Does habitual physical activity increase the sensitivity of the appetite control system? A systematic review

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Title: Does habitual physical activity increase the sensitivity of the appetite control system? A systematic review

Running heading: Physical activity level and appetite control

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Abstract

Background: It has been proposed that habitual physical activity (PA) improves appetite control; however the evidence has never been systematically reviewed.

Objective: To examine whether appetite control (e.g. subjective appetite, appetite-related peptides, food intake) differs according to levels of PA.

Data sources: Medline, Embase and SPORTDiscus were searched for articles published between 1996-2015 using keywords pertaining to PA, appetite, food intake and appetite-related peptides.

Study selection: Articles were included if they involved healthy non-smoking adults (18-64 years) participating in cross-sectional studies examining appetite control in active and inactive individuals; or before and after exercise training in previously inactive individuals.

Study appraisal and synthesis: Of 77 full-texts assessed, 28 studies (cross-sectional = 14; exercise-training = 14) met the inclusion criteria.

Results: Appetite sensations and absolute energy intake did not differ consistently across studies. Active individuals had a greater ability to compensate for high-energy preloads through reductions in energy intake compared to inactive controls. When PA level was graded across cross-sectional studies (low, medium, high, very high), a significant curvilinear effect on energy intake (z-scores) was observed.

Limitations: Methodological issues existed concerning the small number of studies, lack of objective quantification of food intake, and various definitions used to define active and inactive individuals.

Conclusions: Habitually active individuals showed improved compensation to the energy density of foods, but no consistent differences in appetite or absolute energy intake, compared to inactive individuals. This review supports a J-shaped relationship between PA level and energy intake. Further studies are required to confirm these findings.

PROSPERO registration number: CRD42015019696

Key points:

- Habitual physical activity and appetite control are not independent of each other; they are inter-connected.
- The relationship between physical activity and energy intake is J-shaped.
- Objective assessment of all components of energy balance is necessary to improve understanding of this relationship.

1 Introduction

The importance of physical activity in reducing morbidity and all-cause mortality [1] and in weight management [2] has become apparent. There has been increasing interest in the relationship between physical activity and appetite control as both play an integral part in energy balance (e.g. [3-7]). Regular physical activity and exercise training are associated with several physiological adaptations such as improved insulin [8] and leptin sensitivity [9, 10], blood pressure [11], blood lipids [12], substrate metabolism [13], and body composition [14], some of which have been proposed as mechanisms involved in eating behaviour [15, 16]. Scientific studies have tended to focus on the appetite responses to exercise rather than habitual physical activity levels per se. This distinction is important to make, as physical activity encompasses occupational, household, transportation and other activities in addition to structured exercise [17], and the physiological adaptations to exercise and physical activity may differ. Few studies have specifically focused on the appetite control differences between physically active and inactive individuals, but there is some evidence suggesting that habitual physical activity improves appetite control by enhancing satiety signalling [18, 19]. Two recent reviews have included secondary analyses on whether the relationship between acute or long-term exercise and energy intake is influenced by physical activity level [20, 21]. From their meta-analysis, Schubert et al. [21] found that absolute energy intake after acute exercise was greater in active individuals compared to those less active, whereas Donnelly et al. [20] concluded from their systematic review that increased physical activity or exercise, regardless of physical activity level, had no consistent effect on acute or long-term energy intake. However, these reviews only included energy and macronutrient intake as their main outcome measures. This is of importance as appetite control involves the complex co-ordination of a range of homeostatic and non-homeostatic signals in the overall expression of food intake [22]. Therefore, in addition to energy intake it is important to consider other components such as appetite-related peptides, subjective appetite sensations, food choice, and hedonic reward.

It has been proposed that the regulation of the appetite control system and energy intake is improved with increasing levels of physical activity [23]. This issue has yet to be systematically reviewed, and the potential mechanisms behind any improvement in appetite control are unclear. The aim of this systematic review was to examine whether physically active individuals have more sensitive control over appetite than their inactive counterparts and if this confers them the ability to better match energy intake to energy expenditure, and identify behavioural or physiological mechanisms underlying any observed differences.

2 Methods

This systematic review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines (Electronic Supplementary Material Appendix S1) and is registered in the PROSPERO database (registration number CRD42015019696).

2.1 Search strategy

A search was conducted in the databases Ovid Medline, Ovid Embase and SPORTDiscus (EBSCOHost), which included articles published between 1st January 1996 and 15th April 2015 using the strategy (physical activity AND (appetite AND (food intake OR appetite-related peptides))). Previous systematic reviews were screened to identify relevant subject headings and key words to include within each subject category. The specific key words used for the search are listed in Table 1 and the full search strategy for one of the databases consulted can be found in Electronic Supplementary Material Appendix S2. Limits were set to include articles published in English and studies conducted in human adults aged 18-64 years. Reference lists from the resulting articles were also screened to identify any additional articles.

Table 1. Keywords included in database search strategy

Physical activity	**Appetite**	**Food intake**	**Appetite-related peptides**
Motor activity	Appetite	Energy intake	Gut hormone
Exercise	Feeding behavior	Diet	Gut peptide
Oxygen consumption	Food preferences	Dietary proteins	Peptide YY
Physical fitness	Hunger	Dietary fats	PYY
Exercise tolerance	Satiety	Dietary carbohydrates	Ghrelin
Exercise test	Satiation	Calorie intake	Glucagon-like peptide-1
Physical endurance	Fullness	Food intake	GLP-1
Physical activity	Motivation to eat	Meal size	Pancreatic polypeptide
Physical performance	Food choice	Energy compensation	PP
Aerobic	Food selection	Energy density	Leptin
Aerobic capacity	Desire to eat	Macronutrient	Insulin
Training	Palatability		Cholecystokinin
Maximal VO_2	Food reward		CCK
Physical capacity	Hedonic		
	Liking		
	Wanting		

VO_2 Oxygen consumption, *PYY* peptide YY, *GLP-1* glucagon-like peptide-1, *PP* pancreatic polypeptide, *CCK* cholecystokinin

2.2 Study selection, inclusion, and exclusion

Articles were included if they involved healthy adults participating in cross-sectional studies and examined appetite control in physically active and inactive individuals. Longitudinal studies assessing appetite control before and after an exercise-training intervention in previously inactive individuals were also included if the intervention was greater than four weeks (to allow sufficient time for adaptations from regular physical activity to emerge; e.g. [11]) and did not include any concurrent dietary intervention (e.g. energy restriction, supplementation). Articles were excluded if they involved animals, children, adolescents, athletes or older adults (>65 years old) and participants who smoked. Abstracts and full-texts were assessed for eligibility independently by two authors with uncertainty regarding eligibility discussed with an additional author.

2.3 Data extraction and synthesis

One author extracted the following information into a spreadsheet: authors, date of publication, sample size, participant characteristics (age, sex, body mass index (BMI), % body fat, maximal aerobic capacity (VO_{2max}), physical activity details), criteria used to assess physical activity status (cross-sectional studies) or training intervention (longitudinal studies), setting, outcome measures (energy intake, appetite ratings and appetite-related peptides), and results. To determine any statistical relationship between habitual physical activity level and energy intake, where data were available energy intake values were standardised (*z*-scores) and from the definitions provided in the studies, physical activity levels were graded into low (<150 min/wk, <1000 kcal/wk or physical activity level (PAL): 1.4-1.69), medium (150-419 min/wk, 1000-2500 kcal/wk or PAL: 1.7-1.99), high (420-839 min/wk or 2500-3500 kcal/wk), or very high (>840 min/wk or >3500 kcal/wk). One-way analysis of variance (ANOVA) was then used to test for a main effect of graded physical activity level on energy intake score, followed by trend analyses for linear and non-linear functions. Other outcome measures are presented as a qualitative synthesis.

2.4 Risk of bias

Risk of bias was assessed using the Cochrane Collaboration’s tool for assessing risk of bias for sequence generation, allocation concealment, blinding of participants, personnel and outcome assessors, incomplete outcome data, selective outcome reporting, and other sources of bias [24] (Electronic Supplementary Material Table S1). Study inclusion was not influenced by the results of the risk of bias assessment.

3 Results

Figure 1 illustrates the systematic review flow diagram. The database search yielded 2,078 articles, 1,640 of which were eliminated based on titles and abstracts alone. The full text was retrieved from 77 articles and 28 satisfied the inclusion criteria.

Figure 1 here

Fig. 1 Systematic review flow diagram

3.1 Cross-sectional studies

The results from the cross-sectional studies (n = 14) are presented in Table 2.

Table 2 Cross-sectional studies assessing appetite control in physically active and inactive individuals

Study	Participants	Physical activity status	Setting	Outcome measures	Results
Apolzan et al. (2009) [25] Young groups	Men and women Active: n = 11 (63.6 % men); age = 25±3 years; BMI = 23.5±2.0 kg/m^2; body fat =15.7±6.3 %; VO_{2max} = 47.5±6.3 mL/kg/min; PA =2.6±0.7 h/d Inactive: n = 13 (61.5% men); age = 25±4 years; BMI = 26.6±3.6 kg/m^2; body fat = 23.1±5.0 %; VO_{2max} = 33.7±5.8 mL/kg/min; PA = 0.0±0.0 h/d	Paffenbarger PA questionnaire and VO_{2max} Active: Moderate-intensity PA ≥4d/wk,VO_{2max} above average for age, >2500 kcal/wk Inactive: <20min/d ≤2 d/wk, VO_{2max} below average for age, <1000 kcal/wk	Free-living	Hunger, fullness, desire to eat (vertical dashes) Food intake (24-h food record)	No effect of activity status on appetite, EI or macronutrient intake.
Catenacci et al. (2014) [26]	Men and women enrolled in the National Weight Control Registry divided into levels of PA Low: n = 910 (21.6 % men); age = 49±13 years; BMI = 25.8±4.5 kg/m^2; body fat = NR; VO_{2max} = NR; PA = 416±313 kcal/wk Medium: n = 934 (21.5 % men); age = 48±13 years; BMI = 25.2±4.6 kg/m^2; body fat = NR; VO_{2max} = NR; PA = 1615±355 kcal/wk High: n = 779 (26.1 % men); age = 46±12 years; BMI = 24.7±4.7 kg/m^2; body fat = NR; VO_{2max} = NR; PA = 2256±554 kcal/wk Very high: n = 968 (27.6 % men); age = 44±11 years; BMI = 24.5±4.7 kg/m^2; body fat = NR; VO_{2max} = NR; PA = 5477±2179 kcal/wk	Paffenbarger PA questionnaire Low: <1000 kcal/wk Medium: 1000 to <2500 kcal/wk High: 2500 to <3500 kcal/wk Very high: >3500 kcal/wk	Free-living	Food intake (Block FFQ) Restraint, disinhibition and susceptibility to hunger (TFEQ)	No significant differences in EI between groups but higher EI in those reporting the lowest and highest levels of activity (U-shaped relationship with age and sex as covariates) Higher levels of activity had lower % energy from fat and higher % energy from carbohydrates. Cognitive restraint increased with activity level (linear relationship). No differences in disinhibition and susceptibility to hunger between groups.
Charlot & Chapelot (2013) [27]	Men High-fit: n = 9; age = 21±2 years; BMI = 23.5±0.7 kg/m^2; body fat =12.0±2.8 %; VO_{2max} = 51.6±6.1 mL/kg/min; PA = 8.8±4.5 h/wk Low-fit: n = 9; age = 22±2 years; BMI = 26.5±1.3 kg/m^2; body fat =21.2±2.6 %; VO_{2max} = 37.0±5.9 mL/kg/min; PA = 2.0±1.8 h/wk	VO_{2max} High fit: VO_{2max} > 45 and >5h/wk of moderate to intense PA. Low fit: VO_{2max} < 45 and < 3h/wk of moderate to intense PA.	Laboratory and free-living: Test meal 60-min after 60-min cycling at 70% VO_{2max}.	Hunger, desire to eat and fullness (VAS) Food intake (1 test meal and food record until breakfast the next day)	No differences in appetite ratings, EI at test meal, macronutrient intake, and energy compensation. EI from lunch to breakfast and over 24h significantly greater after exercise compared to resting in both groups.
Deshmukh-Taskar et al. (2007) [28]	Men and women n = 1191 (39.4 % men); age = 30±5 years; BMI = 27.3±6.7 kg/m^2; body fat = NR; VO_{2max} = NR; PA (5-point Likert scale) = 3.2±1.1	Answer to "Compared to other people your age and sex, how would you rate your physical activity outside of work during the past year?" from five-item Likert scale where 1=physically inactive/sedentary, 3=moderately active and 5=very active	Free-living	Food choices (Youth/ Adolescent FFQ)	Active reported a greater intake of fruits and 100% fruit juices and lower intake of burgers and sandwiches than inactive.

		Active: ≥4 (n=392) Inactive: ≤3 (n=799)			
Georgiou et al. (1996) [29]	Men Exercisers: n = 89; age = 22±2 years; BMI = 24.8±4.1 kg/m^2; body fat = NR; VO_{2max} = NR; PA = NR Nonexercisers: n = 51; age = 22±2 years; BMI = 25.7±5.2 kg/m^2; body fat = NR; VO_{2max} = NR; PA = NR Women Exercisers: n = 106; age = 21±2 years; BMI = 22.3±3.6 kg/m^2; body fat = NR; VO_{2max} = NR; PA = NR Nonexercisers: n = 73; age = 22±2 years; BMI = 22.8±4.1 kg/m^2; body fat = NR; VO_{2max} = NR; PA = NR	Yes or no response to "Do you engage in regular, planned exercise activities in which you work up a sweat, increase your heart rate or breathe faster?"	Free-living	Food choices (National Cancer Institute Health Habits and History Questionnaire FFQ) Health-related influences on food choice questionnaire Perceived change of fat intake	Female and male exercisers considered it more important to eat the most nutritious foods than nonexercisers. Female and male exercisers ate more nutrient-dense, low-fat foods than nonexercisers. Female exercisers were more likely to rate 2% milk, macaroni and cheese, hamburger, and peanut butter as fattening compared to nonexercisers. Female exercisers reported decreasing intake of high-fat foods (e.g. French fries, cheese and salad dressing) over the prior years.
Gregersen et al. (2011) [30]	Men n = 80; age = 39±12 years; BMI = 25.2±2.7 kg/m^2; body fat = NR; VO_{2max} = NR; PA = NR Women n = 98; age = 41±11 years; BMI = 24.4±3.0 kg/m^2; body fat = NR; VO_{2max} = NR; PA = NR	Self-reported PA level (Subgroup analysis) High/moderate exercise (n =46): training hard ≥4 hr/wk Light/no exercise (n =129): light exercise <4 hr/wk	Laboratory: Standardized evening meal to 35% of individual daily energy requirement.	Hunger, fullness, satiety, PFC (VAS) pre and over 3h post-meal. Palatability	Hard/moderate exercisers had lower mean ratings of post-prandial satiety and higher mean ratings of post-meal hunger and PFC than light/non-exercisers. (Differences became non-significant when age and sex added as covariates.) No differences in palatability between groups.
Harrington et al. (2013) [31]	Non-obese men n = 40; age = 27±4 years; BMI = 23.5±2.5 kg/m^2; body fat = NR; VO_{2max} = NR; PA = NR Non-obese women n = 42; age = 27±5 years; BMI = 22.4±2.0 kg/m^2; body fat = NR; VO_{2max} = NR; PA = NR	Activity-related energy expenditure derived from the residual value of the regression between TDEE from doubly-labeled water and 24-h resting energy expenditure. Activity-related energy expenditure divided into low, middle and high tertiles.	Laboratory	Food intake (test meal) Hunger, fullness, desire to eat and PFC (VAS) pre and post-test meal. SQ	Males in low tertile significantly higher fasting desire to eat, PFC and lower fullness than high tertile. No differences in fasting appetite between groups in women. No differences in appetite ratings after the test meal between groups in both men and women. Males in middle tertile had a significantly lower EI than high tertile and tended to have lower EI than low tertile. Males in high tertile had a significantly lower SQ for each appetite rating compared to middle tertile.
Jago et al. (2005) [32]	Men and women n = 1191 (39.3 % men); age = 30±5 years; BMI = 27.3±6.7 kg/m^2; body fat = NR; VO_{2max} = NR; PA (5-point Likert scale) = 3.2±1.1	Answer to “Compared to other people your age and sex, how would you rate your physical activity outside of work during the past year?” from five-item Likert scale where 1=physically inactive/sedentary, 3=moderately active and 5=very active Group 1: n=74; Group 2: n=181; Group 3: n=544; Group 4: n=180,	Free-living	Food intake (Youth/ Adolescent FFQ)	Groups 3, 4, and 5 reported greater intake of dairy products than group 1. Groups 3, 4 and 5 consumed fewer servings of fried foods than group 2. Group 5 had a greater EI than group 3 but no differences were seen with the other groups. Group 2 consumed greater % energy from fat than group 4.

		Group 5: n=212			
Jokisch et al. (2012) [33]	Men Active: n = 10; age = 21±2 years; BMI = 23.9±1.5 kg/m^2; body fat = 12.6±2.8 %; VO_{2max} = NR; PA = 438±152 min/wk Inactive: n = 10; age = 21±2 years; BMI = 23.0±1.9 kg/m^2; body fat = 15.0±2.3 %; VO_{2max} = NR; PA = 32±43 min/wk	Seven-day PA recall x 2 Active: ≥ 150min/wk moderate-to vigorous-intensity PA Inactive: ≤ 60min/wk	Laboratory: Test meal 60-min after 45-min cycling at 65-75% HR_{max} or rest.	Hunger and liking (VAS) Food intake (1 test meal and food record for remainder of the day)	Inactive had greater EI at ad libitum meal after rest than exercise. Both active and inactive had greater EI during remainder of the day after exercise compared to rest. Tendency for inactive to have greater EI than active. No significant differences in macronutrient intake at test meal but active consumed greater % energy from protein vs. inactive during remainder of day. Difference in energy compensation between groups (positive in active and negative in inactive) at test meal, but no differences in energy compensation for remainder of the day.
Long et al. (2002) [19]	Men High exercisers: n = 7; age = 22±3 years; BMI = 22.5±1.5 kg/m^2; body fat = NR; VO_{2max} = NR; PA = NR Moderate exercisers: n = 7; age = 27±7 years; BMI = 24.1±3.6 kg/m^2; body fat = NR; VO_{2max} = NR; PA = NR Nonexercisers: n = 9; age = 22±2 years; BMI = 24.1±3.6 kg/m^2; body fat = NR; VO_{2max} = NR; PA = NR	Seven-day PA recall x 2 High exercisers: ≥4 exercise sessions/wk Moderate exercisers: 2-3 exercise sessions/wk Nonexercisers: ≤1 exercise session/wk Exercise session: ≥40 min moderate to high intensity PA	Laboratory: LE preload and HE preload followed by test meal.	Hunger and satiety (VAS) Food intake (1 test meal)	EI in exercisers (groups combined) significantly less after HE vs. LE preload. EI after HE preload significantly lower in exercisers vs. nonexercisers. Energy compensation more accurate in active vs. inactive. Hunger before preload significantly higher in nonexercisers under both HE and LE preloads but no other differences in appetite ratings.
Lund et al. (2013) [34]	Men Trained: n = 10; age = 26±3 years; BMI = 22±3 kg/m^2; body fat = 12±3 %; VO_{2max} = 67±6 mL/kg/min; PA = NR Untrained: n = 10; age = 25±3 years; BMI = 22±3 kg/m^2; body fat = 21±3 %; VO_{2max} = 42±6 mL/kg/min; PA = NR	VO_{2max} Trained: Aerobic endurance exercise >3d/wk over several years and VO_{2max} > 60 (Runners, cyclists or triathletes) Untrained: No exercise during last 6 months and VO_{2max} < 50	Laboratory: Liquid meal followed by test meal 3 h later	Hunger, satiety, fullness and PFC (VAS) Meal size (test meal) GLP-1, insulin, acylated ghrelin, PYY, PP	GLP-1 and acylated ghrelin higher at baseline in trained. GLP-1 higher and insulin lower following liquid meal in trained. No group differences in PYY and PP at baseline and in response to liquid meal. No group differences in appetite ratings. Tendency for greater meal size (grams) in trained vs. untrained, significant after removal of outlier in untrained group.
Rocha et al. (2013) [35]	Men Active: n = 15; age = 23±4 years; BMI = 22.6±2.0 kg/m^2; body fat = 14.3±3.4 %; VO_{2max} = 44.6±5.0 mL/kg/min; PA level (TDEE/BMR) = 1.80±0.19 Inactive: n = 15; age = 24±3 years; BMI = 25.1±2.4 kg/m^2; body fat = 22.2±3.8 %; VO_{2max} = 35.5±5.2 mL/kg/min; PA level (TDEE/BMR) = 1.54±0.19	Modified Godin leisure-time exercise questionnaire PA monitor Active: Regular exercisers and >150 min/wk of moderate-intensity PA and PA level 1.70-1.99 Inactive: Did not engage in regular exercise and <150 min/wk of moderate-intensity PA and PA level 1.4-1.69	Laboratory and free-living: Test meal following 60-min cycling at 50% VO_{2max} or rest.	Hunger (VAS) Food intake (1 test meal and food record for remainder of the day and subsequent 3 days)	No effects on hunger and EI at test meal. Active had greater EI during exercise day than rest day. Inactive increased EI on 3rd day after exercise compared to rest. Energy compensation observed in active but not inactive during experimental day.

Rocha et al. (2015) [36]	Women taking oral contraceptives Active: n = 10; age = 23±4 years; BMI = 21.9±1.3 kg/m^2; body fat = 22.5±3.7 %; VO_{2max} = 36.8±3.1 mL/kg/min; PA level (TDEE/BMR) = 1.79±0.13 Inactive: n = 10; age = 22±3 years; BMI = 21.6±2.0 kg/m^2; body fat = 26.7±3.6 %; VO_{2max} = 29.9±4.1 mL/kg/min; PA level (TDEE/BMR) = 1.56±0.15	Modified Godin leisure-time exercise questionnaire PA monitor Active: Regular exercisers and >150 min/wk of moderate-intensity PA and PA level 1.70-1.99 Inactive: Not regular exercisers and <150 min/wk of moderate-intensity PA and PA level 1.4-1.69	Laboratory and free-living: Test meal following 60-min cycling at 50% VO_{2max} or rest.	Hunger (VAS) Food intake (1 test meal and food record for remainder of the day and subsequent 3 days)	No group differences in hunger, EI at test meal or macronutrient intake. Inactive had greater EI over the four days than active. Inactive had lower daily EI the day following exercise compared to rest. No energy compensation observed.
Van Walleghen et al. (2007) [37] Young groups	Men and women Active: n = 15 (45.4 % men); age = 23±4 years; BMI = 23.1±2.7 kg/m^2; body fat = 18.2±8.5 %; VO_{2max} = 55.6±10.5 mL/kg/min; PA = 575±406 min/wk Inactive: n = 14 (50 % men); age = 26±4 years; BMI = 23.5±3.0 kg/m^2; body fat = 27.2±5.6 %; VO_{2max} = 37.9±7.1 mL/kg/min; PA = 16±37 min/wk	Self-reported time spent doing moderate to vigorous PA Active: ≥150min/wk moderate and/or vigorous activity for ≥ 2 yr Inactive: NR	Laboratory and free-living: Preload or no preload followed by test meal.	Hunger and fullness (VAS) Food intake (1 test meal and food record for remainder of the day) Fasting insulin and insulin sensitivity	Active had greater habitual energy intake, lower % energy from fat and greater % energy from carbohydrate than inactive. No group differences in appetite or EI at test meal. Active had greater EI than inactive during the remainder of the day in no preload condition. No group differences for energy compensation at test meal, but compensation over the entire day was significantly more accurate in active vs. inactive subjects.

BMI body mass index, *BMR* basal metabolic rate, *EI* energy intake, *FFQ* food frequency questionnaire *GLP-1* glucagon-like peptide-1, *HE* high-energy, HR_{max} maximal heart rate. *LE* low-energy, *NR* not reported, *PA* physical activity, *PFC* prospective food consumption, *PP* pancreatic polypeptide, *PYY* peptide YY, *SQ* satiety quotient, *TFEQ* Three Factor Eating Questionnaire, *TDEE* total daily energy expenditure, *VAS* visual analogue scale, VO_{2max} maximal aerobic capacity

3.1.1 Study characteristics: Physical activity definitions

The median (range) sample size of the included studies was 15 (7-968) for the active group and 14 (9-910) for the inactive group. Men and women were included in eight studies, of which the median percentage of men was 42.2 (21.5-63.6) % in the active group and 50 (21.6-61.6) % in the inactive group [25, 26, 28-32, 37]. Five studies included only men [19, 27, 33-35] and one study included only women [36].

Physical activity status was determined by self-report (physical activity questionnaire, physical activity level question or physical activity recall) in 11 studies [19, 26, 28-30, 32, 33, 37], a VO_{2max} test in three studies [25, 27, 34], or from total daily energy expenditure (TDEE) and resting energy expenditure or basal metabolic rate (BMR) in three studies [31, 35, 36]. Only three studies used a combination of self-reported and objectively measured physical activity status [25, 35, 36].

The active groups were defined as participating in moderate to vigorous physical activity for at least: 150 min/wk [33, 35-37], 4 h/wk [30], 5 h/wk with a VO_{2max} greater than 45mL/kg/min [27], 3 d/wk with a VO_{2max} greater than 60mL/kg/min [34], 4 d/wk and >2500kcal/wk with a VO_{2max} above average for age [25], or 1000kcal/wk [26]. A TDEE/BMR value between 1.70-1.99 was utilised in two studies [35, 36]. Moderate exercisers participated in 2 to 3 sessions/wk of at least 40 min of moderate to high intensity physical activity [19] or expended between 1000-2500 kcal/wk [26]. High exercisers participated in 4 or more structured exercise sessions/wk of at least 40 minutes of moderate to high intensity physical activity [19] or expended 2500-3500 kcal/wk [26], whereas very high exercisers expended greater than 3500 kcal/wk [26].

The inactive groups were defined as no exercise over the previous 6 months and VO_{2max} less than 50 mL/kg/min [34] or less than: 1 session/wk of moderate- to high-intensity physical activity [19], 20 min/d and 2 d/wk [25], 60 min/wk [33], 1000 kcal/wk [26], 150 min/wk of moderate-intensity physical activity [35, 36], 3 h/wk of moderate- to high-intensity physical activity with a VO_{2max} less than 45 mL/kg/min [27], or 4 h/wk [30]. Two studies used a TDEE/BMR value between 1.4-1.69 [35, 36].

Based on the physical activity definitions above, for the purposes of statistical treatment, we distinguished physical activity levels as low (<150 min/wk, <1000 kcal/wk or PAL: 1.4-1.69), medium (150-419 min/wk, 1000-2500 kcal/wk or PAL: 1.7-1.99), high (420-839 min/wk or 2500-3500 kcal/wk) and very high (>840 min/wk or >3500 kcal/wk) for analysis of standardised energy intake.

3.1.2 Study characteristics: Appetite-related measures

Five studies evaluated appetite measures in a laboratory [19, 30, 31, 33, 34], five studies in free-living conditions [25, 26, 28, 29, 32], and four studies combined laboratory and free-living measures [27, 35-37]. Four studies included exercise (45-60 min cycling at 50-75 % VO_{2max} or HR_{max}) during the laboratory session [27, 33, 35, 36]. Ten studies included fasting and/or daily (area under the curve) subjective appetite ratings, all of which included hunger [19, 25, 27, 30, 31, 33-37]. Other appetite ratings assessed were fullness [25, 27, 30, 31, 33, 34, 37], prospective food consumption (PFC) [30, 31, 34], desire to eat [25, 27, 31], satiety [19, 30, 34], liking [33] and palatability [30]. One study reported restraint, disinhibition and susceptibility to hunger [26]. Eleven studies assessed energy intake, either via a food frequency questionnaire (FFQ) [26, 32], food record [25], laboratory-based test meals [19, 31, 34], or a combination of laboratory-based test meals and food records [27, 33, 35-37]. Six studies reported energy compensation following either a preload [19, 37] or a single bout of exercise [27, 33, 35, 36]. Eight studies reported macronutrient intake [25-27, 32, 33, 35-37]. Three studies assessed food choices via FFQ [28, 29, 32]. Two studies included the assessment of appetite-related peptides [34, 37].

3.1.3 Participant characteristics

The median (range) age was 23 (21-48) years for the active groups and 22 (21-49) years for the inactive groups.

In the 10 studies that reported BMI of the active and inactive groups separately, the median (range) was 23.5 (21.9-25.2) kg/m^2 for the active group and 24.1 (21.6-26.6) kg/m^2 for the inactive group [19, 25-27, 29, 33-37]. In three studies, the inactive group had a significantly greater BMI than the active group [25, 27, 35]. In those that reported BMI of the groups combined, the median (range) was 24.8 (22.4-27.3) kg/m^2 [28, 30-32].

In the seven studies that reported percent body fat, the median (range) was 14.3 (12.0-22.5) % for the active group and 22.2 (15.0-27.2) % for the inactive group [25, 27, 33-37]. In all studies, the inactive group had a significantly greater percent body fat than the active group.

In the six studies that reported VO_{2max}, the median (range) was 49.6 (36.8-67.0) mL/kg/min for the active group and 36.3 (29.9-42.0) mL/kg/min for the inactive group [25, 27, 34-37]. In all studies, the active group had a significantly greater VO_{2max} than the inactive group.

3.1.4 Study results: Appetite ratings

Of the 10 studies that measured appetite ratings, three found differences between the physically active and inactive groups. Harrington et al. [31] reported greater fasting appetite and lower satiety quotient (SQ; [pre-meal appetite rating-post meal appetite rating]/energy intake) for hunger, fullness, desire to eat and prospective food consumption (PFC) in men in the high activity tertile compared to the moderate activity tertile, whereas Long et al. [19] reported greater fasting appetite in the inactive group. Gregersen et al. [30] found greater post-prandial appetite in the active group, however differences became non-significant when age and sex were added as covariates.

3.1.5 Study results: Energy and macronutrient intake

Ten of eleven studies found differences in energy intake between active and inactive individuals. Two studies found greater energy intake (habitual energy intake [37] or with a test meal [34]) in the active compared to the inactive group, whereas one study observed greater energy intake in inactive women over four days than active women [36]. Furthermore, two studies observed a non-linear relationship in energy intake, whereby energy intake was highest in the groups with the lowest and highest levels of physical activity [26, 31], while Jago et al. [32] only observed a greater energy intake in the very active group compared to the moderately active group. In studies assessing energy intake following a preload, Long et al. [19] found that energy intake at an *ad libitum* test meal following a high-energy preload was significantly lower than following the low-energy preload in regular exercisers. The same study showed that compared to nonexercisers, energy intake following the high-energy preload was significantly lower in exercisers. Moreover, Van Walleghen et al. [37] found that the active group consumed more throughout the day following the no preload condition than the inactive group, leading to significantly more accurate short-term energy compensation. Of note, however, there were no differences in energy compensation between groups at the test meal after the preload [37]. In studies measuring energy intake after exercise, two of three studies in men observed energy compensation in the active group, where energy intake following an exercise session was greater compared to rest at test meal [33] or throughout the day (but not at the test meal in this study) [35]. One of these studies observed negative energy compensation in the inactive group, where energy intake was lower following the exercise session compared to rest, suggesting an effect of exercise-induced anorexia [33].

Of the above studies that observed differences between groups, only four were based on objectively measured (test meal) energy intake [19, 31, 33, 34].

As for macronutrient intake, compared to the inactive group, two studies found that the active group consumed a greater percent energy from carbohydrates [26, 37], three found lower percent energy from fat [26, 32, 37], while one study found a greater percent energy from protein [33]. In terms of food choices, active individuals reported a greater intake of nutrient-dense, low-fat foods [29], fruits and 100% fruit juices [28], and dairy products [32], and a lower intake of burgers and sandwiches [28] and fried foods [32] than inactive.

3.1.6 Study results: Standardized energy intake

To further examine the relationship between energy intake and physical activity level, the available energy intake data from all cross-sectional studies [25-27, 31-37] were extracted and transformed into standardized scores then plotted according to our physical activity levels (low, medium, high, very high) as described in section 3.1.1. In the studies that included a preload or an exercise bout [27, 33, 35, 36], energy intake was taken from the control condition. Of these ten studies, eight were based on self-reported daily energy intake [25-27, 32, 33, 35-37] while two were based on energy intake at a test meal [31, 34]. The pattern of means revealed a J-shaped curve for energy intake as habitual physical activity level increased (Figure 2). One-way ANOVA confirmed a main effect of graded physical activity level on energy intake score [$F(3,21)=3.57$, $p=0.03$]. Post hoc trend analyses revealed significant effects for linear [$F=5.79$, $p=0.03$] and curvilinear (quadratic) [$F=8.10$, $p=0.01$] functions.

Figure 2 here

Fig. 2 Standardised energy intake by physical activity level from the 10 cross-sectional studies reporting energy intake (n=25 data points). Trend analysis confirmed significant linear ($p<0.05$) and quadratic ($p<0.01$) relationship between graded physical activity level and energy intake scores. Black line indicates mean of the z-scores, *SEM* standard error of the mean.

3.1.7 Study results: Appetite-related peptides

Van Walleghen et al. [37] found greater insulin sensitivity in the active group. Lund et al. [34] found that in active individuals, glucagon-like peptide-1 (GLP-1) and acylated ghrelin were higher at baseline (insulin tended to be lower), and following a liquid meal, GLP-1 was higher and insulin was lower in active. No group differences were found for peptide YY (PYY) and pancreatic polypeptide.

3.2 Exercise-training interventions

The results from the exercise-training interventions (n = 14) are presented in Table 3.

Table 3 Studies investigating the effect of exercise training on appetite control in previously inactive individuals

Study	Participants	Training intervention	Setting	Outcome measures	Results
Alkahtani et al. (2014) [38]	Overweight and obese men n = 10; age = 29±4 years; BMI baseline = 30.7±3.4 kg/m^2; BMI post = NR; body fat baseline = 31.2±4.7 %; body fat post = NR; VO_{2max} baseline = 28.7±3.4 mL/kg/min; VO_{2max} post = NR	4 wk supervised MIIT 3d/wk (30-45 min of 5-min stages at ±20% workload at 45%VO_{2peak}) 4 wk supervised HIIT 3d/wk (30-45 min of 30-s 90%VO_{2peak} and 30-s rest) Each training block was counterbalanced and separated by a 6-week detraining washout	Laboratory: Test meal following 45-min cycling at 45% VO_{2max} at pre and post both training blocks.	Hunger, desire to eat and fullness (VAS) Liking and wanting (computer-based paradigm) Food intake (test meal)	Tendency for suppression of desire to eat after acute exercise post-training with HIIT compared to MIIT. Tendency for increase with MIIT and decrease with HIIT in explicit liking for high-fat non-sweet foods after acute exercise post-training. No effects of training on food intake and EI. Tendency for fat intake and % energy from fat to increase after MIIT.
Bryant et al. (2012) [39]	Overweight and obese men and women n = 58 (32.7 % men); age = 36±10 years; BMI baseline = 31.8±4.5 kg/m^2; BMI post = 30.7±4.4 kg/m^2; body fat baseline = 34.8±7.8 %; body fat post = 31.9±9.0 %; VO_{2max} baseline = 29.1±5.7 mL/kg/min; VO_{2max} post = NR	12 wk supervised aerobic exercise 5d/wk (500kcal at 70% HR_{max})	Laboratory	Food intake (Self-determined fixed breakfast followed by 2 ad libitum meals and evening snack box) Restraint, disinhibition and susceptibility to hunger (TFEQ)	No change in 24-h EI or susceptibility to hunger. Significant reduction in disinhibition and increase in restraint after training.
Caudwell et al. (2013) [40]	Overweight and obese men n = 14; age = 44±6 years; BMI baseline = 31.3±5.0 kg/m^2; BMI post = 30.5±4.9 kg/m^2; body fat baseline = 34.3±7.0 %; body fat post = 32.4±7.6 %; VO_{2max} = NR Overweight and obese premenopausal women n = 27; age = 42±8 years; BMI baseline = 30.4±3.2 kg/m^2; BMI post = 30.2±3.6 kg/m^2; body fat baseline = 44.0±5.5 %; body fat post = 42.5±5.8 %; VO_{2max} = NR	12 wk supervised aerobic exercise 5d/wk (500kcal at 70% HR_{max})	Laboratory: HE and LE density probe days.	Food intake (Self-determined fixed breakfast, fixed energy lunch and ad libitum dinner and evening snack box)	Significant effect of training on HE density meal size (driven by a lower mean in women as men had a greater mean post-training) but not LE density meal size. No effect of training on daily EI under each dietary condition.
Caudwell et al. (2013) [41]	Overweight and obese men n = 35; age = 41±9 years; BMI baseline = 30.5±8.6 kg/m^2; BMI post = 29.6±1.1 kg/m^2; body fat baseline = 33.8±6.6 %; body fat post = 31.3±3.3 %; VO_{2max} baseline = 34.9±6.9 mL/kg/min, VO_{2max} post = 43.3±6.9 mL/kg/min Overweight and obese premenopausal women n = 72; age = 41±10 years; BMI baseline = 31.8±4.3 kg/m^2; BMI post = 30.9±1.1 kg/m^2; body fat baseline = 44.1±6.0 %; body fat post = 41.6±2.2 %; VO_{2max} baseline = 29.1±6.5	12 wk supervised aerobic exercise 5d/wk (500kcal at 70% HR_{max})	Laboratory	Hunger, fullness and desire to eat (VAS) SQ Food intake (Self-determined fixed breakfast, fixed energy lunch and ad libitum dinner and evening snack box)	No change in 24-h EI with training. Significant increase in fasting hunger but no change in daily hunger AUC. SQ significantly greater post-training.

	mL/kg/min; VO_{2max} post = 35.1±5.5 mL/kg/min				
Cornier et al. (2012) [42]	Overweight and obese men and women n = 12 (41.6 % men); age = 38±10 years; BMI baseline = 33.3±4.3 kg/m^2; BMI post = NR; body fat baseline = 36.5±1.9 %; body fat post = 34.4±2.0 %; VO_{2max} = NR	6 months supervised treadmill walking 5d/wk (building up to 500kcal/d at 75% VO_{2max})	Laboratory and free-living: Test meal breakfast (30% estimated daily energy requirements)	Leptin Restraint and disinhibition (TFEQ) Power of Food Scale Craving and Mood Questionnaire Food Craving Inventory Hunger, satiety and PFC (VAS) Food intake (3-day food record)	Significant reduction in fasting leptin post-training. No change in dietary restraint or disinhibition, food cravings, Power of Food Scale, food desire and appeal, or post-prandial appetite ratings. Self-reported EI lower after training compared to baseline but no change in macronutrient intake.
Guelfi et al. (2013) [43] Exercise groups	Overweight and obese men (age = 49±7 years) Aerobic training: n = 12; BMI baseline = 31.7±3.5 kg/m^2; BMI post = 31.1±3.3 kg/m^2; body fat = NR; VO_{2max} baseline = 2.25±0.51 L/min @ 80% HR_{max}; VO_{2max} post = 2.82±0.60 L/min @ 80% HR_{max} Resistance training: n = 13; BMI baseline = 30.3±3.5 kg/m^2; BMI post = 30.3±3.7 kg/m^2; body fat = NR; VO_{2max} baseline = 1.94±0.39 L/min @ 80% HR_{max}; VO_{2max} post = 2.17±0.54 L/min @ 80% HR_{max}	12 wk supervised (3d/wk) aerobic exercise (40-60 min at 70-80% HR_{max}) or resistance exercise (weight training matched for duration and intensity; 3-4 sets 8-10 repetitions of 9 exercises at 75-85% 1RM)	Laboratory: 2-h, 75-g OGTT	Hunger and fullness (VAS) Active ghrelin, leptin, insulin, insulin sensitivity, PP and PYY	Significant increase in fasting and postprandial fullness following aerobic training only. No change in fasting or postprandial hunger with training. Fasting and postprandial leptin were significantly lower after training. Postprandial insulin was significantly lower after aerobic training only. No change in fasting insulin, and fasting and postprandial AG, PP and PYY post-training. Improvement in insulin sensitivity in both groups post-training.
Jakicic et al. (2011) [44] Exercise groups	Overweight women Moderate-dose: n = 76; age = 44±8 years; BMI baseline = 27.2±1.8 kg/m^2; BMI post = 26.9±2.1 kg/m^2; body fat baseline = 33.5±4.1 %; body fat post = 33.3±4.8 %; VO_{2max} = NR High-dose: n = 88; age = 46±8 years; BMI baseline = 27.0±1.6 kg/m^2; BMI post = 26.7±2.4 kg/m^2; body fat baseline = 33.0±4.1 %; body fat post = 32.3±5.3 %; VO_{2max} = NR	18 months unsupervised moderate-dose (150min/wk), high-dose (300min/wk) ~5d/wk bouts ≥10min moderate to vigorous intensity (55-85% HR_{max})	Free-living	Food intake (FFQ) Eating Behaviour Inventory	No group by time interaction on EI and macronutrient intake. Eating behaviour score improved post-intervention but no differences between groups.
King et al. (2008) [45]	Overweight and obese men and women Compensators: n = 18 (23.5 % men); age = 38±9 years; BMI baseline = 30.7±2.9 kg/m^2; BMI post = NR; body fat baseline = 32.7±8.0 %; body fat post = NR; VO_{2max} baseline = 28.8±5.7 mL/kg/min; VO_{2max} post = NR Noncompensators: n = 17 (33.3 % men); age = 40±13 years; BMI baseline = 33.1±4.7 kg/m^2; BMI post = NR; body fat baseline = 37.2±7.9 %; body fat post = NR; VO_{2max} baseline = 28.4±5.8 mL/kg/min; VO_{2max} post = NR	12 wk supervised aerobic exercise 5d/wk (500kcal at 70% HR_{max})	Laboratory	Hunger, fullness, PFC and desire to eat (VAS) Food intake (Self-determined fixed breakfast followed by 2 ad libitum meals and an evening snack box)	No significant changes in 24-h EI in pooled data with training, however compensators increased EI and % energy from fat and non-compensators decreased EI from baseline to post-intervention. Compensators had greater hunger profile post-training than non-compensators.

King et al. (2009) [18]	Overweight and obese men and women divided into responders (n =32) and non-responders (n =26) to exercise-induced weight loss n = 58 (32.7 % men); age = 40±10 years; BMI baseline = 31.8±4.5 kg/m^2; BMI post = NR; body fat = NR; VO_{2max} baseline = 29.1±5.7 mL/kg/min; VO_{2max} post = NR	12 wk supervised aerobic exercise 5d/wk (500kcal at 70% HR_{max})	Laboratory: Self-determined fixed breakfast	Hunger, fullness, PFC and desire to eat (VAS) SQ	Nonresponders and responders had significantly greater fasting hunger but also had a greater SQ post-training Only nonresponders increased daily motivation to eat (greater hunger, desire to eat and lower fullness) post-training.
Martins et al. (2007) [46]	Men and women n = 25 (44 % men); age = 30±12 years; BMI baseline = 22.7±2.3 kg/m^2; BMI post = 22.8±2.2 kg/m^2; body fat baseline = 23.6±7.8 %; body fat post = 23.0±7.5 %; VO_{2max} baseline = 31.1±4.8 mL/kg/min; VO_{2max} post = 34.3±7.4 mL/kg/min	6 wk unsupervised aerobic exercise ≥4d/wk, 30-45min (continuously or bouts ≥10min each) at 65-75% HR_{max}	Laboratory and free-living: LE preload and HE preload	Hunger, fullness, palatability (VAS) Food intake (1 test meal and food record until breakfast next morning) Fasting insulin and insulin sensitivity	Test meal size and cumulative 24-h EI significantly lower following HE preload vs. LE preload post-training. No improvement in energy compensation at test meal but tendency for improved compensation over 24h. Greater % energy from protein at test meal after training. No change in fasting insulin and insulin sensitivity. No change in appetite ratings.
Martins et al. (2010) [47]	Overweight and obese men and women n =15 (53.3 % men); age = 37±8 years; BMI baseline = 31.3±2.3 kg/m^2; BMI post = 30.1±2.3 kg/m^2; body fat baseline = 35.3±5.6 %; body fat post = 33.5±5.9 %; VO_{2max} baseline = 32.9±6.6 mL/kg/min; VO_{2max} post = 37.7±5.9 mL/kg/min	12 wk supervised aerobic exercise 5d/wk (500kcal at 75% HR_{max})	Laboratory: Standardized breakfast	Hunger, fullness, PFC and desire to eat (VAS) AG, TG, insulin, insulin sensitivity, GLP-1, PYY over 3h post-breakfast.	Significant reduction in fasting and postprandial insulin post-training. Improvement in insulin sensitivity post-training. Increase in fasting AG after training but no change in postprandial AG. No significant training effect on TG, GLP-1 and PYY, but tendency for greater GLP-1 AUC in the late postprandial period after training. Significant increase in fasting hunger, desire to eat and PFC, and decrease in fullness post-training. Greater postprandial hunger and desire to eat post-training.
Martins et al. (2013) [48]	Overweight and obese men and women n =15 (53.3 % men); age = 37±8 years; BMI baseline = 31.3±2.3 kg/m^2; BMI post = 30.1±2.3 kg/m^2; body fat baseline = 35.3±5.6 %; body fat post = 33.5±5.9 %; VO_{2max} baseline = 32.9±6.6 mL/kg/min; VO_{2max} post = 37.7±5.9 mL/kg/min	12 wk supervised aerobic exercise 5d/wk (500kcal at 75% HR_{max})	Laboratory and free-living: 1) Standardized breakfast 2) LE preload 3) HE preload	Hunger, fullness, PFC and desire to eat (VAS) Food intake (1 test meal after preload and food record for remainder of the day) CCK and leptin over 3h post-breakfast	Significant reduction in fasting and postprandial leptin post-training but no change in CCK. No change in test meal EI, but cumulative EI after HE preload significantly lower than LE preload post-training, whereas it was greater than LE at baseline. Greater accuracy in energy compensation post-training. No change in macronutrient intake. No effect of training on appetite ratings after the preloads.
Rosenkilde et al. (2013) [49] Exercise groups	Overweight men Moderate-dose group: n = 18; age = 30±7 years; BMI baseline = 28.6±1.8 kg/m^2; BMI post = 27.5±2.0 kg/m^2; body fat = NR; VO_{2max} baseline = 34.6±24.1 mL/kg/min; VO_{2max} post = 42.3±4.5 mL/kg/min High-dose group: n = 18; age = 28±5 years; BMI baseline = 27.6±1.4 kg/m^2; BMI post = 26.9±1.2 kg/m^2; body fat = NR; VO_{2max} baseline = 36.2±5.3 mL/kg/min; VO_{2max} post = 43.1±6.6	12 wk unsupervised daily endurance exercise expending 300kcal/day (moderate-dose) or 600kcal/day (high-dose) at >50%VO_{2max}	Laboratory: 1) Standardized breakfast 2) Exercise test (1h ~60% VO_{2max})	Hunger, satiety, fullness, PFC, palatability and liking (VAS) Food intake (lunch test meal after breakfast) Restraint, disinhibition and susceptibility to hunger (TFEQ) Insulin, PYY_{3-36}, ghrelin post-breakfast	Fasting and postprandial AUC for insulin significantly lower after both exercise interventions. No training effect on PYY_{3-36} or ghrelin. Fasting and postprandrial fullness increased in the high-dose group post-intervention. No difference in EI, palatability, liking, restraint, disinhibition or susceptibility to hunger within groups.

	mL/kg/min				
Shaw et al. (2010) [50] Exercise group	Men n = 13; age = 28±5 years; BMI = NR; body fat baseline = 26.8±1.5 %; body fat post = 23.3±6.3 %; VO_{2max} = NR	8 wk supervised resistance exercise 3d/wk (3 sets 15 repetitions of 9 exercises)	Free-living	Food intake (3-day food record)	No change in EI and macronutrient intake with training.

AG acylated ghrelin, *AUC* area under the curve, *BMI* body mass index, *CCK* cholecystokinin, *EI* energy intake, *FFQ* food frequency questionnaire, *HE* high-energy, *HIIT* high-intensity interval training, HR_{max} maximal heart rate, *LE* low-energy, *MIIT* moderate-intensity interval training, *NR* not reported, *OGTT* oral glucose tolerance test, *PFC* prospective food consumption, *PP* pancreatic polypeptide, *PYY* peptide YY, PYY_{3-36} peptide YY (3-36), *RM* repetition maximum, *SQ* satiety quotient, *TFEQ* Three Factor Eating Questionnaire, *TG* total ghrelin, *VAS* visual analogue scale, VO_{2max} maximal aerobic capacity, VO_{2peak} peak aerobic capacity.

3.2.1 *Study characteristics: Exercise intervention*

The median (range) duration of the interventions was 12 (4-72) weeks of exercise 5 (3-7) d/wk. Exercise duration was prescribed in minutes or energy expenditure (kcal), at intensities in $\%VO_{2max}$ or % heart rate maximum (HR_{max}). The median exercise prescription was 43.8 (30-60) min or 500 (300-600) kcal per session at 68.5 (45-90) % VO_{2max} or 70 (70-75) % HR_{max}. Eleven training interventions involved aerobic exercise [18, 39-43, 45-49], two interventions involved resistance exercise [43, 50] and one intervention compared moderate intensity interval exercise and high intensity interval exercise in a crossover design [38]. One study did not specify the exercise modality [44]. In 11 of the 14 interventions the exercise was supervised [18, 39-43, 45, 47, 48]. Nine studies collected appetite-related measures in a laboratory [18, 38-41, 43, 45, 47, 49], two studies in free-living conditions [44, 50], and three studies in a combination of laboratory and free-living conditions [42, 46, 48].

3.2.2 *Study characteristics: Appetite-related measures*

Ten studies included fasting and/or daily (area under the curve) appetite ratings, all of which included hunger [18, 38, 40, 42, 43, 45-49]. Fullness [18, 38, 41, 43, 45-49], PFC [18, 42, 45, 47-49], desire to eat [18, 38, 41, 45, 47, 48], satiety [42, 49], liking and palatability [46, 49] were also assessed. Three studies measured restraint, disinhibition and susceptibility to hunger [39, 42, 49], one study included the Power of Food Scale, Craving and Mood Questionnaire and Food Craving Inventory [42], one study included the Eating Behaviour Inventory [44] and one study assessed liking and wanting for foods varying in fat and sweetness [38]. Eleven studies assessed energy intake, either via a FFQ [44], food record [42, 50], test meals [38-41, 45, 49], or a combination of test meals and food records [46, 48]. Two studies measured energy intake following high- and low-energy preloads [46, 48] and one at high- and low-energy density meals [40]. Seven studies reported macronutrient intake [38, 42, 44-46, 48, 50]. Six studies assessed appetite-related peptides in the fasting state [42, 43, 46-49] and three in response to food ingestion [43, 47, 48].

3.2.3 *Participant characteristics*

The median (range) age was 38 (28-49) years. The median (range) sample size of the included studies was 18 (10-88). Men and women were included in nine studies, of which the median percentage of men was 33.7 (23.5-53.3) % [18, 39-42, 45-48]. Four studies only included men [38, 43, 49, 50] and one study only included women [44].

Nine studies reported BMI before and after the intervention [39-41, 43, 44, 46-49], the median (range) was 30.5 (22.7-31.8) kg/m^2 at baseline and 30.1 (22.8-31.1) kg/m^2 post-intervention. Seven of these reported a significantly lower BMI after the exercise intervention [39, 41, 43, 44, 47-49]. In the four studies that only reported baseline BMI [18, 38, 42, 45], the median (range) was 31.8 (30.7-33.3) kg/m^2.

Eight studies reported percent body fat before and after the intervention, the median (range) was 34.3 (23.6-44.1) % at baseline and 32.4 (23.0-42.5) % post-intervention [39-41, 44, 46-48, 50]. Seven of these reported a significantly lower percent body fat after the intervention [39-41, 44, 47, 48, 50]. In the three studies that only reported baseline percent body fat, the median (range) was 34.6 (31.2-37.2) % [38, 42, 45].

In the five studies that reported VO_{2max} before and after the intervention, the median (range) was 32.9 (29.1-36.2) mL/kg/min at baseline and 37.7 (34.3-43.3) mL/kg/min post-intervention [41, 46-49]. In all studies, the increase in VO_{2max} with training was significant. In the four studies that only reported baseline VO_{2max}, the median (range) was 28.8 (28.4-29.1) mL/kg/min [18, 38, 39, 45].

3.2.4 Study results: Appetite ratings

Exercise training led to differences in appetite ratings in five of 10 studies. Three studies found an increase in fasting hunger [18, 41, 47], desire to eat and PFC [47], and a decrease in fullness [47]. However, two studies found that fasting fullness increased following aerobic [43] and high-dose aerobic (600kcal/d) [49] exercise training. King et al. [18] reported a greater daily hunger, desire to eat and lower fullness post-training in a subsample of non-responders to exercise-induced weight loss (i.e. individuals with changes in body composition below that expected based on the total exercise-induced energy expenditure). In response to a standardized breakfast, Martins et al. [47] found an increase in hunger and desire to eat following exercise training, whereas Guelfi et al. [43] found an increase in fullness after an oral glucose tolerance test following aerobic training.

The two studies that included SQ ([pre-meal hunger – post-meal hunger]/energy intake) found increases post-training [18, 41]. Only one of three studies found a reduction in disinhibition and an increase in restraint post-training [39].

3.2.5 Study results: Energy and macronutrient intake

Five of eleven studies found differences in energy intake after the exercise-training interventions. Daily energy intake was lower post-training in one study [42], while it increased in a subsample of compensators in another study [45]. As for high-energy test meal challenges, Caudwell et al. [40] showed a reduction in meal size containing high energy density foods, and two studies demonstrated that energy intake was lower throughout the day after a high-energy preload compared to a low-energy preload [46, 48].

Two studies showed an increase in percent energy from fat in subsample of compensators (individuals whose weight loss after exercise-training was less than predicted based on the total exercise-induced energy expenditure) [45] or after moderate-intensity interval training [38]. Training led to an increase in percent energy from protein in another study [46].

3.2.6 Study results: Appetite-related peptides

Of the studies that assessed fasting peptides, five found differences following exercise training, where leptin [42, 43, 48] and insulin decreased [47, 49], and ghrelin increased [47]. Insulin sensitivity improved after training in two of three studies [43, 47]. Of note, the study that found no improvement in insulin sensitivity was half the duration of the two others (6 vs. 12 weeks) [46]. All three studies that assessed the peptide response to food ingestion found training effects, where postprandial leptin [43, 48] and insulin decreased [43, 47] after aerobic training while there was a tendency for GLP-1 in the late postprandial period to increase with training [47].

4 Discussion

4.1 Appetite control in active and inactive individuals

This systematic review investigated differences in appetite ratings, food intake and appetite-related peptides between active and inactive (or previously inactive) individuals in order to determine whether habitual physical activity improves appetite control. In terms of fasting, postprandial or daily appetite ratings, studies reported mixed results such that no clear differences could be distinguished between physically active and inactive individuals. It has been suggested that combining appetite sensations with objectively measured energy intake to calculate parameters such as the SQ can provide a better indication of the ability of the energy consumed to affect appetite. One cross-sectional study [31] and two exercise-training studies [18, 41] assessed SQ with conflicting results, however the former measured SQ during an *ad libitum* meal while in the latter studies SQ was measured during a standardized meal. These differences, along with differences in the protocols in the other studies, may account for the contradictory results in appetite ratings.

Several studies focused on the measurement of energy intake, but no consistent differences were again found between active and inactive individuals. However, these simple comparisons precluded the possibility that physical inactivity may lead to the dysregulation of appetite and subsequent overconsumption, meaning that differences between active and inactive individuals may not always be apparent. Indeed we have recently argued that the relationship between physical activity and energy intake may follow a curvilinear function [23]. After transforming absolute energy intake into standardized scores and distinguishing levels of physical activity from the definitions of the 'active' groups used in the cross-sectional studies, we were able to test this hypothesis. The results revealed a significant quadratic effect illustrated by a J-shaped curve across physical activity levels (see Figure 2). A similar J-shaped relationship has recently been suggested by Shook et al. [51], who compared estimated energy intake, using an equation based on changes in body composition, across quintiles of physical activity in a large heterogeneous sample of young adults. Their analysis provides further support to our synthesis of the literature which demonstrates that the relationship between physical activity level and energy intake is non-linear as postulated by Mayer et al. almost 60 years ago [52]. In Bengali jute mill workers whose daily occupations ranged from 'sedentary' to 'very heavy' work, daily energy expenditure and daily energy intake were closely matched at higher levels of daily physical activity, but at low levels of daily physical activity this coupling was lost, such that daily energy intake exceeded expenditure in those performing 'sedentary' or 'light' work [52]. This relationship may explain why differences in energy intake may not be obvious between active and inactive individuals as they stand at similar levels on the energy intake curve. As our findings are based on standardized scores from results of studies using various methodologies and protocols [25-27, 31-37] and Shook and colleagues' inferred from changes in body composition [51], confirmation of this J-shaped relationship is required with objective measures of energy intake in studies designed to assess intake across well-defined physical activity levels.

Of interest to this review are the studies that used preload challenges or macronutrient manipulations to examine whether differences exist in the ability to adjust energy intake after previous food intake or in meals that vary in composition. Three studies demonstrated that physically active individuals have a better ability to make adjustments in energy intake following a high-energy preload [19, 46, 48], suggesting an increased sensitivity to previous energy intake (e.g. greater satiety). Another preload study also found more accurate energy compensation in active individuals, where the no preload condition led to an increase in energy intake in active but not inactive individuals [37]. In line with these studies, one study found that exercise training led to a reduction in meal size at a high-energy dense meal but not at a low-energy dense meal [40]. This also supports the proposition of increased sensitivity to the energy density of foods, but this time during a meal (e.g. greater satiation). Interestingly, in this study it appeared that women may have been more susceptible to the effect than men. Therefore, further studies in males and females are required to confirm this finding and the potential interaction between physical activity and energy density on the sensitivity of appetite control. Nonetheless, these data support a J-shaped relationship between physical activity and energy intake, and suggest a better ability to regulate energy intake with increasing levels of physical activity.

Despite the effects observed following a preload, there was no consistent effect of physical activity level on energy compensation immediately after an exercise bout or over several hours or days after exercise [27, 33, 35, 36, 38]. These results do not support a recent meta-analysis that found that absolute energy intake after acute exercise was greater in active individuals compared to those less active [21]. However, this analysis only reported absolute energy intake and not energy compensation. In fact, Charlot & Chapelot [27] report in their study on lean/fit and fat/unfit men that energy compensation after exercise was highly variable and found no clear differences between groups. This raises the concern of the reliability of the measure of energy compensation (discussed in section 4.3). Nevertheless, in the short-term, it appears that in physically active individuals the regulation of energy intake may be more sensitive to previous food intake rather than exercise.

4.2 Differences in the proposed mechanisms of appetite control

Eating behaviour is influenced by several proposed mechanisms, one of which is appetite-related peptides. Acute exercise and exercise training also affect these peptides [53, 54]. The studies that measured the peptide response to food intake found lower postprandial insulin [34, 43, 47, 49] and greater postprandial GLP-1 [34] (and tendency [47]) in active individuals. An emphasis on insulin will be given as it was the most commonly measured hormone in the studies within the review.

Interestingly, the same subjects that showed a preload effect in the study by Martins et al. [48] also showed an improvement in insulin sensitivity [47]. Additionally, the aerobic training group in the study by Guelfi et al. [43] significantly lowered postprandial insulin and improved insulin sensitivity with concomitant changes in postprandial fullness. However, the resistance-training group in the same study had a tendency for lower postprandial insulin (P = 0.066) and also improved insulin sensitivity after training without an effect on postprandial appetite ratings, while another study that showed a preload effect after six weeks of training did not find a significant improvement in insulin sensitivity [46]. Despite the relationship between insulin and appetite control not being consistent in the above studies, a meta-analysis from Flint et al. [55] proposed that insulin resistance could lead to disrupted satiety signalling. This meta-analysis showed that postprandial insulin was associated with satiety in individuals with a healthy weight but not in overweight individuals; however it did not take into account physical activity status of the participants nor their body composition (fat mass and fat-free mass).

Measuring body composition, rather than just BMI, has become important in understanding the mechanisms affecting eating behaviour as fat-free mass (but not fat mass) was found to be associated with daily energy intake and meal size in overweight and obese individuals [56]. In addition to appetite signals from adipose tissue and gut hormones, Blundell et al. [56] have proposed a role for fat-free mass and resting metabolic rate as drivers of food intake. Differences in body composition were apparent in the cross-sectional studies, as six reported lower body fat percentage in active individuals [25, 33-37] despite only two reporting a lower BMI [25, 35]. Three of the former studies reported enhanced appetite control in terms of more accurate energy compensation [33, 35, 37]. No cross-sectional studies compared lean and overweight active individuals, thus a question arises as whether 'fat but fit' individuals would have enhanced appetite control. Four training studies conducted in overweight participants reported improvements in appetite control post-intervention (but also showed significant reductions in fat mass) [40, 41, 43, 48]. Overall, these studies indicate that differences in body composition and insulin sensitivity may be factors promoting more sensitive appetite control in active individuals. Furthermore, a recent study found faster gastric emptying in active compared to inactive males [57], proposing another mechanism by which appetite control (i.e. satiety signalling) could be better regulated in physically active individuals. More studies are required to elucidate the mechanisms involved in the appetite control differences between active and inactive individuals such as body composition, postprandial satiety and hunger peptides, insulin (and possibly leptin [9, 10]) sensitivity, gastric emptying in addition to resting metabolic rate [40, 56] and substrate oxidation [58], which were not covered in this review.

4.3 Methodological considerations

A number of points regarding the methodologies used in the studies included in this review need addressing. In the cross-sectional studies, the definitions used to define active and inactive individuals varied markedly. For example, some studies only used a self-rated measure ('yes or no' question [29] or Likert scale [28, 30, 32]) or a self-reported measure (physical activity questionnaires [26, 37] or diaries/recalls [19, 33]) instead of objectively assessing physical activity via accelerometry. This may have confounded the results of the active groups from participants overestimating their physical activity habits [59, 60]. Moreover, some studies only used VO_{2max} [27, 34] to define the active groups, which may not reflect all aspects of physical activity (e.g. low- to moderate-intensity activity) [61]. Clear definitions of activity levels should be set in place to allow future studies to investigate appetite and energy intake across these defined levels. Along these lines, the studies in this review preclude us from distinguishing the effects of the several aspects of physical activity, such as time spent in low, moderate and vigorous activities, cardiovascular fitness and activity-related energy expenditure, on appetite control. In addition, future studies should assess all components of energy intake and energy expenditure in order to determine their influence on eating behaviour, particularly in light of recent evidence suggesting a plateau in daily energy expenditure above a certain threshold of physical activity [62]. This would allow us to tease out whether changes in cardiovascular fitness and/or physical activity energy expenditure are most important for appetite control. Secondly, food intake was assessed both in laboratory (using test meals) and in free-living conditions (using FFQ and food diaries). Test meals are known to be a rigorous method of assessing energy intake (under controlled laboratory conditions) but food diaries, despite providing a longer window of observation of 'real world' feeding patterns, may lead to underreporting and biased results [59]. It should be noted that the short-term results (daily energy intake) observed in the preload studies were based on food diaries [19, 37, 46, 48]. These data should be replicated in more rigorous conditions to confirm the observed effects. Thirdly, the within-subject (i.e. test re-test reliability) and between-subject (i.e. inter-individual variability) consistency in energy compensation following preload intake is often not acknowledged in studies, and this should be addressed in light of recent studies demonstrating marked inter-individual variability [27, 63-65] and modest test re-test reliability [66] in energy compensation following acute exercise. The composition of the preloads and tests meals should also be further examined to determine whether physical activity enhances the sensitivity to energy density or to specific macronutrients. Finally, the sample size in most of the studies was small, which may have resulted in non-significant results and overlooked relatively small but important effects. The studies were also not designed to test effects of sex, body composition (lean vs. overweight), and exercise mode; therefore this does not allow us to determine specific criteria or characteristics eliciting the reported effects (or lack thereof).

4.4 Review limitations

This review included a limited number of studies assessing a broad range of appetite-related measures between active and inactive individuals using various definitions. This may have led to some of the inconsistent patterns or lack of effects observed. Physical activity encompasses not only exercise training but also activities of daily living, and as most definitions were based on a minimal level of moderate-intensity structured exercise, the studies included in this review lean towards a comparison between exercise-trained and untrained individuals. Therefore, these results should be interpreted with caution while more studies assessing all facets of habitual physical activity become available. Clearly, there is a lot more work to be done to elucidate the effects of physical activity and exercise on the appetite control system.

5 Conclusions

It can be concluded from this review that habitually active individuals appear to have increased sensitivity to the energy density of foods compared to inactive individuals despite the lack of observable group differences in subjective appetite ratings. This review also supports the formulation that the relationship between physical activity level and energy intake may be non-linear, as reflected by the J-shaped curve obtained from analysis of standardized energy intake scores. The mechanisms underlying this effect are not known but could include differences in body composition (fat mass and fat-free mass), postprandial hunger or satiety peptides, or sensitivity to tonic peptides such as insulin or leptin. This characteristic of active individuals could mitigate the risk of overconsumption in an energy-dense food environment. Further studies are required to confirm these findings.

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Conflicts of Interest

Kristine Beaulieu, Mark Hopkins, John Blundell and Graham Finlayson declare that they have no conflicts of interest relevant to the content of this review.

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