Original Article
EPIDEMIOLOGY/GENETICS

Obesity

Physical Activity and Dietary Intake in BMI Discordant Identical Twins

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Objective: Despite the latest discovery of obesity-associated genes, the rapid rise in global obesity suggests a major role for environmental factors. This study investigated the influence of environmental factors on physical activity and dietary intake independent of genetic effects.

Methods: Sixteen female monozygotic twins aged 48.8 ± 9.8 years (range 37-70) with a mean BMI discordance of 3.96 ± 2.1 kg/m^2 (range 0.7-8.2) were studied. Physical activity was determined using 7-day accelerometry and dietary intake using 3-day 24-h recalls.

Results: Heavier cotwins were generally less physically active (mean activity counts × 1,000 per day ± SD; 505.5 ± 155.1 vs. 579.6 ± 185.4, $P = 0.047$) and tended to spend 6.1 min/day less in moderate to vigorous physical activity than leaner cotwins ($P = 0.09$). Energy intake did not significantly differ within pairs. Total fat intake (en%; $P = 0.03$), specifically monounsaturated fat ($P < 0.01$) and polyunsaturated fat ($P = 0.08$), was higher in the heavier cotwins.

Conclusions: After eliminating genetic effects, higher BMI is associated with lower overall and moderate to vigorous physical activity and higher intake of total fat, although the direction of causality cannot be determined. Future identification of the environmental factors responsible for these findings might contribute to developing new strategies in managing obesity.

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Introduction

The global rise in overweight and obesity is a major health concern because of the increased risk for chronic diseases like type 2 diabetes, cardiovascular disease (CVD), and cancer (1). Causes of the obesity epidemic are suggested to be of both environmental and genetic origin. Currently, genes are being identified that predispose to the development of obesity (2). However, since genetic variation has not changed substantially in the past 30 years, genes alone cannot explain the recent increase in obesity rates, suggesting a major role for a changing environment.

At the individual level, body weight increases if energy intake exceeds energy expenditure. Although dietary intake and physical activity are known as lifestyle factors, exposure to these factors has been shown to be under genetic and environmental control. Studies show that an individual's genotype influences the level of exposure to a certain lifestyle factor (gene-environment correlation) (3-5), but also the way an individual responds to this lifestyle factor in terms of body weight gain (gene-environment interaction) (6,7).

In addition to these genetic effects, lifestyle behaviors are also influenced by environmental factors. Identifying environmental factors that influence lifestyle and are amenable for intervention offers a possibility to develop strategies for the prevention and treatment of obesity. To disentangle the effects of the environment from the effects of genes and reduce the impact of gene-environment interaction and gene-environment correlation, we eliminated the influence of genetic factors by using the special design of "clonal controls," rare monozygotic twins discordant for body mass index (BMI) (8,9). Monozygotic twins are identical in their genomic sequence; therefore differences in BMI between cotwins must arise from differences in individual-specific environmental factors. Our aim is to investigate whether lifestyle factors such as physical activity, sedentary behavior, and dietary intake are associated with BMI when genetic factors are eliminated.

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Methods

Subjects

All participants are registered with the Netherlands Twin Register (NTR) (10), which comprises twins and their family members who took part in longitudinal survey studies between 1991 and 2009 and/or in the NTR biobank project between 2004 and 2008 (11,12). BMI data were available for 2,775 monozygotic twin pairs (13). The selection of twins is shown in Figure 1. Twin pairs were selected for this study if measured BMI difference was ≥ 3 kg/m^2 between cotwins at the biobank project. If subjects also had available survey data, twin pairs were selected if BMI difference ≥ 3 kg/m^2 at ≥ 1 survey (most recent), if BMI difference ≥ 2 at ≥ 3 surveys, or if BMI difference ≥ 2 kg/m^2 at the most recent survey. Only female pairs were included for homogeneity purposes.

Fifty-four pairs met the first selection criteria, were invited by letter and contacted by telephone to check further eligibility. Fourteen pairs (26%) were unwilling to participate mostly because of lack of time. Twenty-one pairs (39%) were excluded because of pregnancy ($n = 2$), history of eating disorder ($n = 4$), presence of diabetes mellitus ($n = 1$), serious heart disease ($n = 1$), neurological illness ($n = 3$) or reported BMI difference <2 kg/m^2 due to recent weight change ($n = 7$). Because the subjects also participated in an MRI study, another 3 twin pairs were excluded because of MRI contraindications. Finally, 2 pairs could not be contacted due to loss of follow-up. Thus, 16 female, weight-stable (<5% weight change in previous 3 months) monozygotic pairs (31%) were included in this study. Zygosity of the twins was determined as described previously (12). One pair was part of a monozygotic triplet. All twins lived apart from their cotwin, except for one pair that had lived in the same household since birth. The study was approved by the ethics committee of the VU University Medical Centre and was performed in accordance with the Helsinki Declaration. All subjects provided written informed consent.

Clinical and biochemical assessments

All measurements were done by an experienced research physician and dietician during a 5-h test visit in our research clinic and during the month following this visit. Subjects arrived after a 12-h overnight fast. Information on sociodemographics and health status was collected by a short oral and standardized interview. Weight, height, and waist and hip circumferences were measured without shoes and wearing light clothing only. For the assessment of body composition, bioelectrical impedance analysis (Maltron BF-906 body fat analyzer, Maltron Ltd, Essex, UK) was used. Blood pressure was measured in supine position (Dinamap Pro 100, GE Medical Systems Information Technologies, Inc., Milwaukee, Wisconsin). Heart rate was measured using a 3-lead electrocardiogram (VU University Ambulatory Monitoring System, VU-AMS) (14). Venous blood samples were drawn for the assessment of glucose, HbA1c, total cholesterol, high-density lipoprotein cholesterol and triglycerides. Low-density lipoprotein cholesterol was calculated from the Friedewald formula. All biochemical assessments were done at the clinical chemistry laboratory of the VU University Medical Centre.

Indirect calorimetry was used to estimate resting energy expenditure, while participants remained in supine position with eyes closed for 15 min (Vmax Encore n29; Viasys Healthcare, Houten, Netherlands). Participants completed the 36-item Short Form Health Survey to estimate overall mental and physical health status (15) and the Center for Epidemiologic Studies-Depression (CES-D) questionnaire to screen for depressive symptoms. A CES-D score of 16 or greater identified subjects at risk for clinical depression (16).

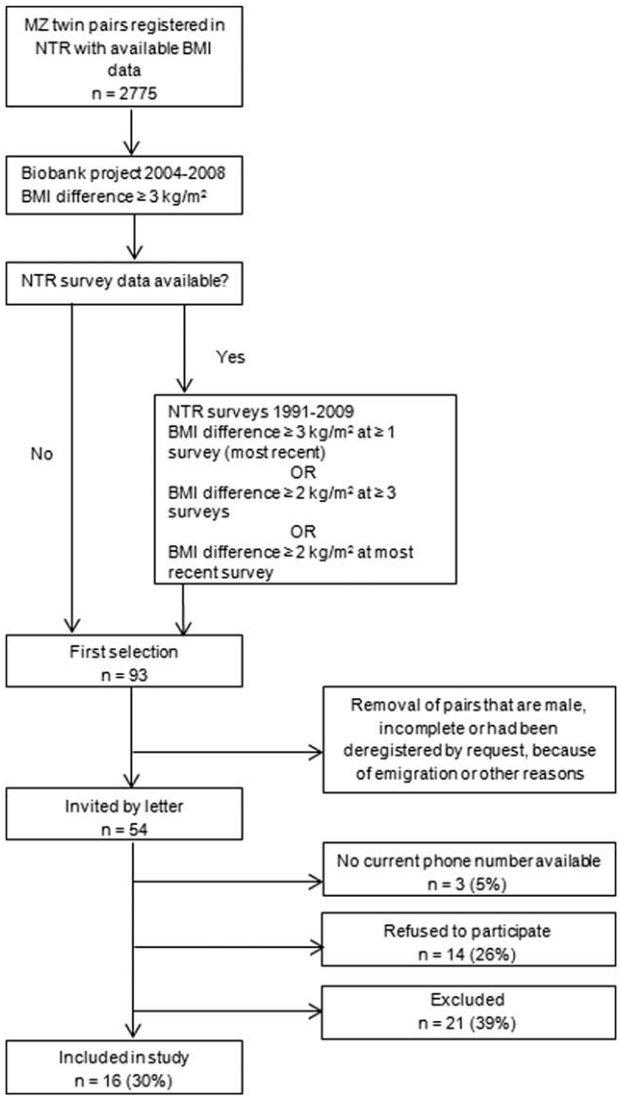

Figure 1 Flowchart of the study population. All numbers in the figure represent numbers of monozygotic twin pairs.

Physical activity

Physical activity was measured using two methods.

Accelerometry. Subjects received an Actigraph GT3X+ accelerometer (Actigraph LLC, Pensacola, FL, USA) (17), and wore the accelerometer attached to an elastic belt on the right hip for all waking hours during a 7-day period, except during water-based activities. Every participant started wearing the device on a Saturday. Recorded data were analyzed using Actilife software (version 6.10.2). Nonwear time was defined and excluded if there were 60 consecutive minutes with zero counts, with allowance of 2 min with counts between 0 and 100. Wear time was considered acceptable

TABLE 1 Clinical and biochemical characteristics of leaner and heavier cotwins

	Leaner cotwins ($n = 16$)	Heavier cotwins ($n = 16$)	*P* value
Age (y)	49.8 ± 9.8	49.8 ± 9.8	-
Height (m)	1.68 ± 0.04	1.68 ± 0.05	0.6
Weight (kg)	68.9 ± 9.2	80.5 ± 11.0	<0.001
BMI (kg/m^2)	24.4 ± 3.1	28.4 ± 3.5	<0.001
Waist-hip ratio	0.80 ± 0.1	0.84 ± 0.1	0.02
Body fat (%)	32.0 ± 6.1	37.8 ± 6.1	<0.001
Systolic RR (mmHg) supine	119.4 ± 21.5	126.5 ± 20.6	0.09
Diastolic RR (mmHg) supine	66.6 ± 12.3	70.3 ± 6.1	0.3
Heart rate at rest (bpm)	59.7 ± 7.3	62.7 ± 8.2	0.3
REE (kcal/day)	1,564.1 ± 144.3	1,701.9 ± 236.3	0.01
REE/LBM (kcal/kg)	33.8 ± 2.8	34.3 ± 2.8	0.5
Glucose (mmol/L)	4.7 ± 0.3	4.8 ± 0.3	0.5
HbA1c (mmol/mol)	36.3 ± 2.6	36.7 ± 2.6	0.3
Total cholesterol (mmol/L)	5.2 ± 1.1	5.3 ± 1.2	0.8
HDL cholesterol (mmol/L)	2.0 ± 0.4	1.7 ± 0.4	0.05
LDL cholesterol (mmol/L)	2.9 ± 1.0	3.2 ± 1.2	0.3
Ratio total/HDL cholesterol	2.7 ± 0.6	3.2 ± 1.0	0.01
Triglycerides (mmol/L)	0.8 ± 0.2	0.9 ± 0.3	0.1

Mean ± SD.
REE, resting energy expenditure; REE/LBM, resting energy expenditure divided by lean body mass; HbA1c, glycated hemoglobin; HDL, high-density lipoprotein; LDL, low-density lipoprotein.

when there was a minimum of 4 days of at least 10 h of wear time per day. Existing cut-points were used to define sedentary (<100 counts/min), light (100-2,019 counts/min), moderate (2,020-5,998 counts/min), and vigorous (>5,999 counts/min)-intensity activity (18).

Questionnaire. Following the 7-day wear period for the accelerometer, participants completed the short version of the International Physical Activity Questionnaire (IPAQ-SF) (19). The IPAQ-SF assesses three types of physical activity over the previous week, including vigorous activity, moderate activity, and walking. According to the IPAQ-SF scoring manual (19) outliers (i.e., cases in which the sum of walking, moderate, and vigorous was greater than 960 min) were excluded. Also, each intensity domain (walking, moderate, vigorous) exceeding 180 min per day was truncated at a duration of 180 min per day. Total physical activity was calculated by multiplying time spent in each intensity domain by their estimated intensity in METs. One MET represents the energy expended while sitting quietly at rest. The MET intensities used were vigorous (8 METs), moderate (4 METs), and walking (3.3 METs).

Dietary intake

Dietary intake data was collected through 24-h recalls on two weekdays and one Sunday by unannounced telephone calls during the month following the test visit (20), using the validated United States Department of Agriculture (USDA) five-step multiple-pass method (21). A food portion size photo book, a table scale type KERN FCE 6 K2 ®, and extensive tableware were used for portion-size estimation. All recalls were conducted by one research physician who was instructed by an experienced nutritionist. Food items were coded with the corresponding NEVO-code (Dutch Food Composition Table) (22) by a dietician blinded to BMI status of the subjects. Portion sizes were entered in gram weights. Food consumption and nutrient intake were determined using the NEVO database (22) and included mean intake of total energy (kcal) and total fat, saturated fatty acids, mono- (MUFA) and polyunsaturated fatty acids (PUFA), protein, carbohydrate, alcohol (en%), and dietary fiber (g/1,000 kcal). We also determined mean intake of micronutrients calcium, iron, folate, and vitamins A, B12, C, and D.

Statistical analysis

All data preparation and analysis were conducted using IBM SPSS Statistics for Windows (version 20, IBM Corp., 2011, Armonk, NY, USA). Results are expressed as mean ± SD for data with a normal distribution. Differences between the leaner and heavier cotwins were tested with paired t-tests for continuous variables (23), McNemar tests for dichotomous variables and Wilcoxon signed-ranks tests for ordinal data. Since IPAQ-SF data are non-normally distributed results are expressed as median and interquartile ranges (19), and differences were tested with Wilcoxon signed-ranks test. In the total group of twins ($n = 32$) linear regression analysis was used to examine whether BMI and body fatness were associated with physical activity and dietary intake. To account for nonindependence of family members, these analyses were done in Stata 13, including family ID as a cluster variable.

Results

Clinical characteristics

Clinical and biochemical characteristics of the leaner and heavier cotwins are presented in Table 1. Selected twins had a mean age of

TABLE 2 Sociodemographic characteristics of leaner and heavier cotwins

	Leaner cotwins ($n = 16$)	Heavier cotwins ($n = 16$)	*P* value
Education			0.3
Only secondary (%)	5 (31.2)	5 (31.2)	
Vocational (%)	7 (43.8)	10 (62.5)	
Higher or academic (%)	4 (25.0)	1 (6.2)	
Work			0.3
Employed (%)	14 (87.5)	12 (75.0)	
Unemployed (%)	2 (12.5)	2 (12.5)	
Retired (%)	0 (0)	2 (12.5)	
Marital status			0.3
Unmarried (%)	4 (25.0)	1 (6.2)	
Married (%)	11 (68.8)	14 (87.5)	
Divorced or widower (%)	1 (6.2)	1 (6.2)	
Smoking status			0.3
Current smoker (%)	4 (25)	3 (18.8)	
Nonsmoker (%)	12 (75)	13 (81.2)	
Menopausal status			0.7
Premenopausal (%)	7 (43.8)	6 (37.5)	
Postmenopausal (%)	6 (37.5)	5 (31.2)	
Unknown (%)	3 (18.8)	5 (31.2)	
Symptoms of depression			
CES-D score	7.1 ± 7.7	6.4 ± 7.1	0.8
CES-D score > 16 (%)	2 (12.5)	3 (18.8)	0.5
Health status			
SF-36 Physical Health	50.7 ± 8.8	51.7 ± 7.2	0.6
SF-36 Mental Health	52.6 ± 6.1	54.7 ± 7.2	0.3

N (%) or mean ± SD.
CES-D, Center for Epidemiologic Studies-Depression; SF-36, 36-item Short Form Health Survey.

TABLE 3 Physical activity of leaner and heavier cotwins measured by 7-day accelerometry

	Leaner cotwins ($n = 16$)	Heavier cotwins ($n = 16$)	*P* value
Sedentary (min/day)	643.8 ± 37.5	656.2 ± 58.6	0.3
Light activity (min/day)	217.5 ± 54.8	195.8 ± 47.7	0.1
MVPA (min/day)	38.5 ± 17.4	32.4 ± 16.7	0.09
Sedentary (%)	71.8 ± 5.8	74.3 ± 6.0	0.1
Light activity (%)	24.0 ± 5.0	22.1 ± 4.9	0.2
MVPA activity (%)	4.2 ± 1.7	3.6 ± 1.8	0.09
Activity count (×1,000 per day)	579.6 ± 185.4	505.5 ± 155.1	<0.05
Steps (per day)	8,294.8 ± 2,708.7	7,338.3 ± 2,573.7	0.05

Mean ± SD.
MVPA, moderate to vigorous physical activity.

48.8 ± 9.8 years (range 37-70). As a result of the selection criteria, cotwins differed significantly in weight, BMI, waist-hip ratio and body fat percentage. Mean BMI difference was 3.96 kg/m^2 (range 0.7-8.2) during the test visit.

Resting energy expenditure was higher in the heavier than in the leaner cotwins. However, relative to lean body mass, resting energy expenditure was similar. Without exception, the cardiovascular and metabolic risk factors were less favorable in the heavier than in the leaner cotwins, but, except for HDL-cholesterol and total/HDL-cholesterol ratio, these differences were not statistically significant. There were no differences between the cotwins in sociodemographic variables, including smoking, marital status, menopausal status, general physical and mental health, and symptoms of depression (Table 2).

Physical activity

Median duration of accelerometer monitoring was 7 days with mean duration of 14.9 h (SD ± 0.9) per day. All participants had acceptable wear time duration and no differences existed in wear time between leaner and heavier cotwins (15.0 ± 0.89 vs. 14.7 ± 0.9; $P = 0.2$). Heavier cotwins had 74,100 lower overall activity counts ($P < 0.05$) and 957 fewer step counts ($P = 0.05$) per day than their leaner cotwins (Table 3). Linear regression analyses in the total group of twins ($n = 32$) showed that activity counts correlated negatively with BMI ($r = -0.2$, $P = 0.07$), fat percentage ($r = -0.3$, $P = 0.03$), and fat mass ($r = -0.3$, $P = 0.03$). Step counts correlated negatively with BMI ($r = -0.3$, $P = 0.055$), fat percentage ($r = -0.4$, $P < 0.05$), and fat mass ($r = -0.4$, $P < 0.05$).

In total, 15 out of 16 (93.7%) leaner cotwins and 11 out of 16 (68.7%) heavier cotwins carried out at least 150 min per week of moderate to vigorous physical activity (MVPA; $P = 0.2$). Mean time spent in MVPA was 6.1 min per day less in heavier cotwins as compared to leaner cotwins ($P = 0.09$).

Different results were obtained with self-reported physical activity measurements.

Completed IPAQ-SF's from five leaner cotwins had to be excluded from the analyses because of outliers, following the IPAQ-SF scoring manual. Median (interquartile range, IQR) total physical activity was 4,638 (IQR, 2,719-6,497) MET/min/week in leaner cotwins and 2,853 (IQR, 2,234-4,788) MET/min/week in heavier cotwins ($P = 0.6$). Also, no significant differences were found in median walking, moderate activity or vigorous activity as measured with IPAQ-SF between heavier en leaner cotwins [walking 1,386 (IQR, 421-1,386) vs. 2,657 (IQR, 792-8,316) MET/min/week, $P = 0.5$; moderate activity 460 (IQR, 210-760) vs. 480 (IQR, 0-1,920) MET/min/week, $P = 0.1$; vigorous activity 0 (IQR, 0-1,060) vs. 480 (IQR, 0-1,920) MET/min/week, $P = 0.09$].

Dietary intake

Mean daily energy intake did not differ between the cotwins (Table 4). However, mean total fat intake was 4.4 en% higher in the heavier than in the leaner cotwins ($P = 0.03$). More specifically, monounsaturated fat intake was higher ($P < 0.01$) and polyunsaturated fat intake tended

TABLE 4 Daily dietary intake for leaner and heavier cotwins as estimated by three 24-h recalls

	Leaner cotwins ($n = 16$)	Heavier cotwins ($n = 16$)	*P* value
Total energy (kcal)	1,971.4 ± 496.8	1,912.8 ± 443.6	0.7
Macronutrients			
Carbohydrates (en%)	47.0 ± 5.0	45.5 ± 5.7	0.4
Protein (en%)	15.3 ± 3.1	15.2 ± 2.9	0.9
Total fat (en%)	31.2 ± 4.1	35.6 ± 6.7	0.03
Saturated fatty acids (en%)	12.3 ± 1.7	13.1 ± 2.8	0.4
Monounsaturated fatty acids (en%)	10.0 ± 1.7	12.1 ± 2.9	<0.01
Polyunsaturated fatty acids (en%)	5.9 ± 2.1	7.1 ± 2.1	0.08
Dietary fiber (g/1,000 kcal)	9.8 ± 1.6	9.2 ± 2.9	0.5
Alcohol (en%)[a]	3.1 (0.2–6.4)	0.1 (0–3.1)	<0.01
Micronutrients			
Calcium (mg)	1,110.9 ± 349.9	957.5 ± 419.2	0.1
Total iron (mg)	10.6 ± 3.0	8.6 ± 2.3	<0.01
Iron heme (mg)	0.6 ± 0.5	0.7 ± 0.4	0.8
Iron nonheme (mg)	9.9 ± 3.1	7.9 ± 2.3	<0.01
Vitamin A (μg)	1,866.3 ± 1,912.7	1,745.6 ± 1,158.4	0.8
Folate (μg)	212.5 ± 61.7	201.5 ± 60.0	0.4
Vitamin B12 (μg)	3.6 ± 1.7	4.1 ± 1.7	0.5
Vitamin C (mg)	85.3 ± 44.1	87.4 ± 54.0	0.8
Vitamin D (μg)	2.4 ± 1.3	2.4 ± 1.2	0.9
Food groups			
Fruits and vegetables (g)	319.6 ± 93.3	305.4 ± 155.4	0.7
Dairy products and cheese (g)	436.8 ± 265.1	327.2 ± 184.0	0.1
Bread, potato, and grain products (g)	317.5 ± 130.4	363.3 ± 121.4	0.2
Meat (g)	95.5 ± 59.2	91.7 ± 33.8	0.8
Fish (g)[a]	0 (0–87.8)	0 (0–75.9)	0.4
Nuts, seeds, crisps, and snacks (g)[a]	36.8 (0–72.0)	50.3 (19.4–104.8)	0.2
Sugar, sweets, and pastries (g)	81.8 ± 38.6	83.9 ± 48.9	0.9
Fats, oils, and savory sauces (g)	34.8 ± 20.4	58.1 ± 29.9	<0.05

Mean ± SD unless otherwise specified.
[a]Median and interquartile range.
en%, percentage of total energy intake.

to be higher ($P = 0.08$) in heavier than leaner cotwins, while no differences were found for saturated fat intake. Leaner cotwins had a higher alcohol intake than heavier counterparts. Micronutrient analyses showed that leaner relative to heavier cotwins had a higher intake of iron, specifically nonheme iron. Heavier cotwins had a higher intake of fats, oils, and savory sauces as compared to leaner cotwins. Linear regression analyses in the total group of twins ($n = 32$) showed that energy intake was not associated with BMI. However, total fat intake was positively associated with BMI ($r = 0.3$, $P < 0.05$) and fat mass ($r = 0.3$, $P < 0.05$).

Discussion

We found that within rare monozygotic twins discordant for BMI, heavier cotwins had a lower level of total physical activity and a trend toward less time spent in MVPA than their leaner cotwins. There were no differences in energy intake, but heavier cotwins had a higher intake of fats, oils, and savory sauces resulting in higher macronutrient intake of total fat, specifically MUFA and PUFA, as compared to their leaner cotwins. Leaner cotwins had an increased intake of alcohol and total iron than their heavier counterparts. These analyses in monozygotic twins with identical genetic backgrounds allow the elimination of confounding by genetic factors and strongly reduce confounding by gene-environment interaction and correlation. Thus, the differences we observed must have emerged from differences in exposure to environmental factors.

Our observations are in line with previous studies investigating lifestyle factors in monozygotic twins discordant for obesity (24,25). A preference for fatty foods was found in cotwins with obesity versus lean cotwins after qualitative recall of food consumption patterns (24). Apparently, this acquired preference was already present at adolescence before onset of BMI discordance, suggesting a causal role in the development of obesity (24). Due to the qualitative

nature of the data, however, the fatty foods preferred by the cotwins with obesity in the previous study could not be subdivided into proportions of saturated and unsaturated fats. In our more quantitative data analyses, we showed that the intake of specifically MUFA was higher in heavier versus leaner cotwins. The effect of MUFA on CVD risk is controversial, as previous meta-analyses of cohort studies showed inconsistent results (26,27). However, subgroup analyses found a significant beneficial effect on CVD of MUFA derived from vegetable oils rather than animal products (28). Olive oil is suggested to be the driver of the beneficial health effects of the Mediterranean diet (29). We were unable to identify the exact food sources of MUFA in our study. However, the higher intake of fats, oils, and savory sauces might give a part of the explanation, since this food group mainly contains fat products derived from plants (e.g., margarine, oils, table sauces). Also the concomitant higher intake of PUFA in the heavier cotwins suggests that MUFA are supplied by vegetables rather than animal products.

Our results are in contrast to a previous study that observed lower rather than higher MUFA and PUFA intakes in the obese compared to nonobese monozygotic cotwins (30). An explanation for this discrepancy might be that in the previous study fat intake was avoided more actively in subjects with obesity, while in our study participants had primarily declared not to be on weight loss diets. Another option is that relative to 24-h recalls, food diaries as used in the previous study are more susceptible to underreporting of unhealthy foods, such as fats, since participants may influence their food intake when they are aware all consumed foods must be recorded.

Similar to our study, no differences were found in total energy intake between lean and obese cotwins in a study using food diaries in monozygotic discordant twins (30). It has been suggested that subjects with overweight and obesity underreport their energy intake during dietary surveys (31). The previous twin study confirmed this underreporting by comparing data from food diaries with doubly labeled water assessments as a measure for true total energy expenditure (30). The USDA five-step multiple-pass method we used in our study is a valuable method for quantitative dietary intake assessments as compared to, for example, food frequency questionnaires and food diaries (20). Nevertheless, we cannot exclude the possibility that obesity-related underreporting affected our results.

Current physical activity guidelines recommend at least 150 min per week of MVPA to reduce risk for many chronic diseases (32). Our data show that 93.7% of leaner and 68.7% of heavier cotwins get sufficient physical activity to meet this requirement, which are similar proportions as in the general population where 7 of 10 individuals reach this demand (33). The clinical relevance of our observations in MVPA remains open to question since the influence of MVPA on body weight is controversial (34). Several accelerometer studies showed inverse associations between MVPA and risk of obesity (35,36), while other longitudinal studies failed to detect an association between self-reported leisure time exercise behavior and BMI (37,38). The discrepancies in these observations might be a result of different definitions of physical activity and different test methods being used. Accelerometers measure motion without distinguishing between voluntary leisure time exercise behavior and other aspects of physical activity such as household activities and walking or cycling to work. Thus, the higher MVPA we observed in the leaner versus heavier cotwins in our study represents activity performed in all domains of activity during a day rather than just exercise behavior.

The lower total physical activity and time spent in MVPA in heavier versus leaner cotwins we observed are in line with two previous studies investigating monozygotic twins discordant for BMI (25,30). Similar to our results, cotwins with obesity versus lean cotwins showed lower accelerometer activity counts (25) and less reported high-intensity activity (30). Another study failed to detect differences in physical activity among BMI discordant monozygotic cotwins (39). This study, however, used retrospective interviews rather than objective assessment tools such as accelerometry. Taken together, the results of two previous studies (25,30) in combination with our results demonstrate that the origin of the association between lower physical activity and higher BMI lies (at least in part) in the exposure to unique environmental factors, independent of genotype.

It could be hypothesized that these unique environmental factors could act through the genome by causing epigenetic differences (40). Alterations in DNA methylation and histone modification before and after birth may influence the development of disease without changing the DNA sequence. A recently published study, however, found no significant differences in gene expression of BMI-associated loci between BMI discordant monozygotic twins (13). However, the assessments were performed in peripheral blood only, leaving role for an epigenetic influence on regulatory pathways underlying BMI discordance through other tissues.

Because of the cross-sectional nature of our study no conclusion can be drawn regarding whether the reduced physical activity resulted in higher BMI or whether the increased weight led to decreased physical activity. However, a previous retrospective monozygotic twin study on leisure time activity observed that the physically inactive cotwin at adolescence had a higher risk of developing obesity compared to the physically active cotwin in adulthood (25), suggesting a causal role for physical inactivity in the development of obesity.

Our final study sample comprised 2 twin pairs that were not strictly BMI discordant during the clinical assessments (BMI differences of 0.71 and 1.02 kg/m^2). This is possibly because subjects guessed their BMI incorrectly at the moment of screening. Post hoc analyses after excluding these 2 pairs did not influence the results in terms of effect sizes, although the decrease in power obviously resulted in less statistical significance of our findings.

We acknowledge that a sample of 16 twin pairs may seem relatively small. However, since body weight is a highly heritable trait, a mean BMI discordance of almost 4 kg/m^2 as seen in our study sample between monozygotic twins is very rare (13). The sample size should be appreciated in light of this design, which involves monozygotic twins discordant for BMI, but perfectly matched with respect to age, gender, and genetic background. This design in combination with the accuracy of the phenotypic measures is optimal with respect to power.

Strengths of our study are the use of accelerometers to objectively measure physical activity and the use of the USDA five-step multiple-pass method to assess dietary intake. Although underreporting remains a subject of concern as in all dietary surveys, the 24-h recall method, in our opinion, is the next best thing by not interfering with actual dietary behavior and keeping respondent burden low.

In summary, we demonstrated that higher BMI is associated with a lower total physical activity, and a higher intake of total fat, specifically MUFA and PUFA. Our finding that these associations were observed within monozygotic twin pairs with an identical genetic background implicates that these associations are independent of genetic factors. Thus, exposure to unique environmental factors is responsible for the more health-compromising lifestyle factors observed in individuals with a higher BMI. However, it cannot be determined whether the lower physical activity and higher fat intake are a cause or a consequence of the increased BMI. Future identification of the underlying unshared environmental factors responsible for our findings, for instance by qualitative in-depth interviews of BMI discordant monozygotic pairs, may provide starting points toward developing new strategies in the management of obesity. O

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References

1. Haslam DW, James WP. Obesity. *Lancet* 2005;366:1197-1209.
2. Locke AE, Kahali B, Berndt SI, et al. Genetic studies of body mass index yield new insights for obesity biology. *Nature* 2015;518:197-206.
3. Stubbe JH, Boomsma DI, Vink JM, et al. Genetic influences on exercise participation in 37,051 twin pairs from seven countries. *PLoS One* 2006;1:e22
4. Teucher B, Skinner J, Skidmore PM, et al. Dietary patterns and heritability of food choice in a UK female twin cohort. *Twin Res Hum Genet* 2007;10:734-748.
5. Vinkhuyzen AA, van der Sluis S, de Geus EJ, Boomsma DI, Posthuma D. Genetic influences on 'environmental' factors. *Genes Brain Behav* 2010;9:276-287.
6. Li S, Zhao JH, Luan J, et al. Physical activity attenuates the genetic predisposition to obesity in 20,000 men and women from EPIC-Norfolk prospective population study. *PLoS Med* 2010;7:1-9.
7. Qi Q, Chu AY, Kang JH, et al. Fried food consumption, genetic risk, and body mass index: gene-diet interaction analysis in three US cohort studies. *BMJ* 2014; 348:g1610
8. Zwijnenburg PJ, Meijers-Heijboer H, Boomsma DI. Identical but not the same: the value of discordant monozygotic twins in genetic research. *Am J Med Genet B Neuropsychiatr Genet* 2010;153B:1134-1149.
9. Friberg L, Cederlof R, Lundman T, Olsson H. Mortality in smoking discordant monozygotic and dizygotic twins. A study on the Swedish Twin Registry. *Arch Environ Health* 1970;21:508-513.
10. Boomsma DI, de Geus EJ, Vink JM, et al. Netherlands Twin Register: from twins to twin families. *Twin Res Hum Genet* 2006;9:849-857.
11. Willemsen G, de Geus EJ, Bartels M, et al. The Netherlands Twin Register biobank: a resource for genetic epidemiological studies. *Twin Res Hum Genet* 2010; 13:231-245.
12. Willemsen G, Vink JM, Abdellaoui A, et al. The Adult Netherlands Twin Register: twenty-five years of survey and biological data collection. *Twin Res Hum Genet* 2013;16:271-281.
13. Van Dongen J, Willemsen G, Heijmans BT, et al. Longitudinal weight differences, gene expression and blood biomarkers in BMI-discordant identical twins. *Int J Obes (Lond)* 2015;39:899-909.
14. de Geus EJ, Willemsen GH, Klaver CH, Van Doornen LJ. Ambulatory measurement of respiratory sinus arrhythmia and respiration rate. *Biol Psychol* 1995;41:205-227.
15. Ware JE Jr., Sherbourne CD. The MOS 36-item short-form health survey (SF-36). I. Conceptual framework and item selection. *Med Care* 1992;30:473-483.
16. Lewinsohn PM, Seeley JR, Roberts RE, Allen NB. Center for Epidemiologic Studies Depression Scale (CES-D) as a screening instrument for depression among community-residing older adults. *Psychol Aging* 1997;12:277-287.
17. Plasqui G, Westerterp KR. Physical activity assessment with accelerometers: an evaluation against doubly labeled water. *Obesity (Silver Spring)* 2007;15:2371-2379.
18. Troiano RP, Berrigan D, Dodd KW, Masse LC, Tilert T, McDowell M. Physical activity in the United States measured by accelerometer. *Med Sci Sports Exerc* 2008;40:181-188.
19. Craig CL, Marshall AL, Sjostrom M, et al. International physical activity questionnaire: 12-country reliability and validity. *Med Sci Sports Exerc* 2003;35: 1381-1395.
20. Ma Y, Olendzki BC, Pagoto SL, et al. Number of 24-hour diet recalls needed to estimate energy intake. *Ann Epidemiol* 2009;19:553-559.
21. Moshfegh AJ, Rhodes DG, Baer DJ, et al. The US Department of Agriculture Automated Multiple-Pass Method reduces bias in the collection of energy intakes. *Am J Clin Nutr* 2008;88:324-332.
22. *NEVO-online version 2013/4.0*. Bilthoven; 2013.
23. Altman DG. *Comparing Groups—Continuous Data. Practical Statistics for Medical Research*. London: Chapman and Hall; 1991. p. 179-228.
24. Rissanen A, Hakala P, Lissner L, Mattlar CE, Koskenvuo M, Ronnemaa T. Acquired preference especially for dietary fat and obesity: a study of weight-discordant monozygotic twin pairs. *Int J Obes Relat Metab Disord* 2002;26: 973-977.
25. Pietilainen KH, Kaprio J, Borg P, et al. Physical inactivity and obesity: a vicious circle. *Obesity (Silver Spring)* 2008;16:409-414.
26. Chowdhury R, Warnakula S, Kunutsor S, et al. Association of dietary, circulating, and supplement fatty acids with coronary risk: a systematic review and meta-analysis. *Ann Intern Med* 2014;160:398-406.
27. Jakobsen MU, O'Reilly EJ, Heitmann BL, et al. Major types of dietary fat and risk of coronary heart disease: a pooled analysis of 11 cohort studies. *Am J Clin Nutr* 2009;89:1425-1432.
28. Schwingshackl L, Hoffmann G. Monounsaturated fatty acids, olive oil and health status: a systematic review and meta-analysis of cohort studies. *Lipids Health Dis* 2014;13:154.
29. Guasch-Ferre M, Hu FB, Martinez-Gonzalez MA, et al. Olive oil intake and risk of cardiovascular disease and mortality in the PREDIMED Study. *BMC Med* 2014;12:78
30. Pietilainen KH, Korkeila M, Bogl LH, et al. Inaccuracies in food and physical activity diaries of obese subjects: complementary evidence from doubly labeled water and co-twin assessments. *Int J Obes (Lond)* 2010;34:437-445.
31. Heitmann BL, Lissner L. Dietary underreporting by obese individuals–is it specific or non-specific? *BMJ* 1995;311:986-989.
32. World Health Organization. *Global Recommendations on Physical Activity for Health*. Geneva, Switzerland: WHO; 2010.
33. Hallal PC, Andersen LB, Bull FC, Guthold R, Haskell W, Ekelund U. Global physical activity levels: surveillance progress, pitfalls, and prospects. *Lancet* 2012; 380:247-257.
34. Malhotra A, Noakes T, Phinney S. It is time to bust the myth of physical inactivity and obesity: you cannot outrun a bad diet. *Br J Sports Med* 2015;49:967-968.
35. Maher CA, Mire E, Harrington DM, Staiano AE, Katzmarzyk PT. The independent and combined associations of physical activity and sedentary behavior with obesity in adults: NHANES 2003-06. *Obesity (Silver Spring)* 2013;21:E730-E737.
36. Yoshioka M, Ayabe M, Yahiro T, et al. Long-period accelerometer monitoring shows the role of physical activity in overweight and obesity. *Int J Obes (Lond)* 2005;29:502-508.
37. Huppertz C, Bartels M, Van Beijsterveldt CEM, Willemsen G, Hudziak JJ, De Geus EJC. Regular exercise behaviour in youth is not related to current body mass index or body mass index at 7-year follow-up. *Obesity Science. & Practice* 2015;1: 1-11. DOI: 10.1002/osp4.2
38. Droyvold WB, Holmen J, Midthjell K, Lydersen S. BMI change and leisure time physical activity (LTPA): an 11-y follow-up study in apparently healthy men aged 20-69 y with normal weight at baseline. *Int J Obes Relat Metab Disord* 2004;28:410-417.
39. Hakala P, Rissanen A, Koskenvuo M, Kaprio J, Ronnemaa T. Environmental factors in the development of obesity in identical twins. *Int J Obes Relat Metab Disord* 1999;23:746-753.
40. Czyz W, Morahan JM, Ebers GC, Ramagopalan SV. Genetic, environmental and stochastic factors in monozygotic twin discordance with a focus on epigenetic differences. *BMC Med* 2012;10:93.