BMJ Open Diabetes Research & Care

Trends in adherence to recommended physical activity and its effects on cardiometabolic markers in US adults with pre-diabetes

Xiaolin Qu,[1] Kun Chen,[1] Jigang Chen ,[2] Junhui Zhang[3]

To cite: Qu X, Chen K, Chen J, *et al*. Trends in adherence to recommended physical activity and its effects on cardiometabolic markers in US adults with pre-diabetes. *BMJ Open Diab Res Care* 2022;**10**:e002981. doi:10.1136/bmjdrc-2022-002981

► Additional supplemental material is published online only. To view, please visit the journal online (http://dx.doi.org/10.1136/bmjdrc-2022-002981).

XQ and KC contributed equally.

Received 9 June 2022
Accepted 18 September 2022

Check for updates

© Author(s) (or their employer(s)) 2022. Re-use permitted under CC BY-NC. No commercial re-use. See rights and permissions. Published by BMJ.

[1]Department of Neurosurgery, Changzheng Hospital, Naval Medical University, Shanghai, China
[2]Beijing Neurosurgical Institute, Beijing Tiantan Hospital, Capital Medical University, Beijing, China
[3]Department of Endocrinology, Southwest Hospital, Third Military Medical University, Chongqing, China

Correspondence to
Dr Jigang Chen; chenjigang2015@126.com and Dr Junhui Zhang; xyjunhui224@tmmu.edu.cn

ABSTRACT

Introduction This study aimed to examine the trends in adherence to Physical Activity Guidelines for Americans (PAG) as well as the association between them and cardiometabolic risk factors among US adults with pre-diabetes.

Research design and methods This study included 6734 participants who were diagnosed with pre-diabetes from the National Health and Nutrition Examination Survey 2007–2008 to 2017–2018. The logistic regression model and linear regression model were used to test the trends in adherence to PAG. The multivariable linear regression model was used to examine the association between adherence to PAG and cardiometabolic risk factors.

Results The rate of adherence to the PAG for aerobic physical activity was not significantly changed (64.1% in 2007–2008 to 66.4% in 2017–2018, p=0.599). The sedentary time changed significantly (5.6, 6.8, and 6.0 hours in 2007–2008, 2013–2014, and 2017–2018, respectively; p<0.001). Adherence to the PAG was significantly associated with levels of waist circumference, body mass index (BMI), high-density lipoprotein cholesterol (HDL-C), triglycerides, insulin, 2-hour postload plasma glucose, and measurements of insulin resistance (homeostatic model assessment for insulin resistance (HOMA-IR)) and β-cell function (homeostasis model assessment of β-cell function (HOMA-β)). There was a significant relationship between sedentary time and levels of waist circumference, BMI, HDL-C, insulin, 2-hour postload glucose, HOMA-IR, and HOMA-β. The associations of adherence to the PAG and sedentary time with the levels of systolic and diastolic blood pressures and hemoglobin A1c were not significant.

Conclusions Adherence to PAG for aerobic activity did not change significantly among US adults with pre-diabetes. The time spent on sedentary behavior peaked in 2013–2014 and then decreased afterward. Adhering to the PAG for aerobic activity and reducing sedentary time significantly improved cardiometabolic health among adults with pre-diabetes.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Physical activity is beneficial to cardiometabolic health in individuals with pre-diabetes, while the impact of adherence to Physical Activity Guidelines for Americans (PAG) on cardiometabolic risk factors in pre-diabetes has not been evaluated.

WHAT THIS STUDY ADDS

⇒ The sedentary time of individuals with pre-diabetes changed significantly from 2007 to 2018.
⇒ Adherence to the PAG was significantly associated with levels of cardiometabolic risk factors in pre-diabetes.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE, OR POLICY

⇒ Adhering to the PAG for aerobic activity and reducing sedentary time may improve cardiometabolic health among adults with pre-diabetes.

INTRODUCTION

Being physically active is one of the most important actions people can do to improve their health. Inadequate physical activity has been regarded as a worldwide public health problem and is responsible for approximately 6%–10% of major non-communicable diseases and 9% of premature mortality in 2008.[1] The USA has the highest economic burdens from physical inactivity, with an associated cost of $24.7 billion in annual health care.[2] The US Department of Health and Human Services released the first edition of the federal Physical Activity Guidelines for Americans (PAG) in 2008 and updated the second edition in 2018.[3 4] Both guidelines recommended that adults should engage in at least 150 min of moderate-intensity aerobic physical activity or at least 75 min of vigorous-intensity aerobic physical activity a week, or an equivalent combination of both. In addition, the second edition of PAG suggests that additional health benefits are gained with moderate-intensity physical activity beyond the equivalent of 300 min a week and that adults should reduce sedentary time. However, although the PAG has been released for more than 10 years, the adherence rate to the PAG for aerobic

BMJ Open Diab Res Care: first published as 10.1136/bmjdrc-2022-002981 on 28 September 2022. Downloaded from http://drc.bmj.com/ on November 26, 2022 by guest. Protected by copyright.

physical activity in US adults has not improved, while the sedentary time has significantly increased from 2007 to 2008 to 2015–2016[5].

Pre-diabetes refers to a health condition in which blood glucose levels are higher than normal but not high enough yet to be diagnosed as diabetes. In the USA, an estimated 88 million adults, which is more than 1 in 3, had pre-diabetes in 2018.[6] Physical exercise helps blood glucose control and is associated with a decreased risk of pre-diabetes, indicating its critical role in slowing down or even preventing disease progression in individuals with pre-diabetes.[7–9] Understanding the current status and trends in adherence to PAG among individuals with pre-diabetes is critical to informing future intervention and public health policy. However, there is little information about the secular changes in adherence to PAG in US adults with pre-diabetes.

Previous studies have found that physical activity has beneficial effects on cardiometabolic health both in individuals with diabetes and pre-diabetes.[10 11] Typically, the objectively measured physical activity and sedentary time were significantly associated with cardiometabolic risk factors in adults with pre-diabetes.[11] However, the impact of adherence to PAG on cardiometabolic risk factors in pre-diabetes has not been evaluated. It is unclear to what extent reported adherence to PAG could be inferred in US adults with pre-diabetes.

To address these knowledge gaps, we analyzed the data from the National Health and Nutrition Examination Surveys (NHANES) between 2007–2008 and 2017–2018 to examine the trends in adherence to PAG for aerobic physical activity and sedentary time among US adults with pre-diabetes and quantified the associations between them with cardiometabolic risk factors.

RESEARCH DESIGN AND METHODS

Data source

With a complex, multistage probability design, NHANES examines a nationally representative sample of the US civilian non-institutionalized population. Since 1999, NHANES collected data continuously and released datasets in 2-years cycles. During each survey, participants undergo a household interview and then a clinical examination in a specially designed and equipped mobile examination center.[12] We included data from NHANES 2007–2008 to 2017–2018 as NHANES used a different questionnaire to assess physical activity before 2007. Our participants were limited to non-pregnant adults (aged 18 years or older) who fasted for a minimum of 8 hours before blood samples were obtained. Participants with missed information on physical activity or sedentary time were excluded.

Data collection

During the household interview, demographic and health-related information was collected by standardized questionnaires. Race/ethnicity was categorized as Mexican American, non-Hispanic white, non-Hispanic black, and others. Education was categorized as less than high school, high school graduate, some college, and college graduate or higher. The income-to-poverty ratio was defined as annual family income divided by the poverty threshold adjusted for family size and inflation and used as a measure of income. Smoking was self-reported and was classified as non-smoker, current smoker, and former smoker. Current excessive alcohol use was defined as drinking more than four drinks a day on average in the past 12 months. Time of healthcare visits was collected based on questions asking ‘times receive healthcare over past year’. The use of statin, metformin, and antihypertensive drug was assessed by self-report and identified by a unique generic drug code from the Multum Lexicon drug database used for drug classification.[13] History of cardiovascular disease and cancer was ascertained by the self-report and cardiovascular disease including stroke, congestive heart failure, angina, and myocardial infarction.

During the examination in the mobile examination center, waist circumference was measured to the nearest 0.1 cm at the superior border of the iliac crest. Weight and height were measured, and the body mass index (BMI) was calculated as weight in kilogram divided by height in meter squared. Systolic and diastolic blood pressures (BPs) were measured by trained staff, and mean BP was determined as the mean of three or four reading according to the standardized protocol. Blood samples were collected, stored at −20°C, and sent to the central laboratories for the measurement of hemoglobin A1c (HbA1c) and total cholesterol. A subgroup of participants fasted for the measurement of triglycerides, high-density lipoprotein cholesterol (HDL-C), glucose, and insulin. The homeostasis model assessment was calculated to determine measurements of insulin resistance (homeostatic model assessment for insulin resistance (HOMA-IR)) and β-cell function (homeostasis model assessment of β-cell function (HOMA-β)) using the formula developed by Matthews *et al*.[14] A subgroup of participants was selected to have an oral glucose tolerance test (OGTT) and obtain 2-hour postload glucose levels. Documentation of the laboratory methodologies, including the calibration of measurements to ensure consistency across different survey cycles, is available online (https://www.cdc.gov/nchs/nhanes/index.htm).

Obesity was defined as BMI of 30 or higher, hypertension as systolic BP of ≥130 mm Hg, diastolic BP of ≥80 mm Hg or the use of antihypertensive medications; dyslipidemia as total cholesterol of ≥240 mg/dL or the use of lipid-lowering medications. Pre-diabetes was defined as an HbA1c of 5.7%–6.4% or a fasting plasma glucose of 100–125 mg/dL among those without reported diabetes.

Physical activity was assessed by the Global Physical Activity Questionnaire, a validated tool that assesses leisure-time physical activity, occupation-related physical activity, and transportation-related physical activity. Leisure-time and occupation-related physical activity

BMJ Open Diab Res Care: first published as 10.1136/bmjdrc-2022-002981 on 28 September 2022. Downloaded from http://drc.bmj.com/ on November 26, 2022 by guest. Protected by copyright.

included questions to assess the intensity (vigorous vs moderate), frequency (per week), and duration (minutes) in a typical week. Transportation-related physical activity included questions to assess the number of days in a typical week and the mean duration per day that they participated in the activity. As validated,[15] the total amount of physical activity was calculated as minutes of moderate-intensity activity plus twice the minutes of vigorous-intensity activity of all three domains. A participant was classified as adhering to the PAG if they had at least 150 min/week of aerobic physical activity. Sedentary time was assessed as the reported hours per day in a typical week.

Statistical analysis

Appropriate 12-year sampling weights were constructed according to the NHANES recommendation to make sure the results are generalizable to the non-institutionalized US population.[16] All statistical analysis was conducted in R V.4.1.0 with the 'survey' package after accounting for the complex sampling design. All statistical tests were two-sided, and $p<0.05$ was considered statistically significant. Skewed continuous variables including BMI, systolic BP, HDL-C, triglycerides, insulin, OGTT, HOMA-IR, and HOMA-β were log-transformed for analysis and then back-transformed to the geometric mean for the presentation of the results. Continuous variables were expressed as means (SE or 95% CI) and categorical variables as percentages (SE).

The logistic regression model was used to test the trends in adherence to PAG for aerobic physical activity across time, with the survey cycle as an independent variable. The linear regression model was used to test the trend in sedentary time in a similar manner. The non-linearity of the trend was tested by adding a quadratic term of the survey cycle into the regression model. We further tested the trends in adherence to PAG for aerobic physical activity and sedentary time by adjusting covariates in the regression models. Based on existing literature,[5 11] the following covariates were selected: age; gender; race/ethnicity; education; income; smoke; alcohol use; obesity; hypertension; dyslipidemia; time of healthcare visits; use of statin, metformin, and antihypertensive drug; history of cardiovascular disease and cancer; and survey cycle. To test whether trends in adherence rates and sedentary time differ across subgroups by age (18–44 years, 45–64 years, and ≥65 years), gender, race/ethnicity, education, and income, a two-way interaction term between survey cycle and subgroups status was added to the model.

The multivariable linear regression model was used to examine the association between adherence to PAG for aerobic physical activity and sedentary time with each cardiometabolic risk factor after adjusting for the aforementioned covariates. Log transformations were directly compared across cardiometabolic risk factors, and the results of linear regression analysis were presented as standardized beta coefficients. The difference in beta coefficients across different glycemic statuses and different subgroups by age, gender, race/ethnicity, education, and income was examined by interaction analyses.

We performed two sensitivity analyses to test the stability of the results. First, meta-analyses were conducted to calculate the summary beta coefficients with a 95% CI based on the results from each of six survey cycles (2007–2008, 2009–2010, 2011–2012, 2013–2014, 2015–2016, and 2017–2018) of NHANES, with adjustment for potential covariates. Second, we defined adherence to PAG for aerobic activity as those who had moderate-intensity physical activity beyond the equivalent of 300 min/week and examined its association with cardiometabolic risk factors.

In addition, to enrich the clinical value of the current study, we examined the effects of adherence to the PAG for aerobic activity and sedentary time on the diagnosis of diabetes based on the HbA1c data alone. We expanded our participants to those with either pre-diabetes (those with an HbA1c of 5.7%–6.4%) or diabetes (those with an HbA1c of over 6.4%). The associations between adherence to PAG for aerobic activity and sedentary time with the proportion of diabetes based on HbA1c were examined with logistic regression analysis with or without adjusting for covariates.

Data and resource availability

The data from NHANES are openly available online (https://www.cdc.gov/nchs/nhanes/index.htm). No applicable resources were generated or analyzed during the current study.

RESULTS

Baseline characteristics and trends in adherence to the PAG and sedentary time

Our final dataset comprised 6374 adults aged 18 years or older with pre-diabetes. The baseline characteristics of participants are presented in table 1.

The rate of adherence to the PAG for aerobic physical activity was not significantly changed, from 64.1% (95% CI 60.4% to 67.9%) in 2007–2008 to 66.4% (95% CI 62.0% to 70.9%) in 2017–2018 (p value for linear trend, 0.599) (figure 1). After adjusting for covariates, the trends remained insignificant. The sedentary time increased from 5.6 (95% CI 5.3 to 5.8) hours in 2007–2008 to 6.8 (95% CI: 6.5 to 7.1) hours in 2013–2014 and then decreased to 6.0 (95% CI 5.6 to 6.3) hours in 2017–2018 (p value for non-linear trend, <0.001) (figure 1). After adjusting for covariates, the trends remained significant. The trends in adherence to the PAG and sedentary time were similar across different subgroups by age, gender, race/ethnicity, education, and income.

Effects of adherence to the PAG on the cardiometabolic risk factors

Multivariable-adjusted means of cardiometabolic risk factors are reported (table 2). Multivariable linear regression analyses demonstrated a significant relationship between adherence to the PAG for aerobic physical

BMJ Open Diab Res Care: first published as 10.1136/bmjdrc-2022-002981 on 28 September 2022. Downloaded from http://drc.bmj.com/ on November 26, 2022 by guest. Protected by copyright.

Table 1 Characteristics of participants with pre-diabetes, National Health and Nutrition Examination Surveys 2007–2008 to 2017–2018

Years	2007–2008	2009–2010	2011–2012	2013–2014	2015–2016	2017–2018
Numbers	1134	1192	982	1024	986	1056
Mean age (years)	49.3 (0.8)	49.8 (0.8)	50.8 (0.7)	49.9 (0.6)	50.9 (0.7)	50.5 (0.8)
Age distribution (%)						
18–44	37.2 (3.0)	38.2 (2.5)	36.9 (2.5)	39.4 (1.6)	36.0 (2.1)	37.6 (2.1)
45–64	44.3 (3.0)	40.5 (2.1)	41.1 (2.6)	39.1 (1.6)	38.6 (2.4)	39.2 (2.5)
≥65	18.6 (1.2)	21.3 (1.0)	22.0 (1.1)	21.5 (1.9)	25.4 (2.1)	23.2 (2.2)
Male (%)	56.4 (1.7)	55.8 (1.5)	54.3 (2.3)	53.8 (2.0)	53.4 (1.8)	54.1 (1.7)
Race/ethnicity (%)						
Mexican American	13.1 (2.5)	13.8 (2.8)	13.8 (2.2)	15.7 (2.6)	15.8 (2.8)	15.7 (2.4)
Non-Hispanic white	71.7 (4.0)	67.7 (3.6)	68.3 (3.4)	64.4 (3.5)	62.3 (3.8)	63.9 (2.1)
Non-Hispanic black	10.3 (2.0)	12.2 (0.9)	11.4 (2.1)	12.3 (1.7)	11.0 (2.2)	10.0 (1.5)
Other	5.0 (1.0)	6.3 (1.1)	6.5 (1.1)	7.7 (1.1)	10.9 (1.6)	10.4 (1.5)
Education (%)						
Less than high school	20.9 (1.9)	21.2 (1.8)	18.5 (2.0)	18.2 (1.9)	16.7 (2.1)	11.3 (1.1)
High school graduate	26.6 (2.0)	24.4 (1.8)	22.1 (2.7)	22.4 (2.0)	23.3 (2.8)	32.1 (1.9)
Some college	26.0 (2.4)	28.2 (1.1)	31.0 (2.6)	31.6 (2.0)	30.8 (2.2)	29.5 (2.2)
College graduate	26.5 (2.2)	26.1 (2.2)	28.4 (2.9)	27.7 (1.6)	29.2 (3.6)	27.2 (3.1)
Income-to-poverty ratio <1 (%)	13.8 (1.8)	14.8 (1.6)	14.5 (2.0)	17.8 (1.8)	15.9 (1.4)	12.4 (1.9)
Smoke (%)						
Non-smoker	49.5 (2.5)	54.8 (2.5)	51.1 (2.8)	54.3 (2.4)	52.0 (2.5)	55.4 (2.0)
Current smoker	22.7 (1.6)	19.8 (1.4)	23.2 (2.1)	19.9 (1.8)	19.3 (2.3)	18.3 (1.6)
Former smoker	27.8 (2.4)	25.4 (2.6)	25.7 (1.9)	25.9 (1.8)	28.7 (2.5)	26.3 (1.9)
Excessive alcohol use (%)	10.1 (1.3)	10.5 (1.4)	10.4 (1.7)	9.4 (1.2)	12.1 (1.7)	7.7 (1.4)
Obesity (%)	34.4 (2.2)	42.1 (1.3)	40.5 (2.4)	43.7 (2.2)	43.1 (2.3)	43.5 (2.2)
Hypertension (%)	49.5 (1.3)	48.6 (2.4)	50.5 (2.9)	53.5 (1.8)	52.3 (3.0)	53.2 (2.6)
Dyslipidemia (%)	29.4 (1.7)	33.7 (1.7)	33.2 (2.7)	33.3 (1.8)	33.1 (2.0)	29.4 (1.5)
Healthcare visits ≤1 (%)	36.9 (2.9)	34.5 (1.6)	34.1 (1.9)	33.1 (2.0)	37.0 (2.1)	34.8 (2.6)
Statin use (%)	28.6 (1.8)	31.2 (1.9)	33.4 (3.0)	34.7 (2.2)	34.9 (2.4)	32.0 (2.4)
Metformin use (%)	1.1 (0.5)	1.7 (0.7)	1.1 (0.6)	2.5 (0.8)	3.9 (1.1)	2.6 (0.9)
Antihypertensive drug use (%)	11.1 (2.1)	13.4 (1.7)	11.3 (2.7)	9.7 (2.1)	10.8 (2.0)	8.1 (1.2)
History of CVD (%)	8.5 (1.0)	9.3 (1.0)	10.4 (1.9)	9.3 (1.3)	10.1 (1.3)	8.6 (1.4)
History of cancer (%)	8.9 (1.2)	10.4 (1.4)	9.8 (1.4)	12.7 (1.5)	13.2 (1.3)	11.2 (1.5)

Data are presented as mean with SE in parentheses.
CVD, cardiovascular disease.

activity and levels of waist circumference, BMI, HDL-C, triglycerides, insulin, 2-hour postload plasma glucose, HOMA-IR, and HOMA-β. There was no significant relationship between adherence to the PAG and levels of systolic BP, diastolic BP, and HbA1c (table 2).

In the subgroup analysis (table 3), the changes in cardiometabolic risk factors between those who adhered or did not adhere to the PAG for aerobic physical activity were broadly consistent in different subgroups except for the waist circumference by age (p value for interaction, 0.029), diastolic BP by age (p value for interaction, 0.018), HDL-C by age (p value for interaction, 0.006) and education (p value for interaction, 0.011), and triglycerides by gender (p value for interaction, 0.044), and HbA1c by age (p value for interaction, 0.038).

In the sensitivity analyses, according to the results of meta-analyses, there was a significant relationship between adherence to the PAG for aerobic physical activity and levels of waist circumference, BMI, HDL-C, insulin, 2-hour postload plasma glucose, HOMA-IR, and HOMA-β (online supplemental table I). When adherence to PAG was defined as those who had

BMJ Open Diab Res Care: first published as 10.1136/bmjdrc-2022-002981 on 28 September 2022. Downloaded from http://drc.bmj.com/ on November 26, 2022 by guest. Protected by copyright.

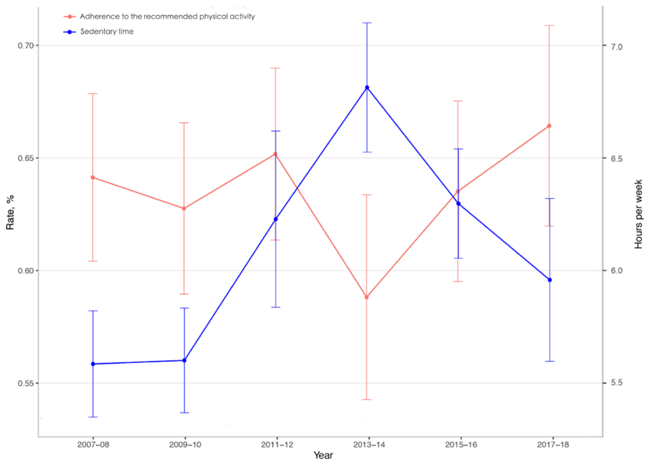

Figure 1 Crude weighted trends in adherence to Physical Activity Guidelines for Americans for aerobic physical activity and sedentary time among US adults with pre-diabetes, National Health and Nutrition Examination Surveys 2007–20008 to 2017–2018. Data were weighted to be nationally representative. Error bars indicate 95% CI.

moderate-intensity physical activity beyond the equivalent of 300 minutes a week minutes a /week, there was a significant relationship between adherence to the PAG and levels of waist circumference, BMI, HDL-C, triglycerides, insulin, 2h -hour post-load plasma glucose, HOMA-IR, and HOMA-β (online supplemental table II).

Effects of sedentary time on the cardiometabolic risk factors

Multivariable linear regression analyses showed that there was a significant relationship between sedentary time and levels of the waist circumference, BMI, HDL-C, insulin, 2-hour postload glucose, HOMA-IR, and HOMA-β (table 4).

Effects of adherence to the PAG for aerobic activity and sedentary time on the diagnosis of diabetes

The associations between adherence to PAG for aerobic activity and sedentary time with the proportion of diabetes based on HbA1c were examined and the results are presented in online supplemental tables III and IV. According to the results, the associations were significant without covariate adjustment and turned insignificant after the adjustment.

DISCUSSION

In this nationally representative study of US adults, we investigated the trends in adherence to the PAG and sedentary time in adults with pre-diabetes. We found that the proportion of people meeting the PAG did not significantly change from 2007 to 2008 to 2017–2018. Despite the guideline recommendations from professional societies, more than one-third of the population with pre-diabetes failed to meet the minimum requirement of PAG. Previous studies have reported the trends in adherence to the PAG in the USA.[5 17–19] However, all these studies except one reported adherence rates based only on the leisure-time domain of aerobic physical activity.[5] Therefore, the reported adherence rates in these studies could not reflect the aerobic physical activity from work and transportation. Furthermore, we limited our participants to those with pre-diabetes, among which the trends in adherence to the PAG have not been reported before. We found that the trends were similar across different subgroups by age, gender, race/ethnicity, education, and income. In contrast to the adherence to the PAG for aerobic physical activity, the time spent on sedentary behavior increased significantly during the past decade, and it was the highest during 2013–2014. The trend was

Table 2 Differences in the cardiometabolic risk factors between adults who adhere or did not adhere to the recommended physical activity

Risk factors	Non-adherence	Adherence	Beta coefficient (95% CI)	P value
Waist (cm)	105.0 (104.1 to 105.9)	102.8 (102.0 to 103.7)	−2.201 (−3.225 to −1.178)	**<0.001**
BMI	30.5 (30.0 to 31.0)	28.9 (28.6 to 29.3)	−0.052 (−0.072 to −0.032)	**<0.001**
Systolic BP (mm Hg)	125.1 (123.9 to 126.3)	125.4 (124.2 to 126.5)	0.281 (−1.217 to 1.779)	0.710
Diastolic BP (mm Hg)	70.1 (69.0 to 71.1)	70.5 (69.7 to 71.4)	0.477 (−0.912 to 1.866)	0.496
HDL-C (mg/dL)	50.6 (49.6 to 51.6)	52.5 (51.5 to 53.5)	0.037 (0.012 to 0.062)	**0.005**
Triglycerides (mg/dL)	117.3 (112.5 to 122.3)	111.2 (108.0 to 114.5)	−0.054 (−0.101 to −0.006)	**0.027**
Insulin (μU/mL)	14.1 (13.4 to 14.7)	12.5 (12.0 to 13.0)	−0.117 (−0.167 to −0.066)	**<0.001**
2-hour glucose (mg/dL)	124.3 (121.2 to 127.4)	119.0 (116.3 to 121.8)	−0.042 (−0.079 to −0.007)	**0.021**
HOMA-IR	3.7 (3.5 to 3.9)	3.3 (3.1 to 3.4)	−0.119 (−0.172 to −0.066)	**<0.001**
HOMA-β	118.8 (113.7 to 124.2)	106.4 (102.7 to 110.3)	−0.110 (−0.158 to −0.062)	**<0.001**
HbA1c	5.62 (5.59 to 5.65)	5.61 (5.59 to 5.63)	−0.008 (−0.043 to 0.027)	0.657

Data are presented as mean with 95% CIs in parentheses.
The P values with statistic significance were boldfaced.
.BMI, body mass index; BP, blood pressure; HbA1c, hemoglobin A1c; HDL-C, high-density lipoprotein cholesterol; HOMA-IR, Homeostatic Model Assessment for Insulin Resistance; HOMA-β, homeostasis model assessment of β-cell function.

BMJ Open Diab Res Care: first published as 10.1136/bmjdrc-2022-002981 on 28 September 2022. Downloaded from http://drc.bmj.com/ on November 26, 2022 by guest. Protected by copyright.

Table 3 P values of interaction testing for age, gender, race/ethnicity, education and income

Risk factors	Age	Gender	Race/ethnicity	Education	Income
Waist (cm)	**0.029**	0.598	0.100	0.577	0.344
BMI	0.101	0.097	0.351	0.578	0.056
Systolic BP (mm Hg)	0.251	0.158	0.336	0.263	0.417
Diastolic BP (mm Hg)	**0.018**	0.749	0.371	0.476	0.904
HDL-C (mg/dL)	**0.006**	0.189	0.497	**0.011**	0.210
Triglycerides (mg/dL)	0.052	**0.044**	0.639	0.212	0.876
Insulin (μU/mL)	0.111	0.361	0.074	0.534	0.604
2-hour glucose (mg/dL)	0.912	0.125	0.078	0.841	0.103
HOMA-IR	0.141	0.432	0.845	0.449	0.755
HOMA-β	0.068	0.243	0.075	0.815	0.273
HbA1c	**0.038**	0.941	0.282	0.442	0.458

BMI, body mass index; BP, blood pressure; HbA1c, hemoglobin A1c; HDL-C, high-density lipoprotein cholesterol; HOMA-IR, Homeostatic Model Assessment for Insulin Resistance; HOMA-β, homeostasis model assessment of β-cell function.

consistent across different subgroups examined. Notwithstanding, the good news is that the sedentary time has decreased since 2013–2014 for two consecutive survey cycles, even though the reasons for this decrease remain unknown and warrant further investigation.

It is well known that exercise training improves body composition, glycemic control, cardiovascular risk, and physical functioning in patients with diabetes and pre-diabetes.[20 21] It is recommended that patients with diabetes or pre-diabetes should aim to accumulate a minimum of 210 min of moderate-intensity or 125 min of vigorous-intensity exercise each week.[22] This recommendation is different from the PAG for aerobic physical activity. In fact, the optimal duration of physical activity in patients with pre-diabetes remains undefined. Most studies targeting pre-diabetes have demonstrated benefits in glycemic control and reduction in the incidence of diabetes from around 210 min/week or more,[23–27] and a dose–response relationship has been identified.[24 27] Even though the recommendation from the PAG that an individual should engage in at least 150 min of moderate-intensity aerobic activity a week is highly practicable and well fitted for patients with chronic diseases, its effect on an individual with pre-diabetes is worth investigating, given the disparities of different recommendations and lacking evidence-based guidelines.

To the best of our knowledge, this is the first study that evaluates the effects of adherence to PAG for aerobic physical activity and sedentary time on the cardiometabolic risk factors among individuals with pre-diabetes. Previous studies have examined the association of adherence to PAG for aerobic physical activity with mortality.[28 29] The results showed that adults who adhere to recommended physical activity of PAG had a greatly reduced risk of

Table 4 Standardized beta coefficients for the association between total sedentary time (hours) and cardiometabolic risk factors

	Beta coefficient (95% CI)	P value
Waist	0.263 (0.108 to 0.419)	**0.001**
BMI	0.008 (0.005 to 0.011)	**<0.001**
Systolic BP (mm Hg)	−0.141 (−0.342 to 0.061)	0.017
Diastolic BP (mm Hg)	−0.007 (−0.179 to 0.166)	0.939
HDL-C (mg/dL)	−0.005 (−0.008 to −0.001)	**0.005**
Triglycerides (mg/dL)	0.008 (−0.001 to 0.016)	0.066
Insulin (μU/mL)	0.013 (0.007 to 0.019)	**<0.001**
2-hour glucose (mg/dL)	0.009 (0.004 to 0.014)	**<0.001**
HOMA-IR	0.013 (0.007 to 0.020)	**<0.001**
HOMA-β	0.009 (0.002 to 0.017)	**0.020**
HbA1c	0.000 (−0.004 to 0.004)	0.935

BMI, body mass index; BP, blood pressure; HbA1c, hemoglobin A1c; HDL-C, high-density lipoprotein cholesterol; HOMA-IR, Homeostatic Model Assessment for Insulin Resistance; HOMA-β, homeostasis model assessment of β-cell function.

BMJ Open Diab Res Care: first published as 10.1136/bmjdrc-2022-002981 on 28 September 2022. Downloaded from http://drc.bmj.com/ on November 26, 2022 by guest. Protected by copyright.

all-cause and cause-specific mortality. Another study has explored the relationship between adherence to physical activity and the impact of that adherence on cardiorespiratory fitness in a population with diabetes.[30] The results showed that adherence to recommended physical activity was the significant predictor of measured peak oxygen consumption to fat-free mass. In our population with pre-diabetes, adherence to PAG for aerobic physical activity was negatively associated with waist circumference, BMI, triglycerides, insulin, 2-hour postload plasma glucose, HOMA-IR, and HOMA-β and was positively associated with HDL-C after accounting for potential confounders. The current study also proved that sedentary time was positively associated with levels of waist circumference, BMI, insulin, 2-hour postload glucose, HOMA-IR, and HOMA-β.

In agreement with our findings, Swindell *et al* found that objectively measured physical activity and sedentary time were associated with cardiometabolic risk factors in adults with pre-diabetes.[11] Moreover, their results showed that the accumulation of total physical activity over the day is as important as achieving the intensity of moderate-vigorous physical activity. These results, together with our findings, support the beneficial role of adherence to PAG for aerobic physical activity in improving cardiometabolic health in participants with pre-diabetes.

We tried to find out if physical activity and sedentary behavior would have an impact on the risk of pre-diabetes to diabetes conversion. We found that participants who adhere to PAG or had reduced sedentary behavior were less likely to be diagnosed with diabetes based on their HbA1c level. However, the results turned insignificant after adjusting for potential covariates, suggesting other factors might mediate the effects of physical activity and sedentary behavior on the conversion of pre-diabetes to diabetes.

This study has important public health implications. Both physical inactivity and prolonged sedentary time are associated with a high risk of adverse cardiometabolic health conditions in individuals with pre-diabetes.[23–27 31] Sedentary behavior has been proven not to be just the opposite part of physical activity,[32] and it is associated with cardiometabolic risk factors independent of total physical activity.[33] Moreover, evidence shows that high levels of moderate-intensity physical activity (about 60–75 min/day) are needed to eliminate the increased risk of death associated with prolonged sedentary time.[34] Thus, advanced efforts are needed to reduce the total sitting time and then to increase the total time of physical activity for individuals with pre-diabetes considering the fact that they are at a higher risk of adverse cardiometabolic events.

Strengths and limitations

Our study has several strengths. First, we used the nationally representative data to allow the generalization of the results to the entire US non-institutionalized adult population. Second, the measurement of fasting glucose and insulin was calibrated according to the recommendation of NHANES for a comparable assessment across survey years. Third, we performed sensitivity analyses to prove the robustness of our results.

Our study also has some limitations. First, the information on physical activity was self-reported, which might lead to recall bias. A previous study based on NHANES 2005–2006 found that physical activity estimates varied substantially, depending on whether self-reported or measured via accelerometer.[35] Therefore, our results should be interpreted with caution. Second, the PAG also suggested that adults should engage in muscle-strengthening activities for at least 2 days a week. However, the information about muscle-strengthening activity was not reported in NHANES 2007–2018. Third, this is a cross-sectional examination, so causal interferences between adherence to PAG and cardiometabolic risk cannot be made. Future research should investigate whether there is a longitudinal relationship between them.

CONCLUSIONS

In summary, this nationally representative estimate suggests that there is no significant change in adherence to PAG for aerobic activity among US adults with pre-diabetes. The time spent on sedentary behavior peaked in 2013–2014 and then decreased afterward. Adhering to the PAG for aerobic activity and reducing sedentary time significantly improved cardiometabolic health among adults with pre-diabetes.

Acknowledgements The authors thank all the National Health and Nutrition Examination Surveys participants and researchers for their substantial contributions.

Contributors XQ conducted the study design and data analysis. XQ and KC carried out the data collection. JC and XQ prepared the manuscript. JC and JZ reviewed and revised the manuscript. JC was the guarantor of this work, had full access to all the data, and takes full responsibility for the integrity of data and the accuracy of the data analysis. JC is the guarantor of this work and, as such, had access to all data and takes responsibility for the integrity of the data and the accuracy of the data analysis.

Funding This study was funded by the National Natural Science Foundation of China (grant number 82101433).

Competing interests None declared.

Patient consent for publication Not applicable.

Ethics approval This study involves human participants and the study protocols were approved by National Center for Health Statistics (NCHS). The data from NHANES are openly available online (https://www.cdc.gov/nchs/nhanes/index.htm). Written informed consent was obtained from each participant (approval ID: protocol #98-12, protocol #2005-06, protocol #2011-17, and protocol #2018-01; Centers for Disease Control and Prevention, NCHS Research Ethics Review Board approval, available from https://www.cdc.gov/nchs/nhanes/irba98.htm). The NHANES data were collected by the NCHS.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data sharing not applicable as no datasets generated and/or analyzed for this study.

Supplemental material This content has been supplied by the author(s). It has not been vetted by BMJ Publishing Group Limited (BMJ) and may not have been peer-reviewed. Any opinions or recommendations discussed are solely those of the author(s) and are not endorsed by BMJ. BMJ disclaims all liability and

BMJ Open Diab Res Care: first published as 10.1136/bmjdrc-2022-002981 on 28 September 2022. Downloaded from http://drc.bmj.com/ on November 26, 2022 by guest. Protected by copyright.

responsibility arising from any reliance placed on the content. Where the content includes any translated material, BMJ does not warrant the accuracy and reliability of the translations (including but not limited to local regulations, clinical guidelines, terminology, drug names and drug dosages), and is not responsible for any error and/or omissions arising from translation and adaptation or otherwise.

Open access This is an open access article distributed in accordance with the Creative Commons Attribution Non Commercial (CC BY-NC 4.0) license, which permits others to distribute, remix, adapt, build upon this work non-commercially, and license their derivative works on different terms, provided the original work is properly cited, appropriate credit is given, any changes made indicated, and the use is non-commercial. See: http://creativecommons.org/licenses/by-nc/4.0/.

ORCID iD

Jigang Chen http://orcid.org/0000-0003-0963-1194

REFERENCES

1 Lee I-M, Shiroma EJ, Lobelo F, *et al*. Effect of physical inactivity on major non-communicable diseases worldwide: an analysis of burden of disease and life expectancy. *Lancet* 2012;380:219–29.
2 Ding D, Lawson KD, Kolbe-Alexander TL, *et al*. The economic burden of physical inactivity: a global analysis of major non-communicable diseases. *Lancet* 2016;388:1311–24.
3 US Department of Health and Human Service. Physical activity guidelines for Americans. Washington DC US Dept of Health and Human Services; 2008.
4 US Department of Health and Human Service. *Physical activity guidelines for Americans*. 2nd ed. Washington DC: US Dept of Health and Human Services, 2018.
5 Du Y, Liu B, Sun Y, *et al*. Trends in adherence to the physical activity guidelines for Americans for aerobic activity and time spent on sedentary behavior among US adults, 2007 to 2016. *JAMA Netw Open* 2019;2:e197597.
6 Centers for Disease Control and Prevetion. National diabetes statistics report, 2020. Available: https://wwwcdcgov/diabetes/pdfs/data/statistics/national-diabetes-statistics-reportpdf [Accessed March 20, 2022].
7 Colberg SR, Hernandez MJ, Shahzad F. Blood glucose responses to type, intensity, duration, and timing of exercise. *Diabetes Care* 2013;36:e177.
8 Wang J, Wu Y, Ning F, *et al*. The association between leisure-time physical activity and risk of undetected prediabetes. *J Diabetes Res* 2017;2017:1–8.
9 Jadhav RA, Hazari A, Monterio A, *et al*. Effect of physical activity intervention in prediabetes: a systematic review with meta-analysis. *J Phys Act Health* 2017;14:745–55.
10 Lamb MJE, Westgate K, Brage S, *et al*. Prospective associations between sedentary time, physical activity, fitness and cardiometabolic risk factors in people with type 2 diabetes. *Diabetologia* 2016;59:110–20.
11 Swindell N, Mackintosh K, McNarry M, *et al*. Objectively measured physical activity and sedentary time are associated with cardiometabolic risk factors in adults with prediabetes: the preview study. *Diabetes Care* 2018;41:562–9.
12 Centers for Disease Control and Prevetion. National health and nutrition examination survey. Available: https://wwwcdcgov/nchs/nhanes/indexhtm [Accessed 15 Mar 2021].
13 National Health and Nutrition Examination Survey. 1988-2020 Data Documentation, Codebook, and Frequencies, Prescription Medications - Drug Information (RXQ_DRUG). Available: https://wwwn.cdc.gov/nchs/nhanes/1999-2000/RXQ_DRUG.htm [Accessed 24 Jun 2022].
14 Matthews DR, Hosker JP, Rudenski AS, *et al*. Homeostasis model assessment: insulin resistance and beta-cell function from fasting plasma glucose and insulin concentrations in man. *Diabetologia* 1985;28:412–9.
15 Divney AA, Murillo R, Rodriguez F, *et al*. Diabetes prevalence by Leisure-, Transportation-, and Occupation-Based physical activity among Racially/Ethnically diverse U.S. adults. *Diabetes Care* 2019;42:1241–7.
16 CDC. NCHS research ethics review board (ERB) approval. Available: https://www.cdc.gov/nchs/nhanes/irba98.htm
17 Ladabaum U, Mannalithara A, Myer PA, *et al*. Obesity, abdominal obesity, physical activity, and caloric intake in US adults: 1988 to 2010. *Am J Med* 2014;127:717–27.
18 Ussery EN, Fulton JE, Galuska DA, *et al*. Joint prevalence of sitting time and leisure-time physical activity among US adults, 2015-2016. *JAMA* 2018;320:2036–8.
19 Carlson SA, Fulton JE, Schoenborn CA, *et al*. Trend and prevalence estimates based on the 2008 physical activity guidelines for Americans. *Am J Prev Med* 2010;39:305–13.
20 Marwick TH, Hordern MD, Miller T, *et al*. Exercise training for type 2 diabetes mellitus: impact on cardiovascular risk: a scientific statement from the American heart association. *Circulation* 2009;119:3244–62.
21 Snowling NJ, Hopkins WG. Effects of different modes of exercise training on glucose control and risk factors for complications in type 2 diabetic patients: a meta-analysis. *Diabetes Care* 2006;29:2518–27.
22 Hordern MD, Dunstan DW, Prins JB, *et al*. Exercise prescription for patients with type 2 diabetes and pre-diabetes: a position statement from exercise and sport science Australia. *J Sci Med Sport* 2012;15:25–31.
23 Pan XR, Li GW, Hu YH, *et al*. Effects of diet and exercise in preventing NIDDM in people with impaired glucose tolerance. The dA Qing IGT and diabetes study. *Diabetes Care* 1997;20:537–44.
24 Tuomilehto J, Lindström J, Eriksson JG, *et al*. Prevention of type 2 diabetes mellitus by changes in lifestyle among subjects with impaired glucose tolerance. *N Engl J Med* 2001;344:1343–50.
25 Li G, Zhang P, Wang J, *et al*. The long-term effect of lifestyle interventions to prevent diabetes in the China dA Qing diabetes prevention study: a 20-year follow-up study. *Lancet* 2008;371:1783–9.
26 Lindström J, Ilanne-Parikka P, Peltonen M, *et al*. Sustained reduction in the incidence of type 2 diabetes by lifestyle intervention: follow-up of the Finnish diabetes prevention study. *Lancet* 2006;368:1673–9.
27 Knowler WC, Barrett-Connor E, Fowler SE, *et al*. Reduction in the incidence of type 2 diabetes with lifestyle intervention or metformin. *N Engl J Med* 2002;346:393–403.
28 Zhao G, Li C, Ford ES, *et al*. Leisure-Time aerobic physical activity, muscle-strengthening activity and mortality risks among US adults: the NHANES linked mortality study. *Br J Sports Med* 2014;48:244–9.
29 Zhao M, Veeranki SP, Magnussen CG, *et al*. Recommended physical activity and all cause and cause specific mortality in US adults: prospective cohort study. *BMJ* 2020;370:m2031.
30 Jarvie JL, Pandey A, Ayers CR, *et al*. Aerobic fitness and adherence to guideline-recommended minimum physical activity among ambulatory patients with type 2 diabetes mellitus. *Diabetes Care* 2019;42:1333–9.
31 van der Velde JHPM, Schaper NC, Stehouwer CDA, *et al*. Which is more important for cardiometabolic health: sedentary time, higher intensity physical activity or cardiorespiratory fitness? the Maastricht study. *Diabetologia* 2018;61:2561–9.
32 van der Ploeg HP, Hillsdon M. Is sedentary behaviour just physical inactivity by another name? *Int J Behav Nutr Phys Act* 2017;14:1–8.
33 Henson J, Yates T, Biddle SJH, *et al*. Associations of objectively measured sedentary behaviour and physical activity with markers of cardiometabolic health. *Diabetologia* 2013;56:1012–20.
34 Ekelund U, Steene-Johannessen J, Brown WJ, *et al*. Does physical activity attenuate, or even eliminate, the detrimental association of sitting time with mortality? A harmonised meta-analysis of data from more than 1 million men and women. *The Lancet* 2016;388:1302–10.
35 Tucker JM, Welk GJ, Beyler NK. Physical activity in U.S.: adults compliance with the physical activity guidelines for Americans. *Am J Prev Med* 2011;40:454–61.

BMJ Open Diab Res Care: first published as 10.1136/bmjdrc-2022-002981 on 28 September 2022. Downloaded from http://drc.bmj.com/ on November 26, 2022 by guest. Protected by copyright.