Associations of moderate-to-vigorous physical activity timing with type 2 diabetes incidence in UK Biobank and prevalent glycemic measures in NHANES

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Diabetes Care
American Diabetes Association

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Diabetes Care 2026;49(3):444–449 | https://doi.org/10.2337/dc25-2095

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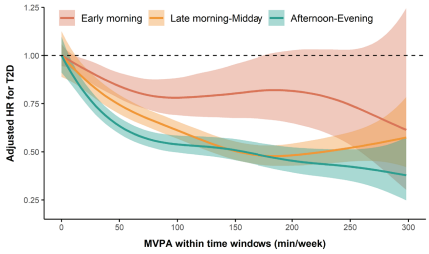
Study Population: Participants with acceleration data **Exposure:** Timing of MVPA **Outcome**: Diabetes and Glycemic measures

UK Biobank—Prospective Outcome: Type 2 diabetes (T2D) incidence

Early morning 0500–959 | Late morning-midday 1000–1459 | Afternoon-evening 1500–2400

The nonlinear association between MVPA within time windows and T2D risk

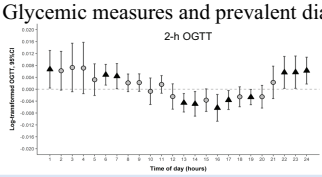


The association between the timing of MVPA (categorical) and T2D risk

Early morning MVPA	Reference
Late morning-midday MVPA	HR = 0.80 (0.68, 0.95)
Afternoon-evening MVPA	HR = 0.71 (0.59, 0.85)
Variable-timing MVPA	HR = 0.75 (0.62, 0.91)

U.S. National Health and Nutrition Examination Surveys — Cross-sectional Outcome: Glycemic measures and prevalent diabetes

Afternoon and early evening MVPA were associated with favorable glycemic measures (most pronounced in result of 2-h OGTT) and lower diabetes prevalence.



Conclusion **When keeping total MVPA volume constant, clustering MVPA in the afternoon-evening was associated with the strongest reduction in incident T2D risk, fewer prevalent diabetes and more favorable glycemic measure.**

HR, hazard ratio; MVPA, moderate-to-vigorous physical activity; NHANES, National Health and Nutrition Examination Survey; OGTT, oral glucose tolerance test.

ARTICLE HIGHLIGHTS

- **Why did we undertake this study?**
  While the benefit of engaging in moderate-to-vigorous physical activity (MVPA) for diabetes prevention is well established, the independent role of MVPA timing during the day remains underexplored.
- **What is the specific question we wanted to answer?**
  We investigated whether MVPA timing was associated with type 2 diabetes risk and glycemic measures.
- **What did we find?**
  The results showed that while keeping total MVPA constant, MVPA clustered in the afternoon-evening was associated with the lowest risk of incident type 2 diabetes, fewer prevalent diabetes, and more favorable glycemic measures.
- **What are the implications of our findings?**
  The timing of MVPA may be a novel strategy for improved type 2 diabetes prevention.

Associations of Moderate-to-Vigorous Physical Activity Timing With Type 2 Diabetes Incidence in UK Biobank and Prevalent Glycemic Measures in NHANES

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Diabetes Care 2026;49:444–449 | https://doi.org/10.2337/dc25-2095

BRIEF REPORT

OBJECTIVE

We assessed the association between timing of moderate-to-vigorous physical activity (MVPA) with incident type 2 diabetes (T2D) and glycemic measures.

RESEARCH DESIGN AND METHODS

Regression models were used to assess associations between accelerometer-derived MVPA timing and incident T2D in UK Biobank (UKB) (*n* = 84,528, prospective), prevalent diabetes, and glycemic measures in the National Health and Nutrition Examination Survey (NHANES) (*n* = 6,998, cross-sectional).

RESULTS

In UKB, with early morning (0500–0959) MVPA as reference and before adjustment for total MVPA, "variable-timing" MVPA was associated with the lowest incident T2D risk; while after adjustment, afternoon-evening MVPA (1500–2400) showed the lowest incident T2D risk. In NHANES, afternoon/early evening MVPA was weakly associated with more favorable glycemic measures and lower diabetes prevalence after adjustment for total MVPA.

CONCLUSIONS

When keeping total MVPA volume constant, clustering MVPA in the afternoon-evening was associated with the strongest reduction in incident T2D risk, fewer prevalent diabetes, and more favorable glycemic measures.

In addition to the generally accepted health benefits of physical activity amount, accumulating evidence has shown associations between physical activity timing and cardiometabolic disease outcomes, such as obesity (1,2), cardiovascular disease (3–5), type 2 diabetes (T2D) (6–8), and glycemic measures (9–13). Our previous studies in the National Health and Nutrition Examination Survey (NHANES) (7) and UK Biobank (UKB) (8) showed that timing of overall physical activity was associated with diabetes risk and glycemic measures. However, overall activity largely reflects fixed routines (e.g., work or household tasks) and is less modifiable. In contrast, moderate-to-vigorous physical activity (MVPA)—primarily representing exercise—is discretionary and more flexibly timed, making it more applicable to exercise recommendations. Some studies observed that MVPA/exercise timing associated with glucose metabolism (11–15), with most (11,13–15) finding greater benefits when

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Received 26 August 2025 and accepted 8 December 2025

This article contains supplementary material online at https://doi.org/10.2337/figshare.30851117.

performed in the afternoon or evening rather than in the morning. However, these studies were generally performed in small samples, and none of them investigated the association between MVPA timing and T2D risk.

We hypothesized that afternoon and evening MVPA has the largest metabolic benefits for diabetes prevention. Here, we examined the associations between MVPA timing and T2D risk in UKB, independent of the total MVPA volume. To provide supportive evidence from prevalent diabetes and glycemic measures, we additionally used cross-sectional data from NHANES.

RESEARCH DESIGN AND METHODS

The current study was performed using available data from the UKB and NHANES. In UKB, time-to-event analyses were performed on T2D embedded in the accelerometer substudy (Supplementary Fig. 1). In NHANES, cross-sectional analyses were performed on prevalent diabetes and glycemic measures (fasting glucose, fasting insulin, HOMA insulin resistance [HOMA-IR], and oral glucose tolerance test [OGTT]) among participants with actigraphy data in the NHANES 2011–2014 cycles (Supplementary Fig. 2). Hourly MVPA was used as exposure in both UKB and NHANES. Associations between hourly MVPA minutes with T2D incidence in UKB and prevalent diabetes and glycemic measures in NHANES were examined using Cox proportional hazard and logistic/linear regression models, respectively. Additionally, in UKB, nonnocturnal hours (0500–2359) were divided into three time windows using a data-driven approach (see Supplementary Methods). Nonlinear associations between MVPA in each time window and T2D risk were modeled using penalized cubic splines. Participants were assigned to different timing groups according to the time of day when their >50% MVPA occurred, and T2D risk across different MVPA timing groups was compared. As sensitivity analyses, the same analyses have been conducted using a non–data-driven approach and sleep-referenced timing windows. Extensive descriptions of methodology are described in the Supplementary Methods.

RESULTS

UKB

Table 1 shows characteristics of the 84,528 UKB participants. Over a median of 7.5 years (638,035 person-years) follow-up, T2D developed in 2,015 participants (2.4%). Participants in the "variable-timing" group had the highest mean total MVPA volume.

As shown in Fig. 1*A*, increasingly later MVPA during daytime hours was associated with increasingly lower T2D risk in model 1. After adjusting for total MVPA in model 2, only MVPA during 1900–1959 (hazard ratio [HR] 0.96, 95% CI 0.94–0.99) was associated with lower T2D risk (Supplementary Table 4). Figure 1*B* shows the nonlinear association between MVPA in three time windows with T2D risk, adjusting for all covariates in model 1, plus MVPA during the other two time windows. In general, higher MVPA within any of the three time windows was associated with lower T2D risk; however, MVPA performed during the two time windows—late morning-midday and afternoon-evening—was associated with a stronger reduction in T2D risk than MVPA in the early morning. In the substitution model, reallocating 20% substitution of MVPA from the early morning to the afternoon-evening was associated with a 9% lower risk of T2D (HR 0.91, 95% CI 0.86–0.95).

In Table 2, compared with the early morning group, the late morning-midday, afternoon-evening, and variable-timing groups all showed lower risks for incident T2D before and after adjusting for total MVPA (models 2 and 3). The variable-timing group showed the lowest risk before adjusting for total MVPA (model 2), while we observed the largest reduction in incident T2D risk in the afternoon-evening group after adjusting for total MVPA (model 3). After additional adjustment for shift work and for BMI or waist circumference (the latter as potential mediators), the lower T2D risk associated with afternoon-evening MVPA persisted, although the effect size attenuated after adjusting for adiposity measures (data not shown). In contrast, the association for the late morning-midday MVPA and variable-timing MVPA and incident T2D disappeared (data not shown). Sensitivity analyses using a non–data-driven approach and sleep-referenced time windows showed similar results (Supplementary Table 5).

NHANES

Participant characteristics are summarized in Supplementary Table 3. We observed (Fig. 2*A*) a trend for a lower likelihood of prevalent diabetes related to afternoon MVPA. While most associations were small to negligible, we observed a lower odd of diabetes with MVPA during 1700–1759 (odds ratio 0.96, 95% CI 0.93–1.00, $P = 0.034$). In addition, a weaker but comparable trend to the lower diabetes prevalence in individuals with afternoon-early evening MVPA was observed for associations of MVPA timing with glycemic measures (plasma glucose after the 2-h OGTT) (Fig. 2*B*), HOMA-IR (Fig. 2*C*), fasting glucose (Supplementary Fig. 3*A*), and fasting insulin (Supplementary Fig. 3*B*).

CONCLUSIONS

In UKB participants, afternoon-evening MVPA was associated with lower risk of incident T2D compared with early morning MVPA. We observed similar trends in NHANES data, with MVPA during afternoon and early evening being weakly associated with lower diabetes prevalence and more favorable glycemic measures.

Our observation of the association of late afternoon/early evening MVPA with a lower risk of T2D partly differed from our previous studies (7,8) on overall physical activity timing, where both late morning and late afternoon activity were observed as optimal. This discrepancy likely reflects the distinction between overall physical activity timing, which captures daily habitual work and life

Table 1—Baseline characteristics in UKB participants having accelerometry data and without preexisting diabetes

Characteristic	Overall (*N* = 84,528)	Early morning MPVA (*n* = 4,469)	Late morning-midday MPVA (*n* = 40,312)	Afternoon-evening MPVA (*n* = 23,489)	Variable timing MVPA (*n* = 16,258)
Age, years	63 (56, 68)	63 (55, 68)	65 (59, 69)	60 (53, 66)	60 (53, 66)
Female sex	48,056 (57)	2,541 (57)	23,069 (57)	13,879 (59)	8,567 (53)
BMI, kg/m^2	25.9 (23.5, 28.8)	26.6 (23.9, 29.7)	26.0 (23.6, 28.8)	25.8 (23.4, 28.8)	25.5 (23.2, 28.2)
European ethnicity	82,062 (97)	4,303 (96)	39,454 (98)	22,584 (96)	15,721 (97)
Townsend deprivation index	−2.48 (−3.83, −0.25)	−2.50 (−3.82, −0.40)	−2.64 (−3.92, −0.62)	−2.36 (−3.77, 0.03)	−2.22 (−3.69, 0.25)
Education					
Degree or above	37,347 (44)	1,662 (37)	16,333 (41)	11,195 (48)	8,157 (50)
Any other qualification	40,546 (48)	2,321 (52)	20,027 (50)	11,021 (47)	7,177 (44)
No qualification	6,635 (7.8)	486 (11)	3,952 (9.8)	1,273 (5.4)	924 (5.7)
Smoking status					
Never	48,891 (58)	2,393 (54)	22,845 (57)	13,888 (59)	9,765 (60)
Previous	30,024 (36)	1,773 (40)	14,903 (37)	7,868 (33)	5,480 (34)
Current	5,613 (6.6)	303 (6.8)	2,564 (6.4)	1,733 (7.4)	1,013 (6.2)
Alcohol intake frequency					
≥3 times per week	42,059 (52)	2,041 (49)	20,258 (53)	11,531 (52)	8,229 (53)
<3 times per week	37,978 (47)	2,124 (51)	17,909 (47)	10,719 (48)	7,226 (47)
Never	294 (0.4)	16 (0.4)	148 (0.4)	81 (0.4)	49 (0.3)
Sleep midpoint	0302 (0230, 0334)	0238 (0204, 0310)	0304 (0231, 0336)	0311 (0238, 0344)	0252 (0222, 0321)
Sleep duration, h	7.33 (6.76, 7.86)	7.25 (6.66, 7.79)	7.44 (6.87, 7.96)	7.25 (6.68, 7.78)	7.24 (6.68, 7.74)
Season wearing accelerometer					
Spring	19,210 (23)	960 (21)	8,771 (22)	5,540 (24)	3,393 (24)
Summer	22,116 (26)	1,102 (25)	9,634 (24)	6,959 (30)	4,421 (27)
Autumn	25,166 (30)	1,324 (30)	12,335 (31)	6,788 (29)	4,719 (29)
Winter	18,036 (21)	1,083 (24)	9,572 (24)	4,202 (18)	3,179 (20)
Diabetes family history	13,417 (16)	745 (17)	6,241 (15)	3,837 (16)	2,594 (16)
Osteoporosis	2,476 (2.9)	120 (2.7)	1,387 (3.4)	626 (2.7)	343 (2.1)
Self-reported diet (weekly)					
Vegetable intake (tablespoon)	28.0 (21.0, 42.0)	28.0 (21.0, 42.0)	28.0 (21.0, 42.0)	28.0 (21.0, 42.0)	28.0 (21.0, 42.0)
Fruit intake (serving)	15.4 (8.4, 22.4)	15.4 (8.4, 22.4)	15.4 (8.4, 22.4)	14.0 (8.4, 22.4)	15.4 (8.4, 22.4)
Processed meat frequency (2–4 times)	21,216 (25)	1,148 (26)	10,062 (25)	5,889 (25)	4,117 (25)
Red meat frequency (2–4 times)	37,276 (44)	2,006 (45)	18,340 (45)	9,977 (42)	6,953 (43)
Sugar sweetened foods/drinks (never)	11,696 (14)	732 (16)	6,054 (15)	2,846 (12)	2,064 (13)
MVPA min/week	240 (122, 407)	209 (92, 361)	223 (109, 391)	209 (101, 357)	340 (206, 525)

Data are presented as median (interquartile range) or *n* (%). MVPA timing: early morning (0500–0959), late morning-midday (1000–1459), afternoon-evening (1500–2400).

routines, and MVPA timing, which more reflects intentional exercise. Given that MVPA may exert more beneficial effects on metabolic health and its timing is more amenable to behavioral modification than overall physical activity, we consider MVPA timing to be more relevant for exercise recommendations. Interestingly, we found that the variable-timing group had the highest mean total MVPA volume and showed the greatest risk reduction before adjustment for total MVPA. This suggests that distributing MVPA across the day may result in higher MVPA accumulation and represents a pragmatic, effective strategy for T2D prevention. However, when total MVPA volume is constant, MVPA performed during evening may be most optimal.

In NHANES, the observed trends reflecting better glycemic measures with late afternoon/evening MVPA were consistent with earlier studies (11,14–16). Two prior studies observed that later-day activity and afternoon MVPA gave stronger HbA_{1c} reduction (15,16). Others observed associations between afternoon/evening MVPA with better glucose homeostasis (14) and lower insulin resistance (11). Concordantly, some intervention studies found benefits of afternoon or evening MVPA/exercise on glycemic measures. For example, two small crossover trials (*n* = 52 and *n* = 11) observed evening exercise was more effective than morning exercise at suppressing nocturnal blood glucose rises (10) and reducing blood glucose concentration (13). However,

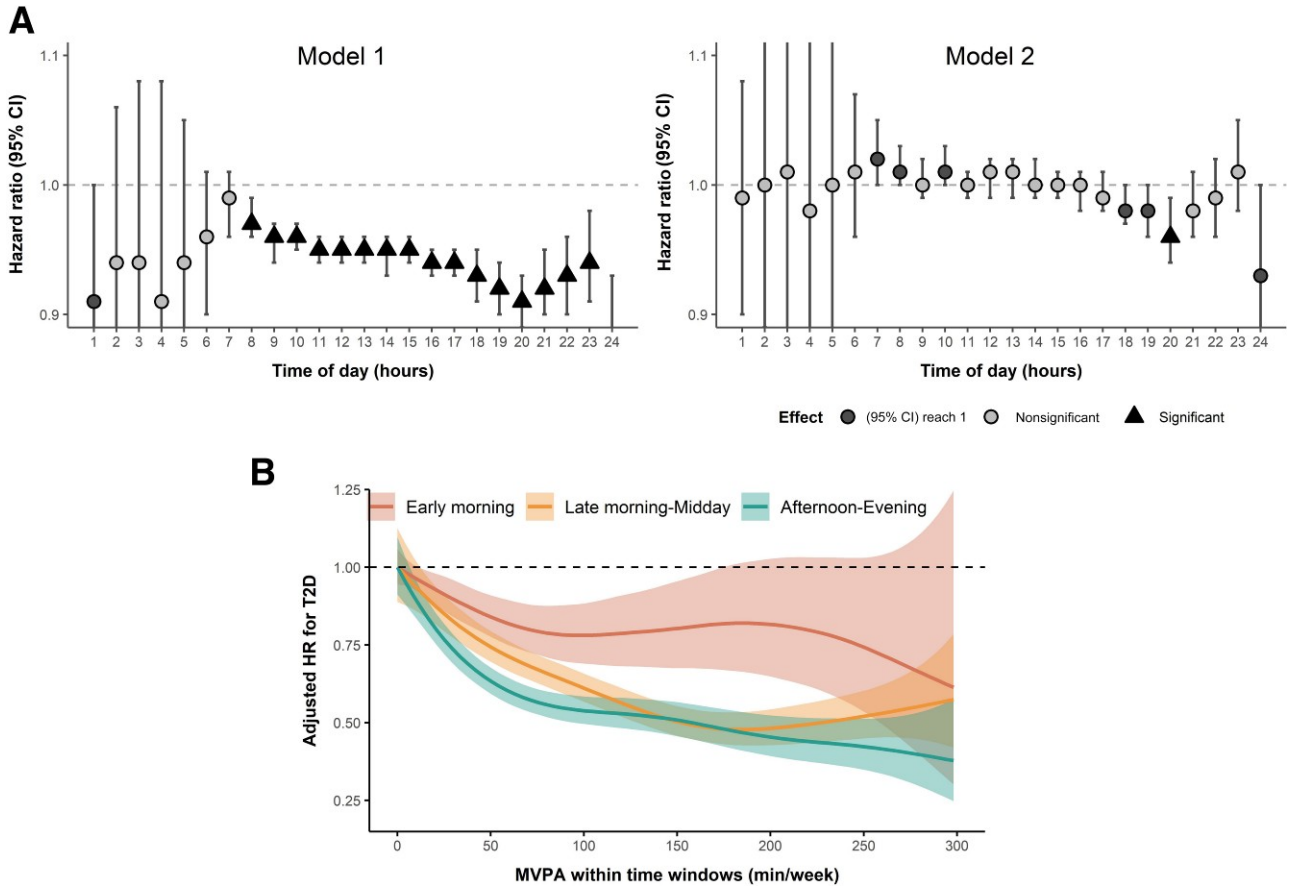

Figure 1—*A*: Associations between MVPA minutes during each hour of the day and T2D risk presented as HRs (95% CI) in UKB, model 1 adjusting for age, sex, ethnicity, Townsend deprivation index, education, smoking status, alcohol intake frequency, sleep midpoint, dietary information, sleep duration, season of accelerometry wear, and family history of diabetes. Model 2 additionally adjusted for total daily MVPA. *B*: Multivariable-adjusted associations between duration of MVPA within three time windows and T2D risk in UKB. For each time window, the reference value is 0 min of MVPA within that window. The HRs were adjusted for age, sex, ethnicity, Townsend deprivation index, education, smoking status, alcohol intake frequency, sleep midpoint, dietary information, sleep duration, season of accelerometry wear, and familial history of diabetes and MVPA volume during other two time windows.

another small trial (n = 40) found no significant differences in glycemic measures between morning and evening exercise (12). Nevertheless, the consistency across multiple observational and intervention studies supports the plausibility of our findings. Collectively, these observations suggest that MVPA in afternoon/evening may confer greater benefits for glucose regulation and T2D prevention.

The potential underlying mechanisms may relate to the circadian rhythm of insulin sensitivity. In humans, insulin sensitivity declines as the day progresses, with a significant reduction in the evening (17), leading to greater postprandial glucose responses of the evening meal (18). Engaging in MVPA in the late afternoon/evening might counteract this circadian decline by enhancing glucose uptake (19) to help suppress higher glucose increase of the evening meal (20). Thus, aligning exercise with the biological window of reduced insulin sensitivity could help stabilize overall glucose balance and therefore lower diabetes risk. Nonetheless, the exact mechanisms remain to be clarified.

The strengths of this study include the large sample size, the use of accelerometry-measured MVPA, and various

Table 2—Differences in T2D risk between different MVPA timing groups in UKB

Group	Events/*n*	Model 1 HR (95% CI)	Model 2 HR (95% CI)	Model 3 HR (95% CI)
MVPA				
Early morning	158/4,469	1.00 (reference)	1.00 (reference)	1.00 (reference)
Late morning-midday	1,058/40,312	0.70 (0.59, 0.83)	0.76 (0.64, 0.90)	0.80 (0.68, 0.95)
Afternoon-evening	502/23,489	0.67 (0.56, 0.80)	0.72 (0.60, 0.87)	0.71 (0.59, 0.85)
Variable timing	297/16,258	0.55 (0.45, 0.66)	0.60 (0.50, 0.73)	0.75 (0.62, 0.91)

Model 1 was adjusted for age and sex. Model 2 was additionally adjusted for ethnicity, Townsend Deprivation Index, education, smoking status, alcohol intake frequency, sleep midpoint, dietary information, sleep duration, season of accelerometry wear, family history of diabetes, and osteoporosis. Model 3 was further adjusted for total daily MVPA.

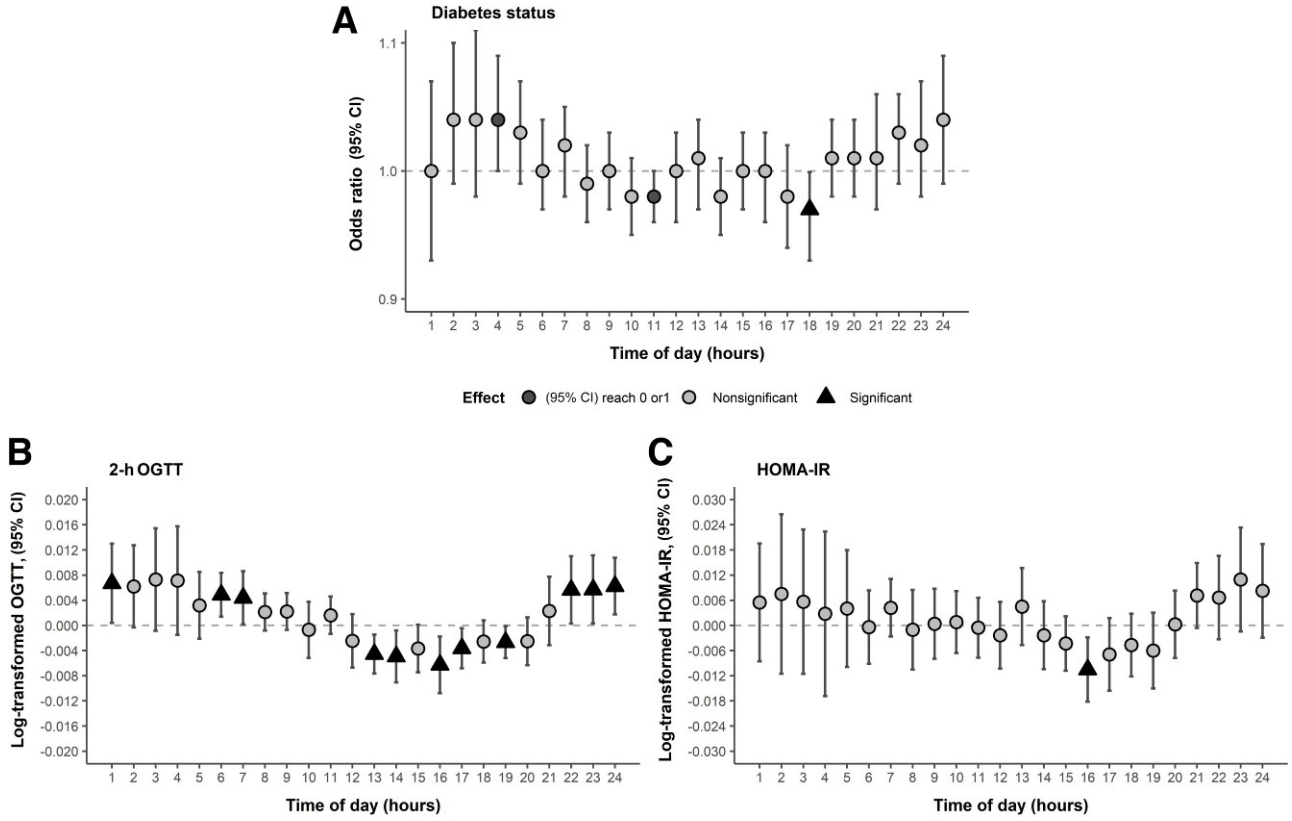

Figure 2—Multivariable-adjusted associations between MVPA minutes during each hour of the day and prevalent diabetes (*A*), 2-h OGTT results (*B*), and HOMA-IR (*C*) among NHANES (2011–2014) participants. Multiple logistic/linear regression models adjusted for age and sex, ethnicity, education, household income, marital status, smoking status, alcohol consumption, total energy intake, Healthy Eating Index (HEI) score, arthritis, sleep duration, sleep midpoint, and total daily MVPA.

outcomes. However, several limitations remain. First, some covariates in UKB were measured years before accelerometer data collection, potentially introducing bias from subsequent changes. BMI might be a mediator between MVPA timing and T2D risk; however, formally evaluating mediation with BMI measured years before the exposure assessment is not possible. Therefore, we included BMI in an additional sensitivity model. Second, the early morning (0500–0959) MVPA group comprised ∼5% of the UKB population (>4,000 individuals), which may limit generalizability. This subgroup may also include individuals with atypical sleep or work schedules, introducing potential selection bias despite sufficient sample size for analysis. Third, there still may be residual and unmeasured confounding, such as meal timing. Finally, the generalizability of findings from UKB data are limited; however, corroborative results in the nationally representative NHANES data enhance the broader applicability of our conclusions.

In conclusion, when keeping total MVPA volume constant, clustering MVPA in the afternoon-evening was associated with the strongest reduction in incident T2D risk, fewer prevalent diabetes, and more favorable glycemic measures.

Acknowledgments. The authors would like to acknowledge the contribution of participants in UK Biobank and NHANES. The study was conducted using the UK Biobank resource (project 81423) and NHANES data.

Funding. Q.F. was supported by a scholarship from the China Scholarship Council (202306240049). The present work was supported by a grant from the Dutch Research Council (NWO, Dutch National Research Agenda, Research along routes by consortia, 2021–2026, BioClock: The Circadian Clock in Modern Society). Support was also received from the Netherlands Organisation for Health Research and Development (ZonMw) Partnership Diabetes (459001010)/Dutch Diabetes Foundation Breakthrough (2018.11.160). This research was supported in part by the Intramural Research Program of the National Institutes of Health.

The contributions of the National Institutes of Health authors (C.E.M. and J.R.F.) are considered works of the U.S. Government. The findings and conclusions presented in this paper are those of the authors and do not necessarily reflect the views of the National Institutes of Health or the U.S. Department of Health and Human Services.

Duality of Interest. No potential conflicts of interest relevant to this article were reported.

Author Contributions. Q.F. wrote the first draft of the manuscript. Q.F., G.A., L.A., H.W., J.H.P.M.v.d.V., J.C.K.d.-J., M.K.R., J.R.F., K.W.v.D., D.v.H., and R.N. edited and reviewed the manuscript. Q.F., G.A., L.A., M.K.R., K.W.v.D., D.v.H., and R.N. interpreted the results. Q.F., K.W.v.D., D.v.H., and R.N. were involved in the conception and design of the study and the analysis of the results. Q.F. and D.v.H. obtained funding. All authors approved the final version of the manuscript. R.N. is the guarantor of this work and, as such, had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

Prior Presentation. Parts of this study were presented at the WEON (Working Group on Epidemiological Research Netherlands) Congress, Leiden, the Netherlands, 5–6 June 2025, and at the European Association for the Study of diabetes (EASD) Annual meeting, Vienna, Austria, 15–19 September 2025.

Handling Editors. The journal editors responsible for overseeing the review of the manuscript were John B. Buse and Stephanie L. Fitzpatrick.

References

1. Chomistek AK, Shiroma EJ, Lee I-M. The relationship between time of day of physical activity and obesity in older women. J Phys Act Health 2016;13:416–418

2. Aqeel M, Guo J, Lin L, et al. Temporal physical activity patterns are associated with obesity in U.S. adults. Prev Med 2021;148:106538
3. Albalak G, Stijntjes M, van Bodegom D, et al. Setting your clock: associations between timing of objective physical activity and cardiovascular disease risk in the general population. Eur J Prev Cardiol 2023;30:232–240
4. Li X, Zeng J, Chen B, et al. Effects of the timing of intense physical activity on hypertension risk in a general population: a UK-Biobank Study. Curr Hypertens Rep 2024;26:81–90
5. Qian J, Walkup MP, Chen S-H, et al. Look AHEAD Research Group. Association of objectively measured timing of physical activity bouts with cardiovascular health in type 2 diabetes. Diabetes Care 2021;44:1046–1054
6. Tian C, Bürki C, Westerman KE, Patel CJ. Association between timing and consistency of physical activity and type 2 diabetes: a cohort study on participants of the UK Biobank. Diabetologia 2023;66:2275–2282
7. Xiao Q, Feng Q, Rutter MK, Albalak G, Wang H, Noordam R. Associations between the timing of 24 h physical activity and diabetes mellitus: results from a nationally representative sample of the US population. Diabetologia 2025;68:1005–1015
8. Feng Q, Albalak G, van Dijk KW, et al. Accelerometer-measured chronoactivity and type 2 diabetes risk: a prospective study in UK Biobank participants. Prev Med 2025;197:108312
9. 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;46:515–522
10. Kanaley JA, Porter JW, Winn NC, et al. Temporal optimization of exercise to lower fasting glucose levels. J Physiol 2024;602:6447–6461
11. van der Velde JHPM, Boone SC, Winters-van Eekelen E, et al. Timing of physical activity in relation to liver fat content and insulin resistance. Diabetologia 2023;66:461–471
12. Teo SYM, Kanaley JA, Guelfi KJ, Marston KJ, Fairchild TJ. The effect of exercise timing on glycemic control: a randomized clinical trial. Med Sci Sports Exerc 2020;52:323–334
13. Savikj M, Gabriel BM, Alm PS, et al. Afternoon exercise is more efficacious than morning exercise at improving blood glucose levels in individuals with type 2 diabetes: a randomised crossover trial. Diabetologia 2019;62:233–237
14. Clavero-Jimeno A, Dote-Montero M, Migueles JH, et al. Impact of lifestyle moderate-to-vigorous physical activity timing on glycemic control in sedentary adults with overweight/obesity and metabolic impairments. Obesity (Silver Spring) 2024;32:1465–1473
15. Qian J, Xiao Q, Walkup MP, et al. Look AHEAD Research Group. Association of timing of moderate-to-vigorous physical activity with changes in glycemic control over 4 years in adults with type 2 diabetes from the Look AHEAD trial. Diabetes Care 2023;46:1417–1424
16. Kerr D, Abbasi M, Bevier W, Glantz N, Larez A, Sabharwal A. Patterns of timing and intensity of physical activity and HbA_{1c} levels in Hispanic/Latino adults with or at risk of type 2 diabetes. J Diabetes Sci Technol 2024;18:106–112
17. Saad A, Dalla Man C, Nandy DK, et al. Diurnal pattern to insulin secretion and insulin action in healthy individuals. Diabetes 2012;61:2691–2700
18. Van Cauter E, Shapiro ET, Tillil H, Polonsky KS. Circadian modulation of glucose and insulin responses to meals: relationship to cortisol rhythm. Am J Physiol 1992;262:E467–E475
19. Sylow L, Kleinert M, Richter EA, Jensen TE. Exercise-stimulated glucose uptake—regulation and implications for glycaemic control. Nat Rev Endocrinol 2017;13:133–148
20. Bellini A, Scotto di Palumbo A, Nicolò A, Bazzucchi I, Sacchetti M. Exercise prescription for postprandial glycemic management. Nutrients 2024;16:1170