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ARTICLE

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Association between objectively measured sleep duration, adiposity and weight loss history

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Abstract

Background An association between sleep and obesity has been suggested in several studies, but many previous studies relied on self-reported sleep and on BMI as the only adiposity measure. Moreover, a relationship between weight loss history and attained sleep duration has not been thoroughly explored.

Design The study comprised of 1202 participants of the European NoHoW trial who had achieved a weight loss of ≥5% and had a BMI of ≥25 kg/m^2 prior to losing weight. Information was available on objectively measured sleep duration (collected during 14 days), adiposity measures, weight loss history and covariates. Regression models were conducted with sleep duration as the explanatory variable and BMI, fat mass index (FMI), fat-free mass index (FFMI) and waist-hip ratio (WHR) as response variables. Analyses were conducted with 12-month weight loss, frequency of prior weight loss attempts or average duration of weight maintenance after prior weight loss attempts as predictors of measured sleep duration.

Results After adjusting for physical activity, perceived stress, smoking, alcohol consumption, education, sex and age, sleep duration was associated to BMI ($P < 0.001$), with the highest BMI observed in the group of participants sleeping <6 h a day [34.0 kg/m^2 (95% CI: 31.8–36.1)]. Less difference in BMI was detected between the remaining groups, with the lowest BMI observed among participants sleeping 8–<9 h a day [29.4 kg/m^2 (95% CI: 28.8–29.9)]. Similar results were found for FMI ($P = 0.008$) and FFMI ($P < 0.001$). We found no association between sleep duration and WHR. Likewise, we found no associations between weight loss history and attained sleep duration.

Conclusion In an overweight population who had achieved a clinically significant weight loss, short sleep duration was associated with higher BMI, with similar associations for fat and lean mass. We found no evidence of association between weight loss history and attained sleep duration.

Introduction

A decrease in self-reported sleep duration has developed parallel to the obesity epidemic [1], and a growing body of evidence supports a link between sleep and obesity [2–4]. However, many studies have relied on self-reported sleep

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data and on body mass index (BMI) as the only measure of adiposity [5].

Cross-sectional studies have shown a rather consistent association between short sleep duration and higher BMI [2, 5], and some have suggested the association to be U-shaped [6, 7]. While causality cannot be determined from cross-sectional data, prospective studies have suggested that insufficient sleep can lead to weight gain and development of obesity [3, 4, 8], possibly due to metabolic changes affecting glucose metabolism, appetite and reward, caloric intake and/or energy expenditure [9]. Other studies have shown that obesity affects sleep by contributing to development of disorders such as sleep apnoea and obesity hypoventilation syndrome [10], suggesting that the relationship could be bidirectional.

Few studies have explored the relationship between weight loss and sleep duration and the current evidence is inconsistent. A 2013 meta-analysis including nine studies of 577 participants found that dietary weight loss programs were effective in reducing the severity of obstructive sleep apnoea [11], and the same beneficial effect has been found for surgical weight loss [12]. Moreover, in a study of 55 individuals, Nam et al. found that a reduction in abdominal subcutaneous fat was associated with improvement in self-reported sleep disturbances [13]. Similar results were found in a study of 19 severely obese adolescents, where Kalra et al. demonstrated improvements in sleep efficiency and sleep fragmentation, as measured by polysomnography, after surgical weight loss [14]. While these studies all suggest a beneficial effect of weight loss on sleep, analysis of 41,610 individuals from the NutriNet-Santé e-cohort suggested that weight loss was associated with an increased risk of short self-reported sleep duration (≤6 h) among women [15].

Several mechanical effects could theoretically explain a direct effect of weight loss on sleep, as obesity is associated with different anatomical changes that increases the risk of airway obstruction, including an increase in neck circumference, fat deposited around the upper airway, upper airway collapsibility and reduced lung volume [16–19]. On the other hand, studies also suggest that both weight loss and weight gain elevates plasma cortisol [20, 21], and that cortisol administration reduces REM sleep and increases time spent awake during the night [22]. Consequently, it is possible that a history of several failed weight loss attempts, and a short duration of weight loss maintenance has adverse effects on sleep duration, but this has generally not been examined previously.

Thus, in the setting of a large European weight loss maintenance trial (NoHoW) including men and women who had achieved a clinically significant weight loss (≥5%) in the 12 months prior to baseline (initial BMI ≥25 kg/m^2), we examined the cross-sectional associations between baseline sleep duration and BMI, fat mass index (FMI), fat-free mass index (FFMI) and waist-hip ratio (WHR). Moreover, we examined whether retrospective 12-month weight loss, frequency of prior weight loss attempts and the average duration of weight loss maintenance after prior weight loss attempts was associated with attained sleep duration.

Material and methods

Study population

The NoHoW study is a randomized controlled trial testing the efficacy of an information and communication technology based toolkit for weight loss maintenance in the United Kingdom (Leeds), Denmark (Copenhagen) and Portugal (Lisbon). The trial is registered with the ISRCTN registry (ISRCTN88405328). A detailed description of the trial can be found elsewhere [23].

The present study was based on information collected during baseline examinations in 2017 and 2018, during which a total of 1627 participants were enroled into the study. All included participants were 18 years or older, had achieved a verified and clinically significant weight loss (≥5%) within the last 12 months, and had a BMI (prior to weight loss) of ≥25 kg/m^2. The exclusion criteria were as follows: lost weight due to illness or surgical procedures; pregnant or breastfeeding; involvement in other research intervention studies that confound with the aims of the intervention; inability to follow written material or telephone conversations in the English, Danish or Portuguese language (depending on the trial centre); diagnosed with an eating disorder; diagnosed with any condition that may interfere with increasing mild to moderate physical activities and which is unstable (i.e. untreated or unable to be controlled by medication); recent diagnosis with type 1 Diabetes; extensive planned travel (e.g. more than 4 weeks); and living in the same household as existing participant in the trial [23]. For the present study, we further excluded participants with missing or insufficient sleep data from the Fitbit device, defined as <1 main period of sleep and <6 valid days and two weekend days of physical activity ($n = 328$), missing information adiposity measures or weight loss history ($n = 50$) and selected covariates ($n = 47$), resulting in a total of 1202 participants. A flowchart illustrating the selection of participants can be found in Supplementary Fig. 1.

Fitbit Charge 2^{TM}

Sleep duration and physical activity was estimated using the Fitbit Charge 2^{TM} (FC2). The FC2 is a wrist-worn activity tracker, with a triaxial accelerometer, providing information on physical activity, sleep and heart rate [24]. According to Fitbit, the device estimates sleep duration and sleep stages using a combination of movement and heart rate patterns. When the user has not moved for an hour, the device assumes the user is sleeping. The device uses duration of movement, to capture movements related to sleep behaviour (e.g. rolling over), and this information is used to estimate that the user is sleeping or awake [25].

A Fitbit account was created for each participant and the Fitbit app was downloaded to their personal phone or tablet. Information on age, gender, height and weight was added to all accounts. A FC2 device was set up for each participant. The device was updated to the latest firmware and placed on the preferred wrist of the participant. Participants were instructed to wear the FC2 for the duration of the study. In the present study, we used data from day 3 to day 16 as a measure of sleep in the 14 days closest to baseline measurements. Day 1 and 2 were excluded to make sure all devices had been properly installed. The 2 weeks of data was included as a compromise between getting sufficient data to represent a robust measure of habitual sleep duration and not going too far from the other baseline measures. From this information, mean total sleep duration was calculated and included in analyses as either a continuous variable (units: hours/day) or a categorical variable: <6, 6–<7, 7–<8, 8–<9 and ≥9 h.

Physical activity measured in units of average steps/day (continuous variable) was included as a potential confounding factor. When no heart rate data was available from the FC2, we considered it as non-wear time. To avoid loss of data due to connectivity issues, gaps of <10 min were imputed with the average of the last measured and the next observed heart rate. Minute-level data was summarised hourly and missing time was determined per hour. Total steps were divided by the number of minutes the device was worn, on the assumption that data missing within each hour was most representative of missing data. Hours with more than 30 min of missing data were removed from the data. Next, hourly averages were summed per day, a minimum of 21 valid hours were required for a valid day. Lastly, total steps were averaged across 14-day period if at least 6 valid days and 2 weekend days were available.

Adiposity measures and weight loss history

Body weight was measured to the nearest 0.1 kg and height was measured to the nearest 0.1 cm using the Seca 704s combined stadiometer and electronic scale. From this, BMI was calculated [BMI = body weight (kg)/height (m)^2]. Bioelectrical impedance was measured using the ImpediMed SFB7 device (software version. 5.4.0), following the manufacturer's instructions. We used the Moissl BMI modification of the mixture theory equations to determine fat and fat-free mass, a method that has been found appropriate over a wide range of body compositions [26]. Using this information FMI [FMI = fat mass (kg)/height (m)^2] and FFMI [FFMI = fat free mass (kg)/height (m)^2] was calculated. Waist circumference was measured using a tape measure to the nearest 0.1 cm, mid-way between the lowest rib and the iliac crest with the subject standing. Likewise, hip circumference was measured using a tape measure to the nearest 0.1 cm, at the maximum circumference over the buttocks. Waist and hip circumferences were taken twice and if the two measures differed by more than 1 cm a third measurement was taken. The median waist and hip circumferences were used in the present study, from which WHR was calculated [WHR = waist circumference (cm)/hip circumference (cm)]. Baseline adiposity measures were included in analyses as continuous variables.

All participants provided verified information on weight loss during the 12 months prior to baseline, and this data was included as a continuous variable in present study (kg). In addition, through an online questionnaire, participants were asked: "How often in your life have you lost more than 5 kilos in a slimming attempt? (never, 1–2 times, 3–5 times, 6–10 times, or more than 10 times)" and "On average how long do you maintain your efforts to lose weight (1–2 weeks, 2–4 weeks, 4–8 weeks, 2–3 months, or longer than 3 months)?"

Covariates

At baseline, participants were asked to report their smoking status in one of the following categories: current smoker, previous smoker (quit in last 5 years), previous smoker (quit more than 5 years ago), or never smoked. For the present study, previous smoker (quit in last 5 years) and previous smoker (quit more than 5 years ago) was collapsed into one category. Likewise, information was collected on alcohol consumption: "During the last 12 months, how often did you usually have any kind of drink containing alcohol? By a drink we mean a unit (every day, 5 to 6 times a week, 3–4 times a week, twice a week, once a week, 2–3 times a month, 3–11 times in the past year, 1 or 2 times in the past year, I did not drink any alcohol in the past year, but I did drink in the past, or I never drank alcohol in my life)". In the present study alcohol consumption was included in the following six categories: every day, 5–6 times a week, 3–4 times a week, twice a week, once a week and less than once a week. Highest level of education was collected and categorized according to the International Standard Classification of Education (ISCED) [27] as high, medium, low or other (including educations not classified by ISCED). Psychosocial stress was assessed with the short version of the perceived stress scale [28]. This scale has the following four items that focus on the assessment of stress and coping over the preceding month: "How often have you felt that you were unable to control the important things in your life?", "How often have you felt confident about your ability to handle your personal problems?", "How often have you felt that things were going your way?" and "How often have you felt difficulties were piling up so high that you could not overcome them?". Responses were made on a 5-point Likert scale (never, rarely, sometimes, often and very often), and the items were then summed to give a total perceived stress score with a range of 0 (least stressed) to 16 (most stressed), which was included as a continuous variable. Finally, information on age (continuous variable) and gender was included.

Statistical analyses

Analysis of covariance was applied to assess mean differences in BMI, FMI, FFMI and WHR across categories of sleep duration (<6, 6–<7, 7–<8, 8–<9 and >9 h). First, crude models, including information on adiposity measures and sleep duration, only, were conducted. Secondly, adjusted analyses were carried out, with added information on smoking status, frequency of alcohol consumption, physical activity, education, perceived stress, age and gender.

Moreover, to explore weight loss history as a predictor of attained sleep duration, mean differences in sleep duration across categories of frequency of weight loss >5 kg (never, 1–2 times, 3–5 times, 6–10 times and >10 times) and duration of prior weight loss attempts (1–2 weeks, 2–4 weeks, 4–8 weeks, 2–3 months and >3 months) were tested using analysis of covariance, while linear regression was applied to assess the association between 12-month weight loss and attained sleep duration. These analyses followed the same adjustment strategy as described above, but with added information on baseline BMI in the adjusted model.

Gender and country/centre interactions were tested in all analyses by adding product terms to the models and stratified analyses were conducted if appropriate. Model assumptions (investigating linearity of effects on outcomes, consistency with a normal distribution and variance homogeneity) were assessed for the fully adjusted models through residual plots.

All statistical tests were two-tailed with a significance level at 0.05. Analyses were performed using Stata SE 14 (StataCorp LP, College Station, Texas, USA). Figures were produced using SigmaPlot 13.0 (San Jose, CA, USA).

Sensitivity analyses

It is well established that there is a linear association between fat and lean mass [29]. Thus, in order to get independent associations in the analyses of sleep duration and FMI and FFMI, we conducted sensitivity analyses mutually adjusting each index for the other. In addition, supplementary analyses were conducted exploring the association between sleep duration and fat mass percentage.

Although most of the included individuals had information on sleep duration from a relatively large proportion of the 14-day baseline period, some individuals only had a few days of data available. Thus, to examine if these individuals would potentially bias our results, sensitivity analyses were conducted in which we excluded individuals with ≤7 days of available sleep information ($n = 15$). Finally, we conducted sensitivity analyses exploring associations between sleep duration and adiposity measures where only weekend sleep measurements were included.

Results

Information on sleep duration, adiposity measures, weight loss history and covariates are shown in Table 1. Sleep duration was collected during an average of 12.6 days (SD: 1.6) throughout the 14-day baseline period. The mean sleep duration was 7.9 h (SD: 0.9), and a longer duration of sleep was observed among women [8.0 h (SD: 0.8)] than men [7.5 h (SD: 1.0); $P < 0.001$].

Sleep duration and adiposity

The associations between sleep duration and BMI, FMI, FFMI and WHR are shown in Fig. 1. After adjustment for potential confounding factors, we found an association between sleep duration and BMI ($P < 0.001$). The highest BMI was observed in the group of participants sleeping <6 h a day [34.0 (95% CI: 31.8–36.1)]. Less difference in BMI was detected between the remaining groups, with the lowest BMI among participants sleeping 8–<9 h a day [29.4 (95% CI: 28.8–29.9)]. Almost identical patterns of association were found for FMI ($P = 0.008$) and FFMI ($P < 0.001$), and the same tendency was seen in the crude model of WHR, though this association was not statistically significant after the adjustment for potential confounding factors ($P = 0.15$).

We found no evidence of interaction between gender and sleep duration (all P-interaction >0.45). Likewise, we found no interaction between country and sleep duration in analyses of BMI, FFMI and WHR (all P-interaction >0.10). However, in the analysis of FMI significant interaction was observed (P-interaction = 0.036), and analysis stratified by country revealed that an association between sleep duration and FMI was only present among participants from the UK sample (Supplementary Fig. 2).

In the sensitivity analyses of FMI and FFMI where each index was mutually adjusted for the other, the observed

Table 1 Information on sleep duration, anthropometry, weight loss history and covariates among men and women from the NoHoW study.

	All ($n = 1202$)[a]	Men ($n = 374$)	Women ($n = 828$)	*P* value[b]
Fitbit data				
Sleep duration (hours/day)	7.9 (0.9)	7.5 (1.0)	8.0 (0.8)	<0.001
Sleep (number of days available)	12.6 (1.6)	12.6 (1.7)	12.7 (1.6)	0.64
Physical activity (steps/day)	10,669 (3629)	11,469 (4051)	10,308 (3362)	<0.001
Anthropometry				
BMI (kg/m^2)	29.8 (5.5)	29.5 (4.8)	29.9 (5.8)	0.85
FMI (kg/m^2)	11.6 (4.7)	9.5 (3.7)	12.5 (4.7)	<0.001
FFMI (kg/m^2)	18.2 (2.5)	20.0 (2.1)	17.4 (2.2)	<0.001
WHR	0.86 (0.09)	0.94 (0.08)	0.83 (0.07)	<0.001
Weight loss history				
Weight loss prior to baseline (kg)	11.7 (6.6)	12.1 (7.0)	11.6 (6.4)	0.20
Weight loss > 5 kg (frequency)				<0.001
Never	3.7	6.4	2.4	
1–2 times	43.3	54.8	38.2	
3–5 times	32.5	24.1	36.4	
6–10 times	11.8	8.4	13.3	
>10	8.7	6.2	9.8	
Prior weight loss attempts (duration)				0.56
1–2 weeks	3.7	2.9	4.1	
2–4 weeks	12.7	12.3	12.8	
4–8 weeks	18.6	21.1	17.5	
2–3 months	23.5	22.7	23.8	
>3 months	41.5	40.9	41.8	
Covariates				
Age (years)	44.9 (11.6)	43.6 (10.8)	45.5 (12.0)	0.002
PSS (possible range: 0–16)	5.8 (2.8)	5.3 (2.6)	6.0 (2.9)	<0.001
Frequency of alcohol consumption (%)				<0.001
Every day	2.0	3.5	1.3	
5–6 times a week	3.5	5.9	2.4	
3–4 times a week	11.4	15.0	9.8	
Twice a week	15.1	17.1	14.1	
Once a week	10.5	12.8	9.4	
Less than once a week	57.6	45.7	62.9	
Smoking status (%)				0.11
Current	8.5	11.0	7.4	
Previous	38.5	38.2	38.7	
Never	53.0	50.8	54.0	
Educational status (%)				0.001
Low	9.2	7.8	9.9	
Medium	21.2	27.0	18.6	
High	65.1	59.1	67.8	
Other	4.5	6.2	3.7	

BMI Body mass index, *FFMI* fat free mass index, *FMI* fat mass index, *PSS* perceived stress scale, *WHR* waist-hip ratio

[a]Results presented as mean (SD) unless otherwise stated

[b]*P* value for gender difference (Wilcoxon rank-sum test or chi-squared test)

association persisted for FFMI ($P = 0.015$), but not for FMI ($P = 0.14$) (Supplementary Fig. 3). No association was observed between sleep duration and fat mass percentage after adjusting for potential confounding factors

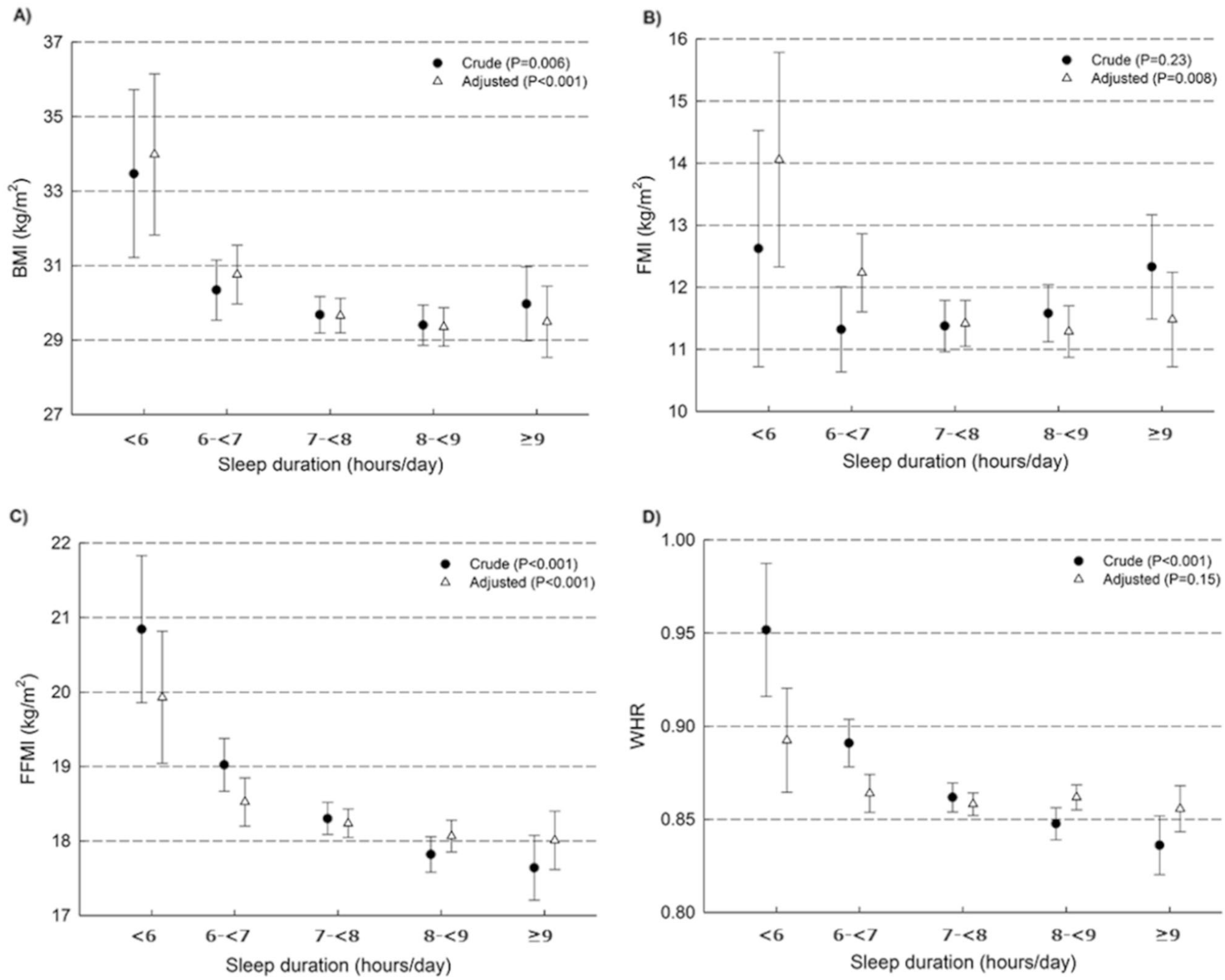

Fig. 1 Association between sleep duration and adiposity measures. Results presented as mean values of body mass index (**a**), fat mass index (**b**), fat free mass index (**c**) and waist-hip-ratio (**d**) (95% CI) in categories of sleep duration. The crude models include information on exposure and outcome, only. Adjusted models contain added information on physical activity, perceived stress, smoking status, frequency of alcohol consumption, education, sex and age. Body mass index (BMI), fat free mass index (FFMI), fat mass index (FMI) and waist-hip ratio (WHR).

(Supplementary Fig. 4). Moreover, excluding individuals with ≤7 days of available sleep information gave similar results (Supplementary Fig. 5). After adjusting for covariates, analyses including weekend sleep duration, only, showed associations with BMI ($P = 0.02$) and FFMI ($P < 0.001$) that were essentially similar to the analyses including all week days, but the association with BMI was attenuated. Moreover, weekend sleep duration was not associated with FMI ($P = 0.35$) or WHR ($P = 0.10$) (Supplementary Fig. 6).

Weight loss history and attained sleep duration

We found no association between 12-month weight loss prior to study inclusion and attained sleep duration ($P = 0.71$) (Table 2). Likewise, no association was observed between the frequency or duration of prior weight loss attempts and attained sleep duration ($P = 0.11$ and $P = 0.51$, respectively) (Table 3). None of these analyses showed statically significant interaction between weight loss history variables and gender (all P-interaction >0.05) or country (all P-interaction >0.44). Moreover, results found before and after excluding individuals with ≤7 days of available sleep information were essentially similar (Supplementary Tables 1 and 2).

Discussion

In this cohort of 1202 European men and women who had overweight or obesity and had achieved a clinically significant weight loss prior to inclusion at baseline, we found that a short sleep duration was associated with a higher

BMI, FMI and FFMI. In analyses where FMI and FFMI were mutually adjusted, the association between sleep duration and FFMI persisted while this was not the case for FMI. We found no association between sleep duration and body shape, as measured by WHR. Likewise, we found no evidence of association between the weight loss history and the attained sleep duration.

The association between short sleep duration and higher BMI observed in our study is consistent with findings from previous studies [2]. Some previous studies have suggested a U-shaped association between sleep duration and BMI (e.g. that both short and long sleepers tend to have a higher BMI) [6, 7, 30–32], a pattern we were unable to replicate in our study. Whereas most of the published studies suggest that the association between short sleep duration and higher BMI is due to an effect of sleep on body fat accumulation through metabolic changes affecting glucose metabolism, hunger or energy expenditure [9, 33], we found the same patterns of associations between sleep duration and both FMI and FFMI, suggesting the effect may be driven by mass load rather than or in addition to metabolic influences. Few previous studies have investigated the association between sleep duration and lean mass, but similar results to ours have been reported among adults from the Korean National Health and Nutrition Surveys [34], and among children participating in the Southampton Women´s Survey [35]. The relationship may to some extent be explained by the direct relationships between total mass, fat and lean mass [29]. However, in the sensitivity analyses where we mutually adjusted FMI and FFMI for the other, the association between sleep duration and FFMI persisted while this was not the case for FMI. It is possible that a high lean mass in itself may affect sleep duration but given the lack of studies that have explored longitudinal associations between sleep duration and lean mass, as well as the potential underlying mechanisms, the nature of this association remains uncertain. In addition, a high degree of the variability observed in sleep duration, body weight and composition can be explained by heritability [36–38] and genetic variants in the *CLOCK* gene have been found associated with both sleep duration and BMI [39]. Thus, the observed associations may also be explained by genetic factors.

Table 2 Association between 12-months weight loss and attained sleep duration.

12 months weight loss	β (95% CI)[a]	*P* value
Crude[b]	−0.10 (−0.50, 0.29)	0.61
Adjusted[c]	0.20 (−0.85, 1.25)	0.71

[a]Results presented as additional hours/day of sleep per kg weight loss

[b]Information on exposure and outcome, only

[c]Added information on baseline BMI, physical activity, perceived stress, smoking status, frequency of alcohol consumption, education, sex and age

In our study, we found no evidence of associations between weight loss history and attained sleep duration. We also did not find previous studies exploring whether the frequency of prior weight loss attempts or the average duration of weight loss maintenance after prior weight loss attempts was associated with attained sleep duration. However, results from an analysis of 41,610 individuals from the NutriNet-Santé e-cohort suggests that weight loss is associated with an increased risk of short sleep duration at least among women [15]. We were unable to replicate this finding and we found no evidence of gender interaction, but given the large difference in sample size, lack of power in our study may explain the different results.

Our study has several strengths, including the objectively measured data on sleep duration collected during a 14-day period, thus providing us with a robust estimate of habitual sleep duration. Although the FC2 is not considered a gold standard for measuring sleep, a recent validation study conducted by Zambotti et al. concluded that the device showed promise in detecting sleep relative to polysomnography among 44 adults in a laboratory setting. The study reported a sensitivity of 0.96 (accuracy to detect sleep) and a specificity of 0.61 (accuracy to detect time wake) [40]. Moreover, we had verified information on

Table 3 Association between weight loss history and attained sleep duration.

Frequency of weight loss > 5 kg[a]	Never	1–2 times	3–5 times	6–10 times	>10	*P* value
Crude[b]	7.65 (7.37–7.93)	7.84 (7.76–7.92)	7.93 (7.84–8.03)	7.83 (7.68–7.99)	7.94 (7.76–8.12)	0.23
Adjusted[c]	7.78 (7.42–7.94)	7.82 (7.74–7.90)	7.93 (7.84–8.02)	7.86 (7.70–8.00)	8.01 (7.84–8.19)	0.11
Duration of prior weight loss attempts	1–2 weeks	2–4 weeks	4–8 weeks	2–3 months	>3 months	
Crude	7.95 (7.67–8.22)	7.97 (7.82–8.12)	7.81 (7.68–7.93)	7.93 (7.82–8.04)	7.82 (7.74–7.91)	0.25
Adjusted	7.92 (7.66–8.18)	7.94 (7.80–8.08)	7.83 (7.72–7.95)	7.92 (7.82–8.02)	7.83 (7.75–7.91)	0.51

[a]Results presented as mean sleep duration in hours per day (95% CI) in categories of weight loss history

[b]Information on exposure and outcome, only

[c]Added information on baseline BMI, physical activity, perceived stress, smoking status, frequency of alcohol consumption, education, sex and age

12-months weight loss prior to baseline, as well as information on several lifestyle factors, including objectively measured physical activity, allowing us to adjust for potential confounders.

On the other hand, our study also has some limitations. The Fitbit app allowed participants to monitor their own sleep habits and we cannot exclude that this may have affected their sleep duration, but differential misclassification as a consequence of this is unlikely. The analyses of associations between sleep duration and adiposity measures were cross-sectional, and thus it is not possible to assess causality. Likewise, although we had verified information on 12-months weight loss prior to baseline, these analyses were limited by the fact that we had no information on sleep duration prior to baseline, which would be necessary to accurately assess an association between weight loss and change in sleep duration. Moreover, we relied on self-reported retrospective information on the frequency of prior weight loss attempts and the average duration of weight loss maintenance after prior weight loss attempts, which is likely to have a low accuracy [41]. Hence, measurement error related to these variables may have biased the results towards the null and led to wider confidence intervals. However, any form of differential misclassification is unlikely. In addition, although we adjusted our analyses for several potential confounding factors, we cannot exclude that some unmeasured or residual confounding has remained. Finally, our results originate from a specific group of men and women with overweight or obesity who had achieved a clinically significant weight loss prior to baseline, and thus generalization to the general population should done with caution. Relatedly, since our population had limited variation in BMI, these results may not apply to normal or underweight individuals.

In conclusion, our results build on the current evidence to suggest that short sleep duration is associated with a higher BMI. Most previous research has suggested that this association is primarily due to an association between sleep and adiposity, but our results suggest that the association also involves lean mass. The causality and the underlying mechanisms of these associations are yet to be determined, but we found no evidence of association between weight loss history and attained sleep duration. Longitudinal studies, with information on objectively measured sleep during extended periods of time in addition to repeated measures of adiposity, are needed to improve our understanding of the observed associations.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval The study was conducted in accordance with the Helsinki Declaration. Ethical approval has been granted by local institutional ethics committees at the Universities of Leeds (17-0082; 27-Feb-2017), Lisbon (17/2016; 20-Feb-2017) and the Capital Region of Denmark (H-16030495; 8-Mar-2017).

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