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ORIGINAL ARTICLE

Epidemiology/Genetics

The diurnal pattern of moderate-to-vigorous physical activity and obesity: a cross-sectional analysis

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Abstract

Objective: Moderate-to-vigorous physical activity (MVPA) is obesity-protective. However, the optimal time of the day to engage in MVPA for weight management is controversial. This study is designed to investigate the influence of the diurnal pattern of MVPA on the association between MVPA and obesity.

Methods: A total of 5285 participants in the 2003 to 2006 National Health and Nutrition Examination Survey (NHANES) were cross-sectionally analyzed. The diurnal pattern of objectively measured MVPA was classified into three clusters by K-means clustering analysis: morning ($n = 642$); midday ($n = 2456$); and evening ($n = 2187$). The associations of MVPA level and the diurnal pattern with obesity were tested.

Results: A strong linear association between MVPA and obesity was found in the morning group, whereas a weaker curvilinear association between MVPA and obesity was observed in the midday and evening groups, respectively. Among those who met the physical activity guidelines, the adjusted means for BMI were 25.9 (95% CI: 25.2–26.6), 27.6 (95% CI: 27.1–28.1), and 27.2 (95% CI: 26.8–27.7) kg/m^2 in the morning, midday, and evening groups, respectively, and for waist circumference were 91.5 (95% CI: 89.4–93.6), 95.8 (95% CI: 94.7–96.9), and 95.0 (95% CI: 93.9–96.1) cm, respectively.

Conclusions: The diurnal pattern of MVPA influences the association between MVPA and obesity. The promising role of morning MVPA for weight management warrants further investigation.

INTRODUCTION

Obesity, a significant risk factor for chronic disease and premature death [1], is a global pandemic that continues to worsen. Physical activity has been widely recognized as an essential component of successful and healthy weight management [2]. Although a beneficial association among the levels of physical activity with obesity has been frequently reported, the optimal timing of physical activity for decreasing obesity remains controversial.

Emerging epidemiological evidence has suggested a role of physical activity timing in weight management. A cross-sectional analysis of the Women's Health Study's accelerometry data revealed that a lower percentage of physical activity accumulated in the morning was independently associated with an increased risk of obesity, supporting the importance of morning physical activity [3]. On the other hand, a recent study found that physical activity accumulated in the evening had a stronger beneficial association with BMI than did physical activity accumulated in the morning [4]. To date, epidemiological evidence has been controversial regarding the optimal timing of physical activity for weight management.

Many physiological and metabolic processes in humans display circadian oscillations. For example, the control of the endogenous clock over glucose metabolism, insulin sensitivity, lipolysis, and lipogenesis has been demonstrated at the whole-body level and at the

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molecular level [5, 6]. In addition, circadian misalignment has been linked to negative health outcomes. For example, shift workers have been found to be at a higher risk of obesity and metabolic disease [7, 8]. The evidence implies that doing the right thing at the right time could be important for maintaining a healthy metabolism and a healthy body weight. Importantly, evidence from short-term experimental studies revealed that the time of day of physical activity may influence energy expenditure and energy intake. Several studies have reported that morning exercise performed after an overnight fast was more effective in promoting fat oxidation compared with evening exercise [9, 10]. This diurnal difference is potentially caused by a greater extent of liver glycogen depletion following fasted-state exercise, which could trigger lipid mobilization and oxidation [9, 11]. Although the appetite-suppressing effect of acute exercise has been observed previously, many studies have failed to find a significant time-of-day effect on post-exercise appetite and subsequent energy intake [12–14], with limited experimental studies supporting a lower energy intake in morning exercisers than in evening exercisers [15]. Notably, an important aspect of circadian physiology that differentiates morning and evening is the overnight fast. It has been suggested that fasted-state exercise reduced 24-hour energy intake compared with fed-state exercise [16, 17], indicating a potential role of early morning fasted-state exercise in weight management. Collectively, the time of day of physical activity could be an important factor in optimizing the obesity-protective benefits of physical activity.

Accelerometers have been widely accepted as an objective measure of physical activity. However, most studies have focused on the frequency, intensity, and duration of physical activity. So far, few studies have investigated the diurnal pattern of accelerometer-measured physical activity to classify the time of day of human movement. It is unclear whether accumulating physical activity at different times of day is equally associated with obesity. Particularly, it is unclear whether meeting the physical activity guidelines (150 min/wk of moderate-to-vigorous physical activity [MVPA]) [18] with different patterns is equally beneficial for reducing obesity. Therefore, this study was designed to investigate whether the diurnal pattern of accelerometer-measured MVPA influences the association between MVPA and obesity.

Study Importance

What is already known?

- Moderate-to-vigorous physical activity (MVPA) is inversely associated with obesity.

What does this study add?

- The association between MVPA and obesity is influenced by the diurnal pattern of MVPA.
- Early morning (07:00–09:00) appears to be the most favorable time of day to enhance the beneficial association between MVPA and obesity.

How might these results change the direction of research?

- Prospective studies and randomized clinical trials are needed to confirm the benefits of morning MVPA on obesity.

METHODS

Study design

The National Health and Nutrition Examination Survey (NHANES) by the Centers for Disease Control and Prevention (CDC) is a collection of data used to represent the US noninstitutionalized population [19]. The survey consists of consecutive cycles of yearly cross-sectional data based on a multistage probability design. More information on the methodology for NHANES can be found at the following link: http://www.cdc.gov/nchs/nhanes.htm. Our analyses were performed using the NHANES data from the 2003-2004 and 2005-2006 cycles because accelerometry was implemented during that time. All participants signed written consent. The survey was approved by the National Center for Health Statistics Ethics Review Board. Initially, there were 20,470 participants in the NHANES 2003 to 2006 sample. We identified 9535 non-pregnant participants aged 20 years or older. After excluding participants without the valid exposure variable and those without the outcome variable, there were 5285 participants included in the final analysis. We also analyzed a sample of 4738 participants after excluding participants with missing covariates ($n = 547$) and a healthy subsample of 3957 participants, excluding those with chronic disease at baseline measurement ($n = 1328$). The diagram of the study sample is presented in Supporting Information Figure S1.

Accelerometry data management

Accelerometers (AM-7164; ActiGraph, Pensacola, Florida) were used for the objective measurement of physical activity among ambulatory participants. Participants were instructed to wear the accelerometer on the right hip during waking hours for seven consecutive days following their on-site examination visits. Participants were asked to remove the device while swimming or bathing. The accelerometer recorded vertical acceleration as activity counts per minute (cpm). Non-wear time was defined as any period of 60 consecutive minutes during which 0 cpm were identified. There was a tolerance during these periods of up to 2 non-zero minutes that were below 50 cpm. Accelerometry data were considered valid if individuals wore the device for at least 4 days (wear time ≥ 10 hours for each day), including at least one weekend day. The data collected by the accelerometers were used to classify the physical activity as sedentary behavior, light-intensity physical activity, or MVPA. Sedentary behavior was

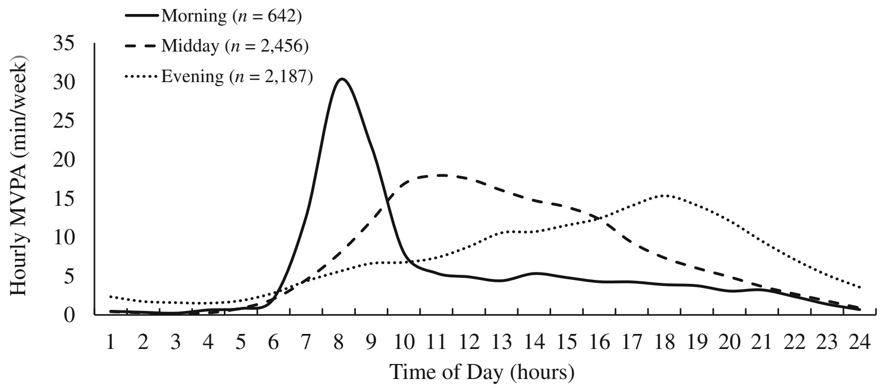

FIGURE 1 The diurnal pattern of MVPA in NHANES 2003–2006. Hourly MVPA was calculated as the MVPA accumulated in each hour of the day (e.g., 06:00–06:59). MVPA, moderate-to-vigorous physical activity; NHANES, National Health and Nutrition Examination Survey

defined by any period of less than 100 cpm, light-intensity physical activity was classified by 100 to 1951 cpm, and MVPA was described by any interval greater than or equal to 1952 cpm [20].

To objectively categorize the diurnal pattern of MVPA, we used a clustering algorithm to explore the pattern of accumulated MVPA in each hour of the day (K-means in R software; R, Vienna, Austria) [21]. K-means is an established algorithm that is commonly used to identify hidden patterns in unlabeled data sets. The main outcome of K-means is a classification variable that assigns individuals into several clusters in a manner that similar individuals are in the same cluster whereas dissimilar individuals are in different clusters. The criterion of similarity is computed based on the Euclidean distance between individual data points and the centroid of the corresponding cluster. We provided a visualized example of the K-means algorithm in Supporting Information Figure S2. In our study, we used the proportions of total MVPA accumulated in each hour rather than the absolute duration of MVPA in each hour. Using proportions is important to generate a pattern variable independent of the level of MVPA. Participants were excluded if they could not be assigned to any groups due to 0 minutes of total MVPA. We set the number of clusters at three ($k = 3$) because two clusters could not differentiate the morning and evening groups whereas four or more clusters produced multiple morning groups, which suggests a risk of overfitting. Finally, the 5285 study participants were classified into three clusters: morning ($n = 642$); midday ($n = 2456$); and evening ($n = 2187$; Figure 1).

Outcome measures

The primary outcomes were BMI and waist circumference (WC). The anthropometric data were collected during the on-site examination visit. All measures were conducted by health technicians who were trained according to the anthropometric standardization reference manual [22]. Body weight was measured using an electronic load-cell scale while the participant wore only undershorts and an examination gown. The standing height was measured with a fixed stadiometer with the participant standing straight with both heels together and touching a vertical board. BMI was calculated as the weight in kilograms divided by height in meters squared. WC in centimeters was measured with a tape measure parallel to the floor. The measurement site was determined by the intersection between the horizontal line just above the uppermost lateral border of the right ilium and the vertical midaxillary line. The results were recorded at the end of the participant's normal expiration.

Statistical analysis

In the descriptive data analysis, mean differences of normally distributed variables were compared using one-way ANOVA across the diurnal pattern clusters. Non-normally distributed variables were compared using the Mood's median test. Categorical variables were compared using the χ^2 test. In the inferential analysis of primary outcomes, the level of MVPA was defined as wear time-adjusted MVPA (minutes per week), a continuous variable based on a restricted cubic spline (three knots at 25th, 50th, and 75th percentiles). The diurnal pattern of MVPA was treated as a categorical variable with the morning cluster as the reference group. We fitted linear regression models to examine the association of MVPA level and the diurnal pattern with obesity. In model one, we adjusted for age, sex, ethnicity, education, tobacco use, alcohol consumption, and sedentary behavior. In model two, we further adjusted for healthy eating index and energy intake per kilogram of body weight (kilocalories per kilogram) to account for dietary confounding. We conducted data imputation for covariates ($n = 547$) based on multivariate imputation by chained equations (five imputations were used). Results were pooled using the Rubin's rule [23]. Detailed definitions of covariates were summarized in Supporting Information Table S1.

We first tested whether there was a statistical interaction of MVPA and the diurnal pattern of clusters with obesity in the regression models. We further investigated the association of MVPA with obesity stratified by the diurnal pattern of clusters. To facilitate data interpretation, we also treated MVPA level as a dichotomous variable (whether meeting the guidelines-recommended 150 min/wk of

TABLE 1 Survey-weighted characteristics of study participants

	Morning (n = 642)	Midday (n = 2456)	Evening (n = 2187)	p value
Socioeconomic variables				
Age (y)	59.9 (17.0)	49.9 (15.5)	46.1 (16.1)	<0.001
Female, n (%)	324 (57.8)	1105 (47.3)	1151 (54.4)	<0.001
Ethnicity, n (%)				
Non-Hispanic White	349 (76.1)	1316 (75.0)	1201 (74.6)	0.01
Non-Hispanic Black	122 (11.1)	417 (8.2)	452 (10.0)	
Mexican American	140 (6.9)	564 (8.3)	369 (6.5)	
Other Hispanic	7 (1.5)	73 (3.7)	57 (2.6)	
Other	24 (4.2)	86 (4.7)	108 (6.2)	
Education, n (%)				
Less than high school	227 (20.8)	681 (15.9)	507 (14.1)	0.0041
High school	144 (25.3)	603 (25.9)	529 (23.9)	
College or higher	271 (53.9)	1172 (58.2)	1151 (62.0)	
Lifestyle factors				
Tobacco use, n (%)				
None	539 (83.6)	1898 (75.4)	1675 (75.2)	0.007
Light	20 (2.8)	125 (4.8)	123 (5.4)	
Moderate	56 (8.7)	265 (12.0)	266 (13.6)	
Heavy	27 (4.9)	168 (7.8)	123 (5.8)	
Alcohol intake, n (%)				
Never	507 (74.1)	1823 (71.4)	1660 (73.8)	0.6
Light	59 (9.7)	226 (9.0)	183 (8.5)	
Moderate	36 (7.1)	213 (9.9)	158 (8.3)	
Heavy	40 (9.0)	194 (9.6)	186 (9.4)	
Healthy eating index	58.6 (13.7)	56.1 (14.1)	55.7 (13.9)	0.004
Calorie intake (kcal/kg/d)	25.8 (11.6)	28.0 (12.1)	28.7 (13.7)	<0.001
Accelerometer parameters				
MVPA (min/d)	11.7 (2.0, 27.7)	19.0 (8.1, 35.0)	16.4 (6.7, 31.4)	<0.001
Total activity counts per day	198,532 (111,599, 290,095)	249,658 (179,545, 341,171)	231,653 (164,783, 316,052)	<0.001
Sedentary time (h/d)	8.7 (2.1)	7.6 (2.1)	7.7 (2.1)	<0.001

Note: Data are mean (SD) for normally distributed variables, median (interquartile range) for non-normally distributed variables, and number (percentage) for categorical variables.

MVPA) and examined the joint association of the diurnal pattern and meeting the physical activity guidelines (≥150 min/wk vs. <150 min/wk) with obesity, using the participants who met the guidelines in the morning cluster as the reference group.

To account for the influence of total physical activity, we conducted a sensitivity analysis that further adjusted for the total volume of physical activity (i.e., total activity counts per day). To address the potential bias caused by missing data management, we conducted sensitivity analyses by repeating the main analysis without data imputation (n = 4738). Finally, to account for the influence of chronic conditions on the outcome, we repeated the main analysis in a subsample of healthy individuals after excluding participants with diabetes, coronary heart disease, stroke, and cancer (n = 3957). The significance level was set at 0.05 for two-sided tests. All statistical analyses were survey-weighted (4-year sample weight). Data analyses were conducted in September 2022 using R software version 4.1.0.

RESULTS

The characteristics of study participants across the three diurnal pattern clusters were compared in Table 1. Overall, participants in the morning cluster were older than those in the other two clusters. The morning cluster had the highest percentage of female individuals among the three clusters. The accelerometry data showed that participants in the morning cluster accumulated less physical activity but more sedentary behavior than did those in the midday and evening clusters. Among the participants who met the guidelines, there was

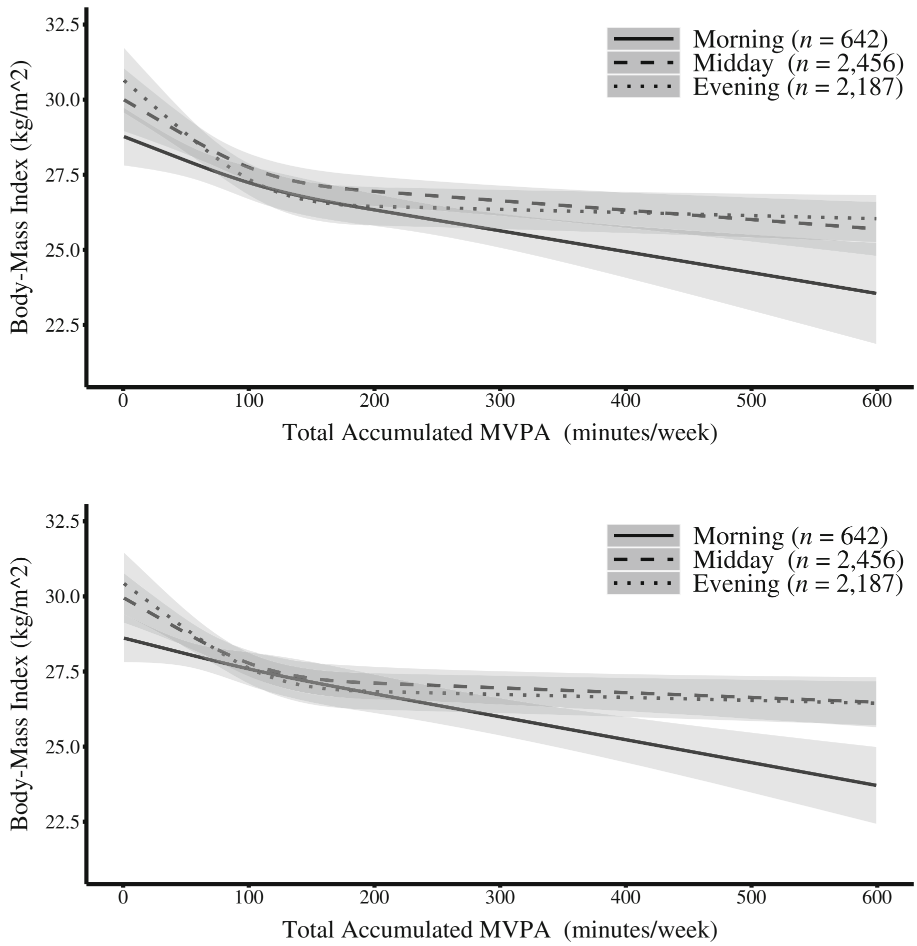

FIGURE 2 The joint association of the diurnal pattern and the level of physical activity with BMI. Upper panel: model one adjusted for age, sex, ethnicity, education, tobacco use, alcohol consumption, and sedentary behavior. Lower panel: model two further adjusted for healthy eating index and energy intake per kilogram of body weight. Accumulated MVPA represents the overall MVPA accumulated throughout the 24 hours (i.e., the sum of hourly MVPA). MVPA, moderate-to-vigorous physical activity

no difference in MVPA between the time-of-day clusters. Among the participants who did not meet the guidelines, the volume of MVPA was ~40% higher in the midday and evening clusters compared with the morning cluster (Supporting Information Table S2). Self-reported dietary recall indicated that participants in the morning cluster had a healthier diet and less daily energy intake per unit of body weight compared with the other clusters.

When examining the association between the diurnal-specific pattern of MVPA with obesity, the morning cluster had a lower BMI and WC compared with the other two clusters after controlling for age, sex, ethnicity, education, tobacco use, alcohol consumption, sedentary behavior, and the amount of MVPA. The adjusted means for BMI in the morning, midday, and evening clusters were 27.4 (95% CI: 27.0–27.8), 28.4 (95% CI: 28.0–28.8), and 28.2 (95% CI: 27.9–28.6) kg/m^2, respectively, and for WC they were 95.9 (95% CI: 94.9–96.8), 97.9 (95% CI: 97.0–98.8), and 97.3 (95% CI: 96.4–98.3) cm, respectively. Further adjustment for dietary quality and calorie intake did not change the strength of the association: BMI in the morning, midday, and evening clusters was 27.5 (95% CI: 27.1–27.8), 28.3 (95% CI: 28.0–28.7), and 28.3 (95% CI: 28.0–28.6) kg/m^2, respectively, and WC was 96.0 (95% CI: 95.1–96.8), 97.8 (95% CI: 97.0–98.6), and 97.5 (95% CI: 96.6–98.3) cm, respectively.

We found a significant interaction between MVPA (continuous variable) and the diurnal pattern clusters in obesity outcomes (p value for interaction = 0.03 and 0.06 for BMI and WC, respectively). There was a strong linear association between MVPA and obesity in the morning cluster, whereas we observed a weaker curvilinear association between MVPA and obesity in the midday and evening groups. Further adjustment for dietary factors did not attenuate the influence of the diurnal pattern on the association between MVPA and obesity (p value for interaction = 0.02 and 0.06 for BMI and WC, respectively; Figures 2 and 3). In the joint analysis of the diurnal pattern clusters and dichotomous MVPA (≥150 min/wk vs. <150 min/wk) with obesity, participants who met the physical activity guidelines in the morning cluster had a lower BMI and WC than those who did in the other clusters (Table 2). Further adjustment for dietary covariates did not affect the outcomes. Further adjustment for total activity counts did not appreciably change the results (Supporting Information Figure S3).

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TABLE 2 Joint association of meeting physical activity guidelines and the diurnal pattern of physical activity with BMI and WC ($N = 5285$)

MVPA per week	≥150 Minutes			<150 Minutes		
Time-of-day category	Morning	Midday	Evening	Morning	Midday	Evening
No. of participants	$n = 176$	$n = 977$	$n = 797$	$n = 466$	$n = 1479$	$n = 1390$
BMI						
Model one[a]	25.8 (ref) (25.1–26.5)	27.4*** (27.0–27.9)	27.0* (26.5–27.5)	28.6*** (28.0–29.2)	29.0*** (28.4–29.6)	29.2*** (28.7–29.7)
Model two[b]	25.9 (ref) (25.2–26.6)	27.6*** (27.1–28.1)	27.2** (26.8–27.7)	28.6*** (28.1–29.1)	28.8*** (28.2–29.3)	29.1*** (28.7–29.5)
WC						
Model one[a]	91.3 (ref) (89.3–93.3)	95.4** (94.3–96.4)	94.3* (93.1–95.6)	99.3*** (97.7–100.7)	99.6*** (98.4–100.8)	99.6*** (98.5–100.7)
Model two[b]	91.5 (ref) (89.4–93.6)	95.8** (94.7–96.9)	95.0** (93.9–96.1)	99.3*** (98.1–100.5)	99.0*** (97.9–100.1)	99.4*** (98.3–100.4)

Note: Data are mean (95% CI)

Abbreviations: MVPA, moderate-to-vigorous physical activity; WC, waist circumference.

[a]Adjusted for age, sex, ethnicity, education, smoking, alcohol consumption, and sedentary behavior.

[b]Further adjusted for healthy eating index and energy intake per kilogram of body weight.

*$p < 0.05$.

**$p < 0.01$.

***$p < 0.001$.

The sensitivity analysis that excluded participants with missing covariates showed consistent outcomes with the main analysis (in model one, p value for interaction = 0.05 and 0.1 for BMI and WC, respectively; in model two, p value for interaction = 0.02 and 0.07 for BMI and WC, respectively; Supporting Information Table S3 and Figures S4 and S5). The sensitivity analysis based on the subsample of healthy participants attenuated the influence of the diurnal pattern on the association between MVPA and obesity (in model one, p value for interaction = 0.1 and 0.2 for BMI and WC, respectively; in model two, p value for interaction = 0.08 and 0.2 for BMI and WC, respectively; Supporting Information Table S4 and Figures S6 and S7).

DISCUSSION

In this cross-sectional study of objectively measured MVPA and obesity measures (i.e., BMI and WC), we classified the diurnal pattern of MVPA into three clusters using a well-established clustering algorithm. The morning cluster had a remarkable spike of MVPA between 07:00 and 09:00 and low levels of MVPA during the rest of the day. The midday cluster was primarily active during the common working hours (09:00–16:00), with MVPA peaking between 11:00 and 13:00. The evening cluster had a progressive increase of MVPA from 07:00 to 17:00, a peak of MVPA between 17:00 and 20:00, and a rapid decrease of MVPA between 20:00 and 24:00. In the linear regression analysis, we found that the diurnal pattern of MVPA influenced the beneficial association between MVPA level and obesity. Among the midday or evening clusters, MVPA was associated with obesity in a curvilinear manner, with little or no further decrease in BMI and WC beyond the physical activity guidelines-recommended 150 min/wk of MVPA. On the contrary, among the morning cluster, there was a linear association between MVPA and obesity, as evidenced by a continuous decrease in BMI and WC with higher levels of MVPA without a noticeable threshold. When dividing MVPA dichotomously (≥150 min/wk vs. <150 min/wk), the between-cluster differences in BMI and WC were only evident in those achieving 150 min/wk of MVPA, whereas BMI and WC were similar between the three clusters among the participants not achieving 150 minutes of MVPA. This is not surprising because the impact of the diurnal pattern on the outcomes would be diminished if the total amount of MVPA is low. Notably, among the participants not meeting the 150-minute guidelines, the morning cluster had a significantly lower MVPA volume compared with the other two clusters. Therefore, another possible explanation of the null findings among those not meeting the guidelines is that the expected favorable outcome in the morning cluster was offset by their lower volume of MVPA.

Our findings substantiated the role of morning MVPA in weight management. However, owing to the observational nature of our data, it remains inconclusive whether morning MVPA is more effective than evening MVPA in reducing obesity. Our observation agrees well with a secondary analysis of the Midwest Exercise Trial 2 by Willis and colleagues [24]. Their study found a greater reduction in body mass and fat mass among participants who attended more than

50% of their training sessions in the morning compared with those who attended more than 50% of their training sessions between 15:00 and 19:00. It was suggested by the authors that the combination of a higher non-exercise energy expenditure and a lower daily energy intake in the morning exercisers was possibly responsible for the observed outcomes. The study by Creasy et al. found that a high amount of MVPA in the morning was a key feature of the physical activity pattern among successful weight loss maintainers, further supporting the important role of morning MVPA in weight management [25]. In another study among successful weight loss maintainers [26], Schumacher and colleagues revealed that consistent morning exercisers had the highest exercise stability over a 1-year follow-up, suggesting that another plausible explanation of our findings could be a better exercise routine among the morning exercisers. In other words, the lower BMI and WC may be due to a better adherence to habitual MVPA in the morning cluster compared with the other clusters.

On the other hand, there has been evidence that favors evening physical activity over morning physical activity. In a quasi-experimental study of 42 postmenopausal women, Di Blasio and colleagues observed a greater reduction in fat mass among the evening exercisers than in the morning exercisers following 3 months of training [27]. The exercise training study by Mancilla and colleagues also reported a greater decrease in fat mass in the evening group than in the morning group [28]. Notably, the group assignment of the two quasi-experimental studies was based on personal preference. Many important confounding factors cannot be ruled out owing to the lack of randomization. Two recent randomized clinical trials directly compared the effects of morning and evening exercise training on weight loss [29, 30]. Both studies found that body mass changes were not different between the morning and evening groups, suggesting a lack of time-of-day effect. However, the intervention duration of the two studies was relatively shorter (12–15 weeks) compared with the Willis et al. study (10 months). In addition, both trials were limited by insufficient statistical power. One trial was a small-scale pilot study [29]. The other trial was powered to detect a difference only between the intervention and control groups and not between the morning and evening groups [30]. Future clinical trials with sufficient statistical power and longer intervention durations are needed.

The mechanism by which the diurnal pattern of MVPA influences the association between MVPA and obesity is not completely understood. Using indirect calorimeter-equipped metabolic chambers, the two experiments conducted by Iwayama and colleagues consistently observed that morning exercise in a fasting state can increase fat oxidation over the 24 hours following exercise, whereas post-lunch and post-dinner exercise did not significantly change 24-hour fat oxidation [9, 10]. Importantly, the studies by Gonzalez et al. and by Bachman et al. both found a greater fat oxidation during fasted-state morning exercise than fed-state morning exercise [16, 31], suggesting an important role of the fasted-state exercise in promoting fat oxidation. The reduced glycogen stores after an overnight fast may cause a shift of substrate use toward fatty substrates. It appears that the favorable obesity-protective outcomes of MVPA in the morning cluster could be driven by fasted-state exercise.

Nutrition is an influential confounder and a potential mediator of the association between MVPA and adiposity. It is important to rule out whether a healthier eating pattern and reduced calorie intake are responsible for the lower BMI and WC among the morning-active participants. In our study, we did observe a higher healthy eating index and a lower energy intake per kilogram of body weight in the morning cluster than in the other two clusters. The finding aligns well with the Schumacher et al. conceptual model that consistent morning exercisers have better self-regulation and healthier lifestyle habits [32]. Interestingly, with adjustment for dietary factors, there was a larger difference in BMI and WC between the morning cluster and the other clusters, especially among those who were physically active (Figures 2 and 3). Similar findings were observed in the joint association of the diurnal pattern and meeting the physical activity guidelines with obesity, suggesting that our findings cannot be solely explained by dietary factors (Table 2). Previous evidence has revealed that structured exercise, especially vigorous-intensity exercise, is efficient in promoting post-exercise fat oxidation [33]. Therefore, our findings might be driven by a higher intensity of structured exercise in the morning cluster than in the other clusters. This is plausible because the morning cluster in our study presented a more concentrated MVPA pattern that may consist of structured exercise as opposed to non-exercise physical activity.

Another interesting finding of our study is that participants in the morning cluster spent a significantly higher amount of time on sedentary behavior than did participants in the other clusters. However, despite the longer duration of sedentary time and the statistical adjustment for sedentary time, the favorable BMI and WC outcomes in the morning cluster persisted. Our finding is in accordance with previous research. In a meta-analysis of 1 million participants, Ekelund and colleagues revealed that high levels of physical activity can substantially reduce the detrimental association between sedentary behavior and health outcomes [34]. In addition, previous evidence has revealed that a single session of morning exercise can elevate metabolic rate for several hours due to excess post-exercise oxygen consumption [33]. It is possible that the adverse effects of the extra sedentary time in the morning-active participants were diminished by the MVPA-induced increase in energy expenditure through the rest of the day, making morning MVPA a promising strategy to improve health among populations with prevalent sedentary behavior (e.g., office-based workers).

Existing evidence regarding accelerometry in the assessment of free-living MVPA has primarily focused on its frequency, intensity, and duration. Our findings propose that the diurnal pattern of MVPA could be another important dimension to describe the complexity of human movement. A common strategy of diurnal pattern classification in previous studies is based on a given percentage of physical activity being accumulated in a predetermined time window (e.g., >50% of physical activity between 06:00 and 12:00) [35, 36]. However, a limitation of the previous approach is that little information is derived from the accelerometry data regarding the nature of human

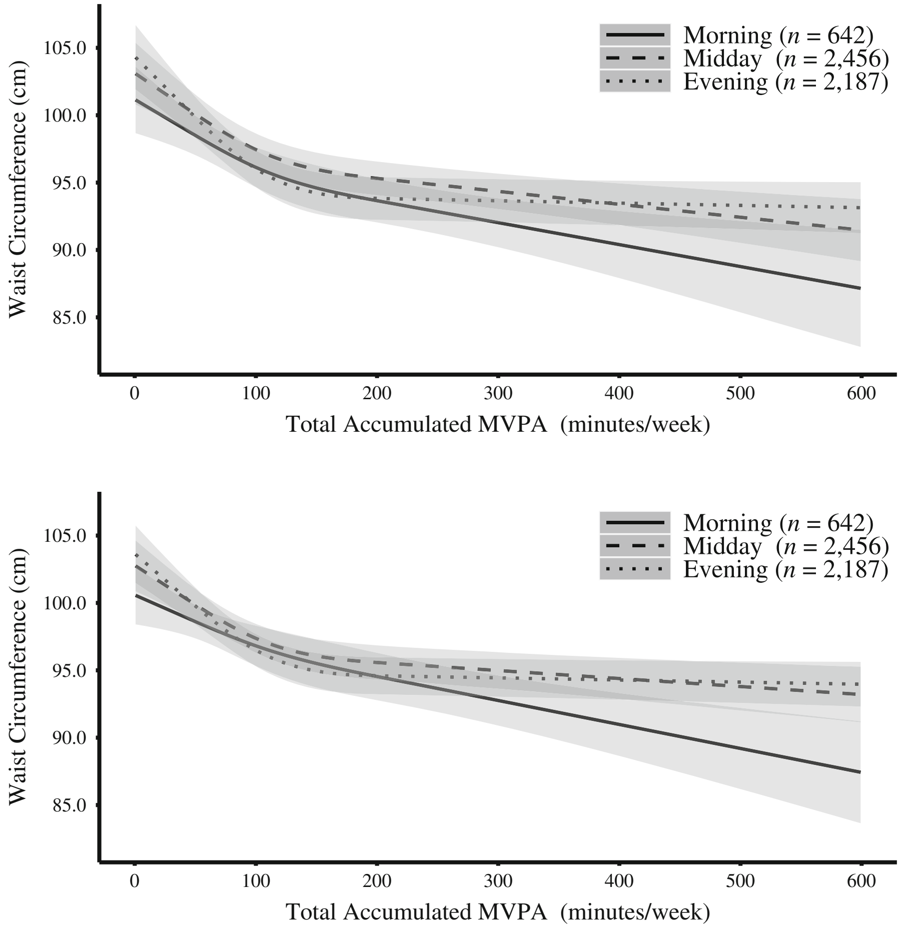

FIGURE 3 The joint association of the diurnal pattern and the level of physical activity with waist circumference. Upper panel: model one adjusted for age, sex, ethnicity, education, tobacco use, alcohol consumption, and sedentary behavior. Lower panel: model two further adjusted for healthy eating index and energy intake per kilogram of body weight. Accumulated MVPA represents the overall MVPA accumulated throughout the 24 hours (i.e., the sum of hourly MVPA). MVPA, moderate-to-vigorous physical activity

movement patterns (e.g., what patterns are the most prevalent among the study population). For example, our study suggests that the morning-active participants accumulated the highest MVPA between 07:00 and 09:00, reflecting a lifestyle of a morning MVPA routine combined with a sedentary occupation. Therefore, using the 06:00 and 12:00 time window is not justified by common lifestyles and this would possibly misclassify the diurnal pattern. Our study provided a novel tool to explore the diurnal pattern of physical activity and to investigate its impact on health outcomes.

Our study has limitations. The cross-sectional design of our study does not demonstrate temporal precedence. Therefore, the causal relationship between the diurnal pattern of MVPA and obesity cannot be established. It is possible that the differences in BMI and WC cause the diurnal pattern of MVPA rather than the diurnal pattern causes changes of BMI and WC. Additionally, the biological clock may vary between individuals, which could lead to interindividual variability in responsiveness to physical activity [37]. Information regarding the chronotypes (i.e., morningness vs. eveningness) of study participants would have enhanced the validity of the study and the interpretation of the diurnal pattern of MVPA. Another limitation of our study is the small number of individuals in the morning cluster, especially among those who met the physical activity guidelines. The observed time-of-day influence on obesity measures could be driven by this small group of individuals who were lean and physically active in the early morning. Additionally, the small number of participants ($n = 176$) in this group may not be able to represent the population of early morning exercisers. The generalizability of our findings needs to be tested in a larger sample with sufficient morning-active participants.

In conclusion, the diurnal pattern of MVPA influences the association between MVPA level and obesity. Early morning (07:00–09:00) appears to be the most favorable time of day to enhance the association between MVPA and obesity. Morning MVPA could have a positive (i.e., obesity-protective) impact on those who are sedentary for most of the day. Prospective studies and randomized clinical trials are needed to confirm our findings.

CONFLICT OF INTEREST STATEMENT

The authors declared no conflict of interest.

DATA AVAILABILITY STATEMENT

All data used in this work are publicly accessible at the following link: https://www.cdc.gov/nchs/nhanes/index.htm

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REFERENCES

1. Hu FB, Willett WC, Li T, Stampfer MJ, Colditz GA, Manson JE. Adiposity as compared with physical activity in predicting mortality among women. *N Engl J Med*. 2004;351(26):2694-2703. doi:10.1056/NEJMoa042135
2. Wing RR, Phelan S. Long-term weight loss maintenance. *Am J Clin Nutr*. 2005;82(1 suppl):222S-225S. doi:10.1093/ajcn/82.1.222S
3. Chomistek AK, Shiroma EJ, Lee IM. The relationship between time of day of physical activity and obesity in older women. *J Phys Act Health*. 2016;13(4):416-418. doi:10.1123/jpah.2015-0152
4. Albalak G, Stijntjes M, Wijsman CA, et al. Timing of objectively-collected physical activity in relation to body weight and metabolic health in sedentary older people: a cross-sectional and prospective analysis. *Int J Obes (Lond)*. 2022;46(3):515-522. doi:10.1038/s41366-021-01018-7
5. Stenvers DJ, Scheer FA, Schrauwen P, la Fleur SE, Kalsbeek A. Circadian clocks and insulin resistance. *Nat Rev Endocrinol*. 2019;15(2):75-89. doi:10.1038/s41574-018-0122-1
6. Gooley JJ. Circadian regulation of lipid metabolism. *Proc Nutr Soc*. 2016;75(4):440-450. doi:10.1017/S0029665116000288
7. Di Lorenzo L, De Pergola G, Zocchetti C, et al. Effect of shift work on body mass index: results of a study performed in 319 glucose-tolerant men working in a southern Italian industry. *Int J Obes (Lond)*. 2003;27(11):1353-1358. doi:10.1038/sj.ijo.0802419
8. Wang F, Zhang L, Zhang Y, et al. Meta-analysis on night shift work and risk of metabolic syndrome. *Obes Rev*. 2014;15(9):709-720. doi:10.1111/obr.12194
9. Iwayama K, Kawabuchi R, Nabekura Y, et al. Exercise before breakfast increases 24-h fat oxidation in female subjects. *PLoS One*. 2017;12(7):e0180472. doi:10.1371/journal.pone.0180472
10. Iwayama K, Kurihara R, Nabekura Y, et al. Exercise increases 24-h fat oxidation only when it is performed before breakfast. *EBioMedicine*. 2015;2(12):2003-2009. doi:10.1016/j.ebiom.2015.10.029
11. Izumida Y, Yahagi N, Takeuchi Y, et al. Glycogen shortage during fasting triggers liver-brain-adipose neurocircuitry to facilitate fat utilization. *Nat Commun*. 2013;4(1):2316. doi:10.1038/ncomms3316
12. Mode WJ, Slater T, Pinkney MG, et al. Effects of morning vs. evening exercise on appetite, energy intake, performance and metabolism, in lean males and females. *Appetite*. 2023;182:106422. doi:10.1016/j.appet.2022.106422
13. Maraki M, Tsofliou F, Pitsiladis YP, Malkova D, Mutrie N, Higgins S. Acute effects of a single exercise class on appetite, energy intake and mood. Is there a time of day effect? *Appetite*. 2005;45(3):272-278. doi:10.1016/j.appet.2005.07.005
14. McIver VJ, Mattin L, Evans GH, Yau AM. The effect of brisk walking in the fasted versus fed state on metabolic responses, gastrointestinal function, and appetite in healthy men. *Int J Obes (Lond)*. 2019;43(9):1691-1700. doi:10.1038/s41366-018-0215-x
15. Alizadeh Z, Younespour S, Rajabian Tabesh M, Haghravan S. Comparison between the effect of 6 weeks of morning or evening aerobic exercise on appetite and anthropometric indices: a randomized controlled trial. *Clin Obes*. 2017;7(3):157-165. doi:10.1111/cob.12187
16. Bachman JL, Deitrick RW, Hillman AR. Exercising in the fasted state reduced 24-hour energy intake in active male adults. *J Nutr Metab*. 2016;2016:1984198. doi:10.1155/2016/1984198
17. Frampton J, Edinburgh RM, Ogden HB, Gonzalez JT, Chambers ES. The acute effect of fasted exercise on energy intake, energy expenditure, subjective hunger and gastrointestinal hormone release compared to fed exercise in healthy individuals: a systematic review and network meta-analysis. *Int J Obes (Lond)*. 2022;46(2):255-268. doi:10.1038/s41366-021-00993-1
18. Piercy KL, Troiano RP, Ballard RM, et al. The Physical Activity Guidelines for Americans. *JAMA*. 2018;320:2020-2028. doi:10.1001/jama.2018.14854
19. Centers for Disease Control and Prevention. National Center for Health Statistics. National Health and Nutrition Examination Survey. Accessed September 1, 2022. http://www.cdc.gov/nchs/nhanes.htm
20. Freedson PS, Melanson E, Sirard J. Calibration of the Computer Science and Applications, Inc. accelerometer. *Med Sci Sports Exerc*. 1998;30(5):777-781. doi:10.1097/00005768-199805000-00021
21. Hartigan JA, Wong MA. Algorithm AS 136: a K-means clustering algorithm. *J R Stat Soc Ser C Appl Stat*. 1979;28(1):100-108. doi:10.2307/2346830
22. Lohman TG, Roche AF, Martorell R. *Anthropometric Standardization Reference Manual*. Human Kinetics Books; 1988.
23. Rubin DB. Multiple imputation after 18+ years. *J Am Stat Assoc*. 1996;91(434):473-489. doi:10.1080/01621459.1996.10476908
24. Willis EA, Creasy SA, Honas JJ, Melanson EL, Donnelly JE. The effects of exercise session timing on weight loss and components of energy balance: Midwest Exercise Trial 2. *Int J Obes (Lond)*. 2020;44(1):114-124. doi:10.1038/s41366-019-0409-x
25. Creasy SA, Hibbing PR, Cotton E, et al. Temporal patterns of physical activity in successful weight loss maintainers. *Int J Obes (Lond)*. 2021;45(9):2074-2082. doi:10.1038/s41366-021-00877-4
26. Schumacher LM, Thomas JG, Wing RR, Raynor HA, Rhodes RE, Bond DS. Sustaining regular exercise during weight loss maintenance: the role of consistent exercise timing. *J Phys Act Health*. 2021;18(10):1253-1260. doi:10.1123/jpah.2021-0135
27. Di Blasio A, Di Donato F, Mastrodicasa M, et al. Effects of the time of day of walking on dietary behaviour, body composition and aerobic fitness in post-menopausal women. *J Sports Med Phys Fitness*. 2010;50(2):196-201.
28. Mancilla R, Brouwers B, Schrauwen-Hinderling VB, Hesselink MK, Hoeks J, Schrauwen P. Exercise training elicits superior metabolic effects when performed in the afternoon compared to morning in metabolically compromised humans. *Physiol Rep*. 2021;8(24):e14669. doi:10.14814/phy2.14669
29. Creasy SA, Wayland L, Panter SL, et al. Effect of morning and evening exercise on energy balance: a pilot study. *Nutrients*. 2022;14(4):816. doi:10.3390/nu14040816
30. Brooker PG, Gomersall SR, King NA, Leveritt MD. The efficacy of morning versus evening exercise for weight loss: a randomized controlled trial. *Obesity (Silver Spring)*. 2023;31(1):83-95. doi:10.1002/oby.23605
31. Gonzalez JT, Veasey RC, Rumbold PL, Stevenson EJ. Breakfast and exercise contingently affect postprandial metabolism and energy balance in physically active males. *Br J Nutr*. 2013;110(4):721-732. doi:10.1017/S0007114512005582
32. Schumacher LM, Thomas JG, Raynor HA, Rhodes RE, Bond DS. Consistent morning exercise may be beneficial for individuals with obesity. *Exerc Sport Sci Rev*. 2020;48(4):201-208. doi:10.1249/JES.0000000000000226
33. Bahr RO, Ingnes IV, Vaage O, Sejersted OM, Newsholme EA. Effect of duration of exercise on excess postexercise O2 consumption. *J Appl Physiol*. 1987;62(2):485-490. doi:10.1016/0026-0495(91)90012-L

34. Ekelund U, Steene-Johannessen J, Brown WJ, et al. Does physical activity attenuate, or even eliminate, the detrimental association of sitting time with mortality? A harmonised meta-analysis of data from more than 1 million men and women. *Lancet*. 2016;388:1302-1310. doi:10.1016/S0140-6736(16)30370-1
35. Schumacher LM, Thomas JG, Raynor HA, et al. Relationship of consistency in timing of exercise performance and exercise levels among successful weight loss maintainers. *Obesity (Silver Spring)*. 2019;27(8):1285-1291. doi:10.1002/oby.22535
36. Qian J, Walkup MP, Chen SH, et al. Association of objectively measured timing of physical activity bouts with cardiovascular health in type 2 diabetes. *Diabetes Care*. 2021;44(4):1046-1054. doi:10.2337/dc20-2178
37. Malin SK, Remchak MM, Smith AJ, Ragland TJ, Heiston EM, Cheema U. Early chronotype with metabolic syndrome favours resting and exercise fat oxidation in relation to insulin-stimulated non-oxidative glucose disposal. *Exp Physiol*. 2022;107(11):1255-1264. doi:10.1113/EP090613

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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