Physical Activity Energy Expenditure and Total Daily Energy Expenditure in Successful Weight Loss Maintainers

Danielle M Ostendorf, Ann E Caldwell, Seth Creasy, Zhaoxing Pan, Kate Lyden, Audrey Bergouignan, Paul S Maclean, Holly R Wyatt, James Hill, Edward L Melanson, et al.

Physical Activity Energy Expenditure and Total Daily Energy Expenditure in Successful Weight Loss Maintainers

Danielle M. Ostendorf [1,2]*, Ann E. Caldwell*[1]*, Seth A. Creasy* [2]*, Zhaoxing Pan*[3]*, Kate Lyden*[4]*, Audrey Bergouignan* [1,2,5,6]*, Paul S. MacLean*[2]*, Holly R. Wyatt*[1]*, James O. Hill*[1]*, Edward L. Melanson*[2,7,8]*, and Victoria A. Catenacci*[1,2]

Objective: The objective of this study was to compare physical activity energy expenditure (PAEE) and total daily energy expenditure (TDEE) in successful weight loss maintainers (WLM) with normal weight controls (NC) and controls with overweight/obesity (OC).

Methods: Participants were recruited in three groups: WLM ($n = 25$, BMI 24.1 ± 2.3 kg/m^2; maintaining ≥ 13.6-kg weight loss for ≥ 1 year), NC ($n = 27$, BMI 23.0 ± 2.0 kg/m^2; similar to current BMI of WLM), and OC ($n = 28$, BMI 34.3 ± 4.8 kg/m^2; similar to pre–weight loss BMI of WLM). TDEE was measured using the doubly labeled water method. Resting energy expenditure (REE) was measured using indirect calorimetry. PAEE was calculated as (TDEE – [0.1 × TDEE] – REE).

Results: PAEE in WLM (812 ± 268 kcal/d, mean ± SD) was significantly higher compared with that in both NC (621 ± 285 kcal/d, $P < 0.01$) and OC (637 ± 271 kcal/d, $P = 0.02$). As a result, TDEE in WLM ($2{,}495 \pm 366$ kcal/d) was higher compared with that in NC ($2{,}195 \pm 521$ kcal/d, $P = 0.01$) but was not significantly different from that in OC ($2{,}573 \pm 391$ kcal/d).

Conclusions: The high levels of PAEE and TDEE observed in individuals maintaining a substantial weight loss (-26.2 ± 9.8 kg maintained for 9.0 ± 10.2 years) suggest that this group relies on high levels of energy expended in physical activity to remain in energy balance (and avoid weight regain) at a reduced body weight.

Obesity (2019) **27**, 496-504. doi:10.1002/oby.22373

Introduction

Changes in energy expenditure that occur with weight loss have been suggested to contribute to the propensity for weight regain after weight loss. Total daily energy expenditure (TDEE) declines with weight loss because of decreases in both resting energy expenditure (REE) and physical activity (PA) energy expenditure (PAEE) that result primarily from the reduction in body mass (1). Some evidence suggests that substantial weight loss may also generate additional decreases in REE and TDEE beyond that expected based on changes in body weight and/

[1] Department of Medicine, Anschutz Health and Wellness Center, University of Colorado Anschutz Medical Campus, Aurora, Colorado, USA. Correspondence Danielle M. Ostendorf (danielle.ostendorf@ucdenver.edu) [2] Department of Medicine, Division of Endocrinology, Metabolism, and Diabetes, University of Colorado Anschutz Medical Campus, Aurora, Colorado, USA [3] Department of Biostatistics and Informatics, University of Colorado Anschutz Medical Campus, Aurora, Colorado, USA [4] KAL Research & Consulting, LLC, Denver, Colorado, USA [5] Department of Ecology, Physiology, and Ethology, Institut Pluridisciplinaire Hubert Curien, Strasbourg, France [6] UMR 7178 Centre National de la Recherche Scientifique, Strasbourg, France [7] Department of Medicine, Division of Geriatric Medicine, University of Colorado Anschutz Medical Campus, Aurora, Colorado, USA [8] Eastern Colorado Veterans Affairs Geriatric Research, Education, and Clinical Center, Denver, Colorado, USA.

See Commentary, pg. 361.

Funding agencies: This work was supported by grants from the National Institutes of Health (NIH K23 DK078913, P30 DK048520, NIH UL1 TR002535, NIH T32 HL116276, NIH K99 DK100465, and NIH R00 DK100465) as well as from the American Heart Association (AHA 16PRE29660012). The contents do not represent the views of the US Department of Veterans Affairs or the US Government.

Disclosure: JOH and HRW are partners in Shakabuku LLC, a company that provides weight management services, outside the submitted work; JOH and HRW have been issued a patent on the "Energy Gap" (US Patent #7,949,506). JOH and HRW received clinical trial grant funding from Novo Nordisk and Gelesis. JOH and HRW received clinical trial grant funding and received payment for speaking for the Cattleman's Beef Association. JOH and HRW report stock options from Retrofit, a company that provides weight management services. JOH serves as a consultant for Zaluvida, Gelesis, and Livongo. HRW accepted personal fees as an advisory board member for Atkins, a low-carbohydrate weight loss program, during the time frame of the study presented. KL is a paid consultant for PAL Technologies, the company that manufactures the device used to measure physical activity in this study. The other authors declared no conflict of interest.

Author contributions: VAC, HRW, and JOH conceived of and designed the study and obtained funding. VAC wrote the protocol and acquired the data. ZP and DMO performed the statistical analysis. DMO, AEC, SAC, ZP, KL, PSM, AB, HRW, JOH, ELM, and VAC interpreted the data. DMO, AEC, SAC, and VAC drafted the manuscript. DMO generated tables and figures. All authors were involved in writing and revising the manuscript and approved the final version of the manuscript.

Clinical trial registration: ClinicalTrials.gov identifier NCT03422380.

Received: 16 August 2018; **Accepted:** 2 November 2018; **Published online 25 February 2019. doi:10.1002/oby.22373**

or composition alone (1-6). To prevent weight regain, a permanent behavior change that leads to either a lower energy intake (EI) and/or a higher level of PA must occur to compensate for the reduction in TDEE. Although caloric restriction is effective for weight loss, it appears to be relatively ineffective as a sole strategy for long-term weight loss maintenance (7-9). The "energy gap" theory proposed by Hill et al. (10) states in part that the decline in TDEE with weight loss creates an energy gap that must be filled in order to remain in energy balance (and avoid weight regain) at a reduced body weight. Because high levels of PA are consistently associated with successful long-term weight loss maintenance (11-19), it is possible that successful weight loss maintainers (WLM) sustain high levels of PAEE to fill this gap. As a consequence of these high levels of PAEE, the EI required to match energy expenditure may be more feasible for weight-reduced individuals to comply with over the long term.

Much of the evidence demonstrating that successful WLM sustain high levels of PA is based on studies that have used self-reported measures (20-22) or activity monitors (16,17,19). Few studies have quantified PAEE in weight-reduced individuals who previously had overweight/obesity using the gold standard doubly labeled water (DLW) method. In weight-reduced women, Schoeller et al. demonstrated that higher PA levels (PAL) measured at the end of the weight loss period were associated with less weight regain 1 year later (11). However, PAL was only measured at baseline. Kerns et al. evaluated 14 contestants who completed "The Biggest Loser," a US televised weight loss competition, and found that 6 years after the competition, the successful WLM demonstrated a higher PAEE (12.2 ± 1.3 kcal/kg/d) compared with those who regained weight (8.0 ± 1.4 kcal/kg/d), whereas changes in EI from baseline were not different between groups (23). However, that study involved a small sample of individuals with severe obesity (class III) who underwent an extreme diet and PA intervention in the context of a reality weight loss competition, which limits the generalizability of these results.

Although successful WLM sustain high levels of PA, how this impacts PAEE and TDEE is not known. The goal of this study was to measure PAEE and TDEE in a sample of successful WLM and compare these measures to two control groups: (1) normal weight controls (NC) whose BMI was similar to the current BMI of the WLM and (2) controls with overweight/obesity (OC) whose current BMI was similar to the pre–weight loss maximum BMI of the WLM. Our global hypothesis was that WLM would sustain higher levels of PAEE compared with both control groups. Moreover, we hypothesized that because of the high levels of PAEE, WLM would sustain a TDEE that was higher than that of NC but not different from that of OC.

Methods

Participants

This case-control study was conducted at the University of Colorado Anschutz Medical Campus and approved by the Colorado Multiple Institutional Review Board. Participants included 106 adults (Figure 1) and were studied between October 2009 and August 2012. We recruited participants through campus-wide flyers and email announcements. To enhance recruitment of WLM, a letter was sent to members of the National Weight Control Registry (NWCR) database living in the Denver, Colorado, metro area. The NWCR was established in 1994 as a prospective cohort study to better understand behavioral patterns of WLM; entry criteria include maintenance of ≥ 13.6-kg weight loss for ≥ 1 year (24). Interested individuals then underwent preliminary telephone screening to determine whether they met eligibility criteria for one of the three study groups: (1) WLM (maintaining ≥ 13.6-kg weight loss for ≥ 1 year), (2) NC (BMI similar to current BMI of WLM) with no history of overweight/obesity, and (3) OC (BMI similar to the pre–weight loss maximum BMI of WLM). A nested subject selection procedure was used to obtain similar distributions for age (categories < 36, 36-49, and ≥ 50 years) and sex (male vs. female) across all three groups. This design also ensured similar distribution between current BMI of NC and WLM (categories < 22, 23-25, and 26-30 kg/m^2) and similar distribution between current BMI of OC and pre–weight loss maximum BMI of WLM (categories 26-30, 31-35, 36-40, and ≥ 41 kg/m^2).

Eligible individuals were invited to attend an in-person screening visit. After providing informed written consent, a health history and physical examination were completed. Individuals were excluded if they had any physical or medical condition that restricted PA (including diabetes, cardiovascular disease, cancer, and significant musculoskeletal, neurologic, or psychiatric disorders), had undergone weight loss surgery or were taking weight loss medications, were smokers, were not weight stable (> 5-kg fluctuation in body weight over past 6 months), or were taking medications known to affect appetite or metabolism. Women who were pregnant or lactating were also excluded. Eligible individuals were then scheduled for a 1-week free-living monitoring period.

Body weight and composition

Weight was measured with a calibrated digital scale (to the nearest 0.2 lb; BWB-800, Tanita Corp., Tokyo, Japan), and height was measured with a wall-mounted stadiometer (to the nearest 0.1 cm). Weight was measured at the screening visit and on days 1 and 8 of the 1-week free-living monitoring period. Waist circumference was measured just over the iliac crests at screening using a tape measure. Fat mass (FM) and fat-free mass (FFM) were measured with dual-energy x-ray absorptiometry (Delphi-W version 13.1.0; Hologic Inc., Bedford, Massachusetts) at screening. One OC participant's supine body width exceeded scan window dimensions, so FM and FFM were determined from bioelectrical impedance analysis (TBF-105, Tanita).

REE

REE was measured using standard indirect calorimetry (Truemax 2400, Parvo Medics, Salt Lake City, Utah) with the ventilated hood technique. Before each test was performed, the metabolic cart gas analyzers and flow meter were calibrated per manufacture recommendations. Participants were instructed to fast for 12 hours overnight, which was confirmed by study staff upon arrival in the clinic. Upon arrival (~7 AM), participants rested supine, awake, and lightly clothed in a thermoneutral (20°C-23°C), dimly lit, quiet room for 30 minutes. REE was calculated using the Weir equation (25). Respiratory gas exchange was measured for 15 minutes, and the last 10 minutes was used to average REE. Criteria employed to determine whether the REE measurement was acceptable included stability (coefficient of variance of the final 10 minutes < 5%) and average metabolic equivalents < 1.10, as previously described (26). REE measurements that did not meet these criteria were considered invalid and were excluded from the analysis. REE was measured on days 1 and 8 of the free-living monitoring period and averaged to produce a single value for REE. Intraclass correlation

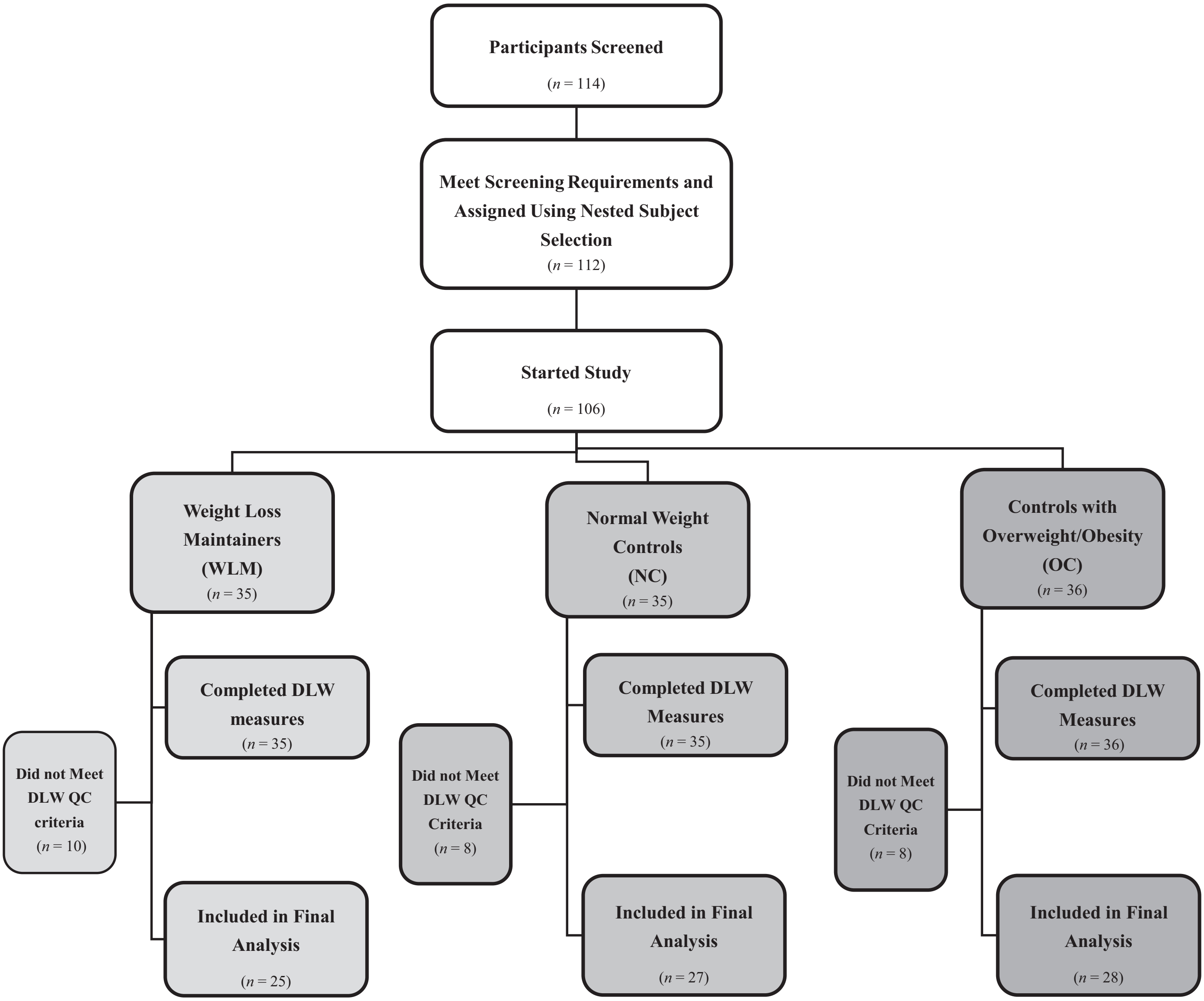

Figure 1 Study CONSORT Diagram. CONSORT, Consolidated Standards of Reporting Trials; DLW, doubly labeled water; QC, quality control.

coefficient for day 1 and day 8 within-subject REE measures was high (0.96).

TDEE, PAEE, and PAL

TDEE over days 1 to 8 was determined using the DLW method (27). On the dosing day, participants arrived at the testing center following a 12-hour overnight fast. Upon arrival, participants voided their bladder and provided a baseline urine sample for determination of background abundances of ^{2}H and ^{18}O. Participants then consumed an oral dose of DLW containing 2.05 g/kg total body water (TBW; estimated as 73% of FFM determined from dual-energy x-ray absorptiometry) of 10 atom percent excess ^{18}O and 0.14 g/kg TBW of 99.8 atom percent excess ^{2}H (ISOTEC; Sigma Aldrich, Miamisburg, Ohio). The dosing cup was rinsed twice with 30 mL of water, and the rinsing dose was consumed. Exact time of dosing was recorded. Participants were instructed to void their bladder 1 to 3 hours after dosing, and additional urine samples were collected 4 and 5 hours after the dosing. On day 8, participants returned to the testing center. They were instructed to void upon waking, and the second and third voids were obtained at the same times as the 4- and 5-hour postdose samples on the dosing day. The urine samples were analyzed for ^{18}O enrichment by isotope ratio mass spectrometry after equilibration with carbon dioxide. ^{2}H was reduced with a platinum catalyst, and the deuterium enrichment was determined by isotope ratio mass spectrometry (DELTA V Advantage; Thermo Electron North America LLC, West Palm Beach, Florida). Each sample was analyzed in a duplicate. If the difference between duplicate runs exceeded 2 δ ‰ for ^{2}H:^{1}H or 1 δ ‰ for ^{18}O:^{16}O for a given sample, then that sample was run again and only duplicate values that fell within this range were used. TBW was calculated as the average of the dilution spaces of ^{2}H and ^{18}O (28), and the rate of carbon dioxide production was calculated using the equation A6 from Schoeller et al. (27). To be included in the analysis, data had to meet the following quality control criteria: (1) valid dilution space ratio, (2) similar TBW estimates from ^{2}H and ^{18}O, (3) similar slopes of elimination using the 4- and 5-hour urine collections on day 1 and day 8, and (4) sufficient abundance of ^{18}O above background at day 8. TDEE was then estimated using the Weir equation, assuming a respiratory quotient of 0.86 (25). PAEE was calculated as (TDEE − [0.1 × TDEE] − REE), which assumes that the thermic effect of feeding is 10% of TDEE. Because the energy cost of PA is proportional to body weight for a given intensity and duration (29), PAEE was also calculated as relative to body weight (in kilograms). PAL was calculated as TDEE/REE.

Steps

Steps were assessed using the activPAL activity monitor (PAL Technologies, Glasgow, Scotland) to provide an additional objective measure of PA. The activPAL is a small (23 × 43 × 5 mm) and lightweight (10 g) device that uses accelerometer-derived information from about thigh position to estimate time spent sitting/lying, standing, and stepping. The device is attached to the anterior thigh and is waterproofed by wrapping it in a nitrile sleeve, allowing for 24-hour measurement. The activPAL is a valid and reliable device for measuring steps per day (30). Participants were asked to wear the device continuously for seven consecutive days. Data were considered valid and used for analysis if the device was worn for > 10 h/d of time spent awake on ≥ 4 days (including ≥ 1 weekend and ≥ 2 weekdays) as previously described (16).

Statistical analysis

Statistical analyses were performed with SAS version 9.4 (SAS System for Microsoft, SAS Institute Inc., Cary, North Carolina), with the type I error rate fixed at 0.05 (two tailed). Fisher exact tests were used to compare categorical demographic characteristics across the three groups. Normality of outcome measures was checked with the Shapiro–Wilk test. For variables for which the Shapiro–Wilk test $P < 0.05$, data transformations were used. A square root transformation was used for PAEE and FM. A log (base 10) transformation was used for minimum weight, maximum weight ever lost, FFM, REE, and PAL. A log (natural base) transformation was used for TDEE. Data are presented as mean ± SD or mean (95% CI) unless otherwise stated. A one-way analysis of variance (ANOVA) (PROC GLM, SAS) was used to estimate between-group differences in all outcome variables. A one-way analysis of covariance (ANCOVA) was used to estimate between-group differences in REE, adjusted for FFM only as well as for FM and FFM. A Pearson correlation coefficient (PROC CORR, SAS) was used to examine the correlation between steps and TDEE, PAEE (unadjusted and relative to body weight in kilograms), and PAL. Power was estimated using PASS (power and sample size) software (NCSS, Kayesville, Utah). Using the most conservative assumptions, we estimated a clinically meaningful difference in TDEE between WLM and controls (NC and OC) would be ≥ 5% (130 kcal/d). Therefore, using a two-sample *t* test, it was estimated that we would need 35 subjects per group to have 80% power to detect this difference. Although < 35 subjects per group were included in the analysis, we retained statistical power to observe a between-group difference of 130 kcal/d as evidenced by the 95% CI of the between-group difference in TDEE (WLM/NC 60 – 538 kcal/d, WLM/OC −316 – 158 kcal/d) (31).

Results

The REE and step data from this cohort have been previously published (16,26). Of the 106 participants who completed the DLW measurements, TDEE data from 26 (WLM = 10, NC = 8, OC = 8) were excluded from the analysis based on the quality control criteria outlined in *Methods*, resulting in a final sample size of 80 participants (25 WLM, 27 NC, 28 OC) (Figure 1). Of these 80 participants, 4 did not have valid REE (1 = NC, 3 = OC), and 12 did not have valid activPAL data (4 = WLM, 8 = OC). The nested subject selection procedures successfully achieved similar group means for age and sex (Table 1). The current BMI of WLM (24.1 [SD 2.3]) was not different from NC (23.0 [SD 2.0]), and maximum BMI of WLM (32.9 [SD 4.4]) was not different from current BMI of OC (34.3 [SD 4.8]). WLM were maintaining a weight loss of (mean ± SD) 26.2 ± 9.8 kg for 9.0 ± 10.2 years. There was no significant change in weight during the free-living week in WLM (0.22 ± 0.67 kg), NC (−0.07 ± 0.59 kg), or OC (0.39 ± 1.16 kg).

PAEE, TDEE, and REE data (mean ± SE) are presented in Table 2. Total PAEE in WLM (812 ± 268 kcal/d) was significantly higher compared with that in both NC (621 ± 285 kcal/d) and OC (637 ± 271 kcal/d; Figure 2A). Similar results were obtained when PAEE was expressed relative to body weight (kcal/kg/d). In addition, PAEE comprised a significantly greater proportion of TDEE in WLM compared with that in both NC and OC, despite the similar body mass of NC and the greater body mass of OC (Figure 3). As a result, TDEE in WLM (2,495 ± 366 kcal/d) was significantly higher than that in NC (2,195 ± 521 kcal/d) but not different from that in OC (2,573 ± 391 kcal/d). Unadjusted REE (kcal/d) of WLM was not different compared with that in NC but was significantly lower compared with that of OC. However, after adjusting for differences in FM and FFM, there were no between-group differences in REE.

The PAL of WLM was significantly higher than that of both NC and OC (Figure 2B). Similarly, daily step counts in WLM were higher than those in both NC and OC (Figure 2C). For correlation analyses, a smaller sample was used because of invalid REE and/or activPAL data (21 WLM, 26 NC, 20 OC). In WLM, daily step counts were strongly and positively correlated with total PAEE (kcal/d, $r = 0.78$, $P < 0.01$), relative PAEE (kcal/kg/d, $r = 0.85$, $P < 0.01$), and PAL ($r = 0.89$, $P < 0.01$), and there was a trend for a moderate, positive correlation with TDEE ($r = 0.41$, $P = 0.07$). In NC, daily step counts were moderately, positively correlated with relative PAEE (kcal/kg/d, $r = 0.45$, $P = 0.02$) and PAL ($r = 0.48$, $P = 0.01$), but not with total PAEE. In OC, there were no significant correlations between daily step counts and PAEE (total or relative), PAL, or TDEE.

Discussion

Study results suggest that PAEE of individuals maintaining a substantial weight loss (WLM, 26.2 ± 9.8 kg maintained for 9.0 ± 10.2 years) is significantly higher than PAEE of both nonreduced NC with similar BMI and OC with significantly higher BMI. As a result of these high levels of PAEE, the TDEE in WLM was significantly higher than that in NC but was not different from the TDEE in OC, whose BMI was similar to the pre–weight loss maximum BMI of WLM. WLM also demonstrated significantly higher levels of objectively measured steps per day as compared with nonreduced controls of both types. The high levels of PAEE and TDEE observed in successful WLM suggest that

TABLE 1 Characteristics of study participants

	WLM ($n=25$)	NC ($n=27$)	OC ($n=28$)	Overall *P* value	*P* value, WLM/NC	*P* value, WLM/OC
Age (y) (mean ± SD)	44.6 ± 12.2	49.4 ± 12.7	47.2 ± 11.5	0.37	0.16	0.44
Anthropometric measures (mean ± SD)						
Weight (kg)	67.8 ± 9.4	63.7 ± 10.8	96.7 ± 17.8	**< 0.01**	0.27	**< 0.01**
BMI (kg/m^2)	24.1 ± 2.3	23.0 ± 2.0	34.3 ± 4.8	**< 0.01**	0.22	**< 0.01**
Waist circumference (cm)[a]	83.6 ± 7.3	83.7 ± 6.9	107.0 ± 13.1	**< 0.01**	1.00	**< 0.01**
Maximum weight (kg)[b]	92.4 ± 14.7	67.9 ± 11.9	103.9 ± 21.5	**< 0.01**	**< 0.01**	**0.01**
Minimum weight (kg)[c,d]	62.4 ± 9.9	56.4 ± 9.4	67.2 ± 16.2	**0.01**	0.05	0.25
Maximum BMI (kg/m^2)[c]	32.9 ± 4.4	24.5 ± 2.3	36.8 ± 5.9	**< 0.01**	**< 0.01**	**< 0.01**
Maximum weight ever lost (kg)[d]	26.2 ± 9.8	6.3 ± 5.6	12.8 ± 7.9	**< 0.01**	**< 0.01**	**< 0.01**
Weight loss maintenance duration (y)	9.0 ± 10.2	n/a	n/a	n/a	—	—
Sex, male [*n*, (%)]	5 (20%)	7 (26%)	6 (21%)	0.87	—	—
Ethnicity [*n*, (%)]				0.69	—	—
Hispanic/Latino	1 (4%)	3 (11%)	3 (11%)			
Not Hispanic/Latino	24 (96%)	24 (89%)	25 (89%)			
Race [*n*, (%)]				**0.04**	—	—
White	25 (100%)	24 (89%)	23 (82%)			
Black/African American	0 (0%)	1 (3.7%)	5 (18%)			
Asian	0 (0%)	1 (3.7%)	0 (0%)			
Not reported	0 (0%)	1 (3.7%)	0 (0%)			
Respiratory quotient (mean ± SD)[e]	0.81 ± 0.04	0.81 ± 0.03	0.80 ± 0.04	0.33	0.58	0.14
Body composition (mean ± SD)						
Fat mass (kg)[f]	18.8 ± 4.6	18.7 ± 4.1	38.7 ± 9.6	**< 0.01**	0.99	**< 0.01**
Fat mass (%)	28.4 ± 6.5	30.1 ± 5.7	40.5 ± 5.1	**< 0.01**	0.29	**< 0.01**
Fat-free mass (kg)[d]	47.6 ± 8.7	44.0 ± 9.4	56.4 ± 10.8	**< 0.01**	0.11	**< 0.01**
Fat-free mass (%)	71.6 ± 6.5	69.9 ± 5.7	59.5 ± 5.1	**< 0.01**	0.29	**< 0.01**

Fisher exact test used for categorical variables; continuous variables analyzed using one-way ANOVA. Significant *P* values (alpha < 0.05) indicated in bold.
[a]$n=26$ for NC and $n=27$ for OC. One NC participant was missing waist circumference, and one OC participant had an invalid waist circumference.
[b]Excluding pregnancy.
[c]After age 18 and excluding illness.
[d]Analyzed using log (base 10) transformation, but untransformed mean ± SD presented.
[e]$n=26$ for NC and $n=25$ for OC.
[f]Analyzed using square root transformation, but untransformed mean ± SD presented.
NC, normal weight controls; OC, controls with overweight/obesity; WLM, weight loss maintainers.

this group relies on high levels of energy expended in PA to remain in energy balance (and avoid weight regain) at a reduced weight.

We observed high levels of PAEE relative to body size in our sample of WLM. Mean relative PAEE in WLM was ~12 kcal/kg/d as compared with ~10 kcal/kg/d in NC and ~7 kcal/kg/d in OC. These results are consistent with two previous studies that used DLW to assess energy expenditure in weight-reduced individuals (11,23). Schoeller et al. followed women for 1 year after weight loss and suggested that PAEE of ~11 kcal/kg/d may be required to prevent weight regain (11). Kerns et al. (23) found PAEE of ~12 kcal/kg/d in contestants from "The Biggest Loser" televised weight loss competition who maintained weight loss of ≥13% at 6-year follow-up, as compared with PAEE of ~8 kcal/kg/d in contestants who regained weight. PAL was also higher in WLM (~1.75) as compared with both NC (~1.61) and OC (~1.55). The PAL of ~1.75 observed in our sample of WLM is consistent with recommendations from the International Association for the Study of Obesity 1st Stock Conference, which recommended PAL of ≥1.70 to 1.75 to prevent weight regain (32). These estimates of PAL equate to approximately 60 to 90 min/d of moderate-intensity PA, such as walking, or 30 to 45 min/d of vigorous-intensity activity, such as running (32). Combined, these data suggest that high levels of PAEE may be critically important for successful long-term weight loss maintenance.

The differences in PAEE across our study groups were reflected in a similar pattern observed in objectively measured steps per day: WLM exhibited significantly higher steps per day (~12,100) compared with both NC (~8,900) and OC (~6,500). The daily step counts observed in our sample of WLM were higher than 10,000 steps per day, a common public health recommendation for PA. These results are consistent with prior studies demonstrating higher levels of objectively measured PA in WLM compared with controls of both types (16,17). Further, in our study, objectively measured steps per day were significantly and positively correlated with relative PAEE in WLM and NC, but this correlation was not observed in OC. This finding suggests that in individuals with normal body weight, actual PA performed (steps per day) may be driving PAEE, whereas in individuals with overweight/obesity, factors other than steps per day (such as the energy cost of moving a higher body mass) may play a stronger role in determining PAEE.

TABLE 2 Comparison of energy expenditure across subject groups

Energy expenditure outcome (least squares mean [95% CI])	WLM (*n* = 25)	NC (*n* = 27)	OC (*n* = 28)	*P* value, omnibus F test	WLM/NC		WLM/OC	
					Difference, (WLM − NC)	*P* value	Difference, (WLM − OC)	*P* value
PAEE								
PAEE (kcal/d)[a,b]	812 (703 to 922)	621 (513 to 728)	637 (528 to 747)	**0.02**	192 (38 to 345)	**0.01**	175 (20 to 330)	**0.02**
PAEE (kcal/body weight kg/d)[a]	12.1 (10.6 to 13.5)	9.6 (8.1 to 11.0)	7.0 (5.5 to 8.4)	**< 0.01**	2.5 (0.5 to 4.6)	**0.02**	5.1 (3.1 to 7.2)	**< 0.01**
REE								
REE (kcal/d)[a,c]	1,433 (1,338 to 1,528)	1,365 (1,272 to 1,458)	1,680 (1,585 to 1774)	**< 0.01**	68 (−65 to 200)	0.21	−247 (−380 to 113)	**< 0.01**
REE (kcal/d), adjusted for fat-free mass[a,c]	1,465 (1,422 to 1,508)	1,468 (1,425 to 1,512)	1539 (1,494 to 1,586)	**0.03**	−3 (−64 to 57)	0.65	−74 (−139 to 10)	**0.03**
REE (kcal/d), adjusted for fat mass and fat-free mass[a,c]	1,489 (1,441 to 1,537)	1,490 (1,442 to 1,538)	1,493 (1,430 to 1,556)	0.61	−1 (−60 to 59)	0.62	−4 (−96 to 89)	0.51
TDEE								
TDEE (kcal/d)[d]	2,495 (2,322 to 2,667)	2,195 (2029 to 2,361)	2,573 (2,411 to 2,736)	**< 0.01**	299 (60 to 538)	**< 0.01**	−78 (−316 to 158)	0.55

Results from one-way ANOVA. Significant *P* values (alpha < 0.05) indicated in bold.
[a]$n = 26$ for NC and $n = 25$ for OC.
[b]Analyzed using square root transformation, but untransformed mean (95% CI) presented.
[c]Analyzed using log (base 10) transformation, but untransformed mean (95% CI) presented.
[d]Analyzed using log (natural base) transformation, but untransformed mean (95% CI) presented.
NC, normal weight controls; OC, controls with overweight/obesity; PAEE, physical activity energy expenditure; REE, resting energy expenditure; TDEE, total daily energy expenditure; WLM, weight loss maintainers.

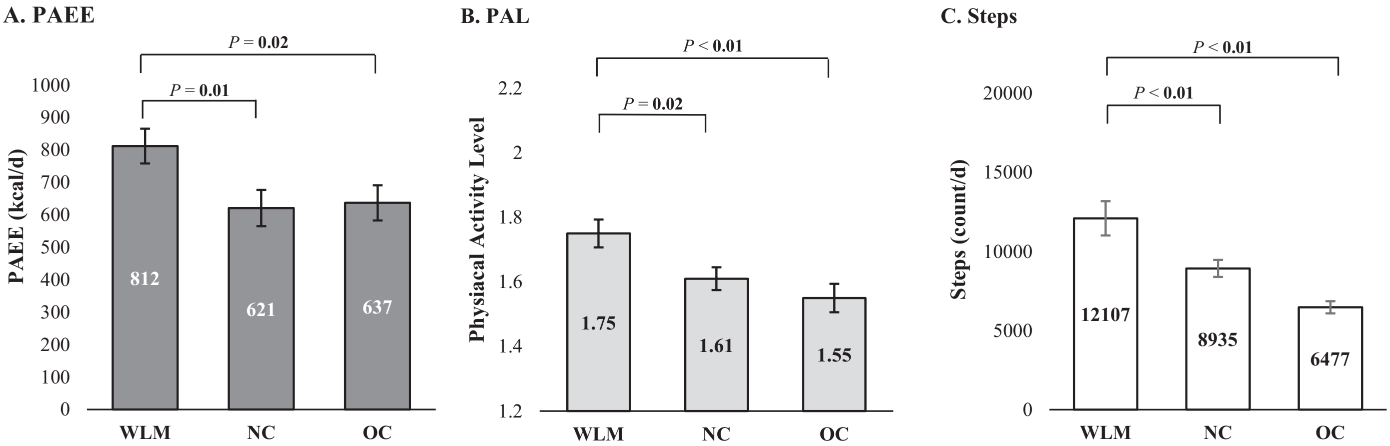

Figure 2 (**A**) PAEE, PAL (**B**), and (**C**) steps across subject group. Results are from one-way ANOVA and are presented as mean ± SE. Significant *P* values (alpha < 0.05) are indicated in bold. PAEE was analyzed using square root transformation, but the untransformed mean ± SE is presented. PAL, calculated as TDEE/REE, was analyzed using log (base 10) transformation, but the untransformed mean ± SE is presented. PAL data are as follows: WLM: $n = 25$, 1.75 ± 0.04; NC: $n = 26$, 1.61 ± 0.04; OC: $n = 25$, 1.55 ± 0.04; WLM/NC $P = 0.02$, WLM/OC $P < 0.01$. Steps data (count per day) are as follows: WLM: $n = 21$, 12,107 ± 1,085; NC: $n = 27$, 8,935 ± 539; OC: $n = 20$, 6,477 ± 385; WLM/NC $P < 0.01$, WLM/OC $P < 0.01$. NC, normal weight controls; OC, controls with overweight obesity; PAEE, physical activity energy expenditure; PAL, physical activity level; WLM, weight loss maintainers.

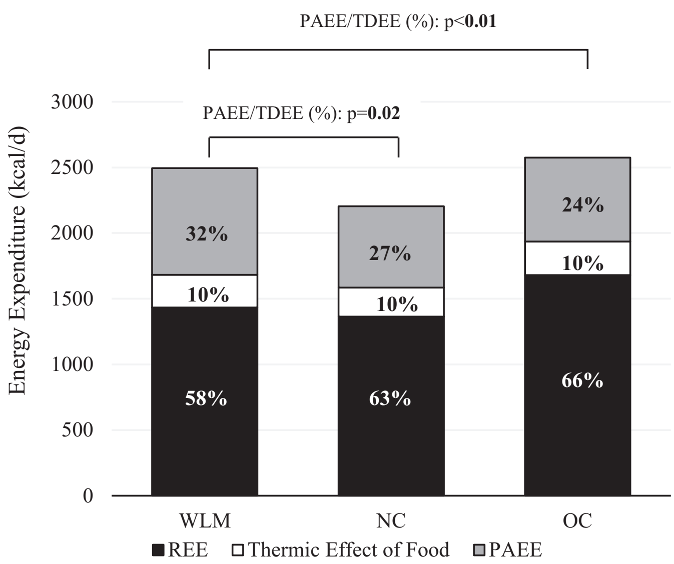

Figure 3 Proportion of PAEE out of TDEE across subject group. Results are from one-way ANOVA and are presented as untransformed mean (kilocalories per day). Significant *P* values (alpha < 0.05) are indicated in bold. Labels represent the mean proportion of each component out of the mean TDEE for each subject group. Mean ± SD of PAEE/TDEE (%): WLM = 32 ± 7%, NC = 27 ± 7%, OC = 24 ± 8%; WLM/NC $P = 0.02$, WLM/OC $P < 0.01$. NC, normal weight controls; OC, controls with overweight/obesity; PAEE, physical activity energy expenditure; REE, resting energy expenditure; TDEE, total daily energy expenditure; WLM, weight loss maintainers.

At weight maintenance, TDEE is equivalent to total daily EI. Participants in this study were weight stable during the 7-day DLW measurement period; thus, TDEE can be interpreted to represent EI during the measurement period. In WLM, TDEE was ~2,500 kcal/d, indicating that total daily EI was likely ~2,500 kcal/d during the measurement period. This estimate of EI is substantially higher than in previous studies that have reported a relatively restricted level of EI in successful WLM (~1,370 to 1,440 kcal/d) (24,33). However, these studies relied on self-reported estimates of EI, which suffer from significant limitations and biases (34). If the short-term DLW measurements are reflective of participants' habitual energy expenditure and intake patterns, our results indicate that EI in WLM was significantly higher than that in NC (of a similar BMI) and not significantly different from that in OC (of a substantially higher BMI). Although we recognize the limitations of the cross-sectional data collection, the implications are that WLM filled the energy gap that resulted from weight loss (10), with high levels of PA rather than with reduced EI. Several studies have documented that long-term adherence to calorie-restricted diets is difficult (7-9). In contrast, results from observational studies (16-18,20) as well as from randomized controlled trials (14,19,22,35,36) have supported the view that PA is critically important for successful weight loss maintenance. The high levels of PAEE and TDEE observed in our sample of WLM suggest they rely on high levels of energy expended in PA (rather than chronic restriction of EI) to achieve energy balance at a reduced body weight.

Our energy expenditure and EI findings are consistent with results from the longitudinal study of "The Biggest Loser" contestants, which indicates that changes in EI (DLW intake-balance method) from baseline to 6 years after the competition were not correlated with amount of weight loss or weight regained at 6 years, whereas changes in PAEE were strongly correlated with weight loss and weight regained (23). Our findings are also consistent with those of Drenowatz et al. (37), who conducted a 2-year observational study to assess changes in weight, EI (DLW intake-balance method), and PA (SenseWear armband) in 195 young adults (age 20-35 years, BMI 20-35). In a subset who lost >5% body weight over the 2 years, EI did not change significantly from baseline, whereas bouts ≥10 minutes of moderate to vigorous PA significantly increased (by ~35 min/d) (37). Taken together, these results suggest PA may play a relatively greater role in weight loss maintenance than chronic restriction of EI.

We did not observe a significantly lower REE in WLM as compared with controls of both types, after adjusting for differences in FM and FFM. Some (but not all) studies have suggested that REE declines to a greater extent than expected from changes in body mass and/or body composition with weight loss (2,38) and that this disproportionate reduction in REE may persist long term (1-6 years) (38-40). For example, Fothergill et al. evaluated longitudinal changes in REE in 14 contestants 6 years after completing "The Biggest Loser" televised weight loss competition. Using contestants' baseline data to develop predictive equations for REE, mean REE after 6-year follow-up was ~500 kcal/d lower than predicted in that sample (38). Our group recently published a more in-depth examination of REE in the current study sample that compared measured REE with predicted REE, using several predictive equations. Our results indicate no consistent evidence of a lower than predicted REE in successful WLM (26). Although results from this study suggest that our sample of WLM does not exhibit substantially lower REE (adjusted for FM and FFM) than controls, these data should be interpreted with caution, as the lack of REE measurements prior to weight loss in this group does not allow us to determine whether REE may have decreased to a greater extent than expected for the amount of weight lost within a given individual.

Our study has several limitations. Because of the case-control study design, we were unable to assess longitudinal changes in PAEE or TDEE within subject groups. It is possible that our sample of successful WLM is inherently different from those who are not successful at weight loss or weight loss maintenance. Thus, future prospective, longitudinal studies of weight loss maintenance using objective measures of energy expenditure and EI are needed. Our WLM sample was relatively small and homogenous (predominantly female and Caucasian); therefore, results may not be generalizable to other populations (31). Despite these limitations, this is the first study to compare objectively measured PAEE and TDEE, using the DLW method, in successful WLM with nonreduced individuals with normal weight and individuals with overweight/obesity. Results from this study provide valuable insight into how individuals successfully achieve long-term weight loss maintenance.

Conclusion

Individuals maintaining a substantial weight loss (−26.2 ± 9.8 kg maintained for 9.0 ± 10.2 years) demonstrated significantly higher total PAEE (kilocalories per day), relative PAEE (kilocalories per kilogram per day), PAL, and objectively measured steps per day compared with normal-weight controls and controls with overweight/obesity. As a result, TDEE in successful WLM was significantly higher than in nonreduced individuals of similar BMI and was not significantly different from TDEE in individuals with overweight/obesity. The TDEE observed in our weight-stable WLM (~2,500 kcal/d) suggests habitual EI in this sample may be substantially higher than the level of EI reported in prior studies, which relied on self-reported EI measures in weight-reduced individuals. The high PAEE and TDEE observed in our sample of WLM strongly supports the hypothesis that these individuals rely on increasing energy expended in activity (rather than chronic restriction of EI) to achieve energy balance at a reduced body weight; however, longitudinal studies are needed to further explore these findings.O

Acknowledgments

We would like to thank all of our study participants as well as Dr. Rena Wing for providing access to the NWCR to assist with recruitment of study participants.

References

1. Ballor DL, Poehlman ET. A meta-analysis of the effects of exercise and/or dietary restriction on resting metabolic rate. *Eur J Appl Physiol Occup Physiol* 1995;71:535-542.
2. Astrup A, Gotzsche PC, van de Werken K, et al. Meta-analysis of resting metabolic rate in formerly obese subjects. *Am J Clin Nutr* 1999;69:1117-1122.
3. Leibel RL, Rosenbaum M, Hirsch J. Changes in energy expenditure resulting from altered body weight. *N Engl J Med* 1995;332:621-628.
4. Melby CL, Paris HL, Foright RM, Peth J. Attenuating the biologic drive for weight regain following weight loss: Must what goes down always go back up? *Nutrients* 2017;9:468. doi:10.3390/nu9050468
5. van Baak MA. Meal-induced activation of the sympathetic nervous system and its cardiovascular and thermogenic effects in man. *Physiol Behav* 2008;94:178-186.
6. Rosenbaum M, Vandenborne K, Goldsmith R, et al. Effects of experimental weight perturbation on skeletal muscle work efficiency in human subjects. *Am J Physiol Regul Integr Comp Physiol* 2003;285:R183-R192.
7. Kramer FM, Jeffery RW, Forster JL, Snell MK. Long-term follow-up of behavioral treatment for obesity: Patterns of weight regain among men and women. *Int J Obes* 1989;13:123-136.
8. Wadden TA. Treatment of obesity by moderate and severe caloric restriction. Results of clinical research trials. *Ann Intern Med* 1993;119(7 Pt 2):688-693.
9. Mark AL. Dietary therapy for obesity is a failure and pharmacotherapy is the future: a point of view. *Clin Exp Pharmacol Physiol* 2006;33:857-862.
10. Hill JO, Peters JC, Wyatt HR. Using the energy gap to address obesity: a commentary. *J Am Diet Assoc* 2009;109:1848-1853.
11. Schoeller DA, Shay K, Kushner RF. How much physical activity is needed to minimize weight gain in previously obese women? *Am J Clin Nutr* 1997;66:551-556.
12. Weinsier RL, Hunter GR, Desmond RA, Byrne NM, Zuckerman PA, Darnell BE. Free-living activity energy expenditure in women successful and unsuccessful at maintaining a normal body weight. *Am J Clin Nutr* 2002;75:499-504.
13. Jakicic JM, Winters C, Lang W, Wing RR. Effects of intermittent exercise and use of home exercise equipment on adherence, weight loss, and fitness in overweight women: a randomized trial. *JAMA* 1999;282:1554-1560.
14. Borg P, Kukkonen-Harjula K, Fogelholm M, Pasanen M. Effects of walking or resistance training on weight loss maintenance in obese, middle-aged men: a randomized trial. *Int J Obes Relat Metab Disord* 2002;26:676-683.
15. Jeffery RW, Wing RR, Sherwood NE, Tate DF. Physical activity and weight loss: does prescribing higher physical activity goals improve outcome? *Am J Clin Nutr* 2003;78:684-689.
16. Ostendorf DM, Lyden K, Pan Z, et al. Objectively measured physical activity and sedentary behavior in successful weight loss maintainers. *Obesity (Silver Spring)* 2017;26:53-60.
17. Catenacci VA, Grunwald GK, Ingebrigtsen JP, et al. Physical activity patterns using accelerometry in the national weight control registry. *Obesity (Silver Spring)* 2011;19:1163-1170.
18. Phelan S, Roberts M, Lang W, Wing RR. Empirical evaluation of physical activity recommendations for weight control in women. *Med Sci Sports Exerc* 2007;39:1832-1836.
19. Jakicic JM, Tate DF, Lang W, et al. Objective physical activity and weight loss in adults: the step-up randomized clinical trial. *Obesity (Silver Spring)* 2014;22:2284-2292.
20. Catenacci VA, Ogden LG, Stuht J, et al. Physical activity patterns in the national weight control registry. *Obesity (Silver Spring)* 2008;16:153-161.
21. Thomas JG, Bond DS, Phelan S, Hill JO, Wing RR. Weight-loss maintenance for 10 years in the national weight control registry. *Am J Prev Med* 2014;46:17-23.
22. Jakicic JM, Marcus BH, Lang W, Janney C. Effect of exercise on 24-month weight loss maintenance in overweight women. *Arch Intern Med* 2008;168:1550-1559; discussion 1559-1560.
23. Kerns JC, Guo J, Fothergill E, et al. Increased physical activity associated with less weight regain six years after "The Biggest Loser," competition. *Obesity (Silver Spring)* 2017;25:1838-1843.
24. Klem ML, Wing RR, McGuire MT, Seagle HM, Hill JO. A descriptive study of individuals successful at long-term maintenance of substantial weight loss. *Am J Clin Nutr* 1997;66:239-246.
25. Weir JB. New methods for calculating metabolic rate with special reference to protein metabolism. *J Physiol* 1949;109:1-9.

26. Ostendorf DM, Melanson EL, Caldwell AE, et al. No consistent evidence of a disproportionately low resting energy expenditure in long-term successful weight loss maintainers. *Am J Clin Nutr* 2018;108:659-666.
27. Schoeller DA, Ravussin E, Schutz Y, Acheson KJ, Baertschi P, Jequier E. Energy expenditure by doubly labeled water: Validation in humans and proposed calculation. *Am J Physiol* 1986;250(5 Pt 2):R823-R830.
28. Racette SB, Schoeller DA, Luke AH, Shay K, Hnilicka J, Kushner RF. Relative dilution spaces of 2H- and 18O-labeled water in humans. *Am J Physiol* 1994;267(4 Pt 1):E585-E590.
29. Schoeller DA, Jefford G. Determinants of the energy costs of light activities: inferences for interpreting doubly labeled water data. *Int J Obes Relat Metab Disord* 2002;26:97-101.
30. Grant PM, Ryan CG, Tigbe WW, Granat MH. The validation of a novel activity monitor in the measurement of posture and motion during everyday activities. *Br J Sports Med* 2006;40:992-997.
31. Goodman SN, Berlin JA. The use of predicted confidence intervals when planning experiments and the misuse of power when interpreting results. *Ann Intern Med* 1994;121:200-206.
32. Saris WH, Blair SN, van Baak MA, et al. How much physical activity is enough to prevent unhealthy weight gain? Outcome of the IASO 1st stock conference and consensus statement. *Obes Rev* 2003;4:101-114.
33. Catenacci VA, Odgen L, Phelan S, et al. Dietary habits and weight maintenance success in high versus low exercisers in the national weight control registry. *J Phys Act Health* 2014;11:1540-1548.
34. Dhurandhar NV, Schoeller D, Brown AW, et al. Energy balance measurement: when something is not better than nothing. *Int J Obes (Lond)* 2015;39:1109-1113.
35. Fogelholm M, Kukkonen-Harjula K. Does physical activity prevent weight gain–a systematic review. *Obes Rev* 2000;1:95-111.
36. Jakicic JM, Marcus BH, Gallagher KI, Napolitano M, Lang W. Effect of exercise duration and intensity on weight loss in overweight, sedentary women: a randomized trial. *JAMA* 2003;290:1323-1330.
37. Drenowatz C, Hill J, Peters J, Soriano-Maldonado A, Blair S. The association of change in physical activity and body weight in the regulation of total energy expenditure. *Eur J Clin Nutr* 2017;71:377-382.
38. Fothergill E, Guo J, Howard L, et al. Persistent metabolic adaptation 6 years after "The Biggest Loser," competition. *Obesity (Silver Spring)* 2016;24:1612-1619.
39. Camps SG, Verhoef SP, Westerterp KR. Weight loss, weight maintenance, and adaptive thermogenesis. *Am J Clin Nutr* 2013;97:990-994.
40. Rosenbaum M, Hirsch J, Gallagher DA, Leibel RL. Long-term persistence of adaptive thermogenesis in subjects who have maintained a reduced body weight. *Am J Clin Nutr* 2008;88:906-912.