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Original Contribution

Joint associations of diet and physical activity with incident type 2 diabetes and hypertension: an analysis of 144 288 UK Biobank participants

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Abstract

Studies examining the joint associations of lifestyle exposures can reveal novel synergistic and joint effects, but no study has examined the joint association of diet and physical activity (PA) with type 2 diabetes (T2D) and hypertension. The aim of this study is to examine the joint associations of PA and diet with incidence of type T2D and hypertension, as a combined outcome and separately in a large sample of adults in the United Kingdom. This prospective cohort study included 144 288 UK Biobank participants aged 40-69. Moderate to vigorous PA (MVPA) was measured using the International Physical Activity Questionnaire and a wrist accelerometer. We categorized PA and diet indicators (diet quality score [DQS] and energy intake [EI]) based on tertiles and derived joint PA and diet variables. Outcome was major cardiometabolic disease incidence (combination of T2D and hypertension). A total of 14 003 (7.1%) participants developed T2D, 28 075 (19.2%) developed hypertension, and 30 529 (21.2%) developed T2D or hypertension over a mean follow-up of 10.9 (3.7) years. Participants with middle and high self-reported MVPA levels had lower risk of major cardiometabolic disease regardless of diet (eg, among high DQS group, hazard ratios [HRs] in middle and high MVPA group were 0.90; 95% CI, 0.86-0.94), and 0.88 (95% CI, 0.84-0.92), respectively. Participants with jointly high device-measured MVPA and high DQS levels had lower major cardiometabolic disease risk (HR, 0.84; 95% CI, 0.71-0.99). The equivalent joint device-measured MVPA and EI exposure analyses showed no clear pattern of associations with the outcomes. Higher PA is an important component in cardiometabolic disease prevention across all diet quality and total EI groups. The observed lack of association between diet health outcomes may stem from a lower DQS.

Key words: type 2 diabetes; hypertension; physical activity; accelerometer; diet; cardiometabolic; metabolic; lifestyle risk factors; wearable sensors.

Introduction

Type 2 diabetes (T2D) and hypertension are 2 of the world's fastest-growing health burdens.[1,2] In 2019, about 460 million people were estimated to live with diabetes, and a further increase to 642 million by 2040 is projected.[3] Hypertension prevalence, which is even more prevalent than T2D, has doubled since 2019, with more than 1 billion cases globally.[4] T2D and hypertension frequently coexist and share substantial overlap in etiology and mechanistic pathways; they both lead to a dramatic increase in risk of major cardiovascular events such as myocardial infarction, stroke, and severe kidney disease.[1,2] The UK Prospective Diabetes Study showed that patients with higher HbA1c and systolic blood pressure levels had a higher risk of diabetes complications, indicating an additive adverse health effect of hyperglycaemia and hypertension.[5]

A healthy diet, recommended levels of physical activity (PA), and low levels of sedentary behavior play a critical role in T2D and hypertension prevention through their beneficial long-term effects on glycemic and blood pressure control.[6-8] A growing body of evidence suggests that comprehensive dietary change, compared to focusing on single nutrient or energy intake (EI), could be a more effective approach for cardiometabolic disease prevention.[9] Several diet quality indices have been shown to be protective against T2D and hypertension.[10] A recent meta-analysis including 1 071 967 participants showed a linear association between total sedentary behavior and T2D and hypertension, with each additional sedentary hour per day increasing the risk for T2D and hypertension by 5% and 4%, respectively.[8]

Observational studies have shown that sufficient moderate to vigorous physical activity (MVPA) is associated with a lower

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risk of T2D and hypertension.[11-14] A prospective study of 174 314 people (mean age, 36.7 years) showed that sufficient baseline PA level (≥150 minutes/week) was associated with a lower risk of incident T2D and hypertension, independently.[11] In a study of 116 134 participants, those who showed an increase in their PA levels had a lower risk of T2D and hypertension compared to those who decreased their PA levels.[12] The CARDIA (Coronary Artery Risk Development in Young Adults) Fitness Study in 2291 men and women aged between 38-50 showed that accelerometer-measured MVPA (defined as mins/day of counts ≥2020/min) was associated with a decreased T2D risk and was marginally associated with reduced hypertension risk.[13] Much of the knowledge on the associations between diet quality and PA with T2D and hypertension is based on studies that have focused on each lifestyle factor separately and each condition separately. Additionally, most of these studies[11,12] used only self-report measures of PA, which showed a correlation between 0.4-0.5 with accelerometers.[14] Despite some behavioral concordance between PA and diet, not all people who achieve recommendations for PA eat a healthy diet and vice versa. Studies examining the joint associations of lifestyle exposures can reveal novel synergistic and joint effects, but to our knowledge, no study has examined the joint association of diet and PA with T2D and hypertension—independently and combined. Using both self-reported and device-based PA assessment methods and multiple dietary indicators, we examined the joint associations of PA and diet with incidence of T2D and hypertension (as a combined outcome and separately) in a large sample of adults in the United Kingdom.

Methods

Sample

This research was conducted using the UK Biobank Resource (application 25813), a population-based prospective cohort study. In this study, around 9.2 million invitations were mailed to recruit participants aged 40-69 years between 2006 and 2010 from 22 centers across the United Kingdom. All participants provided informed consent, and ethical approval was provided by the National Health Service, National Research Ethics Service (Ref11/NW/0382).

We included UK Biobank participants with linked UK primary care data (n = 227 834). We excluded participants with a baseline diagnosis of any diabetes and hypertension based on hospital episodes and primary care linkage data. We also excluded participants who had missing self-reported or device-measured PA exposure data and other covariates data. We also excluded underweight participants (body mass index [BMI] <18.5 kg/m^2) from all analyses to reduce the possibility of biased estimates due to poor general health status. Figure S1 and Figure S2 present the flow chart of participants included in this research.

Physical activity and sedentary behavior

We used the International Physical Activity Questionnaire (IPAQ) short form, which included items on frequency and duration of walking, moderate intensity activity, and vigorous intensity activity. Metabolic Equivalent of Task (MET)-minutes of MVPA/week was calculated by multiplying the MET value of activity by the number of minutes/week.[15] Because the IPAQ short form asks respondents to consider the activities they do at work along with other type of activities, we did not to include occupational PA in our study. For leisure-time physical activity (LTPA), participation in exercise and recreational walking was measured through a close-ended touch-screen questionnaire that asked participants to report if, how often, and for how long they participate in such activities. The total weekly LTPA (METs-min/week) was calculated by multiplying the frequency, duration, and the MET values[16] (Table S1 and Appendices S1). Participants reported their daily TV viewing time and discretionary computer use during baseline and follow-up visits. They responded to the following questions: "In a typical day, how many hours do you spend watching TV?" and "In a typical day, how many hours do you spend using the computer (not including occupational computer use)?" We then combined their TV viewing and discretionary computer time to create a new variable as "discretionary screen time (DST)."

From 2013-2015, 103 684 participants were mailed and wore an Axivity AX3 accelerometer (Newcastle upon Tyne, UK) on their dominant wrist for 24 hours/day for 7 days to measure physical activity. Physical activity intensity was classified with a validated accelerometer-based activity machine learning scheme covering sedentary behavior (SB), light intensity (LPA), moderate intensity (MPA), and vigorous intensity (VPA)[17] (Appendices S2). Activity energy expenditure (AEE) was calculated using a network harmonization approach, [18] and sleep was classified based on wrist tilt angle changes.[19] Monitoring days were considered valid if wear time was greater than 16 hours. To be included in analysis, participants were required to have at least 3 valid monitoring days and have worn the monitor during sleep periods.

Self-reported PA, device-measured PA, LTPA, and sedentary behavior (self-reported DST and device measured sedentary time [ST]) were classified based on sex-specific tertiles as bottom, middle and high.

Diet quality and energy intake

Participants completed a touch-screen food frequency questionnaire (FFQ) for the past 12 months food consumption in the assessment centers. From FFQ, we calculated a previously published[20] diet quality score (DQS) that is based on 10 foods predictive of T2D risk. The scale for each dietary component was from 0 (unhealthiest) to 10 (healthiest) points. The total DQS was calculated as the sum of all the diet component scores and ranged from 0 to 100, with a higher score representing a higher overall diet quality.[20] Participants were grouped based on sex-specific tertiles as low DQS, moderate DQS, and high DQS. We reported a complete description of DQS in Appendices S3.

Total daily EI was assessed by Oxford WebQ 24-hour recall questionnaire. For the analyses, individuals were categorized into 3 groups based on sex-specific tertiles: (1) low EI, (2) moderate EI, and (3) high EI.

Combined (joint) physical activity/sedentary behavior and diet exposure

Participants were classified into 1 of 9 mutually exclusive groups based on their baseline PA or sedentary behavior (bottom MVPA/LTPA/DST/ST, middle MVPA/LTPA/DST/ST, and high MVPA/LTPA/DST/ST) and DQS (low DQS/EI, moderate DQS/EI, and high DQS/EI; Figure S3). We adopted the same approach for baseline PA and total EI (low EI, moderate EI and high EI; Figure S4).

Outcomes

For the purpose of this article, we defined major cardiometabolic disease (MCD) as incidence of either T2D or hypertension. We ascertained incident T2D and hypertension from UK primary care and hospital-linked data. Hospital inpatient records were censored on October 31, 2021, for England and Wales and September 31, 2021, for Scotland. Primary care records were available up to May 2017 for Scotland, September 2017 for Wales, and August

2017 for England. Participants were followed up from the date of attendance at the recruitment center to the date of T2D or hypertension incidence or the above-mentioned censoring dates, whichever came first.

Covariates

Using a framework similar to previous analogous UK Biobank analyses,[21] we adjusted analyses for age (years), sex, ethnic background, education (college/university degree; higher school certificate or equivalent; school certificate or equivalent; secondary education certificate or equivalent; vocational qualification, higher diploma/certificate, or equivalent; other professional qualifications), smoking (never, previous, and current smokers), sleep duration (hours/day; self-reported for self-reported PA analysis and accelerometer measured for device-measured PA analysis), alcohol consumption (UK units of alcohol/week), socioeconomic status (Townsend deprivation index), sedentary behavior (TV and nonwork related computer time for self-reported PA analysis and accelerometer measured sedentary time for device-measured PA analysis), vitamin-mineral supplementation use, family history of hypertension or diabetes, baseline chronic illness (the presence of cardiovascular disease except hypertension), and number of valid accelerometer wear days (for device-measured PA analysis).

Statistical analysis

We used Cox proportional hazard models to examine the associations between exposures and outcomes. We examined the proportional hazards assumption using Kaplan–Meier survival plots (Figure S5) and Schoenfeld residuals, and we noted no apparent violations ($P > .05$ for the association of self-reported and device-measured PA and diet indicators with MCD risk).

We examined the independent associations of PA and diet with the incidence of T2D, hypertension and composite MCD, using the bottom group of each PA indicator, low DQS and high EI as a referent. We also examined the joint association of self-reported/device-measured MVPA and diet with the incidence of T2D, hypertension and MCD, using bottom MVPA+low DQS/high EI joint variable as a referent. Model was adjusted for sex, age at baseline, ethnicity, education, socioeconomic status, discretionary screen time or device-measured sedentary time, smoking status, alcohol consumption, self-reported or device-measured sleep duration, vitamin/mineral supplementation use, chronic illness (cardiovascular disease excluding hypertension), and family history of diabetes. We further adjusted for accelerometer wear time in device-measured PA analyses. In total EI analyses, we also adjusted for DQS. We conducted additional analyses for the joint association of device-measured total PA and diet with the incidence of T2D, hypertension, and MCD, using bottom total PA + low DQS/high EI joint variable as a referent. Because there is a strong physiological drive to match caloric intake to caloric expenditure,[22] we also examined the association between AEE and total EI with the incidence of T2D, hypertension, and MCD, using bottom total AEE + high EI joint variable as a referent. We adjusted for the same covariates as in the main accelerometer analyses.

We tested for statistical interactions by entering an PA*DQS, PA*EI and AEE*EI term in the finally adjusted models.

Sensitivity analyses

We conducted additional joint dose-response analyses for physical activity, DQS, and EI. We used restricted cubic splines with knots at the 10th, 50th and 90th percentile of the MVPA distribution. The reference was 15 minutes of MVPA/week and the lowest dietary index score group or the highest EI group (when appropriate). We adjusted for the same covariates as in the main analyses.

We also repeated the main analysis using the outcomes of incident T2D and hypertension from UK primary care data only. We excluded events in the first 3 years of follow-up from all models of main analyses to minimize the possibility of reverse causation bias—ie, T2D or hypertension affects levels of physical activity or diet, rather than vice versa. We performed the joint association between PA and DQS with T2D and hypertension incidence with additional adjustment of total EI. Because T2D and hypertension risk are higher among people with obesity,[23] we also repeated the main analyses stratifying by obesity status (normal weight 18.5-24.9 kg/m^2 and overweight/obese ≥25 kg/m^2).

Since LTPA may provide additional benefits for glycemic control and blood pressure control,[24] we examined the joint association between LTPA and diet with all outcomes using bottom LTPA+low DQS/high EI joint variable as the reference groups. For LTPA analyses, we additionally adjusted for self-reported PA.

We also examined the joint association of self-reported DST/device-measured ST and DQS on the incidence of T2D, hypertension, and MCD using high DST/high ST + low DQS joint variable as a referent.

All analyses were performed using R statistical software.

Results

Table 1 shows the baseline characteristics of the sample (n = 144 288) by tertiles of self-reported MVPA group. The mean age was 55.3 (SD, 8.1) years, and 42% were males. The mean DQS was 34.7 (11.2; DQS range, 0-100). A total of 14 003 (7.1%) participants developed T2D, 28 075 (19.2%) hypertension and 30 529 (21.2%) MCD (T2D or hypertension) over a mean follow-up of 10.9 (3.7) years. Baseline characteristics of the device-measured PA sample (n = 28 733) were similar (Table S2). We found interaction effects between self-reported MVPA tertiles and DQS for hypertension (P = .029) and MCD (P = .042) incidence, as well as between device-measured MVPA and EI for hypertension (P = .039) and MCD (P = .022) incidence. There was a significant interaction between device-measured AEE and EI for hypertension incidence (P = .034; Table S3).

Independent associations

Major cardiometabolic disease risk was lowered in a dose-response manner with higher MVPA (both self-reported and device-measured) compared to reference group of bottom MVPA (HR, 0.92; 95% CI, 0.90-0.95; and HR 0.89; 95% CI, 0.86-0.91 for self-reported middle and high MVPA group, respectively; and HR 0.91; 95% CI, 0.82-0.99; and HR 0.88; 95% CI, 0.79-0.98 for device-measured middle and high MVPA group, respectively). Diet exposures were not associated with lower MCD (Table S4).

Joint association of PA and diet with incident major cardiometabolic disease

Irrespective of DQS and total EI, participants with middle and high self-reported MVPA levels had lower MCD risk compared to the reference group of bottom MVPA tertile/low DQS or high total EI (Figure 1; Table S5). For example, among high DQS group, HR of MCD risk in middle and high self-reported MVPA group were HR of 0.90 (95% CI, 0.86-0.94), and HR 0.88 (95% CI, 0.84-0.92), respectively.

Table 1. Baseline characteristics of study sample by self-reported moderate to vigorous physical activity tertiles* (n = 144 288).

	Overall	Bottom MVPA	Medium MVPA	High MVPA
Total number	144 288	48 112	48 056	48 120
Age (mean [SD])	55.3 (8.1)	55.3 (7.9)	55.2 (8.1)	55.5 (8.3)
Male , *n*, %	60 421 (41.9)	20 147 (41.9)	20 121 (41.9)	20 153 (41.9)
Follow-up (mean [SD])[a]	10.9 (3.7)	10.7 (3.9)	11.0 (3.7)	11.0 (3.6)
Sleep (mean [SD])	7.2 (1.1)	7.1 (1.1)	7.2 (1.0)	7.2 (1.0)
Diet quality score (DQS; mean [SD])[b]	34.7 (11.2)	32.9 (11.0)	35.0 (11.0)	36.2 (11.4)
Chronic disease, *n*, %[c]	5577 (3.9)	2068 (4.3)	1785 (3.7)	1724 (3.6)
Socioeconomic status	−1.5 (2.9)	−1.4 (3.0)	−1.6 (2.9)	−1.6 (2.9)
Smoking status, *n*, %				
Never	82 603 (57.2)	27 113 (56.4)	28 084 (58.4)	27 406 (55.8)
Current	46 899 (32.5)	15 004 (31.2)	15 688 (32.6)	16 207 (33.7)
Previous	14 786 (10.2)	5995 (12.5)	4284 (8.9)	4507 (9.4)
Body mass index (BMI; mean [SD])[d]	26.8 (4.3)	27.5 (4.7)	26.6 (4.2)	26.3 (4.0)
Alcohol consumption (unit/week)[e]	13.3 (15.8)	12.5 (16.6)	13.5 (15.1)	13.7 (15.7)
Discretionary screen time (hour/day)[f]	3.7 (2.1)	3.9 (2.2)	3.6 (2.0)	3.6 (1.9)
Family history of type 2 diabetes or hypertension	114 616 (79.4)	37 990 (79.0)	38 297 (79.7)	38 329 (79.7)
Vitamin-mineral supplementation use	45 663 (31.6)	13 888 (28.9)	15 339 (31.9)	16 426 (34.2)

Abbreviations: MVPA: moderate to vigorous physical activity; SD, standard deviation.
Data are presented as mean (standard deviation) or n (percentage) as applicable.
*Self-reported MVPA was measured using a modified version of the International Physical Activity Questionnaire (IPAQ) short form. MVPA was quantified in Metabolic Equivalent Task (MET)-min/week, computed by multiplying the activity by the MET value and then summing the number of MET-hours spent performing each activity per week. Bottom PA: ≤116.8 MET-min/week for men and 102.3 MET-min/week for women; Medium PA: 116.8-315.2 MET-min/week for men and 102.3-286.9 MET-min/week for women; High PA: ≥315.2 MET-min/week for men and ≥286.9 MET-min/week for women.
[a]Follow-up years until T2D incident or end of the study, whichever came first.
[b]Diet quality score (DQS) was based on 10 foods predictive of type 2 diabetes risk, emphasizing higher intake of vegetables, fruits, fish, dairy, whole grains, and vegetable oils and lower intake of refined grains, processed meats, unprocessed red meats, and sugar-sweetened beverages. Higher scores indicate better diet quality.
[c]Hospital admissions (cardiovascular disease except hypertension (ICD-10 codes I00 to I99)); primary care data (general practitioner diagnoses of myocardial infarction, ischemic heart disease, cerebrovascular diseases).
[d]Body mass index (BMI) = Weight (kg)/height (m^2).
[e]Alcohol consumption is based on the average weekly intake of standard drinks relative to UK guidelines.
[f]TV and non-work-related computer time.

Participants who had higher device-measured MVPA and high DQS levels had lower MCD risk than participants in the bottom MVPA/low DQS; for example, among middle and high MVPA and high DQS groups, MCD HR were 0.80 (95% CI, 0.68-0.94) and 0.84 (95% CI, 0.71-0.99), respectively (Figure 1; Table S5). The joint device-measured MVPA and EI exposure showed fewer clear associations with MCD risk; despite the similarities in the pattern of point estimates, 95% CIs crossed unity across all groups except from the highest MVPA-lowest EI group (HR, 0.81; 95% CI, 0.66-0.96).

The results for the joint association analysis of self-reported MVPA and diet exposures with T2D risk were broadly in agreement with the main analyses. Device-measured middle and high MVPA were associated with a lower risk of T2D regardless of DQS. T2D risk was lowered only in participants with high device-measured MVPA levels irrespective of EI (Table S5). Self-reported middle and high MVPA were associated with a lower risk of hypertension regardless of DQS and total EI (Table S5).

Sensitivity analyses

The joint dose-response analyses for self-reported PA, DQS, and MCD incidence showed similar results with the main analyses. The risk of MCD risk decreased with higher self-reported PA, irrespective of DQS or EI (Figure S6 and Figure S7). Similar to the main analyses, MCD risk was lower with higher device-measured MVPA among participants who had high DQS levels, indicating a joint association between device-measured MVPA and diet (Figure S8). There was some evidence for a steeper dose-response association for low EI at very high levels of device-measured MVPA (>350 minutes/week) with MCD risk. Increasing MVPA levels did not change the risk of MCD among moderate and high EI groups. Diabetes risk was lower with higher device-measured MVPA irrespective of EI levels (Figure S9). Limiting outcomes to incidence diagnosed in UK primary care data produced consistent results with the main analyses (Table S6). Exclusion of cases that occurred in the first 3 years of follow-up did not appreciably change the results for the joint association between self-reported MVPA and dietary markers with MCD incidence (Table S7). The results for the joint analyses of device-measured MVPA and total EI with exclusion of cases occurring in the first 3 years of follow-up were similar to the main analyses presented in Figure 1 and Table S5. The association between device-measured MVPA and DQS with incident MCD was less clear when the first 3 years of follow-up cases were excluded (Table S7).

Additional adjustment of total EI in the analyses of self-reported MVPA and DQS produced consistent results with the main analyses (Table S8).

Our BMI-stratified analysis showed that participants who were overweight/obese among middle or high self-reported MVPA group had a lower risk of MCD indifferent to their DQS group. However, risk was lowered with higher DQS and lower total EI in a dose-response manner among high level MVPA group in normal weight participants (Table S9). For instance, in the high MVPA group, participants who had high DQS (HR, 0.82; 95% CI, 0.75-0.90) showed slightly lower MCD risk than those who had moderate (HR, 0.85; 95% CI, 0.77-0.94) or low (HR, 0.88; 95% CI, 0.79-0.97) DQS levels. Joint association analysis between LTPA with DQS and total EI produced consistent results with the main self report–based PA analyses (Table S10).

Irrespective of DQS, participants with moderate and low DST levels had lower MCD, T2D, and hypertension risk compared to the reference group of high DST tertile/low DQS (Table S11). Participants with low ST and high DQS had a lower risk of T2D (HR, 0.71; 95% CI, 0.52-0.98; Table S11).

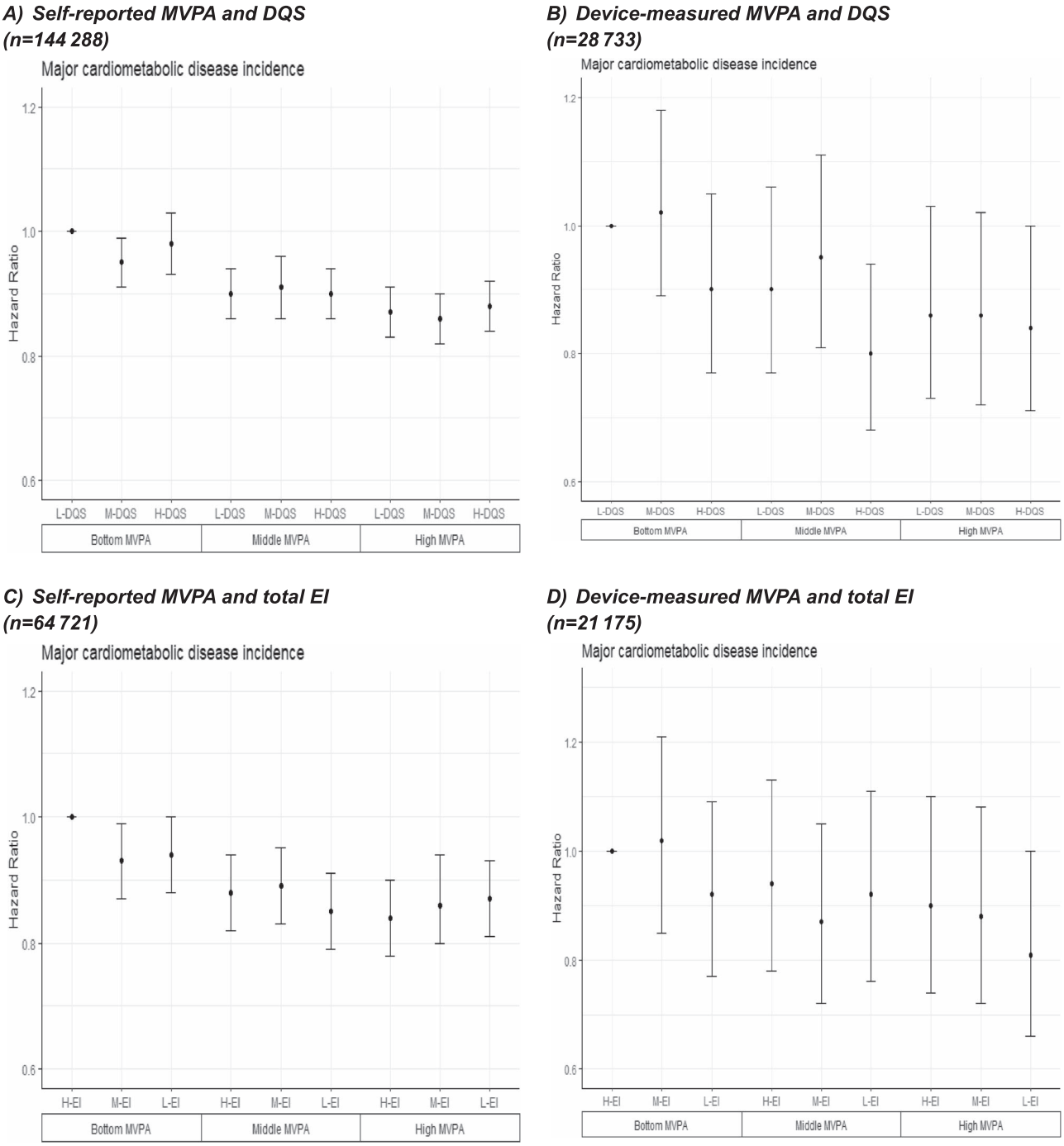

Figure 1. A-D) Joint association between physical activity and dietary markers with major cardiometabolic disease incidence.* Cox proportional hazard model. Model is adjusted for baseline age, sex, ethnic background, education, Townsend Deprivation Index, smoking status, self-reported sleep duration (hours/night)/accelerometer measured sleep duration (hours/night), discretionary screen time (TV and non-work related computer time)/accelerometer measured sedentary behavior (min/week; for accelerometer analyses), alcohol consumption (unit/week), body mass index (kg/m^2), diet quality score (for total EI analyses), vitamin mineral supplementation use, chronic diseases (hospital admissions, cardiovascular disease except hypertension; ICD-10 codes I00 to I99; primary care data; general practitioner diagnoses of myocardial infarction, ischemic heart disease, cerebrovascular diseases), family history of type 2 diabetes or hypertension. Accelerometer analyses further adjusted for accelerometer total wear days. Diet quality score (DQS) was based on 10 foods predictive of type 2 diabetes risk, emphasizing higher intake of vegetables, fruits, fish, dairy, whole grains, and vegetable oils and lower intake of refined grains, processed meats, unprocessed red meats, and sugar-sweetened beverages. Higher scores indicate better diet quality (Zhuang et al). Energy intake (EI) was measured with the Oxford WebQ 24-hour recall questionnaire. Self-reported MVPA was measured using a modified version of the International Physical Activity Questionnaire (IPAQ) short form. Type 2 diabetes and hypertension incidence includes doctor diagnoses and hospital admission records (ICD-9 codes 25 000, 25 002, 25 010, 25 012, 25 020, 25 022, 25 030, 25 032, 25 040, 25 042, 25 050, 25 052, 25 060, 25 062, 25 070, 25 072, 25 080, 25 082, 25 090, 25 092 and ICD-10 code E11 for type 2 diabetes; ICD-9 codes 401 and ICD-10 code I10 for hypertension). *Major cardiometabolic disease incidence includes type 2 diabetes or hypertension incidence.

We found fewer clear associations between device-measured total PA and total EI with MCD incidence. Similar to device-measured MVPA, participants in the highest total PA and low EI had a lower risk of MCD (HR, 0.81; 95% CI, 0.66-1.00; Table S12). Major cardiometabolic disease risk was lowered with lower total EI in a dose-response manner among high level AEE group

(HR, 0.80; 95% CI, 0.65-0.97 for high EI; HR 0.79; 95% CI, 0.64-0.97 for moderate EI; and HR 0.74; 95% CI, 0.60-0.91 for low EI; Table S12).

Discussion

To our knowledge, this study is the first investigation into the joint association of diet and MVPA (self-reported and device-measured) with T2D and hypertension incidence, as well as their combination. We found that higher levels of self-reported MVPA were associated with lower T2D and hypertension risk (separately and combined). We also showed that irrespective of dietary markers, higher self-reported MVPA levels were associated with lower risk of T2D, hypertension, and their combination.

The observed DQS levels (mean DQS, 34.7; DQS range, 0-100) in our study align with findings from prior research conducted in the UK. Diet quality among European populations is quite heterogeneous; for example, Scandinavian and north European regions (Norway, Sweden, Denmark, the Netherlands, United Kingdom, and Germany) have lower dietary scores, while Mediterranean countries (Greece, Italy, Spain, France) have higher dietary scores.[25] In this study, participants engaged in device-measured MVPA for an average of 32.6 minutes/day. Although our physical activity estimates were derived using a very different accelerometer data collection and processing methods, in a previous pooled analysis of 4 European Countries including England, Norway, Portugal, and Sweden, participants from England reported slightly lower daily PA estimates (29.7 minutes/day) than in our study.[26] Another recent pooled analysis of data from 4 cohorts from Norway, Sweden, and the United States using hip accelerometers also reported an average daily estimate of 29 minutes/day of MVPA.[27] This small difference demonstrates the reliability of our device-based wrist measurements which are known to pose greater challenges in estimating MVPA compared to the hip accelerometer, but our meticulous methodological processing approaches provide accurate measures.

Although several small randomized controlled trials in selected samples showed that lifestyle intervention involving diet and PA components is efficacious for preventing T2D,[28,29] our study provides an indication from a large prospective general population cohort to comprehensively examine the joint association of PA and diet with T2D incidence. Previous trials were conducted in high-risk populations, such as participants with impaired glucose tolerance or impaired fasting glucose. The number of participants was small compared to observational studies. In our study, higher PA levels was independently associated with lower T2D, hypertension, and MCD incidence, whereas there was less evidence of an association between diet and risk of MCD. In the joint association analysis, we found that higher DQS levels were not associated with a lower risk of MCD within self-reported PA categories. More recently, Ding et al[30] evaluated 346 627 participants followed for 11.2 years to examine the joint association of diet quality and self-reported PA amounts (measured as MVPA and VPA) with all-cause and cause specific mortality (CVD and cancer) and showed that the lowest mortality risk combinations were consistently associated with the higher levels of PA and the highest DQS. Additionally, previous meta-analyses reported that higher levels of PA and a healthy diet, regardless of the type of diet quality assessment, were associated with a lower risk of T2D (35% and 13-21%, respectively).[31,32] Favorable dietary patterns for preventing T2D are characterized mainly by high consumption of plant-based foods, including whole grains, fruits, vegetables, nuts, as well as fish and poultry, and reduced consumption of red and processed meats, which are at the same time the principal characteristics of the DQS used in our study.[32] The lack of association between diet and MCD could be explained by low DQS levels of participants in this study. The total DQS ranges from 0-100. However, the mean DQS of participants was below 50 points, indicating already low DQS levels, which may neglect the beneficial role of diet and thus show no association between diet and MCD.

We showed that T2D, hypertension, and combined cardiometabolic disease risk was lower with higher levels of self-reported MVPA, irrespective of total EI, whereas only T2D risk was lower with higher levels of device-measured MVPA. There are inconsistent results about the associations between total EI and risk of developing T2D in adults, with some studies showing positive associations[33] and others null associations.[34] This may be due to underreporting of total EI in the observational studies. Our results suggest that focusing on increasing PA levels at least equally to than reducing EI or increasing diet quality will optimally improve health status.[35]

The Global Burden of Disease (GBD) 2019 provided updated disease burden rankings and estimated that deaths and disability-adjusted life-years attributable to low physical activity are less than 10% of those attributable to diet.[36] Such a finding calls into question the comparability of the lifestyle risk factors on a larger scale. The Global Burden of Disease considered diet through 15 different risk factors (9 food groups and 6 nutrients) rather than overall dietary patterns, whereas only total volume of PA was the one and only PA indicator.[37] Our results contradict GBD by suggesting that PA is at least as important as diet to prevent T2D and hypertension.

The 2020 World Health Organization guidelines on physical activity and sedentary behavior concluded that there is strong evidence for inverse relationships between physical activity and T2D and hypertension incidence, based primarily but not solely on self-reported PA.[38] In this study, we observed a lower risk of T2D and MCD in participants with middle and high self-reported MVPA levels, while high levels of device-measured MVPA were associated with a lower risk of T2D only, regardless of DQS and total EI status. In line with our study, a comparison of questionnaire-based and device-based studies in previous research demonstrated a similar dose-response curve for the relationship between physical activity and health outcomes, with device-based studies indicating a more substantial reduction in risk.[39] Results on the joint association of MVPA and diet with hypertension risk were less precise than T2D risk analysis. We found that self-reported middle and high MVPA were associated with a lower risk of hypertension, irrespective of the DQS and total EI group, whereas the association for the joint exposure of device-measured PA and diet with hypertension was less clear. The reasons for the uncertainty in evidence of the association of device-measured MVPA and diet with hypertension are not explicit. Self-reported and device-measured MVPA capture different PA constructs and have different measurement errors, for example self-reported methods capture continuous bouts of MVPA mostly done in leisure time, while accelerometers capture all physical activity regardless of domain, bout length, or intensity.[40] Because of these differences between self-reported and device-measured MVPA, both methodologies may still be necessary to fully understand the effects of PA on health outcomes.

Irrespective of total DQS, we found that T2D, hypertension, and combined cardiometabolic disease risk were lower at lower levels of DST, in line with the previous studies on the association between TV viewing time. In their meta-analysis, Guo et al found

linear associations between TV viewing and T2D and hypertension, with each additional hour per day of TV viewing associated with an 8% and 6% increased risk for T2D and hypertension, respectively.[8]

Our study has several notable strengths, including the large and well-characterized population-based cohort with longitudinal follow-up, adjustment for extensive covariates from health, socioeconomic, and behavioral information, and objective assessment of height and weight by trained staff using standardized techniques and detailed exposure-specific outcomes from hard endpoints. We were able to use self-reported and device-based measured physical activity variables. Accelerometers have several advantages over self-reports, including minimal recall bias and the ability to capture both structured exercise and incidental physical activity of light intensity.[41] We had different diet and PA exposures that allowed us to capture joint effects of multiple aspects of diet and PA. The study has some limitations. Firstly, we relied on self-reported diet, which may lead to underreporting and consequently reporting biases. Still, self-reported dietary measures demonstrated adequate reliability and validity in previous studies.[42] Participants might have overestimated their self-reported PA because of recall and social desirability biases. These biases may have affected our ability to estimate the true magnitude of associations, but substantial measurement error is unlikely as our results are comparable to similar studies.[43] The UK Biobank's low response rate may introduce selection bias and limit the generalizability of findings to the wider population. Two previous studies suggest that it is unlikely that poor representativeness affects materially our study's estimates.[44,45] Batty et al[44] compared the associations between risk factors such as physical activity and obesity, with all-cause mortality in the UK Biobank using a consortium of 18 nationally representative British cohorts comprising 89 895 adults (mean response rate 68%). Despite the substantial difference in response rates between the UK Biobank and other British cohorts, the study found close agreement in risk factor associations with mortality between the 2 data sets. Another more recent study used poststratification to match the UK Biobank sample to the UK population in terms of sociodemographic characteristics and prevalence of lifestyle risk factors (including physical activity and diet).[45] The post-stratified results suggested that physical activity and diet estimates with long-term health outcomes were not materially affected by the low response rates in the UK Biobank. The observational nature of this study precludes inferences about causality, and residual and unmeasured confounding are still possible despite a comprehensive adjustment scheme.

Conclusion

Our results primarily emphasize the role of higher PA as an important component in cardiometabolic disease prevention across all diet quality and total energy intake groups. However, we acknowledge that the absence of a significant association between diet and health outcomes could be attributed to the lower variability of the DQS values, which were mostly concentrated on the lower end of the distribution. Combined interventions encouraging people to increase physical activity and improve their diet may be a promising cardiometabolic diseases prevention intervention.

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Supplementary material

Supplementary material is available at *American Journal of Epidemiology* online.

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Conflict of interest

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

Data availability

The UK Biobank is an open-access resource and bona fide researchers can apply to use the UK Biobank data set by registering and applying at https://www.ukbiobank.ac.uk/enableyourresearch/apply-for-access. Further information is available from the corresponding author upon request.

Ethics approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

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