Cardiovascular Diabetology

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Accelerometer-derived "weekend warrior" physical activity pattern and incident type 2 diabetes

Zhi Cao[1,2], Jiahao Min[2] and Chenjie Xu[2*]

Abstract

Background The guidelines provided by the World Health Organization (WHO) recommend a minimum of 150 min/week of moderate-to-vigorous physical activity (MVPA) for optimal overall health benefits. However, it remains unclear whether there are differential effects on the risk of incident type 2 diabetes (T2D) between concentrated and evenly distributed physical activity (PA) patterns. We aimed to investigate the associations of accelerometer-derived weekend warrior and regularly active pattern with risk of T2D.

Methods A total of 84,656 general participants from the UK Biobank with validated accelerometry data and free of T2D was included. Data on PA was collected using the Axivity AX3 wrist-based triaxial accelerometer worn for one week. Participants were categorized into three PA patterns: inactive (< 150 min/week of MVPA), weekend warrior (≥ 150 min/week with ≥ 50% of total MVPA occurring within 1–2 days), and regularly active (≥ 150 min/week but not meeting weekend warrior criteria).

Results During a median follow-up of 8.4 years, 2464 cases of T2D were documented. In multivariable-adjusted models, the weekend warrior pattern (hazard ratio [HR] 0.75; 95% confidence interval [CI] 0.67–0.84) and the regularly active pattern (HR 0.80, 95% CI 0.69–0.94) exhibited a comparable lower risk of T2D compared to physically inactive participants. When stratified by genetic risk score (PRS) of T2D, the weekend warrior pattern was associated with T2D in the higher PRS group (HR 0.78, 95% CI 0.67–0.91), intermediate PRS group (HR 0.78, 95% CI 0.62–0.97) and lowest PRS group (HR 0.59, 95% CI 0.43–0.80).

Conclusions Engaging in the weekend warrior pattern is associated with a similarly lower risk of T2D to the regularly active pattern, even among individuals with high genetic risk. These findings highlight the weekend warrior pattern as a significant and flexible alternative in preventive intervention strategies for T2D, particularly for those unable to maintain daily activity routines.

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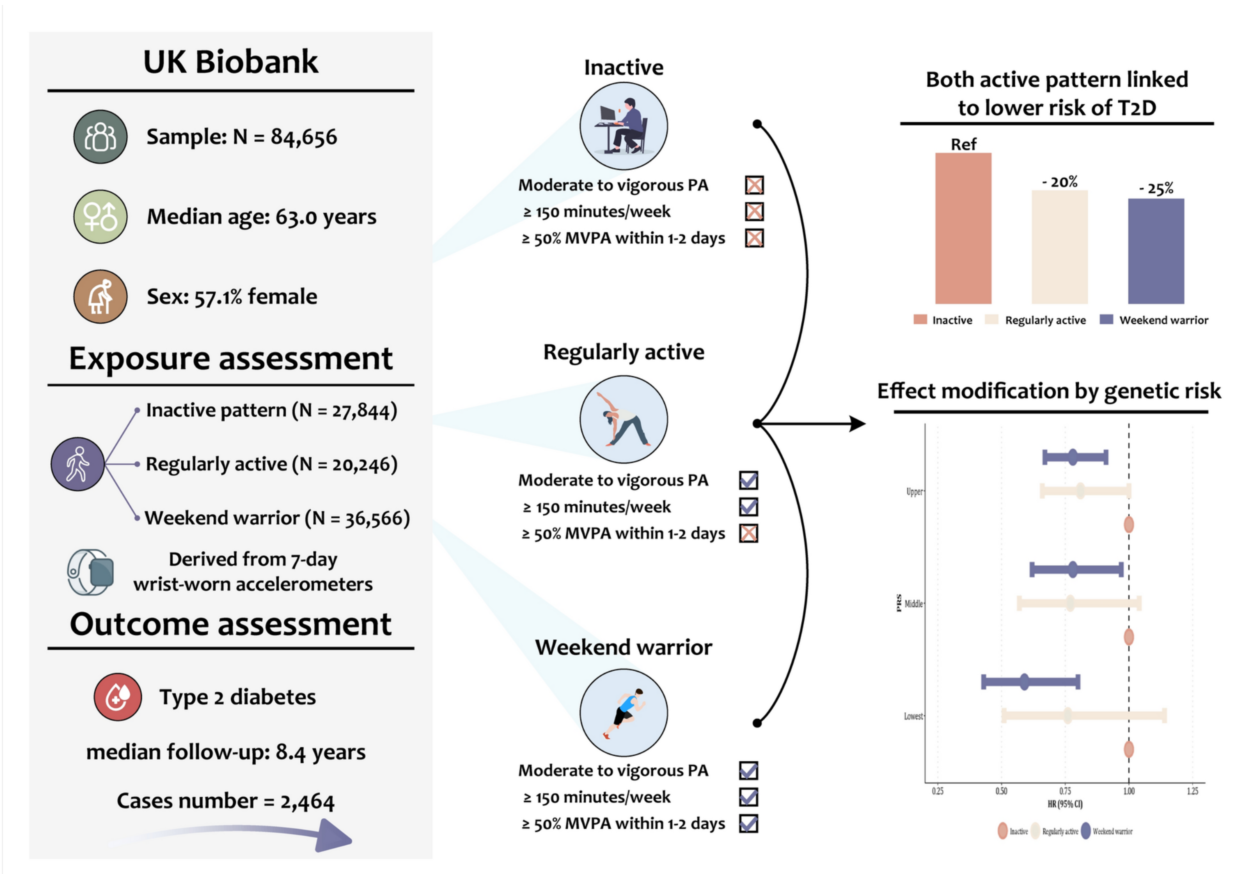
Graphical abstract



Keywords Physical activity, Weekend warrior, Type 2 diabetes

Background

Diabetes has become a rising epidemic in the last century, with an estimated 537 million adults affected in 2021 and a projected increase to 783 million by 2045 [1, 2]. Type 2 diabetes (T2D) is a multifactorial disease influenced by genetic susceptibility, environmental factors, and lifestyle choices, particularly for physical activity (PA) [1]. It is well documented that adequate PA is significantly associated with a lower risk of T2D [3]. The World Health Organization (WHO) guidelines recommended all individuals engaging in 150–300 min of moderate-intensity PA (MPA), 75–150 min of vigorous-intensity PA (VPA), or an equivalent combination of both intensities per week [4]. However, it remains unclear whether the same amount of PA spread over more days or concentrated into 1 to 2 days per week (not necessarily consecutive days, often referred to as the "weekend warrior" pattern [5]) provides equivalent benefits or differs for incident T2D, which is important for individuals striving to meet recommended levels of PA during their constrained leisure time in modern life.

Given that performing leisure-time physical activity during the weekend may be a more convenient option for modern individuals [6], the weekend warrior pattern has emerged as an increasingly popular strategy of behavior engagement, which enables individuals to freely accumulate the recommended weekly duration of PA within a week. Previous findings from several prospective cohort studies conducted using the US National Health Interview Survey, UK Biobank, and Mexico City Prospective Study have consistently demonstrated that the weekend warrior pattern was associated with reduced risks of all-cause and cause-specific mortality [7, 8], cardiovascular events [5], Parkinson's disease [9] and brain health [10], when compared to regularly active PA. Despite the evidence regarding the associations between the weekend warrior pattern and the cardiometabolic conditions from the recently published study [11], the health benefits of the weekend warrior pattern against T2D in adults with obesity or high genetic risk remain unclear. Meanwhile, prior studies were limited by self-reported PA data, which is prone to recall bias and might not accurately reflect actual PA levels.

To address the research gap, the objective of this study was to assess and compare the associations of the weekend warrior and regularly active PA patterns defined as wrist-based accelerometers with the risk of incident T2D in a prospective cohort from the UK Biobank. Furthermore, we also investigated whether the effect of the weekend warrior pattern on the risk of T2D differed from body mass index (BMI) and genetic risk.

Methods

Study population

The data for this study was obtained from the UK Biobank, which recruited over 500,000 participants aged 37–73 years. All participants provided informed consent for linkage to the UK National Health Service (NHS) and resided near one of the 22 recruitment centers during the period from 2006 to 2010. Participants underwent a range of interviews, questionnaire, and physical assessments to gather information on socio-demographic factors, lifestyles, and health status [12]. A subset of approximately 240,000 participants were invited via email to participate in an accelerometer-based study conducted between May 2013 and December 2015. The response rate for this invitation was recorded at around 44%. Accelerometer devices were dispatched to a total of 106,053 participants, from whom data was successfully collected from a group consisting of 103,666 individuals. All UK Biobank participants provided informed consent for this study under protocols approved by NHS National Research Ethics Service (NW/0382), in accordance with the Declaration of Helsinki.

After excluding participants who withdrew from the UK Biobank study (n = 6), had poorly calibrated accelerometer data (n = 11), insufficient wear time (< three days of data or no wear data in each 1-h period of the 24-h cycle; n = 6984), exhibited unrealistically high acceleration values (mean acceleration values > 100 mg; n = 13), unidentified daily accelerometer moderate-to-vigorous physical activity (MVPA) data (n = 1159), missing information on covariates (n = 4048), encompassed less than a full week of acceleration data (n = 3862), and prevalent T2D at baseline (n = 2927), a total of 84,656 participants were finally included in the primary analysis. The flowchart of this study design is provided in Supplementary file 1: Fig. 1.

Accelerometer-measured physical activity patterns

Participants invited to the accelerometry study were instructed to wear Axivity AX3 (Newcastle upon Tyne, UK) triaxial accelerometers on their dominant wrist for consecutive seven days [13]. The device recorded acceleration at a frequency of 100 Hz, with a dynamic range of ± 8 g. More details about data collection and processing can be found elsewhere [13]. The analysis utilized a previously published machine learning algorithm to accurately classify MVPA from other movement behaviors, such as light-intensity PA, sedentary behaviors, and sleep based on data collected from wrist-worn accelerometers. The accuracy of this machine learning method has been validated in a UK-based sample with an average accuracy of 88% and Cohen's kappa coefficient of 0.80 [14].

The duration of MVPA in this study was determined by calculating the daily proportion of time spent engaging in MVPA (Field ID: 40045). Participants were initially categorized into two groups based on the WHO PA guidelines (MVPA ≥ 150 min/week): inactive (below the MVPA threshold) and physically active (meeting the MVPA threshold). Within the physically active group, further stratification was done based on the highest volume of PA over a two-day period, which did not necessarily have to be during weekends or on consecutive days. This resulted in two groups: the weekend warrior group (where at least 50% of total MVPA occurred within 1–2 days) and the regularly active group (where at least 50% of total MVPA was distributed over more than 2 days). It's worth noting that conventional PA recommendations primarily rely on self-reported PA data, which may potentially differ from measurements obtained through devices. We therefore explored multiple thresholds to define the physically active group, including 100 min/week, 125 min/week, and 175 min/week of MVPA in the primary analysis.

Type 2 diabetes

The primary outcome of this study was the incident T2D. T2D events during the follow-up was ascertained through an integration of multiple data sources, including self-reported, primary care, death register, and hospital admissions, (England and Wales: Health Episode Statistics; Scotland: Scottish Morbidity Records). Records were in accordance with 10th Revision of the International Classification of Diseases (ICD-10) code E11, and were described as 'noninsulin dependent diabetes' in the UK Biobank records. Follow-up of this study was censored at the date of incident T2D, death, loss to follow-up or the end of follow-up (May 1, 2023), whichever occurred first.

Covariates

Data on the possible covariates were selected based on existing knowledge and literature regarding the association between PA and T2D, including age at PA data collection, sex, ethnicity, Townsend deprivation index

(TDI), education attainment, smoking status, alcohol intake frequency, diet quality, sleep quality, history of hypertension, season and wear duration recorded by the accelerometers, BMI, and total volume of MVPA. TDI was determined based on residential postcode and used aggregated data on unemployment, car and home ownership, and household overcrowding, which represent the level of deprivation with higher values indicating higher deprivation [15]. Information on age (years), sex (female and male), ethnicity (White and non-White), education attainment (college/university degree and others), smoking status (never, former, and current), alcohol intake frequency (daily or almost daily, three or four times a week, once or twice a week, one to three times a month, special occasions only, and never) was obtained from touchscreen questionnaires or verbal interviews. Diet quality was assessed using a dietary score based on the frequency of consuming fruits, vegetables, fish, processed meat, unprocessed red meat, whole grains, and refined grains, with higher scores indicating a healthier diet quality [16]. Similarly, sleep quality was evaluated using sleep scores ranging from 0 to 5 that incorporated five sleep factors: chronotype, sleep duration, insomnia, snoring, and excessive daytime sleepiness [17]. History of hypertension was categorized into yes and no, obtaining from self-reported questionnaires. BMI was calculated as the weight in kilograms divided by the square of the height in meters, which was obtained by training nurses. The selection of total MVPA volume took into account the influence of PA volume on PA pattern. To mitigate temporal bias due to the temporal fluctuations of certain covariates (such as smoking status, alcohol intake frequency, diet quality, sleep quality, and BMI), the variables were recorded at the time point closest to the accelerometry measurement.

Statistical analysis

Baseline characteristics of participants by different PA patterns were summarized as mean and standard deviation (SD) for continuous variables, and number and percentage for categorical variables.

Cox proportional hazards regression models were used to examine the associations between PA patterns and T2D, hazard ratios (HRs) and their 95% confidence intervals (CIs) were reported. Schoenfeld residuals were used to verify the assumption of proportional hazards for Cox models, and no violation was detected. Two models were developed, each adjusting for different covariates to evaluate the independent association of PA patterns. Base model was adjusted for age, sex, ethnicity, TDI, education attainment, smoking status, alcohol intake frequency, diet scores, sleep scores, history of hypertension, duration of wear, season of wear, and total MVPA volume. We further adjusted for BMI given its role in etiology of T2D.

We further evaluated effect modification by BMI due to its potential effect on the association between PA pattern and T2D. The interaction was detected by Wald test. Furthermore, subgroup analyses were performed according to age (≤ 65 and > 65 years), sex (female and male), ethnicity (White and others), TDI (least deprived and most deprived), education attainment (below college, college or above), smoking status (never, former, and current), alcohol intake frequency (low, moderate, and high), diet scores (< 4 and ≥ 4), sleep scores (< 3 and ≥ 3), history of hypertension (no and yes), and the polygenetic risk score (PRS) (lowest, middle, upper tertiles). The PRS for T2D was sourced from a previous study (https://biobank.ndph.ox.ac.uk/showcase/refer.cgi?id=5202), which validated the score's power for individual risk stratification and its predictive performance [18].

A series of sensitivity analyses were conducted to assess the robustness of the primary findings. First, we further accounted for participants' occupational characteristics, as employed individuals may exhibit a higher inclination towards adopting the weekend warrior pattern. Second, we incorporated sedentary time derived from accelerometers into the models to consider its potential impact on both exercise patterns and T2D. Third, missing covariate values were addressed using chained multiple imputation. Fourth, alternative definitions of the weekend warrior pattern were utilized, including accumulating $\geq 75\%$ of total MVPA over 1–2 days, $\geq 50\%$ of total MVPA over 1–2 consecutive days, and $\geq 50\%$ of total MVPA over 1–2 weekend days, to examine whether there would be any change in the association between being a weekend warrior and T2D. Fifth, we excluded individuals who occurred T2D within the first 1, 3 and 5 years of follow-up to mitigate reverse causation. Sixth, we separated individuals in the regularly active group into two groups based on their total volume of MVPA and repeated the main analysis. Finally, considering their potential impact on PA performance ability, some health conditions such as myocardial infarction, asthma, chronic obstructive pulmonary disease, chronic kidney disease, arthritis, and motor neuron disease were additionally adjusted for in our analyses.

All the analyses were conducted by using STATA V.16 statistical software (Stata Corp) and R software (version 4.1.3). The statistical significance was set as $P < 0.05$ (two-sided test).

Equity, diversity, and inclusion statement

All participants with valid accelerometer-measured physical activity data were included in the study, and 57.1% participants were female. Although only one woman is included in the authorship team, the lead researcher is a woman and we include authors from a variety of career stages and clinical disciplines.

Results

General characteristics of the study population

The primary analysis included a total of 84,656 participants, with a median age of 63 years, and 57.1% participants were female (Table 1). The participants were categorized into three patterns: inactive PA pattern, accounting for 32.9% (n = 27,844); regularly active pattern, accounting for 23.9% (n = 20,246); and the weekend warrior pattern, accounting for 43.2% (n = 36,566). Participants in the weekend warrior group tended to be White, non-smokers, had a higher frequency of alcohol consumption, and engaged in less volume of weekly MVPA compared to participants with a regularly active pattern. The median MVPA volume in the regularly active group (432 min/week) was substantially greater than that of the weekend warrior group (288 min/week), indicating that individuals with regularly active habits were more likely to achieve higher volumes of physical activity. The distribution of daily MVPA depicted in Supplementary file 1: Fig. 2 revealed that the weekend warrior exhibited significantly higher levels of MVPA on their most active 1–2 days compared to the remaining 5 days. In the contrast, participants in the regularly active group exhibited a more evenly distributed pattern of MVPA.

Table 1 Baseline characteristics of participants according to accelerometer-derived physical activity pattern

Baseline characteristics	Total (n = 84,656)	Physical activity pattern, no. (%) of participants		
		Inactive (n = 27,844)	Regularly active (n = 20,246)	Weekend warrior (n = 36,566)
Age, median (IQR), years	63.0 (56.0, 68.0)	64.0 (57.0, 69.0)	61.0 (54.0, 67.0)	63.0 (56.0, 68.0)
Sex				
Female	48,313 (57.1)	18,994 (68.2)	10,419 (51.5)	18,900 (51.7)
Male	36,343 (42.9)	8,850 (31.8)	9,827 (48.5)	17,666 (48.3)
Ethnicity				
White	82,270 (97.2)	26,969 (96.9)	19,619 (96.9)	35,682 (97.6)
Non-white	2386 (2.8)	875 (3.1)	627 (3.1)	884 (2.4)
BMI, median (IQR), kg/m^2	25.9 (23.5, 28.8)	27.0 (24.2, 30.4)	25.2 (22.9, 27.8)	25.6 (23.3, 28.2)
Education attainment				
Other	46,853 (55.3)	17,815 (64.0)	9981 (49.3)	19,057 (52.1)
College or university degree	37,803 (44.7)	10,029 (36.0)	10,265 (50.7)	17,509 (47.9)
TDI, median (IQR)	− 2.5 (− 3.8, − 0.3)	− 2.5 (− 3.9, − 0.4)	− 2.1 (− 3.6, 0.5)	− 2.6 (− 3.9, − 0.6)
Smoking status				
Never	49,267 (58.2)	15,640 (56.2)	11,800 (58.3)	21,827 (59.7)
Former	30,150 (35.6)	9997 (35.9)	7272 (35.9)	12,881 (35.2)
Current	5239 (6.2)	2207 (7.9)	1174 (5.8)	1858 (5.1)
Alcohol intake frequency				
Daily or almost daily	18,746 (22.1)	5404 (19.4)	4802 (23.7)	8540 (23.4)
Three or four times a week	22,362 (26.4)	6220 (22.3)	5632 (27.8)	10,510 (28.7)
Once or twice a week	21,334 (25.2)	7068 (25.4)	4919 (24.3)	9347 (25.6)
One to three times a month	9247 (10.9)	3595 (12.9)	2026 (10.0)	3626 (9.9)
Special occasions only	8123 (9.6)	3528 (12.7)	1756 (8.7)	2839 (7.8)
Never	4844 (5.7)	2029 (7.3)	1111 (5.5)	1704 (4.7)
Diet quality, median (IQR)	4.0 (3.0, 5.0)	4.0 (3.0, 5.0)	4.0 (3.0, 5.0)	4.0 (3.0, 5.0)
Sleep quality, median (IQR)	3.0 (2.0, 4.0)	3.0 (2.0, 4.0)	3.0 (3.0, 4.0)	3.0 (3.0, 4.0)
Weekly MVPA volume, median (IQR)	230.4 (115.2, 403.2)	72.0 (43.2, 115.2)	432.0 (302.4, 604.8)	288.0 (216.0, 432.0)
History of hypertension				
No	67,005 (79.1)	20,744 (74.5)	16,647 (82.2)	29,614 (81.0)
Yes	17,651 (20.9)	7100 (25.5)	3599 (17.8)	6952 (19.0)
Duration of wear, median (IQR), days	6.9 (6.7, 7.0)	6.9 (6.7, 7.0)	6.9 (6.7, 7.0)	6.9 (6.8, 7.0)
Season of wear				
Spring	19,832 (23.4)	5858 (21.0)	4923 (24.3)	9051 (24.8)
Summer	22,696 (26.8)	6724 (24.1)	5524 (27.3)	10,448 (28.6)
Autumn	23,479 (27.7)	7907 (28.4)	5615 (27.7)	9957 (27.2)
Winter	18,649 (22.0)	7355 (26.4)	4184 (20.7)	7110 (19.4)

Diet quality was reflected in a diet score based on the frequency of consumption of fruits, vegetables, fish, processed meat, unprocessed red meat, whole grains, and refined grains, with higher scores indicating a healthier diet quality. Sleep quality assessment encompassed chronotype, sleep duration, insomnia, snoring, and excessive daytime sleepiness, utilizing a scoring system ranging from 0 (poorer) to 5 (healthier)

IQR Interquartile Range, *MVPA* moderate-to-vigorous intensity physical activity, *BMI* body mass index, *TDI* Townsend deprivation index, *SD* standard deviation

Table 2 Association between accelerometer-derived physical activity pattern and risk of incident T2D after adjusting for a wide range of covariates

Activity patterns	Cases/total	Incidence per 1000 person-year (95% CI)	HR (95% CI)	
			Base model	+ BMI†
Inactive	1253/27,844	5.56 (5.26, 5.88)	1.00 (Ref)	1.00 (Ref)
Regularly active	408/20,246	2.43 (2.20, 2.67)	0.80 (0.69, 0.94)	0.91 (0.78, 1.06)
Weekend warrior	803/36,566	2.66 (2.48, 2.85)	0.75 (0.67, 0.84)	0.86 (0.76, 0.96)

Basic model: adjusted for age, sex ethnicity, TDI, education attainment, smoking status, alcohol intake frequency, diet quality, sleep quality, history of hypertension, duration of wear, the season of wear, and total volume of MVPA

T2D type 2 diabetes, *HR* hazard ratio, *CI* confidence interval, *Ref* reference, *BMI* body mass index, *PRS* polygenic risk score, *TDI* Townsend deprivation index

†Additionally adjusted for BMI on the basis of the base model

Table 3 Associations between physical activity pattern and type 2 diabetes using different activity thresholds of MVPA per week

Activity pattern	Case/total	Incidence per 1000 person-year (95% CI)	HR (95% CI)
Active group defined as ≥ 100 min/week of MVPA			
Inactive	886/16,958	6.51 (6.09, 6.95)	1.00 (Ref)
Regularly active	441/21,082	2.52 (2.30, 2.77)	0.73 (0.63, 0.85)
Weekend warrior	1137/46,616	2.96 (2.79, 3.13)	0.70 (0.63, 0.78)
Active group defined as ≥ 125 min/week of MVPA			
Inactive	1109/22,483	6.12 (5.77, 6.49)	1.00 (Ref)
Regularly active	425/20,701	2.47 (2.25, 2.72)	0.71 (0.61, 0.82)
Weekend warrior	930/41,472	2.71 (2.54, 2.89)	0.66 (0.59, 0.74)
Active group defined as ≥ 175 min/week of MVPA			
Inactive	1392/33,012	5.20 (4.93, 5.48)	1.00 (Ref)
Regularly active	380/19,452	2.35 (2.13, 2.60)	0.87 (0.75, 1.03)
Weekend warrior	692/32,192	2.60 (2.41, 2.80)	0.83 (0.73, 0.93)

All analyses were adjusted for age, sex ethnicity, TDI, education attainment, smoking status, alcohol intake frequency, diet quality, sleep quality, history of hypertension, duration of wear, the season of wear, and total MVPA volume

Inactive was defined as the threshold of MVPA/week (100, 125, and 175 min/week of MVPA)

Weekend warrior was defined as at or above the MVPA threshold and had ≥ 50% of total MVPA over 1–2 days

MVPA moderate-to-vigorous physical activity, *HR* hazard ratio, *CI* confidence interval, *Ref* reference

Associations between physical activity patterns and the risk of type 2 diabetes

During a median follow-up pf 8.4 years (interquartile range 7.9–8.9), 2464 cases of T2D were diagnosed. The incidence rate of T2D per 1000 person-year was 5.56 (95% CI 5.26–5.88) for the inactive pattern, 2.43 (95% CI 2.20–2.67) for regularly active pattern, and 2.66 (95% CI 2.48–2.85) for the weekend warrior pattern.

In the multivariable-adjusted model, we found that the regularly active pattern and the weekend warrior pattern were associated with a similarly lower risk of T2D compared to the inactive pattern, with HRs of 0.80 (95% CI 0.69–0.94) and 0.75 (95% CI 0.67–0.84), respectively (Table 2). The risk of T2D was slightly attenuated after adjusting for BMI (HR 0.91, 95% CI 0.78–1.06 for the regularly active pattern; HR 0.86, 95% CI 0.76–0.96 for the weekend warrior pattern).

Active PA patterns at various thresholds and type 2 diabetes

To assess the robustness of our primary findings, we conducted an additional analysis using alternative definitions of the physically active group based on the distribution of weekly MVPA across all participants. Specifically, we categorized participants as active if their weekly MVPA was at or above the level of 100, 125, and 175 min, respectively (Table 3). When we defined the active PA pattern as meeting at least 100 min/week, the findings consistently showed that the weekend warrior pattern (HR 0.70; 95% CI 0.63–0.78) and the regularly active pattern (HR 0.73; 95% CI 0.63–0.85) presented a similarly lower risk of T2D compared to the inactive pattern. At the threshold of 125 min/week of MVPA, both the weekend warrior pattern (HR 0.66; 95% CI 0.59–0.74) and the regularly active pattern (HR 0.71; 95% CI 0.61–0.82) exhibited a lower T2D risk than the inactive PA pattern. Finally, at the threshold of 175 min of weekly MVPA, similar risk reductions were observed for the weekend warrior pattern.

Subgroup analyses

Considering the substantial impact of BMI on the incidence of T2D, we further investigated the association between the weekend warrior pattern and risk of incident T2D stratified by BMI (Fig. 1). We found that weekend warrior pattern was consistently associated with lower risk of T2D in the normal weight (HR 0.60, 95% CI 0.44–0.82), and marginally associated with lower risk of T2D in the obesity group (HR 0.86, 95% CI 0.72–1.02), despite there was no significant difference between normal weight and obesity group against T2D (*P* for interaction = 0.30) (Supplementary file 1: Table 1).When the analyses were stratified by sex, TDI, education, smoking status, alcohol consumption, dietary pattern, sleep quality, and hypertension status, no significant interactions were detected for PA pattern and risk of T2D (all *P* for interaction > 0.05). These findings indicate that individuals across diverse sexes, education levels, and lifestyle factors may experience a comparable benefit from the weekend warrior pattern, highlighting the

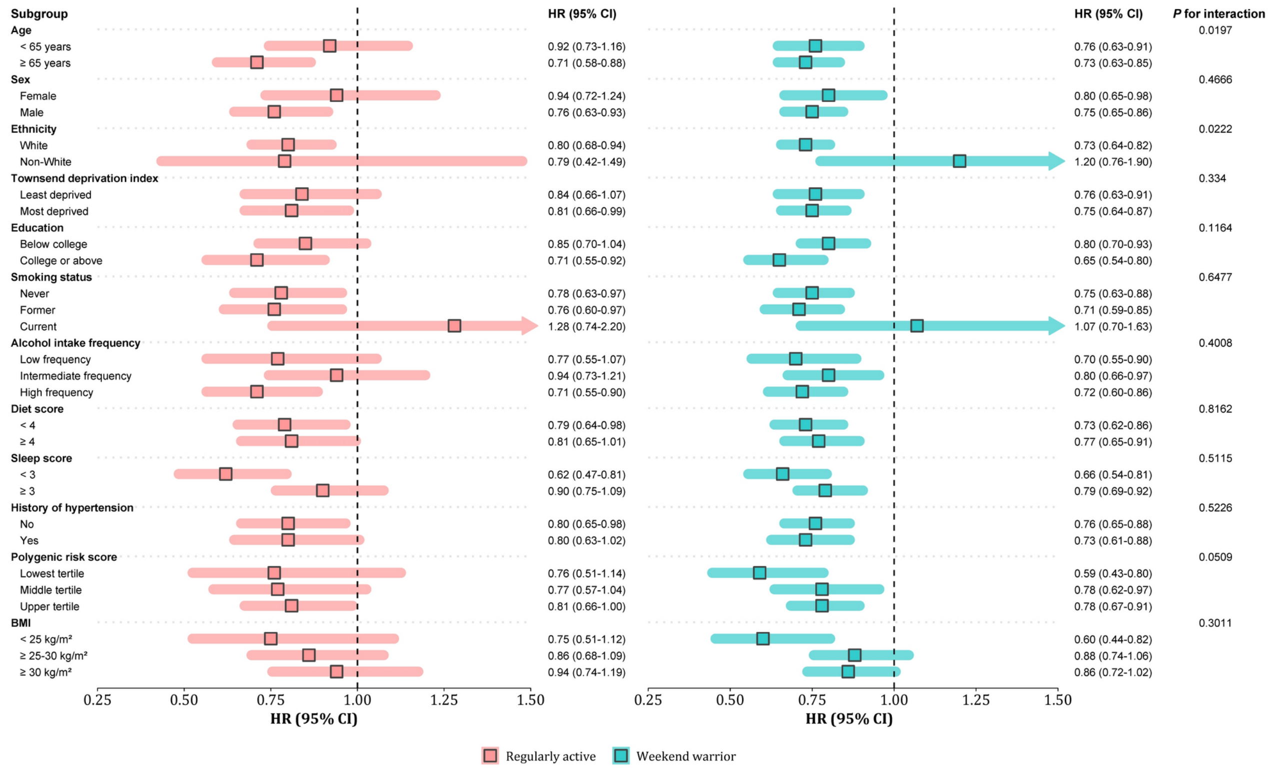


Fig. 1 Subgroup analyses for the association between accelerometer-derived physical activity pattern and risk of incident T2D. *T2D* type 2 diabetes, *HR* hazard ratio, *CI* confidence interval, *PRS* polygenic risk score, *TDI* Townsend deprivation index. All analyses were adjusted for age, sex ethnicity, Townsend deprivation index, education attainment, smoking status, alcohol intake frequency, diet quality, sleep quality, history of hypertension, duration of wear, the season of wear, and total MVPA volume. Interaction term was tested by Wald test

potential public health value of this flexible approach to physical activity. However, it was important to note that the interaction term between PA patterns and PRS for T2D approached statistical significance (*P* for interaction = 0.05), which suggested a potential interaction effect. Stratified analyses by PRS tertiles revealed a trend towards a stronger protective effect of the weekend warrior pattern among individuals with lower genetic risk compared to those with higher genetic risk (HR 0.59, 95% CI 0.43–0.80 for lowest tertile; HR 0.78, 95% CI 0.67–0.91 for highest tertile). Besides, there were significantly statistical interactions observed between PA patterns and age in relation to T2D (*P* for interaction < 0.05). The association between the weekend warrior pattern and T2D was stronger among participants with aged ≥ 65 years (HR 0.73, 95% CI 0.63–0.85) than younger participants (HR 0.76, 95% CI 0.63–0.91) (*P* for interaction = 0.02).

Sensitivity analyses

The sensitivity analyses remained largely consistent with the main analyses when alternative definitions of the weekend warrior pattern were employed in the association with T2D risk (Supplementary file 1: Table 2), missing covariates data were estimated with use of multiple imputations with chained equations (Supplementary file 1: Table 3), further adjusting for occupation or sedentary time (Supplementary file 1: Tables 4 and 5), excluding participants who developed T2D within the first 1 year, 3 years or 5 years of follow-up (Supplementary file 1:Table 6), regularly active group was separated into two groups (Supplementary file 1: Table 7), and additionally adjusting for certain health conditions that may influence the ability to engage in PA (Supplementary file 1: Table 8). These analyses collectively confirmed the comparable risk reduction in T2D for the regularly active and the weekend warrior pattern.

Discussion

In this large population-based cohort study utilizing accelerometer measurements, we found that the weekend warrior pattern and the regularly active pattern were associated with similar reductions in risk of incident T2D. The findings remained consistent after adjusting for BMI or total volume of MVPA per week. The study highlighted that the exercise choices between concentrated PA over 1–2 days and evenly distributed PA throughout the week were equally effective in preventing the future T2D. Moreover, these findings were more broadly applicable to diverse populations across genetic risk. Taken together, our findings provide new insights into the modifiable risk factors for prevention and intervention of T2D.

To our knowledge, only several prospective studies have examined the associations between accelerometer-measured weekend warrior pattern and medical conditions, mainly focusing on cardiovascular diseases [5], Parkinson's disease [9], and brain health [10]. These studies have concluded that MVPA concentrated in one or two sessions per week or MVPA spread over multiple sessions per week may yield similar benefits in relation to the aforementioned outcomes, such information is not yet available for T2D. Given the limited evidence, our study advances prior research by capturing the duration and frequency of MVPA from the largest accelerometer cohort study, revealing the similar benefits of both the weekend warrior and regularly active patterns for reducing the risk of incident T2D. Our findings provided encouraging news for individuals with busy lifestyles who are unable to meet recommended PA levels by engaging in activity spread across the week. Given that performing leisure-time PA during the weekend may be a more available alternative for these people, the weekend warrior pattern is substantial for achieving the recommended levels of PA and serves as a way to help people benefit from preventing diabetes. However, a recent study has suggested that the weekend warrior pattern may be associated with a higher risk of musculoskeletal conditions, injuries, and dermatologic conditions [19]. Moreover, several review studies have raised concerns that the weekend warrior participants may experience an increased risk of shoulder, elbow, and ankle injuries [20, 21]. Therefore, for individuals inclined to adopt the weekend warrior pattern, seeking consultation with healthcare professionals may be an appropriate option. On balance, our study supplements important evidence for the development of exercise guidelines aimed at preventing T2D.

Most of the findings for the PA recommendations for general populations were derived from self-reported PA data, which may be susceptible to misclassification. The heterogeneity in PA questionnaires utilized across studies could potentially lead to incomparable results. In this accelerometry-based study, the weekend warriors constituted the largest segment of the total population (36,566 out of 84,656 [43.2%]), a proportion markedly higher than that observed in previous studies based on self-reported data (9992 out of 350,978 [3.0%] [7]; 11,981 out of 15,4882 [7.4%] [8]). Conversely, previous research utilizing accelerometer data from the NHANES study revealed that 32.3% of participants were identified as weekend warriors, which further supported our findings [22]. The notable discrepancy suggested a higher level of accuracy in evaluating PA patterns using device-measured data as compared to self-reported data. More importantly, our finding indicates that the weekend warrior pattern is more common than other activity patterns examined, emphasizing its convenience and feasibility within the context of busy and fast-paced lifestyles. Thus, future studies should investigate the comprehensive impact of this concentrated physical activity pattern across a wide range of health outcomes to provide further evidence for its potential inclusion in physical activity guidelines.

The observed reductions in T2D risk associated with both weekend warrior and regularly active physical activity patterns likely stem from a combination of interrelated physiological mechanisms. For example, an animal study exploring the effects of short bouts and "weekend warrior"-type exercise modalities demonstrated that both exercise patterns similarly impact metabolic parameters relevant to T2D, such as reducing inflammation, oxidative stress, and mitochondrial damage, provided the total duration of exercise remains consistent [23]. Moreover, substantial evidence indicates that exercise can improve glucose and lipid metabolism, enhance skeletal muscle glucose transport, and increase insulin sensitivity—all key factors in the pathogenesis of T2D [24]. Furthermore, a recent animal study demonstrated that, compared with sedentary T2D rats, all exercise groups, including continuous, short bouts, and weekend warrior exercise, exhibited significant improvement in blood glucose level, insulin sensitivity, capillary density in heart tissue, which may explain the findings of our study [25].

Limitations

The strengths of this study included its large-scale sample size, prospective design, multiple sources of T2D diagnosis, objective-measured PA data, and comprehensive sensitivity analyses. More importantly, our study is the first to investigate the association between the weekend warrior pattern with risk of T2D. There are still some limitations to be noticed. First, the presence of selection bias is inevitable due to the low response rate (5.5%) of the UK Biobank, self-selection into the accelerometry sub-study, as well as the predominantly White ethnicity of participants. Participants included in the primary analyses were generally younger, exhibited healthier lifestyles, and had a lower prevalence of disease (Supplementary file 1: Table 9). Given the selection bias cannot be entirely ruled out, the potential impact on the generalizability of our conclusion is likely limited. The available evidence, however, indicated that the lack of representatives does not compromise the validity and generalization of exposure-disease assessments [26]. Second, the representatives of a 7-day accelerometer measurement for longer-term PA behaviors remain uncertain [27]. Nevertheless, a previous validation study showed a strong correlation between measurements taken over a period of 7 days and PA levels observed over durations as long as 3.7 years [28]. Third, the wrist-worn accelerometer, although validated for measuring PA at various levels in free-living conditions to detect MVPA, may not fully capture certain activities [29] and not allow for differentiation of activity types. This means we cannot ascertain if potential variations in the type of PA undertaken on weekends versus weekdays might influence our findings. Forth, the definition of the weekend warrior remained subjective in this study despite the utilization of multiple thresholds and alternative definitions to categorize participants into different PA groups. More sophisticated approaches for classifying PA patterns are encouraged for future research. Fifth, the generalizability of our findings may be limited by the age profile of our study population. The mean age of participants was 63 years (IQR 56–68 years), indicating a focus on middle-aged to older adults. Therefore, extrapolation of these results to populations with different age demographics should be approached with caution. Moreover, we acknowledge that the lack of external validation constitutes a further limitation. Finally, the possibility of residual or unmeasured confounding cannot be entirely dismissed in any an observational study. Although we have conducted sensitivity analyses to mitigate the likelihood of reverse causation, we cannot completely rule causal association in any an observational study.

Conclusion

Our study utilizing accelerometer data from UK Biobank demonstrated that engaging in a weekend warrior pattern, characterized by concentrated bouts of high-volume MVPA within 1 to 2 days, is associated with a similar risk reduction in T2D to the regularly active pattern. The beneficial effects were widely applicable to diverse population across genetic risk.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12933-025-02676-x.

Supplementary Material 1.

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Author contributions

C.X. and Z.C. contributed to the conception, study design, and ideas. Z.C. and J.M. collected,assembled the data and performed the statistical analysis. Z.C. conducted results interpretation. Z.C. wrote the first and successive drafts of the manuscript. C.X. revised the manuscript forimportant intellectual content. C.X. obtained funding. C.X. provided administrative, technical,and logistic support. All authors reviewed the manuscript and approved the final version. C.X.is the guarantor of this work and, as such, had full access to all the data in the study and takesresponsibility for the integrity of the data and the accuracy of the data analysis.

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Availability of data and materials

The main data used in this study were accessed from the publicly available UK Biobank Resource (https://www.ukbiobank.ac.uk) under application number 79095, which cannot be shared with other investigators due to data privacy laws. The UK Biobank data can be accessed by researchers on the application.

Declarations

Ethics approval and consent to participate

The UK Biobank study was conducted according to the Declaration of Helsinki and ethical approval was granted by the North West Multi-Centre Research Ethics Committee (reference number 06/MRE08/65). At recruitment, all participants gave informed consent to participate and be followed-up through data-linkage.

Competing interests

None of the funder had any role in the design and conduct of the study; the collection, management, analysis, and interpretation of the data; and the preparation, review, or approval of the manuscript.

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