis, transport, and oxidation has been shown to be regulated by the biological clock. This regulation includes processes such as lipogenesis, lipolysis, and β -oxidation of fatty acids. During periods of increased nutrient availability, lipid synthesis and storage in the form of triglycerides are enhanced, whereas during fasting, catabolic processes such as lipolysis and fatty acid oxidation are upregulated. This enables the organism to adapt energy metabolism to the time of day and current physiological demands (M. Liu et al., 2023; Petrenko et al., 2023).

Hormones, whose secretion is also regulated by circadian rhythms, play an essential role in metabolic regulation. One such hormone is cortisol, which reaches its peak concentration in the morning, preparing the body for daytime activity and mobilization of energy resources (Andreadi et al., 2025). Diurnal fluctuations are also observed in hormones involved in appetite regulation, such as leptin and ghrelin, which influence hunger, satiety, and food intake (Farhadipour & Depoortere, 2021).

An increasing number of studies suggest that disruption of the synchronization between circadian rhythms and lifestyle factors may lead to metabolic disturbances and increase the risk of metabolic diseases. Therefore, in recent years, particular attention has been paid to meal timing as a factor that may influence the functioning of the biological clock and the regulation of metabolic processes, forming the basis of the concept of chrononutrition (Peters et al., 2024).

3.3. Time-restricted eating

One of the most commonly investigated dietary strategies in the context of chrononutrition is time-restricted eating (TRE), which involves limiting the daily eating window while extending the fasting period during the remaining hours of the day. Unlike traditional dietary interventions that primarily focus on total caloric intake or diet composition, this approach emphasizes the timing of food intake. The most commonly applied TRE protocols involve consuming all meals within a daily window of approximately 8 to 10 hours, followed by a prolonged period of fasting. In recent years, this strategy has attracted considerable interest in nutritional research due to its potential effects on metabolic regulation and metabolic health (Manoogian et al., 2022).

A systematic review and meta-analysis, including 15 studies with a total of 338 participants, evaluated the effects of TRE combined with physical activity on body composition. The results indicated a modest but significant reduction in fat mass and body fat percentage in individuals following TRE, with no significant changes observed in lean body mass. These

findings suggest that this strategy may promote fat loss without adversely affecting muscle mass (Hays et al., 2025). Similar conclusions were reported in another systematic review and meta-analysis, which included 19 randomized controlled trials involving 568 adult participants. These trials assessed the effects of TRE combined with physical activity on body composition and selected metabolic health indicators. The analysis demonstrated that combining TRE with exercise was associated with greater reductions in body weight and fat mass compared with control groups following standard dietary patterns with similar levels of physical activity. Additionally, favorable changes were observed in certain metabolic parameters, including reductions in triglyceride levels, low-density lipoprotein (LDL) cholesterol, and leptin concentrations. However, no significant differences were found in fasting glucose, insulin levels, or several other lipid parameters (Dai et al., 2024).

Some studies have also reported beneficial effects of TRE on glucose metabolism. In a randomized controlled trial involving 120 patients with overweight and type 2 diabetes, the implementation of a 10-hour eating window over 12 weeks resulted in significant reductions in blood glucose levels and glycated hemoglobin (HbA1c), as well as body weight, compared with the control group. Furthermore, improvements in insulin resistance indices and pancreatic β -cell function were observed, along with favorable changes in selected lipid parameters, including reductions in triglycerides, total cholesterol, and LDL cholesterol (Che et al., 2021). Similar findings were reported in an umbrella review including 7 systematic reviews with 30 meta-analyses, which evaluated the effects of TRE on body weight, fasting glucose, and lipid profile in individuals with overweight and obesity. The results indicated that TRE-based dietary patterns may lead to weight reduction and lower fasting glucose levels. In some analyses, improvements in selected lipid parameters, including LDL cholesterol, were also observed. However, the authors emphasized that the quality of the available evidence is heterogeneous, highlighting the need for further well-designed clinical studies (Chew et al., 2023). Overall, findings regarding the effects of TRE on selected metabolic health outcomes remain inconsistent, which may be attributed to differences in intervention duration, study population characteristics, and variability in the implementation of TRE protocols.

In the literature, increasing attention has also been given to the timing of the eating window within the day. A distinction is made between early TRE, in which food intake is concentrated in the first part of the day, and delayed TRE, where the eating window is shifted to later hours (Manoogian et al., 2022). Some studies suggest that earlier food intake may better align with the body's physiological rhythms, potentially resulting in more favorable metabolic regulation. A network meta-analysis including 12 randomized controlled trials involving 730

adults with overweight or obesity evaluated the effects of early and delayed TRE on body weight and selected metabolic parameters. The results indicated that both early and delayed TRE led to moderate weight loss and reductions in insulin resistance compared with interventions without time restrictions on food intake. However, early TRE was found to be more effective than delayed TRE in improving insulin resistance and additionally showed beneficial effects on glucose metabolism and blood pressure regulation. No significant differences were observed between early and delayed TRE in terms of weight loss or certain metabolic parameters, such as fasting glucose levels or lipid profile (J. Liu et al., 2023). In a randomized controlled trial conducted among young women performing resistance training, greater weight reduction was observed in the early TRE group (8:00-14:00) compared with the delayed TRE group (12:00-18:00) and the control group (8:00-20:00). At the same time, no significant differences were found between the groups in terms of muscle mass gain or improvements in muscular endurance (Yu & Ueda, 2025). Overall, the available evidence suggests that TRE may represent a promising strategy for supporting metabolic health. However, its effectiveness appears to depend on multiple factors, including the timing of the eating window and characteristics of the study population.

3.4. Distribution of energy intake during the day

One of the most frequently analyzed eating behaviors in the context of chrononutrition is breakfast skipping. A growing body of evidence suggests that this dietary pattern may negatively affect metabolic regulation and contribute to disturbances in energy homeostasis. A systematic review and meta-analysis of observational studies demonstrated that breakfast skipping is associated with an increased risk of metabolic syndrome and its components, including abdominal obesity, hypertension, dyslipidemia, and hyperglycemia (Yang et al., 2025). Similar findings were reported in another meta-analysis including 45 studies. This analysis showed a significant association between breakfast skipping and an increased risk of overweight and obesity in both cross-sectional and cohort studies (Ma et al., 2020). In the context of type 2 diabetes risk, a systematic review and meta-analysis of prospective cohort studies found that regular breakfast skipping is associated with a higher risk of developing the disease. A dose-response analysis indicated a nonlinear relationship, with the highest risk observed among individuals skipping breakfast 4-5 days per week (Ballon et al., 2019). However, findings from interventional studies are less consistent. A meta-analysis of randomized controlled trials reported that breakfast skipping may be associated with a modest

reduction in body weight, but also with an increase in LDL cholesterol levels, with no significant changes observed in other metabolic parameters (Bonnet et al., 2020).

Another important aspect of daily energy distribution is evening food intake. It has been suggested that consuming a substantial proportion of daily energy intake during the evening and nighttime hours may adversely affect metabolic regulation. A randomized crossover trial demonstrated that late eating, despite identical energy intake and dietary composition, resulted in increased hunger, unfavorable changes in appetite-regulating hormones, including an increased ghrelin-to-leptin ratio, and reduced energy expenditure. Additionally, changes in adipose tissue gene expression were observed, favoring reduced lipolysis and increased adipogenesis, which may contribute to the development of obesity (Vujović et al., 2022). Furthermore, a systematic review of randomized crossover trials found that carbohydrate consumption in the evening is associated with higher postprandial glycemia compared with morning intake (de Almeida et al., 2023). In a cohort study involving over 100,000 adults, later timing of both the first and last daily meal was associated with an increased risk of cardiovascular diseases, particularly in women (Palomar-Cros et al., 2023). Taken together, these findings suggest that shifting energy intake to later hours of the day may lead to adverse metabolic outcomes, independent of total energy intake.

4. Discussion

The presented evidence highlights the importance of meal timing as a key component of metabolic regulation, extending beyond approaches based solely on energy balance and dietary composition. These relationships appear to arise primarily from the interaction between eating behaviors and the endogenous circadian rhythm (Fuad et al., 2025; Katsi et al., 2022). Misalignment between meal timing and circadian rhythms may be associated with adverse metabolic changes, including impaired glycemic control, dysregulation of lipid metabolism, alterations in appetite regulation, and an increased risk of obesity (Ballon et al., 2019; Bonnet et al., 2020; Ma et al., 2020; Vujović et al., 2022; Yang et al., 2025). In this context, not only the duration of the eating window but also its timing within the day may be important, which may partly explain the variability in findings regarding the effectiveness of different dietary strategies (J. Liu et al., 2023; Yu & Ueda, 2025).

At the same time, it should be emphasized that the available evidence is not uniform. Methodological differences between studies, including study design, duration, methods of dietary assessment, and the degree of control of confounding factors, limit direct comparisons of results. An important limitation is the heterogeneity of the available evidence, including the

presence of observational studies, which restricts the ability to draw clear causal inferences (Ballon et al., 2019; Ma et al., 2020; Yang et al., 2025). In the case of interventional studies, relatively short follow-up periods and small sample sizes are frequently noted (Chew et al., 2023; Che et al., 2021; Dai et al., 2024; Hays et al., 2025). Additionally, in many studies, it is difficult to precisely disentangle the effects of meal timing from other lifestyle factors, such as physical activity, sleep, and diet quality. Another limitation is the lack of standardization in definitions and intervention protocols, particularly in the context of TRE, which complicates comparisons across studies. These differences concern both the duration of the eating window and its timing within the day, which may have important implications for metabolic outcomes.

Future research should focus on well-designed, long-term randomized controlled trials to assess the sustainability of chrononutrition-based interventions. Particular attention should also be given to individual differences, such as chronotype, lifestyle, and comorbidities, which may contribute to the development of more personalized dietary recommendations. Furthermore, a better understanding of the molecular and hormonal mechanisms underlying the observed associations remains an important area for future investigation (Fuad et al., 2025; Raji et al., 2024).

5. Conclusions

From a practical perspective, the available evidence suggests that meal timing may represent a valuable component of strategies aimed at improving metabolic health. At the same time, chrononutrition appears to be a complex approach, the effects of which may depend on multiple factors, including lifestyle and individual characteristics. Given the limitations of the current evidence, a cautious approach to formulating recommendations is warranted, along with the need for further well-designed studies in this field.

Disclosure

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All authors have read and agreed with the published version of the manuscript.

Financing statement

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Conflict of interest

The authors deny any conflict of interest.

Declaration of the use of generative AI and AI-assisted technologies in the writing process

In preparing this work, the author(s) used ChatGPT for language improvement and grammatical correction. After using this tool/service, the author(s) have reviewed and edited the content as needed and accept full responsibility for the substantive content of the publication.

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