Nutrition Journal

RESEARCH **Open Access**

Types of dietary sugars and carbohydrates, cardiometabolic risk factors, and risk of diabetes: a cohort study from the general Danish population

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Abstract

Background The role of carbohydrates in diabetes risk is of particular interest due to conflicting results. This study aims to examine the prospective association between types of dietary carbohydrates (fiber, starch, total sugar, glucose, fructose, lactose, maltose, and added sugar) and the risk of diabetes. Further, this study examines the cross-sectional associations between these nutrients and cardiometabolic risk factors.

Methods Danish Health Examination Survey (2007–2008) investigated 76,484 Danes in a representative sample using online questionnaires. Dietary information using a food frequency questionnaire was obtained from 42,836 participants. Information on incident cases of diabetes was obtained from the Danish National Diabetes Register. Cox proportional hazard models were used to estimate Hazard Ratios (95% CI). Multiple linear regression analyses were used to assess the associations between carbohydrate types and cardiometabolic risk factors measured in a subsample of 12,977 participants.

Results During a median follow-up of 4.9 years, 970 participants developed diabetes. A higher consumption of fructose, but a lower consumption of glucose was associated with a lower risk of diabetes. In subgroup analyses, these associations were only significant among individuals with other risk factors, such as older age, obesity, low fiber consumption, sedentary behavior, smoking status, and hypertension. Participants with a higher intake of fiber tend to have a lower risk of diabetes and healthier anthropometric parameters compared to those with a lower intake.

Conclusions Our findings suggest that a higher intake of dietary fiber and fructose is associated with a lower risk of diabetes and healthier metabolic status, while higher glucose intake is associated with a higher diabetes risk.

Keywords Diabetes, Sugar, Fructose, Dietary fiber, Public health

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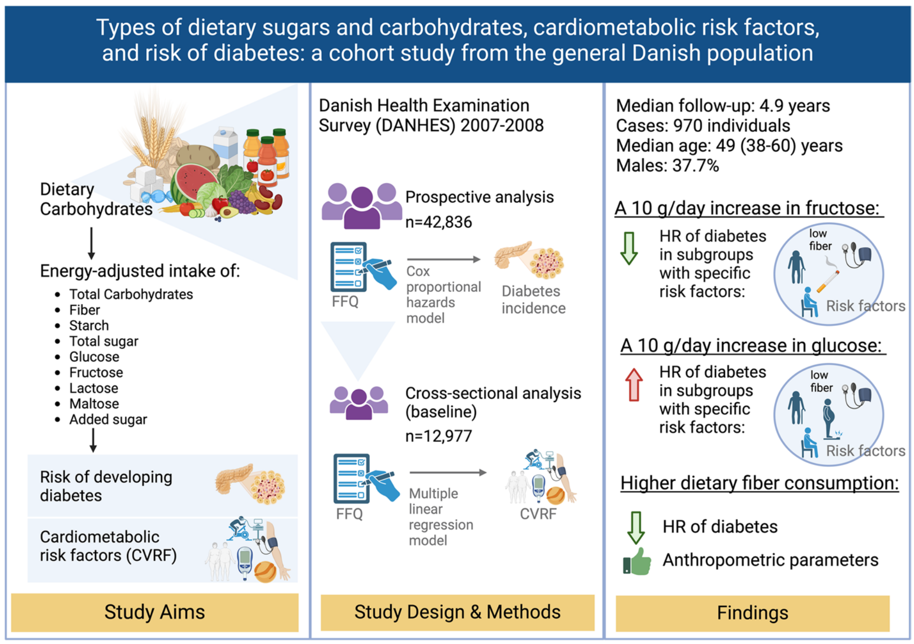
Graphical Abstract



Background

The role of dietary carbohydrates in the development of type 2 diabetes has been a subject of particular interest due to the conflicting results in previous studies [1, 2]. The association between total carbohydrate intake and type 2 diabetes has shown mixed results in previous cohort studies, with the majority showing no significant associations [2]. However, a recent meta-analysis of 18 prospective cohort studies concluded that total carbohydrate intake of more than 70% of total energy intake is associated with a higher risk of type 2 diabetes [3]. In addition, intervention studies suggest that dietary carbohydrate restriction yield benefits for individuals with prediabetes and type 2 diabetes [4, 5]. Conversely, in a healthy population, the evidence regarding the long-term effects of low-carbohydrate diets on type 2 diabetes risk is inconclusive [6].

The recommended daily intake of total carbohydrates is 45–60% of total energy intake, and it is recommended to keep the daily intake of added sugar below 10% [7]. Poor carbohydrate quality has been recognized as an important risk factor for type 2 diabetes. The glycemic index and glycemic load have been positively linked to the risk of type 2 diabetes in the US, Europe and Asia [2], and high dietary sugar intake is associated with type 2 diabetes and cardiovascular disease [8, 9]. On the contrary, other carbohydrate sources, such as whole grain and fiber intake, have consistently shown inverse associations [10, 11]. The term added sugar refers to sucrose, fructose, glucose, starch hydrolysates, or other isolated sugar preparations used as such or added during food preparation and manufacturing [7]. Consuming added sugar in the form of sugar-sweetened beverages (SSBs) and artificially sweetened beverages (ASBs) has been linked to type 2 diabetes [12]. The negative health effects associated with added sugar (often fructose), have resulted in the availability of a large variety of products containing artificial sweeteners as sugar alternatives.

Despite a large body of evidence linking added sugar and chronic diseases, many studies to date have largely assessed total sugar consumption without investigating associations with different sugar types [13]. Evaluating the potential role of specific sugar types on a wide range of cardiometabolic risk factors and risk of diabetes could help refine nutritional recommendations for carbohydrate intake and add new data for setting a tolerable upper intake level for dietary sugars –referring to the maximum level of chronic daily intake of a particular type of sugar from all dietary sources deemed to be unlikely to pose an increased risk of diabetes [13]. Therefore, the present study seeks to evaluate the associations between different carbohydrates and specific sugar types and the risk of developing diabetes. Additionally, we examined the cross-sectional associations between these nutrients and a range of cardiometabolic risk factors, such as blood pressure, serum concentrations of glycated hemoglobin (HbA1c), triglycerides (TG), and total cholesterol, body composition, and physical fitness in a large prospective cohort of the general Danish population.

Methods

Study design and population

We used data from the Danish Health Examination Survey (DANHES) 2007–2008 [14]. DANHES was conducted in 13 of 98 municipalities in Denmark, where all citizens aged ≥ 18 years were invited to complete a questionnaire concerning social factors, lifestyle, and general health (n = 538,497). A random sub-sample was also invited to fill out a supplementary food frequency questionnaire (FFQ) and to participate in a general health examination (n = 180,103). Out of the sub-sample of 180,103 individuals, 47,682 completed the FFQ, and 18,065 participated in the health examination.

The main study population included individuals who completed the FFQ. We excluded individuals with implausible daily calorie intake (< 800 kcal or > 4200 for males and < 600 kcal or > 3500 for females) (n = 2,956) and individuals with a known diagnosis of diabetes (n = 1,890) from the study population. Therefore, the final study population consisted of 42,836 individuals (26,668 females and 16,168 males). Participants in the health examination were included in the present paper to study the cross-sectional associations between dietary intake of different types of sugar and cardiometabolic risk factors. The number of participants with measured cardiometabolic risk factors was 12,977 (7,858 females and 5,119 males) (Supplemental Fig. 1).

Assessment of diet

A self-administered validated semi-quantitative FFQ, incorporating food frequency and portion sizes through photographs of food items, was used to assess dietary intake based on the intake over the previous year [15, 16]. The original questionnaire comprises 92 food items and 40 portion-size photographs and was validated against two times seven-day weighted diet records in 144 middle-aged subjects from the general population in Copenhagen. Pearson correlation coefficients for energy-adjusted nutrient intake were 0.40 (men) and 0.47 (women) for carbohydrates, 0.50 (men) and 0.41 (women) for sucrose, and 0.39 (men) and 0.53 (women) for dietary fiber [15].

In the DANHES the questionnaire was slightly modified for online administration, and very few food items were omitted. The FoodCalc® program was used to calculate the total energy intake (kcal/day), consumption of food groups (g/day), and nutrients (g/day) using food composition tables. Specifically, the following nutrients were included as exposure variables: total carbohydrates, fiber, starch, total sugar, glucose, fructose, lactose, maltose, and added sugar. The daily intake of each exposure variable was divided into energy-adjusted quintiles by sex using the residual method [17], as the correlations between energy intake and individual nutrient intakes differ between females and males.

The food groups that are major contributors to the intakes of total sugars include sweet products, fruits and vegetables, beverages, and dairy products [18–20]. Yogurt and milk were considered sugar sources given the wide range of flavoured options in the supermarkets. Dairy consumption (g/day) did not include ice cream and cheese consumption. Total juice intake was calculated based on the sum of orange/grape, apple, carrot, and tomato/other vegetable juice intake from the FFQ. Total SSBs consumption was the sum of sugar-sweetened soda and diluting juice beverages. Total ASBs consumption includes the sum of light soda and diluting juice beverages. A standard conversion of 200 mL/glass was used to translate portions to milliliters.

Assessment of diabetes

Linkage of participants to the Danish National Diabetes Register, where information on diabetes events during follow-up was obtained, was possible via the unique personal identification number assigned to all citizens in Denmark (follow-up end: December 29, 2012). The registry uses five diagnostic criteria: 1) hospitalization with a diagnosis of diabetes according to the International Classification of Diseases (ICD) 8th or 10th Revisions (ICD-8 codes 249 or 250; ICD-10 codes E10-14, H36.0, or O24 [excluding O24.4]) obtained from the Danish National Patient Registry; 2) registration of chiropody (coded for diabetes) in the Danish National Health Service Register; 3) registration in the Danish National Health Service Register with measurement of blood glucose five or more times within 365 days; 4) two or more annual measurements of glucose during 5 years; and 5) registration in the Danish National Prescription Registry with a prescription of insulin or oral glucose-lowering medication on at least two occasions. If one of these criteria is met, an individual is registered as having diabetes. The register does not distinguish between type 1 and type 2 diabetes.

Participants in DANHES completed questionnaires including sociodemographic information. Information on age and sex was obtained from the Danish Civil Registration System. The following covariates were included: age, sex, body mass index (BMI), total energy intake, smoking status, alcohol consumption, leisure-time physical activity, menopause, family history of diabetes, length of education, hypertension, and dietary factors. Data on self-reported health were obtained from the DANHES-questionnaire, where participants were asked to rate their overall health on a scale of 1 to 10, with 10 being the best possible level of health. All covariates, except for age and sex, were self-reported in the DANHES.

Assessment of cardiometabolic risk factors

Biochemical analysis from non-fasting blood, blood pressure, anthropometric measurements, and aerobic fitness test (Watt-max bike test) were performed by the staff members. Clinical measurements were performed by trained technical health personnel following standard protocols. Detailed information can be found elsewhere [14].

Statistical analyses

Participants were followed from baseline (participation in the DANHES 2007/2008) until the diagnosis of diabetes ($n=970$), emigration ($n=301$), death ($n=529$), or December 29, 2012, whichever occurred first. Cox proportional hazards regression with age as the underlying time scale was used to estimate the risk of diabetes by quintiles of energy-adjusted intake of exposure variables by sex. The reference category was the lowest quintile of energy-adjusted intake. We conducted the Cox proportional hazard models stratified by sex and adjusted for several confounders. Model 1 was adjusted for age. Model 2 was further adjusted for BMI, total energy intake, smoking status, alcohol consumption, physical activity, menopause, family history of diabetes, length of education, and hypertension. Model 3 was further adjusted for the ratio of polyunsaturated fat to saturated fat, trans-fat, and magnesium. The model in which fiber intake is the exposure was additionally adjusted for total sugar intake. The model for starch intake was additionally adjusted for fiber, weekly intake of SSB, and intake of fruits and vegetables. The models for total sugar, fructose, and added sugar were additionally adjusted for fiber. Models for glucose, fructose, lactose, and maltose were mutually adjusted. Tests for linear trends were conducted using quintiles of dietary intake as continuous variables.

To overcome possible reverse causation (individuals with pre-diabetes may have changed their diet), we excluded the first two years of risk time from the analyses. To investigate the non-linear relationship between exposure and the risk of diabetes, analyses were repeated modeling energy-adjusted dietary intake continuously using cubic splines by sex. A restricted cubic spline model with 4 knots was fitted. For each nutrient, the median energy-adjusted intake in the lowest quintile was used as a reference. To minimize the influence of outliers, we excluded participants with total carbohydrate intake below the 1st percentile and those with an energy-adjusted intake of other nutrients below 0 g/day, as well as participants with nutrient intakes above the 99th percentile for all nutrients. We conducted also stratified analyses by age, BMI, hypertension, fiber intake (< median (24.7 g/day) and ≥ median), smoking status, alcohol intake, family history of diabetes, and physical activity, using energy-adjusted nutrient intake values stratified by sex and accounting for a specific daily increase in the consumption of each nutrient. The multiplicative interaction was tested between fructose and glucose (quintiles of energy-adjusted intake by sex) and physical activity (vigorous, moderate, light, sedentary) by a likelihood-ratio test of the multivariable-adjusted model with and without the cross-product interaction term by sex.

Multiple linear regression analyses were used to assess the associations between carbohydrate and sugar intake and cardiometabolic risk factors. Cardiometabolic risk factors that were not normally distributed were logarithmically transformed (systolic blood pressure (SBP), diastolic blood pressure (DBP), total cholesterol, TG, and HbA1c). The means of each cardiometabolic risk factor by sex-specific quintiles of energy-adjusted intake of the exposure variables were calculated as geometric means, along with 95% CI. Model 3 was used as the model of adjustment for all linear regression models. Tests for trends were conducted using quintiles of energy-adjusted intake as continuous variables in the regression models. The significance level was set to a p-value of 0.05 (two-sided). We did not calculate corrected p-values for multiple comparisons, as our focus was on patterns of changes in cardiometabolic factors rather than on individual p-values for significance. Analyses were performed using STATA Software version 18.

Results

Participant characteristics

The final study population included 42,836 individuals aged 18–95 years (median 49 years) of whom 37.7% were males. The study population is broadly representative of the general Danish adult population. However, in the DANHES survey, females aged 45–64 years were overrepresented whereas younger males, eldest females, individuals with lower education, lowest income, and unmarried individuals were underrepresented compared to the general Danish population [14]. About 19% of the population had hypertension which corresponds well with the general Danish population [21]. The median consumption of fruits and vegetables was 557 (384–767) g/day (Table 1). Around 20% of the study population had a fat intake above the recommended 35% of daily energy intake (median: 30, IQR: 26–34%), 8% consumed more than the recommended 60% from carbohydrates

Table 1 Baseline characteristics of the DANHES study population across quintiles-energy adjusted intake of total carbohydrates by sex

	Total	Females			Males		
		Q1	Q3	Q5	Q1	Q3	Q5
Sample from questionnaire							
N	42836	5334	5333	5333	3234	3233	3233
Intake of total carbohydrates[a], g/d	267 (242–292)	205 (189–215)	251 (247–255)	294 (286–309)	238 (219–249)	294 (289–299)	349 (338–366)
Sociodemographics							
Age, years	49 (38–60)	51 (41–61)	48 (36–58)	45 (33–56)	56 (46–64)	51 (39–62)	48 (37–60)
Married or living with a partner, *n* (%)	32918 (76.9)	4054 (76.0)	4053 (76.0)	3844 (72.2)	2603 (80.5)	262 (81.3)	2481 (76.8)
Ethnicity other than Danish, *n* (%)	1275 (3.0)	223 (4.2)	163 (3.0)	133 (2.5)	97 (3.0)	89 (2.8)	61 (1.9)
Education > 14 years, *n* (%)	20466 (49.0)	2430 (46.7)	2567 (49.3)	2724 (52.5)	1394 (44.7)	1470 (46.8)	1559 (49.5)
Lifestyle							
Current smoker, *n* (%)	7584 (17.7)	1283 (24.1)	878 (16.5)	724 (13.6)	931 (28.8)	493 (15.3)	394 (12.2)
Alcohol, drinks/week	6 (2–11)	7 (3–13)	4 (2–8)	3 (1–6)	14 (7–24)	8 (4–13)	6 (2–10)
Moderate to vigorous leisure time PA, *n* (%)	12457 (29.2)	1282 (24.1)	1272 (24.0)	1559 (29.3)	959 (29.8)	1219 (37.8)	1441 (44.8)
Fruit and vegetables intake, g/d	557 (384–767)	520 (358–725)	553 (392–747)	701 (504–948)	461 (318–628)	498 (345–677)	677 (483–910)
Weekly intake of SSB, *n* (%)	11970 (27.9)	1034 (19.4)	1161 (21.8)	1437 (26.9)	1078 (33.3)	1145 (35.4)	1362 (42.1)
Family history of diabetes, *n* (%)	6785 (16.4)	946 (18.4)	846 (16.4)	805 (15.6)	500 (16.1)	480 (15.4)	478 (15.3)
Hypertension, *n* (%)	8494 (19.8)	1124 (21.1)	981 (18.4)	931 (17.5)	858 (26.5)	663 (20.5)	607 (18.8)
BMI, kg/m^2	24.3 (22.1–26.9)	24.0 (21.7–26.9)	23.6 (21.6–26.5)	23.3 (21.2–26.0)	25.8 (23.8–28.3)	25.3 (23.4–27.5)	24.8 (23.0–26.9)
Poor self-rated health, *n* (%)	1238 (2.9)	227 (4.3)	164 (3.1)	129 (2.4)	127 (3.9)	74 (2.3)	74 (2.3)
Sub-sample from health examination							
N	12977	1572	2571	1571	1024	1024	1023
Intake of total carbohydrates[a], g/d	274 (249–298)	229 (214–239)	275 (271–279)	316 (308–332)	218 (200–229)	1024 (269–279)	329 (318–346)
Sociodemographics							
Age, years	52 (42–62)	54 (44–61)	52 (41–61)	49 (39–59)	57 (48–65)	53 (42–63)	51 (40–62)
Married or living with a partner, *n* (%)	10501 (81.0)	1227 (78.2)	1256 (80.0)	1198 (76.5)	866 (84.6)	863 (84.4)	841 (82.3)
Ethnicity other than Danish, *n* (%)	418 (3.2)	76 (4.8)	42 (2.7)	43 (2.7)	34 (3.3)	30 (2.9)	24 (2.3)
Education > 14 years, *n* (%)	5765 (45.2)	683 (44.2)	701 (45.4)	731 (47.4)	431 (43.1)	449 (44.7)	429 (42.5)
Lifestyle							
Current smoker, *n* (%)	1975 (15.2)	344 (2399)	200 (12.8)	183 (11.6)	251 (24.5)	146 (14.3)	107 (10.5)
Alcohol, drinks/week	6 (2–11)	7 (3–13)	4 (2–8)	3 (1–6)	14 (7–24)	8 (4–14)	5 (2–9)
Moderate to vigorous leisure time PA, *n* (%)	3824 (29.7)	310 (19.9)	408 (26.2)	463 (29.5)	301 (29.7)	389 (38.2)	438 (43.2)
Fruit and vegetables intake, g/d	593 (421–795)	548 (384–745)	587 (437–791)	734 (543–974)	490 (344–668)	540 (379–721)	729 (539–964)
Weekly intake of SSB, *n* (%)	3532 (27.2)	272 (17.3)	336 (21.4)	395 (25.1)	337 (32.9)	366 (25.7)	412 (40.3)
Family history of diabetes, *n* (%)	2198 (17.4)	299 (19.5)	246 (16.1)	256 (16.7)	168 (17.1)	159 (15.9)	174 (17.6)
Hypertension, *n* (%)	2673 (20.6)	340 (21.6)	307 (19.5)	300 (19.1)	257 (25.1)	209 (20.4)	200 (19.6)
BMI, kg/m^2	24.3 (22.2–26.8)	23.9 (21.6–26.7)	23.6 (21.6–26.3)	23.3 (21.3–25.7)	25.8 (23.9–28.1)	25.3 (23.5–27.4)	24.8 (23.0–26.6)
Poor self-rated health, *n* (%)	311 (2.4)	61 (3.9)	41 (2.6)	31 (2.0)	30 (2.9)	14 (1.4)	15 (1.5)

Data are presented as median (IQR) unless otherwise specified as numbers (%)

BMI Body mass index, *DANHES* Danish Health Examination Survey, *N* sample size, *PA* Physical activity, *Q* Quintile, *SSB* Sugar-sweetened beverages

[a] Expressed as energy-adjusted intake

(median: 50, IQR: 45–55%), and 10% consumed more than the recommended 10% of added sugars (median 4.4, IQR: 2.7–6.8%). Half of the study population did not follow the recommended intake of at least 25 g/day of fiber (median: 25, IQR: 18–32 g/day) [7].

Table 1 presents the baseline characteristics of the study population, as well as those of the health examination subsample, categorized by total carbohydrates (Q1, Q3, and Q5). Baseline characteristics for all quintiles can be found the Supplemental Table 1. Participants with a higher intake of total carbohydrates were younger, less likely to be current smokers, consume fewer alcoholic drinks, have a higher intake of fruit and vegetables, and were less likely to have poor self-rated health than participants with a lower intake. The proportion of participants with a weekly intake of SSB was higher for participants with a higher intake of total carbohydrates. Those with higher total carbohydrate consumption were more likely to engage in moderate to vigorous physical activity. This pattern was more pronounced among males.

Independent associations of nutrient intakes with the risk of diabetes

During a median follow-up of 4.9 years, 970 participants were diagnosed with diabetes. The incidence of diabetes cases per 10,000 person-years was higher among males than in females across all quintiles of carbohydrate and sugar intake. The associations between the intake of carbohydrates and types of sugars and the risk of diabetes are presented in Table 2. HR for all quintiles can be found in Supplemental Tables 2 and 3.

A significantly lower risk of diabetes was found with higher fructose intake in males (*p*-trend: 0.040), after adjusting for lifestyle, nutritional factors, and the intake of other individual sugars (model 3). A similar trend was also observed in females (HR: 0.59 (0.34–1.03) and *p*-trend: 0.051). Results from the restricted cubic spline model in females also showed an inverse association between fructose intake, particularly around 27 (22–32) g/day, and diabetes risk. Conversely, higher glucose consumption was associated with a higher risk of diabetes in males (Q5 vs. Q1 HR: 1.91; 95% CI: 1.09, 3.34) (Table 2, Supplemental Table 3 and Supplemental Fig. 2), and among females, each 10 g/day increase in glucose intake was significantly associated with a 27% (5–52%) higher risk of diabetes. Results on the consumption of fructose and glucose food sources by energy-adjusted intake quintiles showed a higher intake of fruits, fruits and vegetables, and fruit and vegetable juices and less intake of SSB and red meat in the highest fructose and glucose quintiles. Sugar and sweet intake were also higher across all glucose quintiles (Supplemental Table 4 and 5). Sociodemographic characteristics across fructose and glucose energy-adjusted intake quintiles differ in age (only among fructose quintiles), education, smoking, and level of leisure physical activity. Individuals in the higher quintiles of fructose and glucose (Q5) were older, had higher education, less likely to be smokers, more physically active and with a higher consumption of dietary fiber (Supplemental Table 4 and 5).

There was a significant inverse association between fiber intake and diabetes risk in age-adjusted models for both males and females. However, the associations were attenuated when other risk factors were included in the models. The restricted cubic spline models for fiber showed an inverse association with diabetes risk in both sexes, although non-significant (Supplemental Fig. 2). Our findings remained consistent after excluding the first two years of risk time from the analyses, except for fructose, where the protective association was attenuated, and for glucose in female, where the association disappeared. The inverse trends between added sugar and risk of diabetes among female also disappeared around 40 g/day (Supplemental Fig. 2) and after excluding the first two years of follow-up (*p*-trend: 0.472). No significant associations were found for other subtypes of sugar, starch, or total carbohydrate intake.

Subgroup analyses

A higher intake of total carbohydrates was inversely associated with diabetes in individuals with a BMI below 30 kg/m^2, with fiber intake equal to or greater than the total cohort median ($\geq$24.7 g/day), those with no family history of diabetes, or those with low leisure-time physical activity. A 20 g/day increase in fiber intake was also associated with a lower risk of diabetes, but only among participants with a BMI of 30 kg/m^2 or above, those who had never smoked, those with no family history of diabetes, or those with low leisure-time physical activity (Table 3).

A 10 g/day increase in glucose or fructose showed opposite results, with fructose being protective, in subgroups at higher risk for diabetes—including older individuals ($\geq$60 years), those with obesity ($\geq$30 kg/m^2), those with low fiber consumption (<24.7 g/day) and those with sedentary behavior. Higher fructose intake was also inversely associated with diabetes risk among current and former smokers, as well as among individuals with hypertension (Table 3). We observed a significant multiplicative interaction between physical activity and risk of diabetes for both 10 g increase in fructose and glucose (*p*-value fructose*physical activity: 0.001; *p*-value glucose*physical activity: 0.027) among males.

Table 2 HR and 95% CI of diabetes by quintiles of energy-adjusted intake of carbohydrates and sugars by sex

	Females					Males				
	Quintile of energy-adjusted intake			*P* for trend	HR (95% CI) for *x* g increase in nutrient intake	Quintile of energy-adjusted intake			*P* for trend	HR (95% CI) for *x* g increase in nutrient intake
	Q1	Q3	Q5			Q1	Q3	Q5		
Total carbohydrates										
Cases/10,000 person-years	51.8	41.3	36.5			85.7	45.2	39.2		
Median intake (g/d)	205	251	294		*100 g increase*	238	294	349		*100 g increase*
Model 1	1.00 (Ref.)	0.92 (0.71–1.18)	0.89 (0.68–1.16)	0.184	0.83 (0.66–1.05)	1.00 (Ref.)	0.63 (0.47–0.84)	0.62 (0.46–0.84)	0.002	0.70 (0.58–0.86)
Model 2	1.00 (Ref.)	1.05 (0.79–1.38)	0.97 (0.72–1.29)	0.568	0.92 (0.71–1.19)	1.00 (Ref.)	0.78 (0.57–1.07)	0.81 (0.57–1.14)	0.394	0.90 (0.72–1.13)
Model 3	1.00 (Ref.)	1.02 (0.77–1.36)	0.99 (0.72–1.38)	0.705	0.93 (0.70–1.24)	1.00 (Ref.)	0.73 (0.53–1.00)	0.73 (0.50–1.07)	0.183	0.84 (0.65–1.09)
Fiber										
Cases/10,000 person-years	42.9	40.3	35.7			72.4	57.2	53.0		
Median intake (g/d)	16.1	24.4	33.7		*20 g increase*	17.2	26.9	37.8		*20 g increase*
Model 1	1.00 (Ref.)	0.80 (0.61–1.04)	0.69 (0.53–0.92)	0.007	0.69 (0.54–0.90)	1.00 (Ref.)	0.68 (0.51–0.90)	0.63 (0.48–0.84)	0.001	0.64 (0.51–0.80)
Model 2	1.00 (Ref.)	1.04 (0.77–1.39)	0.89 (0.65–1.21)	0.300	0.88 (0.67–1.15)	1.00 (Ref.)	0.82 (0.60–1.10)	0.90 (0.66–1.21)	0.526	0.88 (0.68–1.12)
Model 3	1.00 (Ref.)	1.00 (0.74–1.36)	0.87 (0.61–1.23)	0.288	0.85 (0.62–1.17)	1.00 (Ref.)	0.79 (0.58–1.08)	0.81 (0.57–1.15)	0.257	0.79 (0.59–1.06)
Starch										
Cases/10,000 person-years	47.9	34.0	38.0			80.7	48.6	50.5		
Median intake (g/d)	53.5	81.8	114.4		*50 g increase*	72.2	106.8	148.1		*50 g increase*
Model 1	1.00 (Ref.)	0.68 (0.52–0.90)	0.80 (0.61–1.04)	0.169	0.95 (0.79–1.13)	1.00 (Ref.)	0.61 (0.46–0.81)	0.70 (0.53–0.92)	0.013	0.83 (0.71–0.96)
Model 2	1.00 (Ref.)	0.78 (0.59–1.05)	0.88 (0.66–1.16)	0.540	1.02 (0.85–1.22)	1.00 (Ref.)	0.72 (0.53–0.97)	0.87 (0.64–1.17)	0.440	0.95 (0.81–1.12)
Model 3	1.00 (Ref.)	0.77 (0.56–1.05)	0.85 (0.60–1.23)	0.530	1.06 (0.84–1.34)	1.00 (Ref.)	0.73 (0.52–1.01)	0.80 (0.53–1.02)	0.382	0.94 (0.74–1.18)
Total sugar										
Cases/10,000 person-years	46.9	35.9	30.4			67.7	54.4	49.3		
Median intake (g/d)	61.5	95.6	135.8		*50 g increase*	65.9	103.3	149.9		*50 g increase*
Model 1	1.00 (Ref.)	0.79 (0.60–1.03)	0.78 (0.59–1.03)	0.162	0.93 (0.80–1.07)	1.00 (Ref.)	0.85 (0.64–1.14)	0.90 (0.67–1.20)	0.221	0.93 (0.81–1.07)
Model 2	1.00 (Ref.)	0.90 (0.68–1.20)	0.78 (0.58–1.06)	0.195	0.93 (0.80–1.08)	1.00 (Ref.)	0.87 (0.64–1.18)	0.96 (0.72–1.35)	0.601	0.97 (0.84–1.12)
Model 3	1.00 (Ref.)	0.88 (0.65–1.17)	0.74 (0.53–1.03)	0.128	0.91 (0.77–1.07)	1.00 (Ref.)	0.83 (0.60–1.14)	0.89 (0.63–1.25)	0.259	0.92 (0.79–1.08)
Glucose										
Cases/10,000 person-years	44.2	34.3	39.7			55.6	70.8	58.1		
Median intake (g/d)	6.6	12.7	21.3		*10 g increase*	5.4	11.7	21.7		*10 g increase*
Model 1	1.00 (Ref.)	0.78 (0.59–1.03)	0.87 (0.66–1.14)	0.073	0.96 (0.84–1.10)	1.00 (Ref.)	1.23 (0.93–1.63)	0.97 (0.72–1.30)	0.049	0.87 (0.76–1.00)
Model 2	1.00 (Ref.)	0.88 (0.66–1.19)	1.00 (0.75–1.33)	0.619	1.04 (0.91–1.19)	1.00 (Ref.)	1.48 (1.09–2.01)	1.24 (0.90–1.72)	0.456	0.95 (0.83–1.09)
Model 3	1.00 (Ref.)	1.00 (0.67–1.48)	1.45 (0.90–2.32)	0.188	1.27 (1.05–1.52)	1.00 (Ref.)	1.91 (1.22–2.99)	1.91 (1.09–3.34)	0.304	1.06 (0.86–1.33)
Fructose										
Cases/10,000 person-years	41.2	41.6	38.6			56.5	58.5	54.7		
Median intake (g/d)	6.8	15.3	27.4		*10 g increase*	5.1	13.0	26.9		*10 g increase*
Model 1	1.00 (Ref.)	0.87 (0.67–1.14)	0.70 (0.53–0.92)	0.003	0.89 (0.80–0.99)	1.00 (Ref.)	0.84 (0.63–1.13)	0.72 (0.53–0.96)	0.002	0.87 (0.79–0.97)

Table 2 (continued)

	Females					Males				
	Quintile of energy-adjusted intake			*P* for trend	HR (95% CI) for *x* g increase in nutrient intake	Quintile of energy-adjusted intake			*P* for trend	HR (95% CI) for *x* g increase in nutrient intake
	Q1	Q3	Q5			Q1	Q3	Q5		
Model 2	1.00 (Ref.)	1.04 (0.58–1.39)	0.84 (0.62–1.03)	0.141	0.95 (0.85–1.06)	1.00 (Ref.)	1.06 (0.77–1.46)	0.92 (0.66–1.27)	0.195	0.94 (0.84–1.05)
Model 3	1.00 (Ref.)	0.95 (0.63–1.43)	0.59 (0.34–1.03)	0.051	0.88 (0.71–1.09)	1.00 (Ref.)	0.70 (0.44–1.11)	0.53 (0.28–1.01)	0.040	0.84 (0.68–1.05)
Lactose										
Cases/10,000 person-years	41.3	33.7	36.3			67.5	47.9	65.6		
Median intake (g/d)	2.3	11.8	29.8		*10 g increase*	2.9	13.9	35.3		*10 g increase*
Model 1	1.00 (Ref.)	0.96 (0.72–1.27)	1.17 (0.88–1.54)	0.230	1.05 (0.98–1.12)	1.00 (Ref.)	0.84 (0.62–1.13)	1.40 (1.07–1.84)	0.007	1.09 (1.03–1.15)
Model 2	1.00 (Ref.)	1.06 (0.78–1.45)	1.17 (0.86–1.58)	0.361	1.02 (0.96–1.10)	1.00 (Ref.)	0.80 (0.57–1.11)	1.30 (0.97–1.75)	0.015	1.07 (1.01–1.13)
Model 3	1.00 (Ref.)	1.05 (0.76–1.43)	1.09 (0.78–1.52)	0.685	1.00 (0.91–1.09)	1.00 (Ref.)	0.75 (0.54–1.05)	0.19 (0.85–1.66)	0.145	1.05 (0.98–1.12)
Maltose										
Cases/10,000 person-years	51.2	36.4	33.6			72.8	58.1	42.6		
Median intake (g/d)	1.6	3.6	6.4		*5 g increase*	2.1	4.5	7.6		*5 g increase*
Model 1	1.00 (Ref.)	0.78 (0.59–1.01)	0.93 (0.71–1.22)	0.361	0.97 (0.77–1.22)	1.00 (Ref.)	0.86 (0.65–1.14)	0.83 (0.61–1.13)	0.213	0.86 (0.69–1.07)
Model 2	1.00 (Ref.)	0.86 (0.64–1.15)	0.91 (0.68–1.21)	0.389	0.91 (0.72–1.14)	1.00 (Ref.)	0.95 (0.71–1.28)	0.92 (0.67–1.27)	0.506	0.91 (0.72–1.14)
Model 3	1.00 (Ref.)	0.84 (0.63–1.12)	0.87 (0.64–1.18)	0.254	0.86 (0.67–1.09)	1.00 (Ref.)	0.93 (0.69–1.26)	0.86 (0.61–1.21)	0.315	0.85 (0.67–1.09)
Added sugar										
Cases/10,000 person-years	51.4	37.6	39.9			68.6	59.8	53.4		
Median intake (g/d)	7.7	23.8	51.5		*20 g increase*	9.7	27.9	60.6		*20 g increase*
Model 1	1.00 (Ref.)	0.78 (0.60–1.02)	1.04 (0.80–1.35)	0.663	1.02 (0.94–1.12)	1.00 (Ref.)	0.94 (0.71–1.24)	1.04 (0.78–1.38)	0.736	1.00 (0.92–1.09)
Model 2	1.00 (Ref.)	0.75 (0.55–1.01)	0.85 (0.64–1.12)	0.106	0.94 (0.86–1.03)	1.00 (Ref.)	1.03 (0.75–1.41)	1.05 (0.77–1.44)	0.785	0.98 (0.90–1.07)
Model 3	1.00 (Ref.)	0.71 (0.52–0.97)	0.78 (0.57–1.07)	0.036	0.92 (0.83–1.02)	1.00 (Ref.)	1.05 (0.76–1.45)	1.07 (0.76–1.49)	0.862	0.98 (0.89–1.07)

HRs and 95% CI were calculated with the use of Cox proportional hazard regression model

Model 1: age (continuous); Model 2: model 1 + BMI (< 21, 21- < 23, 23- < 25, 25- < 27, 27- < 30, 30- < 33, 33- < 35, 35- < 40, ≥ 40), total energy intake (kcal/day in quintiles), smoking status (never, past, current 1–15/day, current > = 15/day), alcohol consumption (0, 1–5, 6–10, 11–15, > 15), leisure time physical activity (vigorous, moderate, light, sedentary), menopause (yes, no), family history of diabetes (yes, no), education (< 10 years, 10–12 years, 13–14 years, ≥ 15 years), hypertension (yes, no); Model 3: model 2 + ratio of polyunsaturated fat to saturated fat (quintiles by sex), trans fat (quintiles by sex), and magnesium (quintiles by sex). The model for fiber was additionally adjusted for total sugar intake (energy-adjusted quintiles). The model for starch was additionally adjusted for fiber (energy-adjusted quintiles), sugar-sweetened beverages (yes, no), and intake of fruit (energy-adjusted quintiles) and vegetables (energy-adjusted quintiles). Models total sugar, fructose and added sugar were additionally adjusted for fiber (energy-adjusted quintiles). Glucose, fructose, lactose and maltose intake were mutually adjusted (energy-adjusted quintiles)

Test for trend based on quintile of energy-adjusted dietary intake as continuous variables

Q Quintiles

Table 3 HR and 95% CI of diabetes for *x* g increase in nutrient intake stratified by age, BMI, hypertension, fiber intake, smoking status, alcohol intake, family history of diabetes, and physical activity

HR (95% CI) for *x* g increase in energy-adjusted nutrient intake by sex									
	Total carbohydrates (100 g increase)	**Fiber (20 g increase)**	**Starch (50 g increase)**	**Total sugar (50 g increase)**	**Glucose (10 g increase)**	**Fructose (10 g increase)**	**Lactose (10 g increase)**	**Maltose (5 g increase)**	**Added sugar (20 g increase)**
Age < 60 years	0.78 (0.60–1.02)	0.76 (0.55–1.03)	0.89 (0.68–1.15)	0.92 (0.79–1.08)	1.27 (0.97–1.66)	0.78 (0.58–1.04)	1.04 (0.96–1.12)	0.81 (0.65–1.02)	0.95 (0.87–1.04)
Age ≥ 60 years	0.92 (0.70–1.20)	0.78 (0.58–1.06)	1.24 (0.97–1.59)	0.89 (0.75–1.06)	1.32 (1.01–1.72)	0.72 (0.54–0.97)	1.03 (0.96–1.11)	0.98 (0.74–1.29)	0.94 (0.84–2.19)
BMI < 30 kg/m^2	0.77 (0.61–0.97)	0.80 (0.61–1.04)	1.00 (0.81–1.24)	0.84 (0.73–0.97)	1.15 (0.92–1.45)	0.93 (0.84–1.02)	1.00 (0.94–1.07)	0.88 (0.71–1.09)	0.92 (0.84–1.01)
BMI ≥ 30 kg/m^2	0.80 (0.57–1.12)	0.58 (0.40–0.86)	0.99 (0.72–1.35)	0.98 (0.81–1.18)	1.54 (1.12–2.13)	0.95 (0.82–1.10)	1.09 (1.00–1.19)	0.79 (0.59–1.06)	0.95 (0.86–1.06)
No Hypertension	0.85 (0.65–1.11)	0.75 (0.55–1.03)	1.15 (0.90–1.46)	0.98 (0.83–1.15)	1.29 (1.01–1.66)	0.79 (0.60–1.05)	1.04 (0.97–1.12)	0.77 (0.60–0.97)	0.92 (0.83–1.02)
Hypertension	0.85 (0.65–1.12)	0.79 (0.59–1.06)	0.92 (0.71–1.19)	0.84 (0.71–0.99)	1.22 (0.93–1.61)	0.70 (0.52–0.94)	1.02 (0.95–1.10)	0.97 (0.76–1.23)	0.98 (0.89–1.09)
Fiber intake ≥ median	0.73 (0.55–0.96)	0.76 (0.54–1.06)	1.02 (0.82–1.28)	0.82 (0.70–0.97)	1.19 (0.88–1.16)	0.79 (0.62–1.02)	1.09 (1.01–1.18)	0.84 (0.66–1.08)	0.85 (0.76–0.95)
Fiber intake < median	1.02 (0.76–1.39)	0.70 (0.44–1.10)	1.11 (0.82–1.50)	1.00 (0.85–1.18)	1.68 (1.20–2.35)	0.56 (0.39–0.83)	0.98 (0.91–1.06)	0.80 (0.60–1.05)	1.03 (0.94–1.12)
Never smoker	0.84 (0.61–1.15)	0.64 (0.45–0.92)	1.08 (0.82–1.42)	0.93 (0.78–1.12)	1.20 (0.90–1.60)	0.91 (0.67–1.23)	1.02 (0.94–1.11)	0.80 (0.61–1.05)	0.99 (0.89–1.11)
Former smoker	1.04 (0.77–1.41)	0.90 (0.64–1.25)	1.09 (0.81–1.45)	0.94 (0.78–1.14)	1.30 (0.96–1.75)	0.67 (0.49–0.94)	1.07 (0.99–1.16)	1.04 (0.79–1.36)	1.01 (0.90–1.12)
Current smoker	0.61 (0.40–0.91)	0.75 (0.46–1.21)	0.90 (0.61–1.32)	0.81 (0.63–1.05)	1.54 (0.99–2.42)	0.51 (0.27–0.89)	0.97 (0.87–1.09)	0.69 (0.47–0.98)	0.89 (0.77–1.04)
No alcohol consumption	0.75 (0.46–1.23)	0.70 (0.40–1.24)	0.95 (0.61–1.47)	0.87 (0.66–1.16)	1.37 (0.87–2.15)	0.60 (0.35–1.02)	0.99 (0.86–1.13)	0.68 (0.45–1.03)	0.90 (0.77–1.06)
≤ 10 drinks/week	0.85 (0.65–1.11)	0.76 (0.57–1.03)	1.09 (0.86–1.38)	0.90 (0.76–1.05)	1.29 (1.00–1.66)	0.78 (0.60–1.03)	1.02 (0.95–1.10)	0.94 (0.75–1.19)	0.96 (0.87–1.06)
> 10 drinks/week	0.91 (0.66–1.25)	0.83 (0.57–1.20)	0.99 (0.70–1.40)	0.98 (0.80–1.22)	1.20 (0.84–1.72)	0.78 (0.52–1.16)	1.08 (0.99–1.19)	0.87 (0.63–1.20)	0.97 (0.84–1.11)
No family history of diabetes	0.77 (0.61–0.96)	0.69 (0.53–0.86)	1.03 (0.84–1.27)	0.90 (0.79–1.03)	1.35 (1.09–1.68)	0.72 (0.56–0.92)	1.02 (0.96–1.08)	0.75 (0.61–0.92)	0.93 (0.86–1.02)
Family history of diabetes	1.10 (0.77–1.58)	1.02 (0.68–1.54)	1.05 (0.75–1.48)	0.93 (0.75–1.15)	1.07 (0.74–1.55)	0.80 (0.54–1.17)	1.06 (0.96–1.17)	1.19 (0.88–1.62)	1.00 (0.88–1.13)
Moderate/vigorous leisure time PA	0.92 (0.57–1.48)	1.03 (0.60–1.75)	0.76 (0.49–1.17)	1.14 (0.85–1.53)	0.93 (0.61–1.43)	1.32 (0.85–2.07)	1.05 (0.91–1.20)	0.81 (0.52–1.28)	0.81 (0.65–1.01)
No or light leisure time PA	0.80 (0.65–0.99)	0.68 (0.54–0.87)	1.12 (0.93–1.36)	0.86 (0.76–0.98)	1.38 (1.12–1.71)	0.64 (0.51–0.81)	1.03 (0.98–1.09)	0.85 (0.71–1.03)	0.97 (0.90–1.05)

HRs and 95% CI were calculated with Cox proportional hazard regression models

Model 3 was used for adjustment: age (continuous) and sex, BMI (< 21, 21- < 23, 23- < 25, 25- < 27, 27- < 30, 30- < 33, 33- < 35, 35- < 40, ≥ 40), total energy intake (kcal/day in quintiles), smoking status (never, past, current 1–15/day, current > = 15/day), alcohol consumption (0, 1–5, 6–10, 11–15, > 15), leisure time physical activity (vigorous, moderate, light, sedentary), menopause (yes, no), family history of diabetes (yes, no), education (< 10 years, 10–12 years, 13–14 years, ≥ 15 years), hypertension (yes, no), ratio of polyunsaturated fat to saturated fat (continuous), trans fat (continuous), and magnesium (continuous). The model for fiber was additionally adjusted for total sugar intake (continuous). The model for starch was additionally adjusted for fiber intake (continuous), weekly intake of sugar-sweetened beverages (yes, no), and intake of fruit and vegetables (continuous). Models total sugar, fructose and added sugar were additionally adjusted for fiber (continuous). Glucose, fructose, lactose and maltose intake were mutually adjusted (continuous). Continuous dietary component intakes were energy-adjusted separately for females and males

BMI Body mass index, *PA* Physical activity

Associations between nutrient intakes and cardiometabolic risk factors

The geometric means of various cardiometabolic indicators across quintiles of energy-adjusted intake of different carbohydrates and specific sugars are shown in Supplemental Table 6 and 7. Both total carbohydrates and dietary fiber intake were associated with lower values across all anthropometric indicators—including waist circumference (WC), waist-to-hip ratio (WHR), BMI, and body fat percentage—in males and females. Similar associations with anthropometric indicators were observed for total sugar and added sugar intakes, but only in males. Accordingly, increased consumption of total carbohydrates, dietary fiber, and total sugar was associated with higher aerobic fitness scores in males and females, while added sugar intake was specifically linked to higher fitness scores in males.

In females, higher intakes of total carbohydrates, total sugar, and lactose were associated with elevated TG levels. In contrast, in males, higher TG levels were linked to greater glucose intake but lower fructose intake. Additionally, increased fructose intake in females was associated with higher WC and BMI, while higher starch consumption was linked to lower WC, BMI, and body fat percentage in both sexes. All results can be found in Supplemental Table 6 and 7.

Discussion

In a large prospective cohort of 42,836 participants from the Danish Health Examination Survey, we found that a higher intake of fructose was associated with a lower risk of diabetes, while a higher glucose intake was associated with higher diabetes risk. In subgroup analyses, these associations were only significant among individuals with other risk factors, such as older age, obesity, low fiber consumption, sedentary behavior, smoking status, and hypertension. More specifically, there was an interaction between fructose and glucose and diabetes risk and levels of physical activity in males. Higher fiber consumption was also associated with a lower risk of diabetes among individuals with obesity, never smokers, without a family history of diabetes, or with sedentary behavior. In addition, findings from cross-sectional analyses in 12,977 participants indicated that a high intake of dietary fiber was favorably associated with healthier anthropometric indicators and better aerobic fitness score. This positive association was also observed in males with a higher consumption of added and total sugar. The uniqueness of the present analysis is the ability to examine specific carbohydrate subtypes in relation to a range of metabolomic biomarkers and the incidence of diabetes in a large study cohort representative of the Danish population [22].

We found a significant trend towards a lower risk of diabetes with a higher intake of fructose in both females and males. Previously, a meta-analysis from 2017 of 7 cohort studies, with evidence of substantial heterogeneity among studies ($I^2 = 71\%$, p-value < 0.01), was unable to determine any association between fructose intake and diabetes [23]. Some other literature suggests a higher risk of diabetes with higher fructose intake, given the widespread use of fructose in SSB. These discrepancies could be explained by the different metabolic effects of fructose from types of food sources [24–26], such as fruits and vegetables. The World Health Organization recommends at least 5 servings (~400 g/day) of fruits and vegetables daily for preventing noncommunicable diseases like type 2 diabetes [27] and our cohort population reported a median consumption of 556.6 g/day (7–7.5 servings/day), but slightly lower than the current Danish recommendations of > 600 g/day [28]. Our findings also indicated that individuals with sedentary behavior had a lower risk of diabetes with a higher intake of fructose [29]. In addition, a previous meta-analysis showed that fructose intake from 0–90 g/day has beneficial effects on HbA1c, that a threshold of over 50 g/day is needed to have significant effects on postprandial triacylglycerols, and that fructose intake below 100 g/day in adults does not significantly impact body weight. Therefore, they concluded that moderate fructose consumption (< 50 g/day, or < 10% total energy intake) may be acceptable and potentially beneficial in a general population cohort [30].

Inconsistencies between animal model studies or intervention studies [31] and observational studies [32] regarding the effects of fructose intake suggest that the reduced risk of diabetes linked to this sugar might be more related to specific dietary patterns (such as a greater intake of fruits and vegetables) rather than the higher consumption of fructose. Indeed, a study aiming to assess the association between different dietary fiber intakes and chronic diseases, using the large-scale NutriNet-Santé prospective cohort (2009–2019), found an inverse association between dietary fiber from fruit and the risk of type 2 diabetes. Non-significant results were found for vegetables fiber, potato/tuber fiber, legume fiber, and whole grain fiber [11]. Fructose intake was slightly higher than glucose intake, with dose ranges comparable to previous studies [32, 33]. Similar discrepancies have been observed in observational studies examining the association between glucose intake and diabetes risk [32, 33]. The present findings help fill existing data gaps of possible confounders in the relationship between fructose and glucose intake and the incidence of diabetes, including age, BMI, hypertension, fiber consumption, smoking status, alcohol consumption, family history of diabetes, and physical activity.

The trend towards a lower risk of diabetes among participants with a high intake of dietary fiber aligns with previous studies showing a consistent inverse relationship [34, 35]. Benefits include improved blood glucose control, higher insulin sensitivity, lower total cholesterol and SBP, and better weight management [22, 34]. While no association was found with Hb1Ac levels, healthier body fat parameters were observed i.e., WC, WHR, BMI, and body fat (%). Additionally, the association was stronger among participants without a family history of diabetes but with well-known metabolic risk factors such as obesity or low physical activity. Our results align with the recommendations of at least 25 g/day of fiber, with additional benefits expected with higher intake [22], although only 50% of participants met this recommended level.

Based on data from randomized controlled trials, the level of certainty in the positive relationship between added sugar for type 2 diabetes is low (> 15–50% probability); and observational studies do not suggest positive relationships between the intake of added or free sugars in isocaloric exchange with other macronutrients and risk of type 2 diabetes [13]. The present results contribute to our understanding of a potential upper limit for added and total sugar intake; however, a definitive value is still lacking due to insufficient studies to make a conclusive scientific-based strong recommendation. [13]. On the other hand, the fact that only 10% of the participants had a consumption above the recommended limit for added sugar intake (< 10% of total energy intake) could also explain these findings. Additionally, the counterbalanced effects of glucose and fructose might also contribute to explaining the non-significant outcome related to total sugar intake, as well as the heterogeneous group of food sources and dietary patterns that represents.

Although higher consumption of starch was associated with better obesity indicators, we did not observe significant associations between starch intake and diabetes risk. This is consistent with some studies [9, 36–38] but contradicts others [39–41]. Some previous analyses have considered starch from whole and refined grains or starchy and non-starchy vegetables separately, finding counterbalancing effects [41–43]. We focused on starch intake while adjusting for fiber, vegetable, and fruit consumption. It is plausible that other dietary factors, independent of starch, such as cooking techniques or other nutrients in starch-containing foods, could account for the observed starch health effects described by some researchers. Starch, when considered as a composite variable regardless of its source, may not accurately capture the aspects of carbohydrate quality that are relevant for glycemic control and, consequently, diabetes risk. Finally, the consumption of total carbohydrates was within the dietary recommendations for many of the cohort participants. Indeed, a wide range of total carbohydrate intake is acceptable and reflected by the authoritative dietary guidelines [7]. Given our findings, dietary strategies to restrict carbohydrates should maintain adequate dietary fiber intake by making careful food substitutions.

The strengths of this study include 1) its large sample size, 2) the ascertainment of the dietary exposure by a validated FFQ, 3) the register-based data on diabetes, 4) the uniqueness of having > 10,000 individuals with body composition and fitness score measurements, 5) the population-based longitudinal design with a median follow-up of 4.9 years, and 6) the comprehensive data collection and therefore the adjustment for well-known confounders. On the other hand, the limitations associated with this study are 1) the misreporting bias associated with some self-reported data, 2) some missing residual confounding, and 3) the one-time data collection at baseline years before diabetes diagnosis [44]. In addition, diabetes diagnoses from the registries do not distinguish between type 1 and type 2 diabetes. However, due to the prevalence and the nature of new cases among this study-population characteristics, it is nonetheless close to the type 2 diabetes new cases. This approach has been used in previous articles from this cohort before [45].

Conclusions

In summary, a higher consumption of fiber and fructose but a lower consumption of glucose was associated with a lower risk of diabetes. In subgroup analyses, these associations were only significant among individuals with other risk factors, such as older age, obesity, low fiber consumption, sedentary behavior, smoking status, and hypertension. The benefits of dietary fiber were particularly significant in subgroups with established cardiometabolic risk factors (BMI ≥ 30 kg/m^2, sedentarism) and supported by cross-sectional associations with obesity indicators, reinforcing the importance of dietary modifications as a key public health strategy. There were notable differences in the characteristics of individuals across the quintile groups of carbohydrate intake and an interaction between fructose and glucose intake and leisure-time physical activity was found in males. While a wide range of carbohydrate intakes can be acceptable in diet, recommendations on diabetes prevention should be focused on specific food groups and carbohydrate types. Additional information to establish a tolerable upper intake level for dietary sugars is still lacking.

Abbreviations

BMI	Body mass index
DANHES	Danish Health Examination Survey
DBP	Diastolic blood pressure
FFQ	Food frequency questionnaire
HbA1c	Glycated hemoglobin

HR	Hazard ratio
ICD	International Classification of Diseases (ICD)
PUFA/SFA ratio	Polyunsaturated fatty acids/saturated fatty acids ratio
Q	Quintile
SBP	Systolic blood pressure
SSB	Sugar- sweetened beverages
TG	Triglycerides
WC	Waist circumference
WHR	Waist-to-hip ratio

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12937-025-01071-2.

Supplementary Material 1.

Authors' contributions

MT-S, MB, MKJ, JST, and MG-F were involved in the conception and design. MT-S and MB. conducted the analysis. MT-S, MB, and MG-F did the interpretation of the results, wrote the first draft of the manuscript and all authors edited, reviewed, and approved the final version. All the authors read and approved the final version of the manuscript. JST is the guarantor of this work and, as such, had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

Funding

Open access funding provided by Copenhagen University This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors. The collection of data to DANHES was funded by the Ministry of the Interior and Health and the Tryg Foundation. M.T-S and M.G-F were supported by Novo Nordisk Fonden Research grant NNF18CC0034900.

Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

The study protocol was approved by the Ethics Committee for the Capital Region of Denmark (journal nos: H-A-2008–126 and H-C-2007–0118) and conducted with compliance with the Declaration of Helsinki.

Consent of publication

All study participants gave their informed consent to the research, and the publication of results was approved by the Danish Data Protection Agency (2007–41-1567).

Competing interests

The authors declare no competing interests.

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Received: 20 August 2024 Accepted: 2 January 2025
Published: 16 January 2025

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