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Non-Linear Association Between Physical Activities and Type 2 Diabetes in 2.4 Million Korean Population, 2009–2022: A Nationwide Representative Study

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ABSTRACT

Background: Although excessive physical activity (PA) does not always confer additional health benefits, there is a paucity of studies that have quantitatively examined the dose-response relationship between PA and type 2 diabetes. Therefore, this study investigated the relationship between the type 2 diabetes prevalence and intensity, frequency, and metabolic equivalent of task (MET) score of PA in a large population sample.
Methods: We conducted a nationwide cross-sectional analysis examining sociodemographic variables, PA habits, and type 2 diabetes prevalence in 2,428,448 participants included in the Korea Community Health Survey. The non-linear association between MET score and odds ratios (ORs) for type 2 diabetes prevalence was plotted using a weighted generalized additive model. Categorical analysis was used to examine the joint association of moderate-intensity PA (MPA) and vigorous-intensity PA (VPA), and the influence of PA frequency.
Results: MET score and diabetes prevalence revealed a non-linear association with the nadir at 1,028 MET-min/week, beyond which ORs increased with additional PA. Joint analysis of MPA and VPA showed the lowest OR of 0.79 (95% confidence interval, 0.75–0.84) for those engaging in 300–600 MET-min/week of MPA and > 600 MET-min/week of VPA concurrently, corresponding with World Health Organization recommendations. Additionally, both "weekend warriors" and "regularly active" individuals showed lower ORs compared to the inactive, although no significant difference was noted between the active groups.

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Disclosure
The authors have no potential conflicts of interest to disclose.

Data Availability Statement
The data are available upon request. Study protocol and statistical code: Available from Dong Keon Yon (yonkkang@gmail.com). Dataset: Available from the Korea Disease Control Agency (KDCA) through a data use agreement.

Conclusion: In a large South Korean sample, higher PA is not always associated with a lower prevalence of type 2 diabetes, as the association follows a non-linear pattern; differences existed across sociodemographic variables. Considering the joint association, an adequate combination of MPA and VPA is recommended. The frequency of PA does not significantly influence the type 2 diabetes prevalence.

Keywords: Metabolic Equivalent of Task; Physical Activity; Type 2 Diabetes; Prevalence; South Korea

INTRODUCTION

Adequate physical activity (PA) is associated with reduced overall mortality and offers various health benefits, including enhanced physical and cognitive function, as well as improved sleep quality.[1,2] Previous studies have shown that engaging in 150 minutes of moderate-to-vigorous PA (MVPA) per week reduces relative mortality by approximately 33%.[3] However, exercising beyond this threshold appears to provide no additional health benefits.[3] Also, the correlation between PA and life expectancy has been reported as an "inverted J-curve."[4] Additionally, a study on the association between PA and mental burden has also shown that more exercise is not necessarily better, highlighting the need to determine the optimal amount of PA for various health outcomes.[5]

Meanwhile, type 2 diabetes (T2D) is one of the leading noncommunicable diseases (NCDs), affecting an estimated 529 million people globally in 2021.[6] The global prevalence of T2D has steadily increased, with age-standardized prevalence rising from 3.2% in 1990 to 6.1% in 2021.[7] This trend poses a serious threat to public health, highlighting the need for strategies to prevent T2D. T2D is a metabolic disease that is primarily affected by lifestyle factors such as diet and exercise habits.[8] Obesity, frequently caused by a sedentary lifestyle, along with inactivity itself, are well-established major risk factors for the development of T2D.[9,10] Consequently, maintaining optimal PA is crucial for the prevention of T2D.[7,11]

Although a few prior studies have looked into the relationship between PA and T2D, there has been a shortfall of quantitative research that identified the dose-response relationship.[12] Therefore, our study aimed to investigate the quantitative relation between T2D prevalence and PA among adults aged 30 years and older in South Korea, covering the period from 2009 to 2022.[13] Also, further stratified analysis was done, based on various sociodemographic and lifestyle variables. Furthermore, we sought to determine the optimal frequencies and combinations of moderate-intensity PA (MPA) and vigorous-intensity PA (VPA) linked to a reduced prevalence of T2D.

METHODS

Survey design and participants

This nationwide cross-sectional study aimed to investigate the association between PA and T2D using large-scale nationwide data. This study utilized data from the Korea Community Health Survey (KCHS), a nationwide survey conducted by the Korea Disease Control and Prevention Agency (KDCA) from 2009 to 2022. Since KCHS lacked PA-related questionnaires in 2018, the 2018 dataset was excluded from the analysis.[14,15] Study participants were South

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Author Contributions
Data curation: Kim S[1]; Supervision: Hwang J, Rhee SY, Yon DK; Validation: Kim S,[2] Lee H, Park J, Lee K, Kang J; Visualization: Son Y, Pizzol D; Writing - original draft: Jang W, Kim S,[1] Son Y.

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Korean adults aged 30 years and older who were selected based on existing criteria for T2D research and were at risk of T2D. Data with missing values or missing responses were excluded from the analysis, resulting in a total nationally representative sample of 2,428,448 individuals. Statistical analyses were performed using weighting and sample clustering techniques to ensure the reliability and representativeness of the results.[16]

Health outcomes

The primary objective of the study was to examine the association between PA and T2D in a sample of 2,428,448 adults in South Korea. Participants were asked questions related to their diabetes diagnosis, including the question, "Have you ever been diagnosed with diabetes by a doctor?" These responses were used to define T2D status.[17]

Exposure

The World Health Organization (WHO) advises that adults should engage in at least 150 minutes of MPA or 75 minutes of VPA per week, or a combination of both, amounting to a minimum of 600 metabolic equivalent of task (MET)-min/week.[14] Moreover, WHO recommends increasing PA to over 300 minutes of MPA or over 150 minutes of VPA weekly, or an equivalent mix, to gain additional health benefits, which is equivalent to more than 1,200 MET-min/week. In the KCHS survey, PA was assessed through specific questions about the frequency and duration of vigorous and moderate activity. Participants were asked how many days in the past week they had engaged in vigorous activities, such as running or fast cycling, for at least 10 minutes, as well as the typical duration of such activities on those days. Similar questions were asked about moderate activity, such as brisk walking or light biking. The MET score is determined by multiplying the intensity coefficient (4.0 for MPA and 8.0 for VPA) by the minutes of PA per day and the PA days per week, with the total MET score being the aggregate of MET scores of MPA and VPA. To minimize potential statistical anomalies, a 99% winsorization was applied to the durations of PA reported.[5] This adjustment means that any durations exceeding 480 minutes per week for MPA and 420 minutes per week for VPA were capped at the 99th percentile values.

Covariates

Our study utilized data from the South Korean adult population sourced from the KCHS. It encompassed various sociodemographic variables including sex (male and female), age (30–39, 40–49, 50–59, 60–69, and ≥ 70 years), region of residence (urban and rural),[18] body mass index (BMI) group (underweight, normal, overweight, and obese), educational background (elementary school or lower, middle school, high school, and college or higher), household income (lowest, second, third, and highest quartiles), smoking status (non-smoker, ex-smoker, and smoker), stress status (mild, moderate, high, and severe), and depression. BMI group was categorized into underweight (< 18.5 kg/m^2), normal weight (18.5–22.9 kg/m^2), overweight (23–24.9 kg/m^2), and obese (≥ 25.0 kg/m^2) according to Asian–Pacific guidelines.[19]

Statistical analysis

Our study investigated the association of T2D and each covariate. We utilized weighted binary logistic regression models to estimate weighted odds ratios (ORs) and adjusted ORs with 95% confidence intervals (CIs). The full set of covariates used in adjustment includes sex, age, region of residence, BMI, educational background, household income, smoking status, stress status, and depression.

To analyze non-linear associations between PA and the prevalence of T2D, we used a weighted generalized additive model (GAM), thereby enhancing predictive performance compared to conventional linear models.[5,20] The model included penalized cubic regression splines term for MET score, adjusting for the full set of covariates.[5,20] The performance of the GAM model was also assessed using likelihood ratio tests, comparing it to the conventional linear model ($P < 0.001$).[20] We then constructed a plot from the model with 95% CI to characterize the overall relationship between MET score and adjusted OR of T2D prevalence. In addition, we conducted a stratified analysis to present categorized plots for MET and adjusted OR for each subgroup, stratified by each covariate.[5] The covariates used in these adjustments include sex, age, region of residence, BMI, educational background, household income, smoking status, stress status, and depression.

An additional analysis was performed to investigate the joint associations of MPA and VPA on T2D prevalence. MPA and VPA were categorized as < 300, 300–600, and ≥ 600 MET-min/week. The criteria for these categories were selected from the WHO's recommendation for PA and the distribution of MET scores observed in our study population.[20,21] The joint association of MPA and VPA was depicted with an adjusted OR matrix.[20]

Within the combination of MPA and VPA that exhibited the lowest OR from the matrix, we compared the prevalence of T2D across different PA patterns. Individuals who reported performing activity on two or fewer days per week were termed "weekend warriors," while those distributing activity over three or more days per week were defined as "regularly active."[21-23] Participants who reported no PA were classified as "inactive," and those with MET scores below 600 MET-min/week (failing to meet WHO recommendation) were labeled "insufficiently active."[14,22] By comparing the adjusted ORs across these PA patterns, we aimed to examine the associations between each PA pattern and the prevalence of T2D.[22] Additionally, since differences in PA patterns could result in variations in PA amounts, we performed an adjustment for MPA and VPA durations, to calculate the OR of 'regularly active' with reference to 'weekend warrior.'[14,22] To evaluate the ratio of ORs (rOR), we calculated the ratio of the ORs for each variable across different MET levels. The rOR was defined as the ratio of the ORs of the variables for T2DM at a specific MET level. To determine if the risk associated with each variable significantly differs at a particular MET level, we assessed whether the 95% CI of the rOR includes 1.00. If the 95% CI does not include 1.00, it indicates a statistically significant difference in the risk of T2DM for the variable at that MET level. All statistical inferences were defined as significant at a two-sided P value less than 0.05. Statistical analyses were performed using R (version 4.3.2; R Foundation, Vienna, Austria) and SAS (version 9.4; SAS Institute Inc., Cary, NC, USA).[24,25]

Secondary analysis

To overcome the inherent limitations regarding causality in our cross-sectional study, we conducted a secondary analysis focusing on the association between newly diagnosed diabetes and PA amount and pattern. We collected responses to the question "At what age were you diagnosed with diabetes?" from the KCHS in 2009 and 2019–2022 to define newly diagnosed diabetes as cases where the difference between the current age and the age of diagnosis was within two years.[26] We then conducted the statistical analyses using the same methods as those applied to the population without restriction on diabetes duration.

Ethics statement

The Institutional Review Board of Kyung Hee University (KHSIRB-23-384(EA)) and the KDCA approved the study protocol. The KCHS data used in this study were anonymized, and written informed consent was obtained from all participants before study participation. Ethical considerations were upheld, adhering to the Declaration of Helsinki.

RESULTS

Data from a total of 2,428,448 participants were analyzed using data from the KCHS from 2009 to 2022. Among the participants, 11.3% (275,153/2,428,448) had been previously diagnosed with diabetes, and of those with diabetes, 12.5% (123,674/985,762) were newly diagnosed with diabetes within the past two years. The characteristics of the study population divided by sociodemographic factors are shown in **Table 1**. **Table 2** shows the ORs and adjusted ORs for T2D prevalence, for each subgroup. Higher age, higher BMI, lower educational background, lower household income, higher stress, male sex, smoking behavior, residing in urban regions, and depression were associated with higher ORs. It is noteworthy that urban residents exhibited higher adjusted ORs compared to rural residents, and people with higher stress showed higher adjusted ORs than those with lower stress, in contrast to the unadjusted ORs.

Fig. 1 illustrates the OR for T2D prevalence, plotted as a function of MET score. The nadir is reached at 1,028 MET-min/week, where the OR is 0.842 (95% CI, 0.834–0.850). Beyond this point, the OR increases with additional PA. **Fig. 2** displays these results stratified by each subgroup, showing a similar overall pattern with a nadir of around 1,000 MET-min/week. The rOR between each subgroup is presented in **Supplementary Fig. 1**. Factors associated with a lower minimum OR for T2D prevalence according to PA include female sex (OR, 0.823; 95% CI, 0.818–0.829), older age (0.804; 95% CI, 0.791–0.818), residing in an urban region (0.841; 95% CI, 0.832–0.850), high BMI (0.836; 95% CI, 0.825–0.848), low household income (0.810; 95% CI, 0.801–0.820), non-smoking behavior (0.814; 95% CI, 0.809–0.819), and depression (0.793; 95% CI, 0.771–0.815), compared to their respective counterpart subgroups.

Fig. 3 presents an OR matrix illustrating the joint association between MPA and VPA. The lowest OR of 0.79 (95% CI, 0.75–0.84) was observed for people engaging in 300–600 MET-min/week of MPA and more than 600 MET-min/week of VPA concurrently (**Supplementary Table 1**). This MET score range results in a total MET > 900 MET-min/week, aligning closely with the optimal PA level of around 1,000 MET-min/week as noted in **Fig. 1**, and overlapping with the WHO recommendation PA range of 600 to 1,200 MET-min/week. However, the OR does not show additional decrement among the most physically active individuals (those exceeding 600 MET-min/week in both MPA and VPA). **Fig. 4** displays the ORs for T2D prevalence according to PA patterns. Even the "insufficiently active" group is associated with a lower OR than that of the "inactive" group (OR, 0.87; 95% CI, 0.85–0.89).[27] Furthermore, both the "weekend warrior" group (OR, 0.74; 95% CI, 0.64–0.86) and the "regularly active" group (OR, 0.80; 95% CI, 0.75–0.85) exhibit lower ORs than the insufficiently active group. However, there is no statistically significant difference between the "weekend warrior" and "regularly active" groups (OR, 1.02; 95% CI, 0.83–1.27; **Supplementary Tables 2** and **3**).

Supplementary Table 4 presents the characteristics of the study population for secondary analysis, categorized by sociodemographic factors, while **Supplementary Table 5**

Table 1. Weighted demographic characteristics of the participants in the Korea Community Health Survey from 2009 to 2022 (N = 2,428,448)

Characteristics	Total	Diabetes status	
		Individuals with T2D	Individuals without T2D
Overall	2,428,448	275,153	2,153,295
Sex			
Male	49.31 (49.25–49.38)	54.92 (54.66–55.18)	48.72 (48.65–48.79)
Female	50.69 (50.62–50.75)	45.08 (44.82–45.34)	51.28 (51.21–51.35)
Age, yr			
30–39	21.94 (21.84–22.05)	3.03 (2.93–3.14)	23.96 (23.84–24.07)
40–49	25.07 (24.97–25.17)	10.46 (10.28–10.65)	26.63 (26.52–26.73)
50–59	23.83 (23.74–23.93)	24.39 (24.14–24.64)	23.77 (23.68–23.87)
60–69	15.50 (15.43–15.58)	28.90 (28.66–29.15)	14.08 (14.00–14.15)
≥ 70	13.65 (13.58–13.72)	33.21 (32.95–33.47)	11.57 (11.50–11.64)
Region of residence			
Urban	80.68 (80.48–80.88)	76.51 (76.23–76.80)	81.12 (80.92–81.32)
Rural	19.32 (19.12–19.52)	23.49 (23.20–23.77)	18.88 (18.68–19.08)
BMI group[a]			
Underweight	4.10 (4.07–4.14)	2.69 (2.61–2.77)	4.25 (4.21–4.29)
Normal	41.56 (41.47–41.65)	31.21 (30.96–31.46)	42.66 (42.57–42.76)
Overweight	25.11 (25.04–25.19)	26.68 (26.44–26.92)	24.95 (24.86–25.03)
Obese	29.23 (29.14–29.31)	39.42 (39.15–39.69)	28.14 (28.05–28.23)
Educational background			
Elementary school or lower	14.40 (14.32–14.47)	30.61 (30.36–30.86)	12.67 (12.60–12.74)
Middle school	10.20 (10.14–10.26)	16.95 (16.75–17.15)	9.48 (9.42–9.54)
High school	32.99 (32.88–33.09)	30.37 (30.11–30.63)	33.26 (33.16–33.37)
College or higher	42.42 (42.28–42.56)	22.07 (21.81–22.33)	44.59 (44.44–44.73)
Household income			
Lowest quartile	12.40 (12.31–12.48)	24.13 (23.88–24.37)	11.04 (10.97–11.12)
Second quartile	31.03 (30.90–31.16)	37.49 (37.21–37.76)	30.29 (30.16–30.42)
Third quartile	29.15 (29.03–29.27)	21.06 (20.82–21.29)	30.08 (29.96–30.21)
Highest quartile	27.42 (27.26–27.58)	17.33 (17.09–17.57)	28.58 (28.42–28.74)
Smoking status			
Current smoker	20.78 (20.70–20.86)	19.91 (19.68–20.14)	20.87 (20.79–20.96)
Ex-smoker	20.05 (19.97–20.12)	27.99 (27.75–28.24)	19.20 (19.13–19.28)
Non-smoker	59.17 (59.09–59.25)	52.10 (51.83–52.37)	59.92 (59.84–60.01)
Stress status			
Mild	19.08 (19.00–19.16)	26.33 (26.09–26.56)	18.31 (18.23–18.39)
Moderate	54.96 (54.86–55.06)	48.00 (47.73–48.28)	55.70 (55.60–55.80)
High	22.45 (22.37–22.53)	21.68 (21.45–21.91)	22.53 (22.44–22.61)
Severe	3.51 (3.48–3.55)	3.99 (3.88–4.10)	3.46 (3.42–3.50)
Depression			
Yes	6.46 (6.41–6.51)	9.06 (8.90–9.23)	6.18 (6.13–6.24)
No	93.54 (93.49–93.59)	90.94 (90.77–91.10)	93.82 (93.76–93.87)

Values are presented as weighted % (95% confidence interval).
T2D = type 2 diabetes, BMI = body mass index.
[a]BMI was divided into four groups according to Asian-Pacific guidelines: underweight (< 18.5 kg/m^2), normal (18.5–22.9 kg/m^2), overweight (23.0–24.9 kg/m^2), and obese (≥ 25 kg/m^2).

displays the weighted odds ratios for the prevalence of newly diagnosed T2D across each sociodemographic factor. In this analysis, which is limited to newly diagnosed diabetes, results similar to those of the primary analysis (which included all cases) were observed. **Supplementary Fig. 2** suggests that for newly diagnosed diabetes, the relationship between MET score and the OR of diabetes prevalence also exhibits a U-curve, with the minimum value occurring around MET = 1,000. Furthermore, when stratified by socioeconomic factors, the pattern of this non-linear relationship remained consistent, and the relative ordering of the odds ratio values across factors was also preserved (**Supplementary Fig. 3**). However, unlike the results without limiting the duration of diabetes, the lowest OR (0.74; 95% CI, 0.62–0.89) was found with a VPA of 300–600 MET-min/week and MPA greater than 600

Table 2. Weighted ORs in the prevalence of T2D for each sociodemographic factor based on data obtained from the Korea Community Health Survey

Variables	OR (95% CI)	*P* value	aOR (95% CI)	*P* value
Sex				
Female	1.00 (ref)		1.00 (ref)	
Male	**1.28 (1.27–1.30)**	**< 0.001**	**1.22 (1.19–1.24)**	**< 0.001**
Age, yr				
30–39	1.00 (ref)		1.00 (ref)	
40–49	**3.10 (2.98–3.23)**	**< 0.001**	**3.02 (2.90–3.15)**	**< 0.001**
50–59	**8.10 (7.80–8.42)**	**< 0.001**	**7.54 (7.25–7.83)**	**< 0.001**
60–69	**16.22 (15.62–16.84)**	**< 0.001**	**13.88 (13.35–14.43)**	**< 0.001**
≥ 70	**22.67 (21.83–23.54)**	**< 0.001**	**19.31 (18.55–20.10)**	**< 0.001**
Region of residence				
Rural	1.00 (ref)		1.00 (ref)	
Urban	**0.76 (0.75–0.77)**	**< 0.001**	**1.04 (1.03–1.06)**	**< 0.001**
BMI group[a]				
Underweight	1.00 (ref)		1.00 (ref)	
Normal	**1.15 (1.12–1.19)**	**< 0.001**	**1.49 (1.44–1.54)**	**< 0.001**
Overweight	**1.69 (1.63–1.74)**	**< 0.001**	**2.00 (1.94–2.07)**	**< 0.001**
Obese	**2.21 (2.14–2.28)**	**< 0.001**	**2.95 (2.85–3.05)**	**< 0.001**
Educational background				
College or higher	1.00 (ref)		1.00 (ref)	
High school	**1.84 (1.81–1.88)**	**< 0.001**	**1.26 (1.24–1.28)**	**< 0.001**
Middle school	**3.61 (3.54–3.68)**	**< 0.001**	**1.42 (1.39–1.45)**	**< 0.001**
Elementary school or lower	**4.88 (4.80–4.96)**	**< 0.001**	**1.41 (1.37–1.44)**	**< 0.001**
Household income				
Highest quartile	1.00 (ref)		1.00 (ref)	
Third quartile	**1.15 (1.13–1.18)**	**< 0.001**	**1.05 (1.03–1.07)**	**< 0.001**
Second quartile	**2.04 (2.01–2.08)**	**< 0.001**	**1.15 (1.13–1.17)**	**< 0.001**
Lowest quartile	**3.60 (3.54–3.67)**	**< 0.001**	**1.18 (1.16–1.21)**	**< 0.001**
Smoking status				
Non-smoker	1.00 (ref)		1.00 (ref)	
Smoker	**1.38 (1.36–1.39)**	**< 0.001**	**1.31 (1.29–1.34)**	**< 0.001**
Stress status				
Mild	1.00 (ref)		1.00 (ref)	
Moderate	**0.60 (0.59–0.61)**	**< 0.001**	0.99 (0.98–1.00)	0.157
High	**0.67 (0.66–0.68)**	**< 0.001**	**1.20 (1.18–1.22)**	**< 0.001**
Severe	**0.80 (0.78–0.83)**	**< 0.001**	**1.37 (1.32–1.42)**	**< 0.001**
Depression				
No	1.00 (ref)		1.00 (ref)	
Yes	**1.51 (1.48–1.54)**	**< 0.001**	**1.32 (1.29–1.35)**	**< 0.001**

The adjusted model is adjusted for sex, age, region of residence, BMI group, educational background, household income, smoking status, stress status, and depression.
Numbers in bold indicate a significant difference ($P < 0.05$).
T2D = type 2 diabetes, OR = odds ratio, CI = confidence interval, aOR = adjusted odds ratio, BMI = body mass index.
[a]BMI was divided into four groups according to Asian-Pacific guidelines: underweight (< 18.5 kg/m²), normal (18.5–22.9 kg/m²), overweight (23.0–24.9 kg/m²), and obese (≥ 25 kg/m²).

MET-min/week in the secondary analysis (**Supplementary Table 6**). Additionally, while the insufficiently active, "weekend warriors," and "regularly active" groups showed lower ORs compared to the inactive group, the "weekend warrior" and "regularly active" groups lacked statistical significance due to a small sample size (**Supplementary Table 7**). Still, there was no statistically significant difference between the weekend warrior and regularly active groups (OR, 0.91; 95% CI, 0.46–1.79; **Supplementary Table 8**).

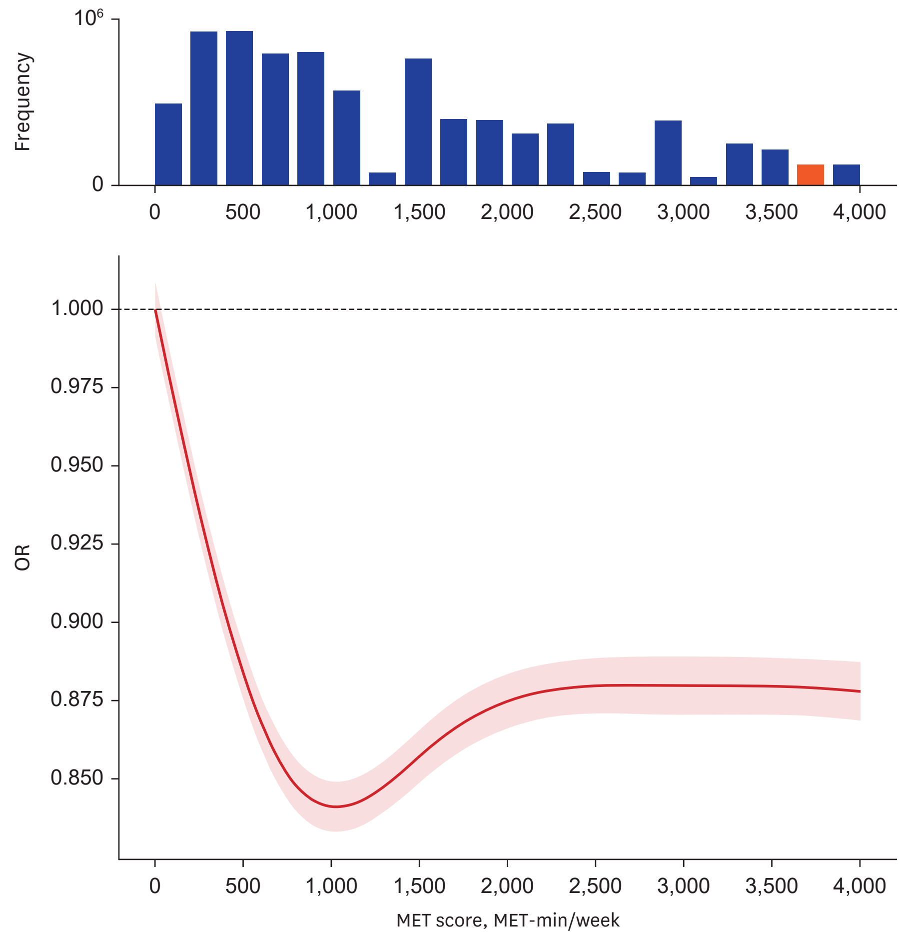

Fig. 1. Adjusted ORs of type 2 diabetes as a function of MET based on data obtained from the Korea Community Health Survey. ORs were adjusted for all covariates. The line represents smoothed conditional means with generalized additive model smoothing, with ribbons representing 95% confidence intervals. The dashed line indicates an OR of 1. The frequency of 0 MET-min/week was not shown in the histogram.
OR = odds ratio, MET = metabolic equivalent of task.

DISCUSSION

We utilized nationwide, large-scale population data to examine the association between the MET score and T2D prevalence and patterns of PA. We found that within a PA range of up to approximately 1,000 MET-min/week, increased PA is associated with lower T2D prevalence; however, no further reductions in prevalence occur beyond this level of activity. When stratified by sociodemographic variables, the association of PA and prevalence significantly varied among subgroups. Notably, MPA of 75 to 150 minutes per week and VPA of at least 75 minutes per week were associated with a lower prevalence of T2D, aligning with the WHO recommendation of PA level for adults. There was no observed difference in T2D prevalence between individuals meeting these activity levels through sporadic and intense sessions and those engaging in regular PA. These findings were also observed in individuals with newly diagnosed diabetes, except for the specific values in the optimal combination of MPA and VPA amounts. Future cohort studies are necessary to further explore the relationship between PA patterns and the incidence of other NCDs as well as T2D.

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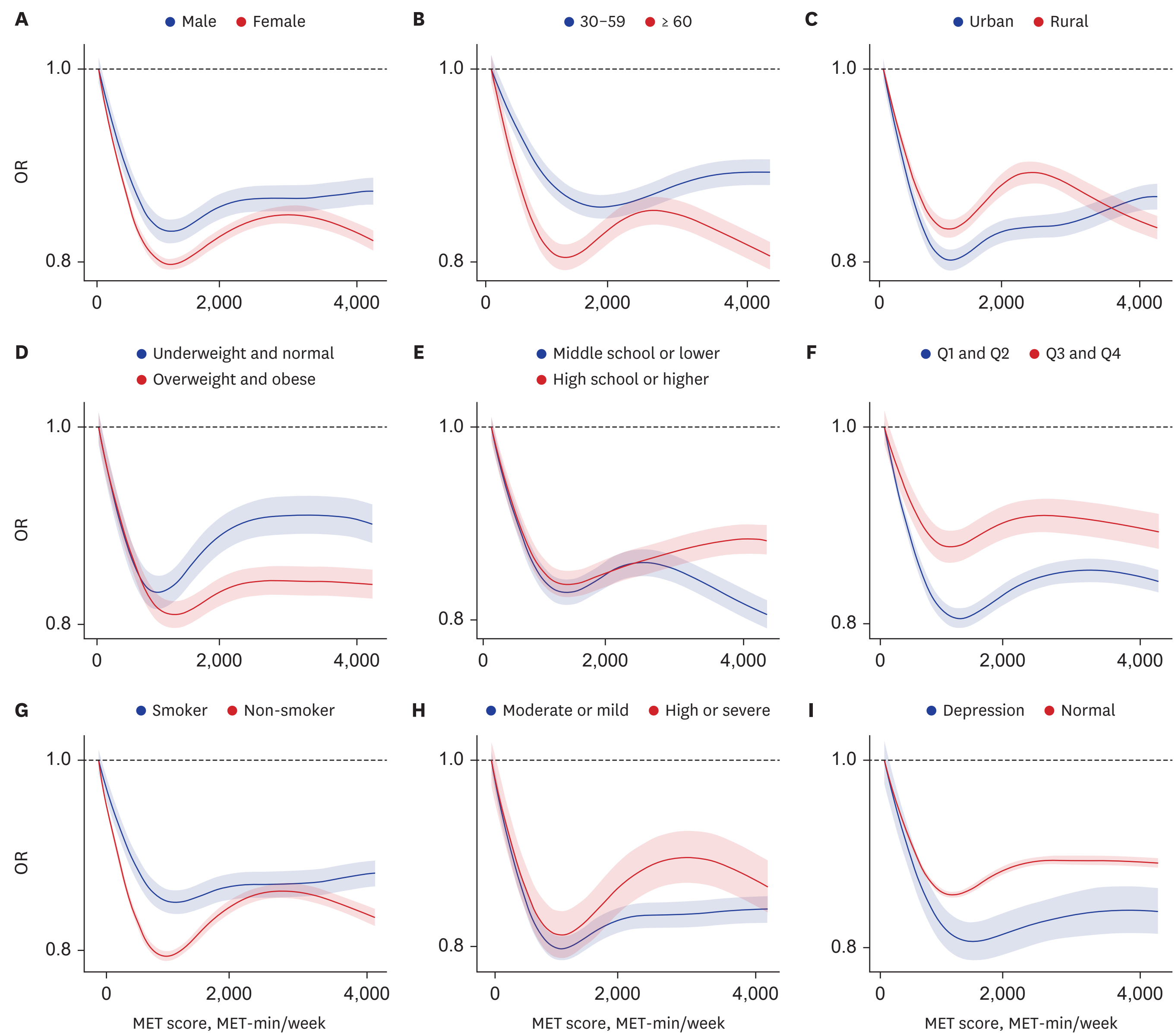

Fig. 2. Adjusted ORs of T2D as a function of MET by each sociodemographic factor based on data obtained from the Korea Community Health Survey. ORs were adjusted for all covariates except for the one used for the stratification. Lines represent smoothed conditional means with generalized additive model smoothing, with ribbons representing 95% confidence intervals. Dashed lines indicate an OR of 1. BMI was divided into four groups according to Asian-Pacific guidelines: underweight (< 18.5 kg/m^2), normal (18.5–22.9 kg/m^2), overweight (23.0–24.9 kg/m^2), and obese (≥ 25 kg/m^2). ORs of T2D as a function of MET by (**A**) sex, (**B**) age, (**C**) region of residence, (**D**) BMI group, (**E**) educational background, (**F**) household income, (**G**) smoking status, (**H**) stress status, and (**I**) depression.
OR = odds ratio, T2D = type 2 diabetes, MET = metabolic equivalent of task, BMI = body mass index,.

A cohort study of 94,739 participants from the UK Biobank indicated that the association between PA and heart failure is an inverted J-curve, presenting a risk matrix for the joint association of MPA and VPA.[20] Another cross-sectional study involving 1,237,194 U.S. adults has suggested a non-linear relationship between exercise duration and mental burden.[5] Additionally, a cohort study of 63,591 adults in England and Scotland found no significant differences in all-cause, cardiovascular disease, and cancer mortality between the "weekend warrior" and "regularly active" groups.[22] Several other studies have also shown a non-linear relationship between PA dose and disease morbidity and mortality, without differences in PA patterns.[28] These findings align with our study, although they focus on different types of

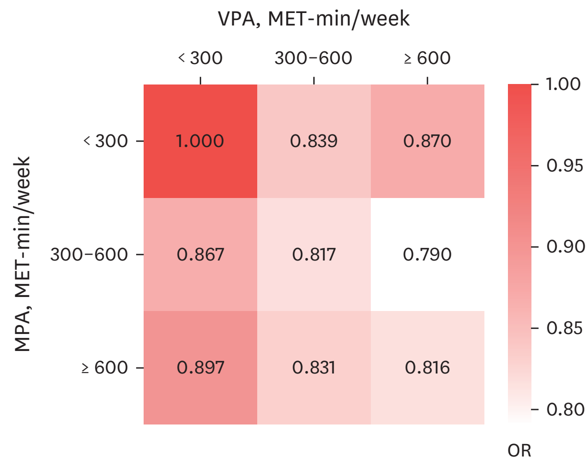

Fig. 3. Adjusted OR matrix for the joint association of MPA and VPA with type 2 diabetes. ORs were adjusted for all covariates.
VPA = vigorous-intensity physical activity, MET = metabolic equivalent of the task, MPA = moderate-intensity physical activity, OR = odds ratio.

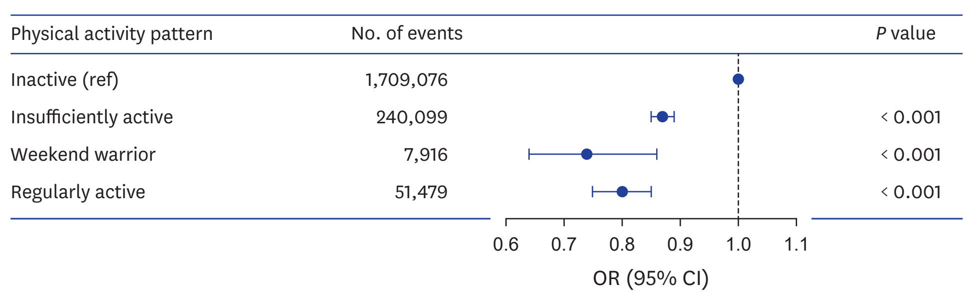

Fig. 4. Association of physical activity pattern with type 2 diabetes (results for participants with the lowest OR in metabolic equivalent of task combination). ORs were adjusted for all covariates.
OR = odds ratio, CI = confidence interval.

non-communicable diseases or health status. Thus, considering consistency across studies as per Hill's criteria, we can hypothesize that the relationship we observed between MVPA patterns and T2D prevalence might also apply to T2D incidence, despite our study being cross-sectional. What distinguishes our study is that we further analyzed the dose-response relationship of PA by sociodemographic factors, which could be utilized for future public health strategies targeting specific groups.

Contrary to the common belief that more PA is always beneficial for health, this study suggests that PA beyond a certain level may not offer additional benefits in preventing T2D. Appropriate levels of PA can help consume excess calories, improve insulin resistance caused by adipose tissue, and promote the expression of glucose transporter type 4 proteins in muscles, thereby preventing T2D.[29] However, once PA exceeds a certain threshold, it may no longer provide meaningful benefits in terms of improving insulin sensitivity or managing blood glucose. Excessive PA may stimulate the hypothalamic-pituitary-adrenal axis, promoting the secretion of cortisol, a stress hormone. Cortisol can enhance gluconeogenesis and inhibit insulin secretion from the pancreas, potentially contributing to the development of diabetes.[30] Furthermore, excessive exercise may increase oxidative stress and deplete antioxidant defense systems, which could negatively impact pancreatic β-cells that are less equipped to handle oxidative stress. The loss of oxidative homeostasis in β-cells can impair the endocrine function of the pancreas, ultimately increasing the risk of T2D.[31]

In this context, the impact of PA on the prevalence of T2D may vary depending on the amount and pattern of activity. Regular, MPA provides sufficient recovery time for muscles and energy recharging, helping to alleviate oxidative stress and effectively improve insulin sensitivity.[32] On the other hand, short, high-intensity interval training maximizes energy expenditure in a short time and can be effective for increasing muscle strength, but it may also lead to oxidative stress if exercise intensity and duration are not properly managed. With sufficient rest and appropriate intensity control, high-intensity exercise can offer similar health benefits to regular moderate exercise.[33]

Differences in PA levels between urban and rural areas further complicate this relationship. Urbanization brings significant changes in economic activity, socioeconomic conditions, occupational roles, and social, cultural, and physical environments, which can affect PA in various ways.[34] For example, in urban areas, physically demanding jobs are being replaced by sedentary or service-oriented occupations, leading to a decrease in PA. Additionally, the introduction of technologies that automate household tasks can reduce physical demands, potentially increasing the prevalence of T2D. In contrast, rural participants tend to adopt a more active lifestyle, which may be supported by community programs and urban amenities.[35] The interaction of these factors demonstrates the complex nature of urbanization's impact on PA, ultimately leading to mixed results in observations.

There are also plausible mechanisms that explain the variations observed in the relationship between PA and T2D across different sociodemographic factors. For example, older adults may have more linear relationships with T2D risk due to chronic health issues and mobility limitations, making it difficult to engage in PA. Additionally, nonsmokers are more likely to adopt healthier lifestyle habits, which may obscure the relationship between PA and T2D risk, as their lower risk may be influenced by factors other than PA levels. Furthermore, individuals with lower levels of education may have limited access to health information, resulting in low participation in either high or low levels of PA, and consequently, their diabetes risk profiles may differ from the general population. All these factors highlight the complex influence of sociodemographic variables on the relationship between PA and the prevalence of T2D, suggesting that further exploration is needed to fully understand these effects.

Our study has several strengths. Primarily, it is a nationwide study involving a large population of over 2.5 million participants, spanning 13 years from 2009 to 2022. We carefully examined the sociodemographic variables and lifestyles of all participants, adjusted the model for these variables, and investigated their PA patterns. Furthermore, the study population consists of individuals from a homogeneous South Korean ethnic and cultural background, which minimizes confounding due to participant heterogeneity. Additionally, our study challenges existing preconceptions about the relationship between exercise and T2D, suggesting a recommended total amount and pattern of MVPA that aligns with WHO guidelines. It could be utilized in shaping future public health policies.

Nevertheless, this study has several limitations due to the inherent nature of the dataset. First, because hematologic values associated with diabetes are not available in the KCHS dataset, the diagnosis of diabetes was established based on self-reported responses to the experience of diagnosis. This can lead to recall bias. Additionally, there may be potential confounding variables that were not fully accounted for or measured in the study. For example, many factors can influence the development of diabetes, including diet and genetics, but these variables may not have been fully controlled for in the study. This could affect the accuracy and reliability of the study's findings. In addition, self-reported PA measures may be subject to information bias compared to device-measured PA and may not capture unbouted PA lasting a few minutes or low-intensity PA. This can affect the accuracy and reliability of study results.[36] Second, the cross-sectional nature of the data limits our ability to establish causal relationships. However, the consistency of our findings with the aforementioned previous cohort studies provides some assurance regarding causality. Also, we performed a secondary analysis on newly diagnosed cases to enhance the reliability of our findings concerning causal relationships. Third, our data did not specify the types of PA, such as swimming or walking, leading us to focus solely on the frequency and duration of activity. To address these limitations, future longitudinal studies should utilize device-measured PA and stratify by type of activity.

Another limitation is that our study focused solely on the prevalence of T2D, constrained by the available diseases observable over a long duration in our data set. Consequently, we could not explore the effects of MET score on the management, complications, and mortality of T2D, which would necessitate further randomized controlled trials or cohort studies. Also, although we adjusted for sociodemographic factors, other unadjusted variables, such as the remaining comorbidities of participants still exist. This is critical, as populations with serious medical conditions typically have very low levels of PA.[37] We attempted to mitigate this issue by employing a large, nationwide sample to reduce the influence of confounders.

Our study provides objective evidence supporting the PA guidelines recommended by WHO and suggests an effective combination of MPA and VPA duration.[3] It also offers ideas for a time-efficient exercise strategy suitable for busy modern society. Considering the consistency with prior research, excessive PA might not offer additional benefits for preventing diabetic development compared to more moderate PA. Additionally, a significant portion of our study population engages in PA levels exceeding the optimal amount. This suggests that populations with high baseline activities, such as athletes or construction workers, may benefit from targeted education.[38] Moreover, our stratified analysis revealed that the association between PA and diabetes prevalence varies significantly among subgroups. This highlights the importance of adopting customized exercise strategies tailored to specific groups to address the heterogeneous effects of PA on diabetes prevalence.

This study provides new evidence that a higher PA level is not always associated with a lower prevalence of T2D, illustrating a non-linear relationship between MET score and the prevalence. Our study also examined the joint association of MPA and VPA using an OR matrix. Within the combination that showed the lowest OR in the matrix, the frequency of PA does not significantly influence T2D prevalence. As the specific associations between PA and T2D may differ according to sociodemographic variables, future health policies should tailor exercise strategies for each target subgroup. Further investigation through a cohort study could establish a stronger causal relationship between PA and the incidence of various NCDs, including T2D.

SUPPLEMENTARY MATERIALS

Supplementary Table 1
Adjusted OR matrix with 95% confidence intervals for the joint association of MPA and VPA with T2D

Supplementary Table 2
Association and comparison of physical activity pattern with T2D (results for participants with the lowest OR in MET combination)

Supplementary Table 3
Comparison of physical activity patterns with T2D

Supplementary Table 4
Weighted demographic characteristics of the participants with newly-diagnosed T2D and without type 2 diabetes in the Korea Community Health Survey from 2009 and 2019–2022 (N = 985,762)

Supplementary Table 5
Weighted ORs in the prevalence of newly-diagnosed T2D for each sociodemographic factor from the Korea Community Health Survey from 2009 and 2019–2022

Supplementary Table 6
Adjusted OR matrix with 95% confidence intervals for the joint association of MPA and VPA with newly-diagnosed T2D

Supplementary Table 7
Association and comparison of physical activity pattern with newly-diagnosed T2D (results for participants with the lowest OR in MET combination)

Supplementary Table 8
Comparison of physical activity patterns with newly-diagnosed T2D

Supplementary Fig. 1
The rORs of T2D as a function of MET by each sociodemographic factor based on data obtained from the Korea Community Health Survey. Ribbons with line representing 95% confidence intervals. Dashed lines indicate a rOR of 1. BMI was divided into four groups according to Asian-Pacific guidelines: underweight (< 18.5 kg/m^2), normal (18.5–22.9 kg/m^2), overweight (23.0–24.9 kg/m^2), and obese (≥ 25.0 kg/m^2).

Supplementary Fig. 2
Adjusted ORs of newly-diagnosed T2D as a function of MET based on data obtained from the Korea Community Health Survey. ORs were adjusted for all covariates. The line represents smoothed conditional means with generalized additive model smoothing, with ribbons representing 95% confidence intervals. The dashed line indicates an OR of 1. The frequency of 0 MET-min/week was not shown in the histogram.

Supplementary Fig. 3

Adjusted ORs of newly- diagnosed T2D as a function of MET by each sociodemographic factor based on data obtained from the Korea Community Health Survey. ORs were adjusted for all covariates except for the one used for the stratification. Lines represent smoothed conditional means with generalized additive model smoothing, with ribbons representing 95% confidence intervals. Dashed lines indicate an OR of 1. BMI was divided into four groups according to Asian-Pacific guidelines: underweight (< 18.5 kg/m^2), normal (18.5–22.9 kg/m^2), overweight (23.0–24.9 kg/m^2), and obese (≥ 25 kg/m^2). ORs of type 2 diabetes as a function of MET by (**A**) sex, (**B**) age, (**C**) region of residence, (**D**) BMI group, (**E**) educational background, (**F**) household income, (**G**) smoking status, (**H**) stress status, and (**I**) depression.

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