MINI REVIEW

Diet- but not exercise-induced iso-energetic deficit induces compensatory appetitive responses

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Abstract
Although physical exercise and dietary restriction can be both used to induce energy deficits, they have been suggested to favor different compensatory appetitive responses. While dietary restriction might favor increased subsequent energy intake and appetite sensations, such compensatory responses have not been observed after a similar deficit by exercise. The present work provides a first overview of the actual evidences discussing the effects of iso-energetic deficits induced by exercise versus dietary restriction on subsequent energy intake, appetite sensations, and on the potentially involved hedonic and physiological mechanisms.

Introduction
The high worldwide prevalence of obesity and related comorbidities reinforces the need to better understand the mechanisms governing energy balance and associated perturbations. In a simplistic sense, energy balance is determined by the interaction between the energy ingested and expended. While energy intake corresponds to the consumption of food and drinks, total energy expenditure (TEE) is determined by the resting metabolic rate (RMR; ≈50–70% of TEE), diet-induced thermogenesis (DIT; ≈5–10% TEE), and physical activity energy expenditure (PAEE; ≈25% TEE). Interventions seeking to create an energy deficit and induce weight loss, therefore, require a reduction in energy intake and/or an increase in PAEE. Interestingly, while energy intake and energy expenditure were historically considered as two independent influences on energy balance, accumulating evidence has described a more complex interaction. In particular, physical exercise has been shown to indirectly contribute to the control of appetite and energy intake in healthy adults, youth, and people with obesity [1, 2]. Acute exercise, depending on its characteristics, can modulate appetite sensations, appetite-related hormones, energy intake, food preferences, and reward (for review, see refs. [3–6]). Blundell et al. first summarized the effects of exercise on appetite and energy intake in the early 1990s [7] but have recently updated their working model which more clearly describes physiological and hedonic influences [8].

Briefly, as perfectly described in the authors’ recent review [8], this model illustrates how energy expenditure is related to energy intake and particularly details the contribution from physical activity energy expenditure, which influences both tonic and episodic processes. It particularly illustrates how body composition influences appetite control through both a drive and an inhibitory system. It is proposed...
that fat-free mass, via resting metabolic rate, reflects the
energy needs of our human body and then composes a drive
to eat. In opposition, fat mass plays a tonic inhibitory role on
eating. Both processes will dialogue with complex neuronal
processes and once integrated will determine behaviors.
These tonic pathways will be periodically interrupted by
episodic signals from the gastrointestinal system that will
also be integrated with neuronal processes. This model then
greatly presents how physical activity and acute exercise will
impact the control of appetite and energy intake (for details
and review, see Blundell et al. [8]).

Interestingly, while single bouts of exercise do not
commonly increase appetite or energy intake, even when
energy expenditure is high [9–11], dietary energy restriction
favors strong compensatory mechanisms with increased
appetite and food ingestion [12, 13]. Therefore, it appears
that appetitive responses to short-term energy deficits are
differentially mediated by the nature of the stimulus (exercise
versus diet-induced).

With the aim of stimulating further research and dis-
cussion in this important research area, this manuscript
provides a narrative overview of the available studies that
have directly compared the short-term appetitive responses
(appetite sensations, energy intake, and related hormones)
to iso-energetic deficits induced by either acute exercise or
dietary energy restriction, including the potential hedonic
and physiological mechanisms.

**Exercise versus diet-induced energy deficit**

In 1997, Hubert and collaborators compared the appetitive
response to similar energy deficits induced by either food
restriction or physical exercise [13]. In their study, the
authors asked 12 healthy normal-weight women (aged 23 ±
2.7 years) to randomly perform four experimental conditions
during which energy balance was manipulated by consum-
ing either a low (≈251 KJ) or high (≈2092 KJ) energy
breakfast and by performing or not an acute bout of cycling
(energy expenditure =1326 KJ) (details are displayed in
Table 1). According to their results, ad libitum energy intake
was increased when the energy deficit was induced through
the low energy breakfast, with or without exercise (increased
by 20%). These results were the first to suggest that energy
restriction, but not exercise, led to a compensatory rise in
food consumption [13]. This was moreover accompanied by
a higher pre-lunch sensation of hunger as well as the higher
end of day hunger, preoccupation with food, frequency and
strength of food cravings, when the energy deficit was
induced through the low-energy breakfast consumption,
independently of exercise [13].

In a sample of healthy males, King et al. compared
appetitive responses to relatively large (≈4602 KJ) short-term
energy deficits induced by exercise versus food restriction
[14]. In their exercise condition, the participants ran for
90 min on a treadmill at a moderate-to-vigorous intensity
(≈70% VO2max). Conversely, in the food-deficit condition, a
proportional amount of energy was withheld from standar-
dized breakfast and lunch meals. Supporting the previous
findings of Hubert et al. [13], the researchers saw rapid and
robust compensatory appetite responses to food restriction
that were not observed in the exercise condition. Free-choice
energy intake mirrored this response when measured from a
buffet meal at the end of the 9-h trials. Notably, King et al.
[14] also showed that circulating concentrations of appetite-
related peptides responded in a manner consistent with the
appetite changes. Specifically, circulating concentrations of
acylated ghrelin remained high after the consumption of
small meals but were unaffected after exercise. Conversely,
food restriction led to smaller postprandial PYY3-36 con-
centrations; again, not matched by exercise. These findings
are consistent with the suggestion that appetite is sensitive to
the passage of food through the gastrointestinal tract, but less
so to acute energy balance perturbations [15]. The same
research group subsequently performed a similar study (using
the same methodology as detailed in Table 1) among healthy
normal-weight women, inducing a mean energy deficit of
3500 KJ, and observed similar results for appetite, energy
intake, and appetite-related hormones (acylated ghrelin and
PYY3-36 concentrations) [16] (Table 1).

To scrutinize the effects of more modest energy deficits
(≈1465 KJ), Deighton et al. studied appetite, energy intake,
and appetite-related hormone (acylated ghrelin and PYY3-36)
responses to an acute bout of cycling (30 min, 55% VO2max)
and matched energy restriction. Once more, exercise did not
elicit any compensatory appetitive responses, whereas subtle
energy restriction produced higher appetite ratings in com-
parison to control and exercise. Conversely, the smaller level
of energy restriction did not influence ad libitum energy
intake or appetite-related hormones. These data suggest that
appetite perceptions are sensitive to relatively minor reduc-
tions in food intake, whereas a larger energy deficit is required
to alter ad libitum food intake and appetite-related hormones.

**Appetitive response to a 24-h full energy
deficit**

More recently, the appetitive responses to a full 24-h fasting
condition (as food restriction) have been compared with a
similar deficit induced by exercise [17]. On their exercise-
induced deficit condition, 12 healthy lean males (21.5 ± 0.5
years) cycled for about 290 min at 70% VO2max (they
exercised on four different occasions during the day: twice
in the morning and twice in the afternoon) to reach the
deficit induced during the 24-h fast (11,209 ± 1326 KJ). Ad
Table 1 Description of the methods and main results of the included studies.

| Authors     | Population                          | Protocol                                                                 |EI and appetite-related measures                                                                 | Main results                                                                 |
|-------------|-------------------------------------|--------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Hubert et al., [13] | 12 healthy lean women               | Two-by-two repeated measures design                                       | Ad libitum EI: lunch buffet meal                                                                 | Ad libitum EI: EI NELB and ELB > NEHB and EHB (p < 0.05)                     |
|             | 11 completed regular exercisers     | One factor being exercise (or no exercise) and the other being a high-energy breakfast (or low-energy breakfast). BF: LEB (EX and NE): 267 ± 29 KJ BF: NEHB = 2092 ± 175 KJ BF: EHB = 2071 ± 150 KJ Exercise: modality: cycling Workload: 111 ± 13 W Duration: 41 ± 1 min EE: 1326 ± 184 KJ Ad libitum EI: Appetite sensations: EARS (Electronic appetite rating system) computerized system every hour during experimental sessions: hunger, desire to eat, fullness, thirst, contentment, lethargy, and tension End of day questionnaires for mood, motivation to eat, and craving Exercise EE: indirect calorimetry | Morning hunger: LEB > other conditions without exercise effect (p > 0.05) Pre-lunch hunger: LEB EX < 0.05) and LEB NE (p < 0.0005) > NEHB and EHB Afternoon hunger: No BF or exercise effect End of day: hunger, preoccupation with food, frequency of strong craving or eat particular food and strength of cravings were higher in LEB (without exercise effect) (p < 0.05) Ad libitum EI: EI Def-EX > CON (p < 0.001) and Def-EX (p = 0.058). Absolute fat intake Def-EX > CON and Def-EX (p < 0.001) Absolute protein and CHO intake Def-EX > CON (p < 0.05) % CHO Def-EX < CON and Def-EX (p < 0.044) Appetite sensations: Fasting sensations: no difference Hunger and PPC Def-EX > Def-EX and CON (p < 0.001) Satisfaction and fullness Def-EX < Def-EX and CON (p < 0.001) Blood samples: Fasting AG: no difference AUC AG Def-EX > CON (p = 0.002) and Def-EX (p < 0.001) Fasting PYY3-36: no difference AUC PYY3-36 Def-EX < Def-EX (p = 0.004) and Def-EX (p < 0.001) Ad libitum EI: EI did not differ between conditions Energy balance Def-EX (1628 ± 915 KJ) and Def-EI (1373 ± 1047 KJ) < CON (p < 0.001) Appetite sensations: Fasting sensations did not differ between conditions Appetite Score Def-EX > Def-EX (p = 0.023) Blood samples: Fasting AG did not differ between conditions ∆AUC AG from 0–1 h Def-EX < CON and Def-EX (after removal of outliers) (p = 0.05) and across the entire trial (p = 0.075) Fasting PYY3-36 did not differ between conditions ∆AUC PYY3-36 Def-EX > CON and Def-EX from 0–1 h (p > 0.01) and Def-EX > Def-EX from 1–4 h and overall day (p < 0.05) ∆AUC PYY3-36 negatively correlated with appetite changes from 0–1 h (r = −0.514; p = 0.001), 4–8 h (r = −0.340; p = 0.043) and the entire 8 h (r = −0.349; p = 0.037). |
| King et al., [14] JCEM | 12 healthy lean males Age: 23.4 ± 1.0 years | Randomized-counterbalanced 9-h trials: Control exercise-induced energy deficit Diet-induced energy deficit exercise: modality: treadmill Intensity: 69.8 ± 9% VO2max Mean heart rate: 173 ± 3 beats/min Duration: 90 min EE: 4715 ± 113 KJ Energy def by food restriction: 4820 ± 151 KJ Energy def by exercise: 4715 ± 113 KJ (ns) | Ad libitum EI: 30-min buffet meal (semi skimmed-milk, three varieties of cereal, cereal bars, white bread, brown bread, ham, cheddar cheese, tuna, mayonnaise, butter, margarine, cookies, chocolate rolls, apples, oranges, and banana) Appetite sensations: 100 mm VAS every 30 min: hunger, fullness, satisfaction, and PFC Blood samples: Baseline, 2, 3, 4, 7, 6, 7, 8, 9 h AG and PYY3-36 | Ad libitum EI: EI Def-EX > CON (p < 0.001) and Def-EX (p = 0.058). Absolute fat intake Def-EX > CON and Def-EX (p < 0.001) Absolute protein and CHO intake Def-EX > CON (p < 0.05) % CHO Def-EX < CON and Def-EX (p < 0.044) Appetite sensations: Fasting sensations: no difference Hunger and PPC Def-EX > Def-EX and CON (p < 0.001) Satisfaction and fullness Def-EX < Def-EX and CON (p < 0.001) Blood samples: Fasting AG: no difference AUC AG Def-EX > CON (p = 0.002) and Def-EX (p < 0.001) Fasting PYY3-36: no difference AUC PYY3-36 Def-EX < Def-EX (p = 0.004) and Def-EX (p < 0.001) Ad libitum EI: EI did not differ between conditions Energy balance Def-EX (1628 ± 915 KJ) and Def-EI (1373 ± 1047 KJ) < CON (p < 0.001) Appetite sensations: Fasting sensations did not differ between conditions Appetite Score Def-EX > Def-EX (p = 0.023) Blood samples: Fasting AG did not differ between conditions ∆AUC AG from 0–1 h Def-EX < CON and Def-EX (after removal of outliers) (p = 0.05) and across the entire trial (p = 0.075) Fasting PYY3-36 did not differ between conditions ∆AUC PYY3-36 Def-EX > CON and Def-EX from 0–1 h (p > 0.01) and Def-EX > Def-EX from 1–4 h and overall day (p < 0.05) ∆AUC PYY3-36 negatively correlated with appetite changes from 0–1 h (r = −0.514; p = 0.001), 4–8 h (r = −0.340; p = 0.043) and the entire 8 h (r = −0.349; p = 0.037). |
| Deighton et al., 2014 | 12 healthy men Age: 24 ± 5 years | Randomized-counterbalanced 8-h trials: Control exercise-induced energy deficit Diet-induced energy deficit Energy def by food restriction: 1478 ± 275 KJ and by exercise: 1469 ± 256 KJ (ns) Exercise: 30 min cycling at 186(38) W EX: oxygen consumption equivalent: 64.5 ± 3.2% VO2max EX net energy expenditure: 1469 ± 256 KJ | Ad libitum EI: Fusilli pasta buffet meal Appetite sensations: 100 mm VAS: baseline, 0.25, 0.5, and then every 30 min: hunger, fullness, satisfaction and PFC Overall appetite score calculated as the mean value of the four appetite perceptions after inverting the values for satisfaction and fullness Blood samples: Baseline, 1, 2.5, 4, 5, 6, 7, 8, 9 h AG and PYY3-36 | Ad libitum EI: EI did not differ between conditions Energy balance Def-EX (1628 ± 915 KJ) and Def-EI (1373 ± 1047 KJ) < CON (p < 0.001) Appetite sensations: Fasting sensations did not differ between conditions Appetite Score Def-EX > Def-EX (p = 0.023) Blood samples: Fasting AG did not differ between conditions ∆AUC AG from 0–1 h Def-EX < CON and Def-EX (after removal of outliers) (p = 0.05) and across the entire trial (p = 0.075) Fasting PYY3-36 did not differ between conditions ∆AUC PYY3-36 Def-EX > CON and Def-EX from 0–1 h (p > 0.01) and Def-EX > Def-EX from 1–4 h and overall day (p < 0.05) ∆AUC PYY3-36 negatively correlated with appetite changes from 0–1 h (r = −0.514; p = 0.001), 4–8 h (r = −0.340; p = 0.043) and the entire 8 h (r = −0.349; p = 0.037). |
| Authors                  | Population | Protocol                                      | EI and appetite-related measures                                                                                                        | Main results                                                                                   |
|-------------------------|------------|-----------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|
| Alajmi et al., [16]     | 12 healthy females | Randomized-counterbalanced 9-h trials: Control exercise-induced energy deficit Diet-induced energy deficit Energy deficit of 3500KJ Exercise: 90-min run at 8.6 ± 1.0 km/h. Oxygen consumption: 70.2 ± 1.5% VO\textsubscript{max} | Ad libitum EI: 30-min buffet meal (milk, three varieties of cereal, cereal bars, white bread, brown bread, ham, cheese, tuna, mayonnaise, butter, margarine, cookies, chocolate rolls, apples, oranges, and bananas) Appetite sensations: 100 mm VAS: baseline and every 30 min: hunger, fullness, satisfaction and PFC Overall appetite score calculated as the mean value of the four appetite perceptions after inverting the values for satisfaction and fullness Blood samples: Baseline; 2, 3, 4.75, 6, 7, 8, 9 h AG and PYY\textsubscript{3-36} | Ad libitum EI: EI Def-El (3966 ± 1409 KJ) > Def-EX (2774 ± 1682 KJ) and CON CON (2560 ± 1112 KJ) (p > 0.0005) Fat, protein and CHO intake Def-El > Def-Ex and CON (p < 0.004, data not detailed). Appetite sensations: Overall appetite score not different at baseline between conditions Overall 9-h AUC Appetite Def-El > Def-Ex and CON (p < 0.0005) Blood samples: Results available on n = 11 No condition difference for fasting AG 9-h AUC AG Def-El > CON and Def-EX (p > 0.0005) 9-h AUC AG Def-EX < CON and Def-El (p < 0.0005) No condition difference for fasting PYY\textsubscript{3-36} 9-h AUC PYY\textsubscript{3-36} Def-El > Def-EX and CON (p > 0.0005) 9-h AUC PYY\textsubscript{3-36} Def-EX > Def-El and CON (p > 0.0005) |
| Cameron et al., [18]    | 10 healthy males | Randomized-counterbalanced 3-day trials: CON-Def-El-Def-EX or CON-Def-EX-Def-El. Control exercise-induced energy deficit Diet-induced energy deficit Energy deficit = 25% of CON (2966 ± 359 KJ) Exercise: treadmill running Intensity: 50% VO\textsubscript{max} Duration: 64 ± 8 min | Ad libitum EI: 30-min buffet meal on day 4 of each condition composed of five snack food items and four fruit items Appetite sensations: 100-mm VAS: desire to eat, hunger, fullness, PFC, and palatability Blood samples: Fasting leptin and total ghrelin on day 1 and 4 Food Reward: Relative-reinforcing value of food assessed using computer task Olfaction: Nasal chemosensory performance assessed with sniff’ sticks | Ad libitum EI: EI Def-El > CON (p = 0.01) EI Def-El > Def-EX (p = 0.017) Appetite sensations: AUC palatability Def-El > CON (p = 0.03) AUC palatability Def-EX > CON (p = 0.009) DTE (p = 0.03), hunger (p = 0.02), PFC (p = 0.01) Def-El > CON Blood samples: No condition effect for leptin and total ghrelin. Food reward: No RRVF difference on day 1 Def-El snack earned point on day 4 > CON (p = 0.001) Def-Ex snack earned point on day 4 > Def-El and CON (p = 0.001) Olfaction: No olfaction difference on day 1 Odor threshold Def-El > CON (p = 0.01) No difference for odor discrimination on day 1 and 4. |
| Authors | Population | Protocol | EI and appetite-related measures | Main results |
|---------|------------|----------|---------------------------------|--------------|
| Thivel et al., [17] | 12 healthy lean males | 12 healthy lean males | Randomized control trial | Ad libitum EI: |
| Age: 21.5 ± 0.5 years | | CON: condition control with 24 h habitual intake and EE | Buffet meal (lunch day 2) | EI De-EI > CON (p = 0.03) |
| BW: 71.1 ± 6.7 kg | Def-EI: 24 h habitual EI and full fasting | Self-reported 12 h post session EI. | No difference for % energy ingested from macronutrients | No difference for EI Aftemoon snack |
| BMI: 22.5 ± 1.7 kg/m² | Def-EX: 24 h habitual EI with exercise (with EE covering the whole energy ingested) | Appetite sensations: | No difference for EI and absolute EI from macronutrients at dinner. | EI from fat on afternoon snack (p = 0.04) |
| BF: 11.6 ± 4.2% | Exercise: | 150 mm VAS: hunger, fullness, PFC, and DTE | No difference for EI and absolute EI from macronutrients at dinner. | No difference for EI and absolute EI from macronutrients at dinner. |
| FFM: 59.5 ± 4.2 kg | Cycling at 70% VO₂max. | Food reward: | Appetite sensations: | No difference for EI and absolute EI from macronutrients at dinner. |
| | Four bouts of exercise during the day | Pre and post meal leads food preference questionnaire | No difference for fasting sensations | Diet- but not exercise-induced iso-energetic deficit induces compensatory appetitive responses 1429 |
| | Total duration: 4h52 (±40 min) | | Appetite sensations: | No difference for fasting sensations |
| | Deficit: 11.209 ± 1326 KJ | | No difference for daily AUC hunger, fullness, PFC, and DTE | No difference for daily AUC hunger, fullness, PFC, and DTE |
| Thivel et al., [19] | 14 adolescents with obesity | 14 adolescents with obesity | Randomized-counterbalanced 12-h trials (CON -Def-EI - Def-EX or CON-Def-EX-Def-EI) | Ad libitum EI: |
| Seven girls and seven boys | Age: 14.2 ± 1.0 years | CON: normal EE and EI Def-EI: normal EE and 25% energy deficit on the lunch meal (based on CON lunch) | EI De-EI > CON (p = 0.03) | EI De-EI > CON (p = 0.03) |
| BW: 103.7 ± 13.5 kg | Def-EX: normal EI with exercise to reach the 25% energy deficit of the CON lunch meal | Ad libitum EI: | No difference for % energy ingested from macronutrients | No difference for % energy ingested from macronutrients |
| BMI: 36.6 ± 5.0 kg/m² | Exercise: | EI on a buffet meal at dinner | No difference for % protein intake | No difference for % protein intake |
| z-BMI: 2.4 ± 0.29 | Cycling at 65% VO₂max. | Appetite sensations: | % energy ingested from fat Def-EX and Def-EI > CON (p < 0.05) | % energy ingested from fat Def-EX and Def-EI > CON (p < 0.05) |
| FM%: 41.2 ± 5.2% | Duration: 21–50 min | 100 mm VAS: hunger, fullness, PFC, and DTE | Significant correlation: | Significant correlation: |
| FFM: 58.4 ± 8.1 kg | 25% energy deficit: 1062 ± 385 KJ | | The higher the absolute energy deficit and the higher the ad libitum EI on Def-EX (r = 0.0569, p < 0.05) | The higher the absolute energy deficit and the lower the ad libitum EI on Def-EX (r = −0.643, p < 0.05) |
| | | | Appetite sensations: | Appetite sensations: |
| | | | No difference for fasting sensations | No difference for fasting sensations |
| | | | No difference for daily AUC hunger, fullness, PFC, and DTE | No difference for daily AUC hunger, fullness, PFC, and DTE |
| | | | Hunger Def-EX and Def-EI before test meal > CON (p = 0.07) | Hunger Def-EX and Def-EI before test meal > CON (p = 0.07) |
| | | | Fullness CON > Def-EI and Def-EX (p < 0.05) | Fullness CON > Def-EI and Def-EX (p < 0.05) |
Ad libitum energy intake was assessed at lunch on the following day and was significantly increased after the 24-h fast but not after the exercise condition. Although the total self-reported intake for the rest of the day was not significantly different between conditions, the consumption of fat was found to be significantly higher in response to food restriction. As detailed in Table 1, the overall area under the curve (AUC) for hunger, desire to eat (DTE), and prospective food consumption (PFC) were significantly higher when the deficit was induced by dietary restriction while the AUC for fullness was lower. Using the Leeds Food Preference Questionnaire (LFPQ), the authors also found a higher pre-test meal fat bias in food choice after the fasting condition and a higher pre-test meal fat bias for implicit wanting on both energy depletion conditions [17], reinforcing the results observed by Cameron et al. concerning the potential role played by the hedonic system in response to energy deficit, particularly when induced by energy restriction [18].

Which responses to prolonged energy deficits (several days)?

While the previous studies characterized the effect of short-term energy deficits (several hours), Cameron and colleagues recently assessed the appetitive response to 3 days of energy depletion by diet or exercise in healthy young males (aged 23.7 ± 5.1 years) [18]. In their study, the dietary-induced energy deficit was based on 25% of the participants’ energy balance in the preceding 3-day control condition, which corresponded to a mean deficit of 2970 KJ per day. In the exercise condition, to reach this deficit, the participants had to run on a treadmill for ≈65 min per day at 50% VO_{2\text{max}}. Once more, their results demonstrated an increase in ad libitum food intake at the buffet test meal in response to the food restriction compared to both the exercise and control conditions, without any difference between the latter two. This was accompanied by higher sensations of hunger, palatability, and DTE during the diet-induced deficit condition compared with control. The authors however did not observe any difference between conditions for the plasma concentrations of total ghrelin, with also similar levels of leptin [18]. Interestingly, Cameron et al. also assessed other aspects of the control of appetite and energy intake and compared the food reward and olfactory responses to such deficits. Concerning olfaction, while they did not show any difference regarding the level of odor discrimination, they observed a significantly higher odor detection threshold during the dietary-induced deficit condition compared with the control condition [18]. These results suggest the implication of some sensory drivers in the compensatory rise in food intake and appetite sensations in response to dietary-induced energy deficit but not after an iso-energetic deficit induced by exercise.

Regarding their food reward results, the authors observed a higher relative-reinforcing value of food after the 3 days of dietary-induced deficit compared with the control condition. The reinforcing value was however also significantly higher in response to the exercise-induced deficit compared to both the control and diet-induced deficit conditions. While this might suggest a potential uncoupling between the response of the food-reward system and the effective energy consumption in response to exercise, further studies are needed to better understand the effects of exercise, depending on its characteristics (intensity, duration, modality, etc.), on the hedonic control of food intake.

What do we know in patients with obesity?

While the previously mentioned studies enrolled healthy normal-weight young participants, we found one study that used the same methodology among adolescents with obesity [19]. After a control condition during which the investigators assessed the overall daily energy intake and expenditure of 14 boys and girls with obesity (14.2 ± 1.0 years, z-BMI: 2.4 ± 0.29); a mean energy deficit of 1062 ± 384 KJ (which individually corresponded to 25% of the lunch meal of the control condition) was induced once by the dietary restriction on the lunch meal and once by a cycling exercise set at 65% VO_{2\text{max}}. Contrary to what was observed in healthy adults, both strategies of energy deficit (exercise and dietary restriction) prompted increased energy intake at the subsequent ad libitum buffet meal compared to the control session with however a significantly higher absolute consumption of fat in response to the dietary-induced deficit compared to the exercise and control conditions. This higher intake on both deficit conditions was accompanied by a higher sensation of hunger immediately before the test meal. Interestingly, however, the authors observed significant correlations between the individual absolute degree of deficit induced (in KJ) and the total ad libitum intake; correlations that were in the opposite direction depending on the nature of the induced deficit. Indeed, the higher was the individual absolute energy deficit during the diet-induced deficit, the higher was the adolescent’s energy compensation at the following meal (ad libitum intake); and inversely when the deficit was induced by exercise (the higher the deficit, the lower the intake compensation) [19].

Altogether, these results clearly point to the beneficial effects of exercise over dietary restriction when it comes to the creation of an acute energy deficit, mainly through its anti-compensatory effects on energy intake. Although diet has been found to be more efficient for rapid and large weight loss, exercise becomes highly important for sustainable weight maintenance and its effects on the control of appetite,
minimizing the compensatory responses produced solely by dietary restriction. Figure 1 summarizes these results.

Limitations and perspectives

These results must be interpreted with consideration of some limitations. The exercise intensities implemented in the previously detailed studies is one consideration. While moderate-intensity aerobic exercise ranging from 50% to 70% VO\textsubscript{2}max was used, exercise at higher intensities has been shown to not only avoid compensatory responses but also favor anorexigenic responses [5, 20]. Thus, higher-intensity exercise may enhance the overall effect of exercise on energy balance. Similarly, the available studies induced short-term energy deficits, ranging from a few hours (9 h) to 3 days, and additional studies are needed to characterize more long-term responses (which has more relevance to energy balance and weight management). In this regard, future studies also need to examine responses in a wider range of participant groups, including women, and individuals with overweight and obesity.

Another limitation of the studies reviewed is the inclusion of healthy adults only (except for one study that enrolled adolescents with obesity [19]). Energy deficits are mainly used among patients with overweight and obesity or elite athletes, who might show different responses to what was observed here. The results observed so far come from populations with quite similar characteristics and these responses to deficits should be also questioned among individuals with different metabolic profiles and physical capacities. Longer energy deficits should be induced in patients with weight issues to potentially take clinical advantages of these differentiated appetitive responses to energy depletion induced by exercise versus dietary restriction [21]. Importantly, while exercise training alone might lead to less than expected weight loss, further studies should be conducted to explore to what extent the addition of exercise to dietary-induced energy deficits can optimize the reduction of energy balance through both energy depletion and the avoidance of nutritional compensatory responses.

Conclusion

To conclude, physical exercise seems to provide a double effect on energy balance by inducing an increase in energy expenditure while avoiding the activation of some physiological and hedonic mechanisms that have been shown to favor compensatory appetitive responses after similar energy deficits induced by dietary restriction alone. Further studies are required to characterize responses over a longer time frame, among patients concerned with weight loss or weight maintenance.

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Author contributions While DT and JK led the writing of this paper, all the co-authors significantly and equally contributed to this manuscript.

Compliance with ethical standards

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

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