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Increases in physical activity are associated with a faster rate of weight loss during dietary energy restriction in women with overweight and obesity

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Abstract

This secondary analysis examined the influence of changes in physical activity (PA), sedentary time and energy expenditure (EE) during dietary energy restriction on the rate of weight loss (WL) and 1-year follow-up weight change in women with overweight/obesity. Measurements of body weight and composition (air displacement plethysmography), RMR (indirect calorimetry), total daily EE (TDEE) and activity EE (AEE), minutes of PA and sedentary time (PA monitor) were taken at baseline, after 2 weeks, after ≥5 % WL or 12 weeks of continuous (25 % daily energy deficit) or intermittent (75 % daily energy deficit alternated with *ad libitum* day) energy restriction, and at 1-year post-WL. The rate of WL was calculated as total %WL/number of dieting weeks. Data from both groups were combined for analyses. Thirty-seven participants (aged 35 (SD 10) years; BMI = 29·1 (SD 2·3) kg/m^2) completed the intervention (WL = –5·9 (SD 1·6) %) and 18 returned at 1-year post-WL (weight change=+4·5 (SD 5·2) %). Changes in sedentary time at 2 weeks were associated with the rate of WL during energy restriction (r = –0·38; P = 0·03). Changes in total (r = 0·54; P < 0·01), light (r = 0·43; P = 0·01) and moderate-to-vigorous PA (r = 0·55; P < 0·01), sedentary time (r = –0·52; P < 0·01), steps per d (r = 0·39; P = 0·02), TDEE (r = 0·46; P < 0·01) and AEE (r = 0·51; P < 0·01) during energy restriction were associated with the rate of WL. Changes in total (r = –0·50; P = 0·04) and moderate-to-vigorous PA (r = –0·61; P = 0·01) between post-WL and follow-up were associated with 1-year weight change (r = –0·51; P = 0·04). These findings highlight that PA and sedentary time could act as modifiable behavioural targets to promote better weight outcomes during dietary energy restriction and/or weight maintenance.

Key words: **Physical activity: Sedentary time: Energy expenditure: Weight loss: Weight regain**

It has been reported that up to 80 % of individuals who achieve clinically significant weight loss (WL) fail to sustain this WL after 1 year or more[1]. While researchers have attempted to identify predictors of WL and WL maintenance, inconsistent findings are reported and potential predictors of WL often have limited explanatory value[2,3]. Identification of predictive factors is important as it would allow proactive changes to be made during a WL intervention, potentially improving longer-term weight management success. Two factors that have been previously highlighted as predictors of WL are early changes in body weight (2 to 6 weeks)[4,5] and the amount of physical activity (PA) performed during periods of WL[6].

Previous research has reported that PA may decline during dietary-induced WL[7–9], with a systematic review by Silva *et al.* reporting decreases in PA and/or non-exercise activity thermogenesis in 50 % (seven out of fourteen studies) of diet-only interventions[7]. However, several studies have reported no changes in PA during WL[10,11]. For instance, after 12 weeks of continuous or intermittent energy restriction to about 12·5 % WL, Coutinho *et al.* did not observe any within- or between-group differences in the number of steps per d[10]. Inter-individual variability in WL and body composition outcomes is commonly observed in studies of dietary energy restriction[12,13], but whether individual differences in changes in PA and sedentary behaviours influence WL and WL maintenance success remains unclear.

While the role of PA and exercise in weight management has been questioned[14], interventions combining both dietary energy restriction and changes in PA usually promote a greater WL which is better sustained over time[15]. For instance, a

Abbreviations: AEE, activity energy expenditure; EE, energy expenditure; PA, physical activity; TDEE, total daily energy expenditure; WL, weight loss.

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systematic review observed that combining dietary energy restriction and exercise lead to a 20 % greater total WL in comparison with dietary modifications alone[16]. Furthermore, during 6 months of a lifestyle WL intervention, participants on the higher PA group had an increase of 47 min/d (and a reduction in sedentary time of 52 min/d), achieving a greater total WL[17]. However, findings regarding the role of PA or exercise in weight management are not always consistent, with a recent systematic review reported no significant effects of exercise on WL maintenance[18].

Of note, few studies have objectively measured PA during dietary-induced WL, and in particular, during the early stages of WL, to examine whether changes in free-living PA influences the dynamics of WL, for example, rate, extent or composition of WL. Examining the early- and longer-term changes in PA at the individual level during dietary-induced energy restriction would allow for a better understanding of the role of PA in facilitating or resisting early and/or sustained WL and would provide a framework in which effective behaviour change interventions could be designed to improve weight management success rates[19].

Therefore, the aim of this secondary analysis was to examine the influence of early (baseline to week 2) and post-intervention changes in objectively measured PA and sedentary time during dietary energy restriction on (1) the rate of WL and (2) 1-year follow-up weight change in women with overweight and obesity.

Material and methods

Healthy women with overweight and obesity were recruited from the University of Leeds and the surrounding area via posters and email lists to take part in a study examining 'the effects of a personalised WL meal plan on body composition and metabolism' (NCT03447600). In this study, participants were randomised to either continuous (CER; daily 25 % energy restriction – all foods were provided) or intermittent (IER; 75 % energy restriction days alternated with *ad libitum* eating days – food was only provided on 'fast' days) energy restriction until ≥ 5 % WL or 12 weeks (even if WL target was not achieved). The present analyses represent exploratory analysis of secondary outcomes from this study, and previous findings from the main dietary energy restriction study have been reported elsewhere[20,21]. Specific details of the dietary intervention during the WL phase are provided elsewhere[22], and for the purposes of this paper, findings from both dietary groups were combined as no group differences existed in the main outcomes reported here (see section 2·4). No instructions were given to nor contact kept with participants after the WL phase, and thus they were not required to maintain the same dietary pattern. Participants that completed the WL phase (≥ 5 % WL or within 12 weeks) were invited for a 1-year follow-up 4 weeks before the measurements to avoid influencing their behaviours throughout the 12 months. Therefore, while this was not a weight maintenance intervention, the aim of the follow-up measurement was to attempt to highlight factors (during and after dietary-induced energy restriction) associated with post-WL weight change as these could have important implications regarding weight management interventions.

Participants were excluded if they had health problems that could affect study outcomes, history of eating disorders, taking medication, supplements or treatment known to affect appetite/weight within the past month and/or during the study, pregnant, planning to become pregnant or breast-feeding, known food allergies/intolerances, smokers or had ceased smoking in the past 6 months, lost significant amount of weight in the previous 6 months (±4 kg), exercised > 3 d per week, significantly changed their PA patterns in the past 6 months or intended to change them during the study, worked in appetite/feeding related areas, or were shift workers. Participants provided written informed consent before taking part and were remunerated £100 upon completion of the WL protocol, and £30 after the 1-year follow-up measurements. The study received approval from the School of Psychology Research Ethics Committee at the University of Leeds (ref: PSC-238, date: 10/01/2018; amendment to include 1-year follow-up – ref: PSC-669, date: 11/04/2019).

Study design

Participants completed a free-living week of measurements where a PA monitor was worn continuously to assess minutes of PA and to estimate total daily energy expenditure (TDEE) and activity energy expenditure (AEE). Upon completion of the free-living week of measurements, participants attended the laboratory for a testing day which took place after a 10–12-h overnight fast. This day included assessments of body composition, RMR, as well other variables (e.g. appetite ratings and eating behaviour traits) reported elsewhere as these were not the main aim of the current secondary analysis[20–22]. Upon completing both free-living and laboratory measurements, participants were randomised to either CER or IER until they reached ≥ 5 % WL or 12 weeks, as previously described[22]. Participants had weekly meetings with a dietitian to monitor body weight and adjust the meal plan if needed. Upon reaching ≥ 5 % WL on a weekly meeting, participants completed a final free-living week of measurements while still on CER or IER, emailing their fasted body weight each day to the research dietitian. Measurements were collected at baseline (before diet allocation), after 2 weeks of energy restriction (to examine the associations between early changes and longer-term outcomes), at ≥ 5 % WL (or 12 weeks) and at 1-year post-WL. To assess the impact of early changes in physiological and psychological outcomes, measurements were collected after 2 weeks of the diet so as to avoid the first phase of WL in which rapid changes in body water and glycogen stores can occur, and because it is not uncommon for a 5 % WL (the target WL in this study) to occur within 4–6 weeks[23].

Free-living measurements

Physical activity. Participants wore a PA monitor (SenseWear Armband; BodyMedia, Inc.) to assess PA and estimate TDEE and AEE over 7 d at baseline (before the diet intervention), after 2 weeks of dietary energy restriction, post-WL and at 1-year follow-up. The SenseWear Armband is a device which has been shown to provide valid estimates of PA and EE[24]. The SenseWear Armband uses body weight, height and age, as well galvanic skin response, skin temperature, heat flux and complex pattern recognition algorithms to determine activity type, to estimate TDEE. Minutes spent in sedentary (< 1·5 MET), light (1·5–2·0 MET), moderate (3·0–5·9 MET) and vigorous (≥ 6·0 MET) activities, as well daily steps and sleep duration were calculated using proprietary algorithms presented in the device's accompanying software (version 8.0 professional), previously validated[24]. AEE was calculated using the following equation:

$$Activity\ Energy\ Expenditure = TDEE \times 0 \cdot 9 - RMR$$

Participants were instructed to wear the monitor halfway between their elbow and shoulder for at least 23 h per d (including overnight, although daily and nightly activities have not been discriminated), only removing during activities that involved contact with water (e.g. shower and swimming). Compliance with utilising the monitor was defined as having a minimum of 22 h of verifiable time per d for at least 5 d (including one weekend day). All participants wore the PA monitor for at least 5 d, with a mean wear time per d of 23 h and 40 min (from 23 h and 7 min to 23 h and 54 min). Participants were instructed not to change their structured exercise habits for the duration of the WL phase, for example, start an exercise programme if this was not already part of their routine. However, no specific instructions were given regarding habitual daily PA behaviours, and these behaviours were not restricted or controlled throughout the intervention to allow quantification of the degree of spontaneous non-exercise PA changes. As changes in PA behaviours may naturally occur in response to periods of negative energy balance despite the absence of specific recommendations[7], the aim of this analysis was to examine how these spontaneous changes could influence body weight outcomes. An important factor to consider is that AEE and TDEE are influenced by changes in body weight. Therefore, when exporting the data from the SenseWear Armband, the value for body weight was updated to control for the reduction in EE induced by losses of body mass. Furthermore, steps per d and minutes of total, light and moderate-to-vigorous PA, and sedentary time, were examined as these are commonly used measurements of PA independent of body weight and body composition. No instructions were given to participants between the post-WL phase and the 1-year follow-up in terms of PA (or dietary) patterns, and therefore, participants could have started or stopped any type of formal exercise routines during these 12 months.

Laboratory measurements

Body weight and composition. Body weight and composition were measured, whilst participants were wearing tight-fitting clothing and a swimming cap using air displacement plethysmography (BodPod, COSMED Inc.). Fat mass and FFM were estimated to the nearest 0·01 kg, and manufacturer's instructions were followed and the Siri equation[25] was used to estimate body fat percentage.

Rate of weight loss. In the present study, total percentage of WL and the time to complete the intervention (i.e. final day of measurements) ranged from 3·2 % to 8·3 % and 35 to 93 d, respectively. As individuals with different starting body masses were being compared, which could alter the absolute amount of WL[26], relative changes in body weight were reported as a percentage. To control for the variability in intervention duration and total WL between participants, mean rate of WL throughout the intervention was calculated. In the scientific literature[27–31], rate of WL has been calculated using the following equation:

$$Rate\ of\ Weight\ Loss\ (\%\ per\ week) = \frac{Total\ Weight\ Loss\ (\%)}{Time\ (weeks)}$$

The mean rate of WL was calculated at weeks 2 and post-WL. As the timing for the follow-up measurements was matched between participants (approximately 1 year), percentage of body weight change from post-WL to 1-year follow-up was calculated.

RMR. RMR was measured with an indirect calorimeter fitted with a ventilated hood (GEM, Nutren Technology Ltd). Participants were asked to remain in a supine position for 40 min without moving, talking or falling asleep. Before each measurement, an individual calibration process was performed. RMR was calculated using the 5-min steady state method[32], and data were entered into the Weir equation[33].

Statistical analyses

Data are presented as mean values and standard deviation. Data were analysed using SPSS software version 25 (IBM Corp.). The Shapiro–Wilk test was used to examine for normality of distribution, and all data were normally distributed. Analyses were conducted with data from participants that completed the intervention (≥ 5 % WL or 12 weeks). Differences between intervention groups (CER and IER) at baseline were examined using Welch's *t* tests. Changes over time were analysed with repeated-measures maximum-likelihood linear mixed models to account for missing data, using SPSS (version 26, IBM). Measures day (baseline, week 2, post-WL and 1-year post-WL), intervention group (CER and IER) and their interaction were analysed as fixed factors and subject as random factor. Bonferroni adjustments were applied to *post hoc* analyses. Data are presented as estimated marginal means and 95 % CI.

For the analyses pertaining to the rate of WL, data from both groups were combined as no statistical differences existed between groups[22]. Partial correlations (adjusted for WL group and baseline values) were conducted to examine the associations between baseline characteristics, changes from baseline to week 2 and from baseline to post-WL with the mean rate of WL, as the rate of WL was different between dietary groups (CER: 0·8 (SD 0·3) %/week; IER: 0·6 (SD 0·3) %/week; $P = 0·01$). Pearson's correlations were also conducted to examine the associations between changes from post-WL to follow-up and 1-year weight change. However, as 1-year weight change was similar between groups and these were not following a particular dietary pattern, these associations were not adjusted for group. The main study from which these secondary analyses have been conducted was originally powered to detect an interaction in self-selected meal size (*ad libitum* energy intake) between two groups and two repeated measurements[22], but

Table 1. Participant characteristics of the completers at baseline and 1-year follow-up
(Number, mean values and standard deviations)

	Baseline			1-year follow-up					
	Chapter 1 CER Chapter 2 (*n* 19)	Chapter 3 IER Chapter 4 (*n* 18)	Chapter 5 Total Chapter 6 (*n* 37)	CER (*n* 11)		IER (*n* 7)		Total (*n* 18)	
Age (years)	Chapter 7 34 (SD 9)	Chapter 8 36 (SD 11)	Chapter 9 35 (SD 10)	38	9	37	12	38	10
Body weight (kg)	Chapter 10 79·6 (SD 10·3)	Chapter 11 80·1 (SD 11·1)	Chapter 12 79·9 (SD 10·6)	73·7	6·8	77·1	13·3	75·0	9·6
Height (cm)	Chapter 13 165·1 (SD 7·8)	Chapter 14 165·5 (SD 8·7)	Chapter 15 165·3 (SD 8·1)	161·5	4·6	161·5	6·6	161·5	5·2
BMI (kg/m^2)	Chapter 16 29·1 (SD 2·4)	Chapter 17 29·1 (SD 2·2)	Chapter 18 29·1 (SD 2·3)	28·2	2·2	29·5	4·0	28·7	3·0
Fat mass (kg)	Chapter 19 32·8 (SD 8·1)	Chapter 20 33·5 (SD 6·7)	Chapter 21 33·1 (SD 7·4)	28·8	5·7	34·2	10·0	30·9	7·9
Fat mass (%)	Chapter 22 40·7 (SD 6·1)	Chapter 23 41·6 (SD 4·1)	Chapter 24 41·2 (SD 5·2)	38·8	5·2	43·6	5·9	40·7	5·8
Fat-free mass (kg)	Chapter 25 46·9 (SD 5·4)	Chapter 26 46·6 (SD 6·1)	Chapter 27 46·7 (SD 5·7)	44·9	3·9	42·9	4·6	44·1	4·2

CER, continuous energy restriction; IER, intermittent energy restriction.

power calculations (G × Power v3.1) indicated that a sample size of 23 would be sufficient to see a correlation coefficient of 0·50 between PA and weight change with $\alpha = 0{\cdot}05$ and $1\text{-}\beta = 0{\cdot}8$ (based on a previous study that observed a correlation coefficient of $r = -0{\cdot}69$[34]). Statistical significance was defined as $P < 0{\cdot}05$.

Results

Participant flow

A total of fifty-four participants were enrolled in the trial, forty-six completed baseline measurements, with no differences between groups (all $P > 0{\cdot}18$) and were randomly allocated to a diet group (CER – 22; IER – 24), and thirty-seven reached ≥5 % WL or 12 weeks (CER – 19; IER – 18). Eighteen participants returned for the 1-year follow-up (CER – 11; IER – 7). Characteristics of the participants that completed the WL intervention (*n* 37), and that returned after 1-year (*n* 18) can be found in Table 1 and a participant flow chart can be found in Fig. 1.

Changes during the intervention

Mean values for each group at each time point during the intervention can be seen in Table 2. No baseline differences were observed between dietary groups (all $P > 0{\cdot}12$). Both groups achieved a similar total WL (CER: 6·2 (SD 0·8) %; IER: 5·5 (SD 2·1) %; $P = 0{\cdot}17$). The mean rate of WL was similar between groups at week 2 (CER: 0·2 (SD 0·1) %/week; IER: 0·2 (SD 0·1) %/week; $P = 0{\cdot}79$), but different throughout the entire intervention (CER: 0·8 (SD 0·3) %/week; IER: 0·6 (SD 0·3) %/week;
$P = 0{\cdot}01$). Both groups presented a similar weight change from post-WL to 1-year follow-up (CER: 5·0 (SD 6·0) %; IER: 3·7 (SD 4·0) %; $P = 0{\cdot}62$). One participant (CER) displayed weight regain of 19·7 %, and when removed, weight regain was near identical (CER: 3·6 (SD 3·7) %; IER: 3·7 (SD 4·0) %; $P = 0{\cdot}93$). Weight change from post-WL to 1-year follow-up in the whole group ranged from –2·1 % to +19·7 % (–1·4 to +14·0 kg), or from –2·1 % to 9·7 % (–1·4 to +8·2 kg) when the outlier was removed.

There was a main effect of time ($P < 0{\cdot}001$) but no effect of group or interaction ($P \geq 0{\cdot}15$) for body weight, fat mass, fat-free mass, body fat percentage, RMR, TDEE and AEE. *Post hoc* analyses are shown in Table 2. There were no time, group or interaction effects for daily steps, sleep duration, total PA, light PA, moderate-to-vigorous PA or sedentary time ($P \geq 0{\cdot}07$).

Associations between changes at week 2 and mean rate of weight loss

No associations were seen between baseline PA, sedentary time, sleep duration, TDEE or AEE with the mean rate of WL throughout the intervention ($P > 0{\cdot}05$).

Changes in total PA ($r = 0{\cdot}29$; $P = 0{\cdot}10$), light ($r = 0{\cdot}03$; $P = 0{\cdot}86$) and moderate-to-vigorous PA ($r = 0{\cdot}25$; $P = 0{\cdot}16$), steps per d ($r = 0{\cdot}19$; $P = 0{\cdot}26$), sleep duration ($r = 0{\cdot}18$; $P = 0{\cdot}32$), TDEE ($r = 0{\cdot}07$; $P = 0{\cdot}72$) and AEE ($r = 0{\cdot}07$; $P = 0{\cdot}70$) from baseline to week 2 were not associated with the mean rate of WL throughout the intervention. As shown in Fig. 2, mean rate of WL ($r = 0{\cdot}42$; $P = 0{\cdot}01$) and changes in sedentary time ($r = -0{\cdot}37$; $P = 0{\cdot}03$) from baseline to week 2 were associated with the mean rate of WL throughout the energy restriction phase.

Associations between changes throughout the intervention and mean rate of weight loss

Changes in sleep duration ($r = 0{\cdot}06$; $P = 0{\cdot}73$) were not associated with the mean rate of WL during the energy restriction phase. Changes in total PA ($r = 0{\cdot}55$; $P < 0{\cdot}01$), light PA ($r = 0{\cdot}43$; $P = 0{\cdot}01$), moderate-to-vigorous PA ($r = 0{\cdot}51$; $P < 0{\cdot}01$), sedentary time ($r = -0{\cdot}56$; $P < 0{\cdot}01$), steps per d ($r = 0{\cdot}39$; $P = 0{\cdot}02$), TDEE ($r = 0{\cdot}41$; $P = 0{\cdot}02$) and AEE ($r = 0{\cdot}47$; $P < 0{\cdot}01$) were associated with the mean rate of WL (Fig. 3). Associations were also found between the days to reach 5 % WL (which ranged from 35 to 93 d) and changes throughout the energy restriction phase in total PA ($r = -0{\cdot}49$; $P = 0{\cdot}004$), light PA ($r = -0{\cdot}43$; $P = 0{\cdot}01$), moderate-to-vigorous PA ($r = -0{\cdot}47$; $P = 0{\cdot}007$), sedentary time ($r = 0{\cdot}55$; $P = 0{\cdot}001$) and steps per d ($r = 0{\cdot}36$; $P = 0{\cdot}04$).

Factors associated with post-weight loss 1-year weight change

Changes in light PA ($r = -0{\cdot}32$; $P = 0{\cdot}24$), sedentary time ($r = 0{\cdot}39$; $P = 0{\cdot}13$), steps per d ($r = -0{\cdot}39$; $P = 0{\cdot}12$), sleep duration ($r = -0{\cdot}08$; $P = 0{\cdot}77$), TDEE ($r = -0{\cdot}07$; $P = 0{\cdot}80$) and AEE ($r = -0{\cdot}06$; $P = 0{\cdot}81$) from post-WL to 1-year follow-up were not associated with 1-year weight change. However,

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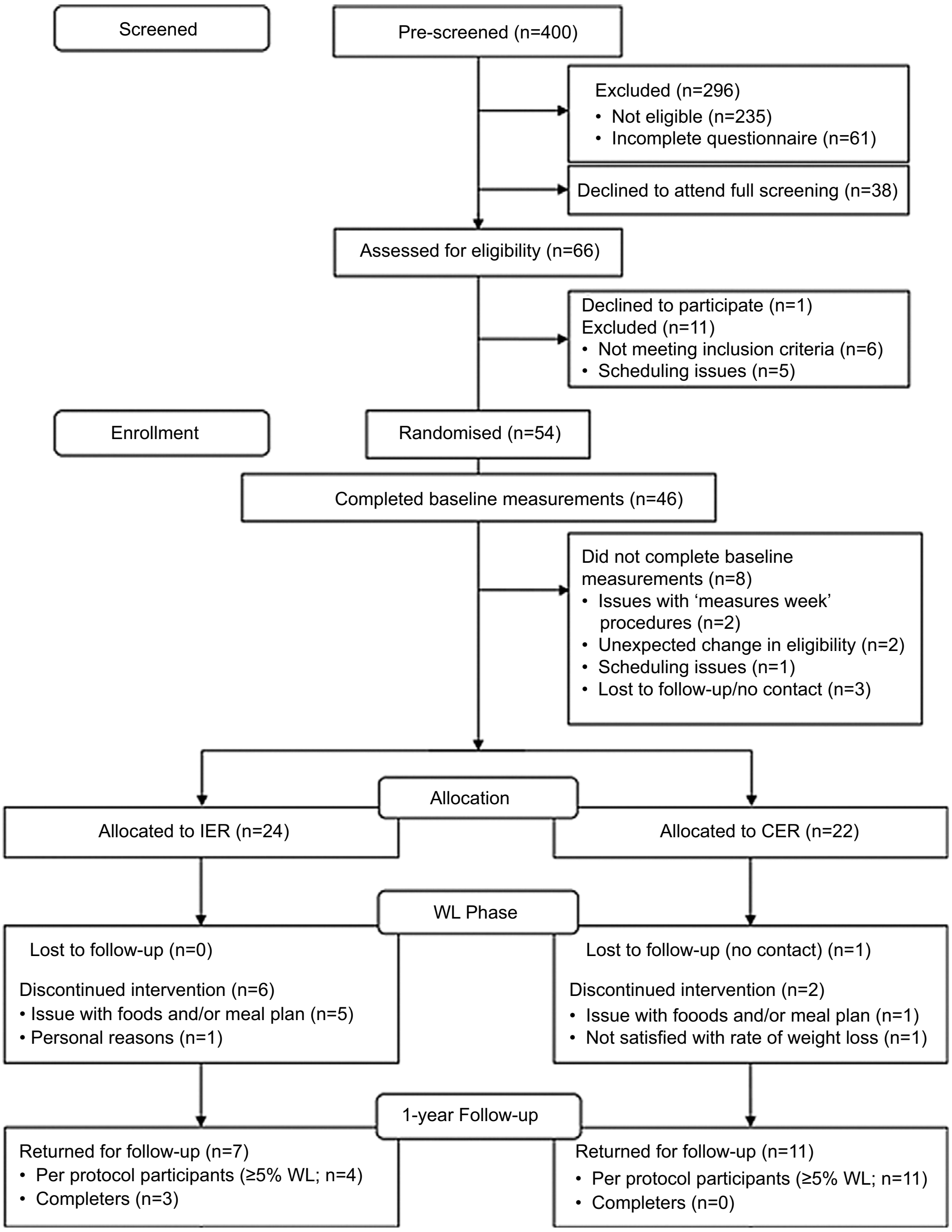

Fig. 1. Participant flow chart. CER, continuous energy restriction; IER, intermittent energy restriction.

changes in total PA ($r=-0{\cdot}50$; $P=0{\cdot}04$) and moderate-to-vigorous PA ($r=-0{\cdot}61$; $P=0{\cdot}01$) were associated with 1-year weight change (Fig. 4).

Discussion

The aim of this secondary analysis was to explore whether changes in objectively measured PA, sedentary time and EE were associated with the rate of WL during dietary energy restriction and 1-year weight change post-WL. In these data, baseline characteristics were not associated with longer-term WL outcomes, but the rate of WL and changes in sedentary time after 2 weeks were associated with the mean rate of WL during the dietary intervention period. Changes in total PA, light PA, moderate-to-vigorous PA, sedentary time, steps per d, TDEE and AEE from baseline to post-WL were associated with the mean rate of WL during the energy restriction phase, while changes in total PA and moderate-to-vigorous PA from post-WL to 1-year follow-up were associated with the change in body weight during the non-contact follow-up period. Changes in sleep duration were not associated with body weight outcomes at any time points. Data from this secondary analysis suggest that increases (or smaller reductions) in PA behaviours during dietary energy restriction may help facilitate WL and attenuate weight regain. As such, these data highlight the potential importance of considering PA and sedentary time in dietary weight management interventions.

Table 2. Mean values for participants of both CER and IER that completed the intervention at baseline, week 2, post-WL and at 1-year follow-up
(Mean values and 95 % confidence intervals)

		Baseline		Week 2		Post-WL		1-year follow-up				
		Marginal means	95 % CI	Marginal means	95 % CI	Marginal means	95 % CI	Marginal means	95 % CI	Baseline *v.* week 2	Baseline *v.* post-WL	Post-WL *v.* follow-up
Body weight (kg)	CER	79·63	74·82, 84·45	77·72	72·91, 82·53	74·71	69·89, 79·52	78·21	73·35, 83·07	< 0·001	< 0·001	< 0·001
	IER	80·09	75·15, 85·03	78·18	73·24, 83·12	75·66	70·72, 80·61	78·58	73·52, 83·64			
Fat mass (kg)	CER	32·75	29·42, 36·08	31·22	27·89, 34·55	29·08	25·75, 32·41	31·93	28·53, 35·32	0·008	< 0·001	< 0·001
	IER	33·52	30·10, 36·94	32·65	29·23, 36·07	30·48	27·06, 33·90	32·94	29·38, 36·51			
Fat-free mass (kg)	CER	46·88	44·25, 49·51	46·50	43·87, 49·13	45·63	43·00, 48·26	46·28	43·63, 48·92	< 0·001	< 0·001	0·051
	IER	46·57	43·87, 49·27	45·52	42·82, 48·22	45·19	42·49, 47·89	45·66	42·92, 48·39			
Body fat (%)	CER	40·73	38·30, 43·15	39·78	37·36, 42·21	38·52	36·09, 40·94	40·46	37·97, 42·94	0·568	< 0·001	0·001
	IER	41·64	39·15, 44·13	41·58	39·09, 44·08	40·07	37·58, 42·56	41·36	38·74, 43·98			
RMR (kcal/d)	CER	1456	1370, 1542	1433	1347, 1519	1435	1349, 1521	1657	1564, 1750	1·000	1·000	< 0·001
	IER	1435	1346, 1523	1459	1371, 1548	1478	1389, 1566	1638	1533, 1742			
TDEE (kcal/d)	CER	2352	2214, 2489	2311	2173, 2448	2263	2125, 2400	2376	2232, 2520	0·005	< 0·001	0·015
	IER	2455	2309, 2600	2333	2187, 2478	2296	2150, 2442	2385	2223, 2548			
AEE (kcal/d)	CER	661	568, 753	647	554, 740	601	509, 694	472	365, 579	0·084	0·001	0·060
	IER	773	675, 871	639	541, 737	595	495, 695	514	380, 647			
Total PA (min/d)	CER	235	194, 277	244	202, 285	255	214, 297	226	181, 271	1·000	1·000	1·000
	IER	257	213, 301	241	198, 285	247	203, 292	239	185, 293			
sed time (min/d)	CER	760	714, 805	739	693, 784	723	677, 768	791	741, 841	1·000	0·670	0·166
	IER	744	696, 792	739	691, 787	743	695, 792	746	686, 806			
Light PA (min/d)	CER	168	137, 198	173	143, 204	182	152, 212	141	107, 174	1·000	1·000	0·054
	IER	180	148, 212	177	145, 209	176	143, 208	162	123, 202			
MVPA (min/d)	CER	68	53, 84	72	56, 87	74	58, 89	86	69, 104	1·000	1·000	0·821
	IER	77	61, 94	65	48, 81	72	56, 89	77	56, 98			
Steps per d	CER	8623	7380, 9865	8715	7473, 9958	8455	7213, 9698	9643	8266, 11 019	1·000	1·000	0·833
	IER	9262	7949, 10 576	8469	7155, 9782	8578	7251, 9905	8712	7060, 10 364			
Sleep (min/d)	CER	424	398, 450	437	411, 463	443	417, 469	405	376, 434	0·297	0·597	0·832
	IER	417	389, 444	433	406, 461	423	395, 451	430	395, 466			

CER, continuous energy restriction; IER, intermittent energy restriction; WL, weight loss; TDEE, total daily energy expenditure; AEE, activity energy expenditure; PA, physical activity; Sed time, sedentary time; MVPA, moderate-to-vigorous physical activity.

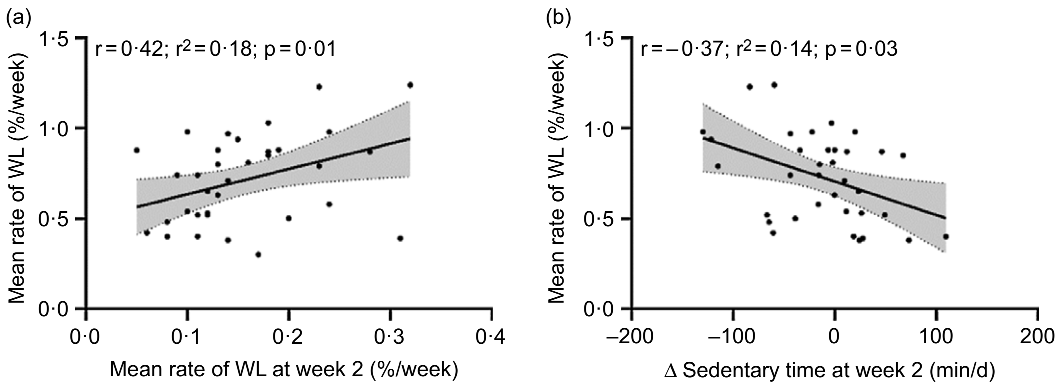

Fig. 2. Associations between mean rate of weight loss in the participants that completed the intervention with (a) mean rate of weight loss at week 2 and (b) changes in sedentary time at week 2. Grey bands represent the 95 % CI. WL, weight loss.

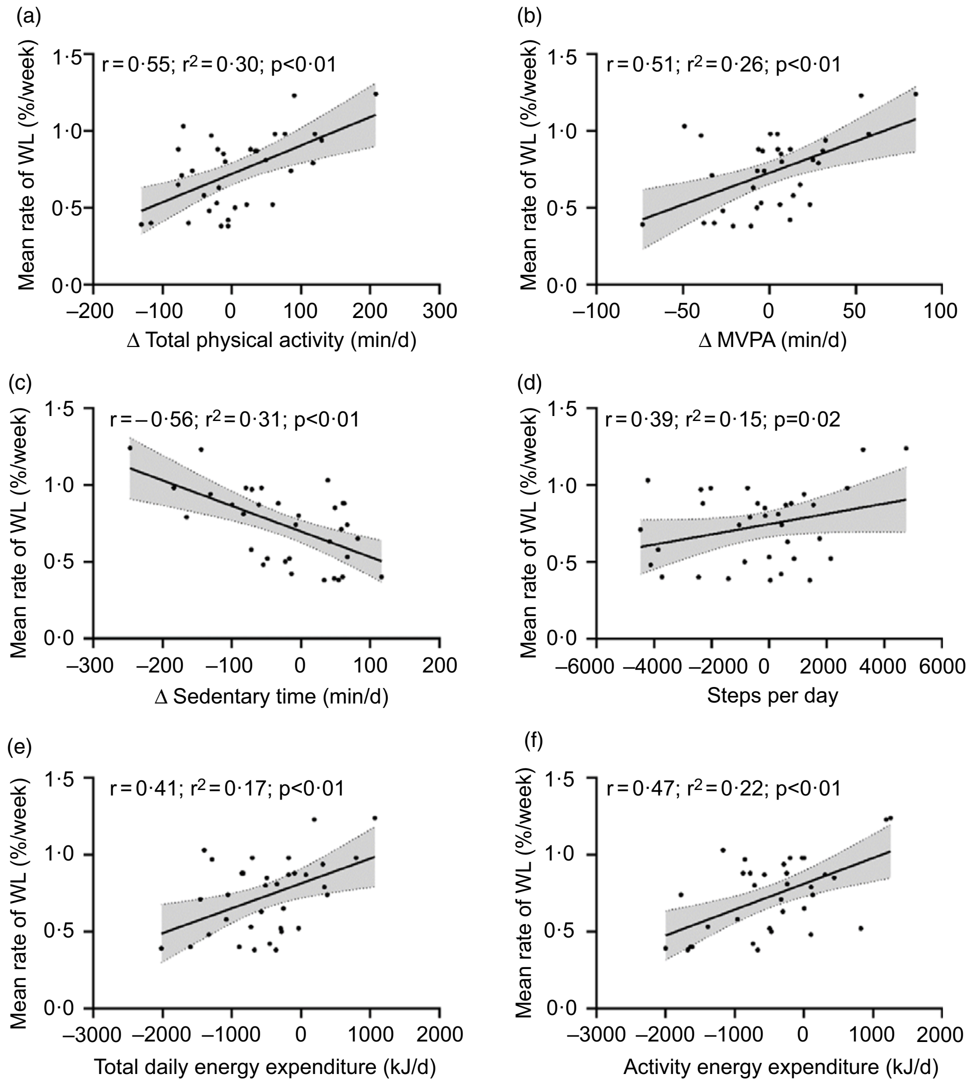

Fig. 3. Associations between mean rate of weight loss in the participants that completed the intervention with changes throughout the intervention in (a) total physical activity, (b) moderate-to-vigorous physical activity, (c) sedentary time, (d) steps per d, (e) total daily energy expenditure and (f) activity energy expenditure. Grey bands represent the 95 % CI. WL, weight loss.

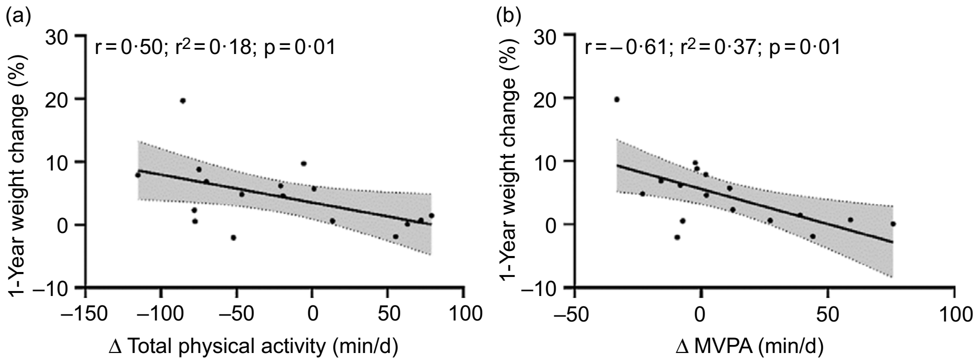

Fig. 4. Associations between 1-year weight change and changes between post-WL and 1-year follow-up in (a) total physical activity and (b) moderate-to-vigorous physical activity. Grey bands represent the 95 % CI. The mean rate of WL during the WL phase was not associated with 1-year weight change ($r = –0·01$; $P = 0·97$). However, changes in total PA ($r = –0·50$; $P = 0·04$), moderate-to-vigorous PA ($r = –0·64$; $P < 0·01$), sedentary time ($r = –0·71$; $P < 0·01$) and TDEE ($r = –0·48$; $P = 0·04$) from baseline to post-WL were negatively associated with the changes from post-WL to 1-year follow-up, with greater increases in PA or TDEE during the WL phase being associated with greater decreases during the 1-year post-WL phase.

Changes in physical activity during diet-induced weight loss

It has been previously suggested that diet-induced WL may lead to reductions in PA, with a recent systematic review reporting that seven out of fourteen diet-only interventions observed decreases in non-exercise PA[7]. In the current study, no changes were observed in mean PA or sedentary time over time, and no differences in PA or sedentary time were seen between dietary groups. This corroborates the findings from a previous study comparing intermittent to continuous energy restriction[10] and other diet-only interventions that did not observe reductions in the amount of PA[11,35]. However, despite the absence of mean changes in PA in the present study, a large inter-individual variability was observed. For instance, changes in total PA from baseline to post-WL ranged from –130 to +209 min/d, while the mean change was only +5 min/d ($P = 1·00$). As such, focusing on the changes in PA at the group level may mask important information regarding how individual differences in PA influence the rate of WL at the individual level.

Associations between early changes in physical activity and the mean rate of weight loss

Several studies have reported that WL in the first weeks of an intervention (2–6 weeks) is a predictor of longer-term total WL[36–38]. For instance, Tronieri *et al.* observed that participants that lost more weight in the first 4 weeks lost more weight at week 14 ($r^2 = 0·61$; $P < 0·001$) and presented a faster rate of WL[38]. In the current study, a faster rate of WL during the first 2 weeks of energy restriction and a decrease in sedentary time during the first 2 weeks were associated with a faster mean rate of WL during the total energy restriction period. Furthermore, early changes in PA (i.e. baseline to week 2) were strongly correlated with the baseline to post-WL changes ($r = 0·60–0·70$; $P < 0·001$), suggesting that the early changes in PA were maintained across the full dietary energy restriction period. While few studies have looked into the influence of early changes in PA or EE on WL outcomes, these findings are in agreement with a study by Reinhardt *et al.* in which changes in TDEE in response to a 24-h fast were associated with WL after 6 weeks[39]. In this study, individuals that presented a greater decrease in TDEE (which is influenced by PA) during 24 h of fasting presented a slower rate of WL. However, as this was measured in a respiratory chamber (in which PA could be artificially limited), it remains unknown whether this association between changes in 24-h TDEE and 6-week WL was due to changes in PAEE or some other TDEE component (although the authors reported that changes in sleeping metabolic rate were not associated with WL). These findings suggest that early changes in body weight and PA (2 weeks in the case of the current study) during diet-induced energy restriction may reflect how well someone will respond in terms of longer-term WL. If this is the case, this could improve weight management success as practitioners would be able to be proactive and adjust an intervention early based on shorter-term responses. However, future studies should aim to replicate these findings to confirm whether early changes in PA allow to predict how individuals will lose weight in the longer term.

Associations between changes throughout the intervention and the mean rate of weight loss

An important finding from the current study was that changes in PA and sedentary time throughout the diet intervention were associated with the mean rate of WL, with participants that had greater increases in PA and decreases in sedentary time presenting faster mean rates of WL. These findings are in agreement with a previous WL study (meal plan and instructions to increase PA) in which the group of individuals that had greater increases in moderate-to-vigorous PA lost more weight after 6 months[6], suggesting that maintaining or increasing PA during periods of dietary-induced energy restriction may be an important behavioural strategy to facilitate WL. Overall, these findings corroborate previous literature reporting that the combination of diet and PA leads to better WL outcomes[16,18].

Although the amount of PA performed (e.g. minutes per d) and AEE are related, PA is a behaviour while AEE represents the EE associated with movement and is therefore also influenced by the mass and composition of an individual[40]. In this data, PA levels were strongly associated with AEE (total PA – $r = 0·70$;

$P < 0·001$; moderate-to-vigorous PA – $r = 0·74$; $P < 0·001$; sedentary time – $r = –0·64$; $P < 0·001$), suggesting that a potential mechanism to explain the current findings is that the changes in PA and sedentary time helped to better maintain or increase the energy deficit created via energy restriction. It is important to report these objectively measured effects, since some recent pronouncements have claimed a limited relationship between PA and AEE which could undermine a rationale for promoting the beneficial effects of PA on body weight (or body fat)[41].

In the present study, participants exercised ≤ 3 d per week at baseline and were instructed not to change their exercise habits during the dietary intervention (e.g. start a structured exercise regimen alongside the dietary intervention), but no strict restrictions were placed on other PA behaviours during the intervention. However, it is important to highlight that time spent performing moderate-to-vigorous PA in the current study was on average > 60 min/d, suggesting the participants included were relatively active. Whether the changes in PA and sedentary time during the WL intervention were intentional is unknown, and an important question that should be addressed in future research is whether individuals who demonstrate better WL outcomes during energy restriction actively increase their PA to augment WL. While PA levels are readily modifiable, it cannot be ruled out that individuals became more active as a result of their greater WL. Therefore, the hypothesis that PA may increase as a consequence of WL, rather than increases in PA leading to a faster rate of WL, cannot be ruled out and should be explored in future studies.

Factors associated with 1-year weight change

Changes in moderate-to-vigorous PA from post-WL to 1-year follow-up were associated with 1-year weight change. These findings are in agreement with previous studies highlighting PA as a robust predictor of WL maintenance[3,42,43], but not all[44]. An interesting observation in the present study was that participants that increased PA during the WL phase had lower baseline values, but these individuals also demonstrated greater reductions in PA between the end of the WL phase and the 1-year follow-up point. This perhaps suggests that participants with a greater rate of WL consciously increased their PA, but after the WL phase terminated, the absence of a specific WL goal may have led to a return to baseline PA levels. However, it is important to consider that since the sample size was limited to eighteen individuals (from thirty-seven participants that finished the WL phase), these findings should be interpreted cautiously. Nonetheless, the observed associations in this secondary analysis should be viewed as an initial proof of concept highlighting the relevance of PA for sustained WL, and this enquiry should be replicated in future studies with larger sample sizes.

Limitations

The equation used to calculate the rate of WL, as well assessing changes in PA at baseline, week 2, post-WL and after 1-year assumes that these changes are linear over time. This may be inaccurate due to the daily fluctuations in both EI and EE that may occur during periods of negative energy balance[45,46]. However, the main aim of this study was to identify the factors associated with WL variability and not with the intra-individual variability in weekly changes in body weight. Therefore, this calculation allowed for an examination of the factors that explain why some individuals lose weight faster (on average). Furthermore, changes in PA at week 2 and post-intervention were strongly associated (all $r = 0·60–0·70$; $P < 0·001$), as well with changes between post-WL and 1-year follow-up, suggesting that the individual changes in PA were consistent across the study period. It is also important to acknowledge that the sample size, especially at 1-year follow-up, was small and consisted only of women, potentially limiting the generalisability of the findings. Lastly, as there was no contact between post-WL and 1-year follow-up, it is not known whether changes in PA and sedentary time were conscious and voluntary remains unknown.

Conclusion

The results from this secondary analysis corroborate previous findings demonstrating that baseline characteristics may not be good indicators of longer-term WL. However, increases in PA behaviours after 2 weeks and throughout the intervention were associated with a faster mean rate of WL. Furthermore, decreases in PA behaviours were associated with a greater 1-year weight regain. Conversely, an increase in sedentary time was associated with a slower rate of WL and greater weight regain. These findings highlight the potential contribution of PA during dietary weight management interventions, and as a potentially modifiable component of TDEE, may be an important behavioural target during dietary energy restriction that promotes better weight outcomes during dietary energy restriction.

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There are no conflicts of interest.

References

1. Wing RR & Phelan S (2005) Long-term weight loss maintenance. *Am J Clin Nutr* **82**, 222S–225S.
2. Greaves CJ, Sheppard KE, Abraham C, *et al.* (2011) Systematic review of reviews of intervention components associated with increased effectiveness in dietary and physical activity interventions. *BMC Public Health* **11**, 119.
3. Paixão C, Dias CM, Jorge R, *et al.* (2020) Successful weight loss maintenance: a systematic review of weight control registries. *Obes Rev* **21**, e13003.

4. Yank V, Xiao L, Wilson SR, *et al.* (2014) Short-term weight loss patterns, baseline predictors, and longer-term follow-up within a randomized controlled trial. *Obesity* **22**, 45–51.
5. Unick JL, Pellegrini CA, Demos KE, *et al.* (2017) Initial weight loss response as an indicator for providing early rescue efforts to improve long-term treatment outcomes. *Curr Diabetes Rep* **17**, 69.
6. Fazzino TL, Fabian C & Befort CA (2017) Change in physical activity during a weight management intervention for breast cancer survivors: association with weight outcomes. *Obesity* **2**, S109–S115.
7. Silva AM, Judice PB, Carraca EV, *et al.* (2018) What is the effect of diet and/or exercise interventions on behavioural compensation in non-exercise physical activity and related energy expenditure of free-living adults? A systematic review. *Br J Nutr* **119**, 1327–1345.
8. de Groot LC, van Es AJ, van Raaij JM, *et al.* (1990) Energy metabolism of overweight women 1 mo and 1 y after an 8-week slimming period. *Am J Clin Nutr* **51**, 578–583.
9. Weigle DS (1988) Contribution of decreased body mass to diminished thermic effect of exercise in reduced-obese men. *Int J Obes* **12**, 567–578.
10. Coutinho SR, Halset EH, Gasbakk S, *et al.* (2018) Compensatory mechanisms activated with intermittent energy restriction: a randomized control trial. *Clin Nutr* **37**, 815–823.
11. van Dale D, Schoffelen PF, ten Hoor F, *et al.* (1989) Effects of addition of exercise to energy restriction on 24-hour energy expenditure, sleeping metabolic rate and daily physical activity. *Eur J Clin Nutr* **43**, 441–451.
12. Yancy WS, Olsen MK, Guyton JR, *et al.* (2004) A low-carbohydrate, ketogenic diet versus a low-fat diet to treat obesity and hyperlipidemia: a randomized, controlled trial. *Ann Intern Med* **140**, 769–777.
13. Gardner CD, Trepanowski JF, Del Gobbo LC, *et al.* (2018) Effect of low-fat *v.* low-carbohydrate diet on 12-month weight loss in overweight adults and the association with genotype pattern or insulin secretion: the DIETFITS randomized clinical trial. *JAMA* **319**, 667–679.
14. Malhotra A, Noakes T & Phinney S (2015) It is time to bust the myth of physical inactivity and obesity: you cannot outrun a bad diet. *Br J Sport Med* **49**, 967–968.
15. Jakicic JM, Rogers RJ, Davis KK, *et al.* (2018) Role of physical activity and exercise in treating patients with overweight and obesity. *Clin Chem* **64**, 99–107.
16. Curioni CC & Lourenço PM (2005) Long-term weight loss after diet and exercise: a systematic review. *Int J Obes* **29**, 1168–1174.
17. DeLany JP, Kelley DE, Hames KC, *et al.* (2014) Effect of physical activity on weight loss, energy expenditure, and energy intake during diet induced weight loss. *Obesity* **22**, 363–370.
18. Bellicha A, van Baak MA, Battista F, *et al.* (2021) Effect of exercise training on weight loss, body composition changes, and weight maintenance in adults with overweight or obesity: an overview of 12 systematic reviews and 149 studies. *Obes Rev* **22**, e13256.
19. Stubbs RJ, Duarte C, O'Driscoll R, *et al.* (2019) Developing evidence-based behavioural strategies to overcome physiological resistance to weight loss in the general population. *Proc Nutr Soc* **78**, 576–589.
20. Beaulieu K, Casanova N, Oustric P, *et al.* (2020) An exploratory investigation of the impact of 'fast' and 'feed' days during intermittent energy restriction on free-living energy balance behaviours and subjective states in women with overweight/obesity. *Eur J Clin Nutr* **75**, 430–437.
21. Oustric P, Beaulieu K, Casanova N, *et al.* (2021) Food liking but not wanting decreases after controlled intermittent or continuous energy restriction to ≥ 5 % weight loss in women with overweight/obesity. *Nutrients* **13**, 182.
22. Beaulieu K, Casanova N, Oustric P, *et al.* (2019) Matched weight loss through intermittent or continuous energy restriction does not lead to compensatory increases in appetite and eating behavior in a randomized controlled trial in women with overweight and obesity. *J Nutr* **150**, 623–633.
23. Heymsfield SB, Thomas D, Nguyen AM, *et al.* (2011) Voluntary weight loss: systematic review of early phase body composition changes. *Obes Rev* **12**, e348–61.
24. O'Driscoll R, Turicchi J, Beaulieu K, Scott S, Matu J, Deighton K, *et al.* (2018) How well do activity monitors estimate energy expenditure? A systematic review and meta-analysis of the validity of current technologies. *Br J Sports Med* **54**, 332–340.
25. Siri W (1961) Body composition from fluid space and density. In *Techniques for Measuring Body Composition*, pp. 223–2441961 [J Brozek & A Hanschel, editors]. Washington, DC: National Academy of Science.
26. Hatoum IJ & Kaplan LM (2013) Advantages of percent weight loss as a method of reporting weight loss after Roux-en-Y gastric bypass. *Obesity* **21**, 1519–1525.
27. Finkler E, Heymsfield SB & St-Onge M-P (2012) Rate of weight loss can be predicted by patient characteristics and intervention strategies. *J Acad Nutr Dietetics* **112**, 75–80.
28. Nackers LM, Ross KM & Perri MG (2010) The association between rate of initial weight loss and long-term success in obesity treatment: does slow and steady win the race? *Int J Behav Med* **17**, 161–167.
29. Vink RG, Roumans NJ, Arkenbosch LA, *et al.* (2016) The effect of rate of weight loss on long-term weight regain in adults with overweight and obesity. *Obesity* **24**, 321–327.
30. Coutinho SR, With E, Rehfeld JF, *et al.* (2018) The impact of rate of weight loss on body composition and compensatory mechanisms during weight reduction: a randomized control trial. *Clin Nutr* **37**, 1154–1162.
31. Turicchi J, O'Driscoll R, Finlayson G, *et al.* (2019) Associations between the rate, amount, and composition of weight loss as predictors of spontaneous weight regain in adults achieving clinically significant weight loss: a systematic review and meta-regression. *Obes Rev* **20**, 935–946.
32. Sanchez-Delgado G, Alcantara JMA, Ortiz-Alvarez L, *et al.* (2018) Reliability of resting metabolic rate measurements in young adults: impact of methods for data analysis. *Clin Nutr* **37**, 1618–1624.
33. Weir JB (1949) New methods for calculating metabolic rate with special reference to protein metabolism. *J Physiol* **109**, 1–9.
34. Aadland E & Robertson L (2012) Physical activity is associated with weight loss and increased cardiorespiratory fitness in severely obese men and women undergoing lifestyle treatment. *J Obes* **2012**, 810594.
35. Weinsier RL, Hunter GR, Zuckerman PA, *et al.* (2000) Energy expenditure and free-living physical activity in black and white women: comparison before and after weight loss. *Am J Clin Nutr* **71**, 1138–1146.
36. Barnes RD, Ivezaj V, Pittman BP, *et al.* (2018) Early weight loss predicts weight loss treatment response regardless of binge-eating disorder status and pretreatment weight change. *Int J Eat Disord* **51**, 558–564.
37. James BL, Roe LS, Loken E, *et al.* (2018) Early predictors of weight loss in a 1-year behavioural weight-loss programme. *Obes Sci Pract* **4**, 20–28.
38. Tronieri JS, Wadden TA, Chao AM, *et al.* (2019) Early weight loss in behavioral treatment predicts later rate of weight loss and response to pharmacotherapy. *Ann Behav Med* **53**, 290–295.

39. Reinhardt M, Thearle MS, Ibrahim M, *et al.* (2015) A human thrifty phenotype associated with less weight loss during caloric restriction. *Diabetes* **64**, 2859–2867.
40. Westerterp K (2013) Physical activity and physical activity induced energy expenditure in humans: measurement, determinants, and effects. *Front Physiol* **4**, 90.
41. Pontzer H, Durazo-Arvizu R, Dugas LR, *et al.* (2016) Constrained total energy expenditure and metabolic adaptation to physical activity in adult humans. *Curr Biol* **26**, 410–417.
42. Ostendorf DM, Lyden K, Pan Z, *et al.* (2018) Objectively measured physical activity and sedentary behavior in successful weight loss maintainers. *Obesity* **26**, 53–60.
43. Ostendorf DM, Blankenship JM, Grau L, *et al.* (2021) Predictors of long-term weight loss trajectories during a behavioral weight loss intervention: an exploratory analysis. *Obes Sci Pract* **7**, 569–582.
44. Washburn RA, Szabo-Reed AN, Gorczyca AM, *et al.* (2021) A randomized trial evaluating exercise for prevention of weight regain. *Obesity* **29**, 62–70.
45. Melby CL, Paris HL, Foright RM, *et al.* (2017) Attenuating the biologic drive for weight regain following weight loss: must what goes down always go back up? *Nutrients* **9**, 468.
46. Casanova N, Beaulieu K, Finlayson G, *et al.* (2019) Metabolic adaptations during negative energy balance and their potential impact on appetite and food intake. *Proc Nutr Soc* **78**, 279–289.

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