Energy compensation and adiposity in humans

Highlights

- Energy compensation in humans was analyzed from daily and basal energy expenditure
- Reduced BEE results in energy compensation of 28%
- Degree of energy compensation varied between people of different body composition

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In brief

Energy compensation is the concept that not all the energy spent when activity levels increase translates to additional energy spent that day, but it is poorly characterized. Careau, Halsey et al. find that in humans, energy compensation averages 28%, i.e., only 72% of the extra calories we spend on additional activity translates into extra calories burned that day.
Understanding the impacts of activity on energy balance is crucial. Increasing levels of activity may bring diminishing returns in energy expenditure because of compensatory responses in non-activity energy expenditures.1–3 This suggestion has profound implications for both the evolution of metabolism and human health. It implies that a long-term increase in activity does not directly translate into an increase in total energy expenditure (TEE) because other components of TEE may decrease in response—energy compensation.4

We used the largest dataset compiled on adult TEE and basal energy expenditure (BEE) (n = 1,754) of people living normal lives to find that energy compensation by a typical human averages 28% due to reduced BEE; this suggests that only 72% of the extra calories we burn from additional activity translates into extra calories burned that day. Moreover, the degree of energy compensation varied considerably between people of different body compositions. This association between compensation and adiposity could be due to among-individual differences in compensation: people who compensate more may be more likely to accumulate body fat. Alternatively, the process might occur within individuals: as we get fatter, our body might compensate more strongly for the calories burned during activity, making losing fat progressively more difficult. Determining the causality of the relationship between energy compensation and adiposity will be key to improving public health strategies regarding obesity.
three energy expenditure models (Figure 1) for individuals with
unremarkable lifestyles generating natural variation in TEE over
time, and without food restriction. Determining which of these
energy expenditure models apply to humans under typical,
free-living conditions, and quantifying its effects, will progress
our understanding of the evolution and control of metabolism,
and may provide key physiological information for management
strategies for weight control.

We extracted paired measurements of BEE (respirometry) and
TEE (doubly labeled water [DLW]) for 1,754 adults from the In-
ternational Atomic Energy Agency DLW database v.3.1.2. All
estimates of TEE were made using a standard calculation across
cases of BMI.29


to account for the thermic effect of food. A multiple regression
model regressing TEE as a function of BEE. Note that, in prin-
ciple, one mechanism that does not represent energy compensa-
tion and yet could, in principle, create the observed patterns is
that people who are more active (and have a higher AEE) have
a greater proportion of muscle mass,22 which increases FFM without substantially increasing BEE,23 resulting in more active
people having a low mass-corrected BEE. However, this possi-
bility can be disregarded given that our analysis indicates energy
compensation in people having accounted for variation in their
FFM by its inclusion as a covariate (as both a main effect and
as an interaction term with BEE and age).

Thus, humans living typical modern lives—not undertaking
exceptional levels of activity or experiencing chronic food short-
ages—exhibit a fairly strong compensation between the energy
they expend on activity and that expended on basal metabolic
processes; over the long term, more than a quarter of the extra
calories burned by people during activity do not translate into ex-
tra calories expended that day. Presumably, such compensation
would have been adaptive for our ancestors because it mini-
imized food energy demands and hence reduced the time
needed for foraging, the advantages of which may include
reducing exposure to predation. However, it is potentially mal-
adaptive for modern-living humans exercising to try to burn off
excess food consumption, given the chain of association linking
high-density foods to greater energy intake,26 obesity,25 and its
related diseases.26

Public health initiatives often include prescribed increases in
activity in part to increase TEE and thereby control weight gain
or promote fat loss.27 Such a prescription, however, often as-
sumes that costs of activity are additively related to basal
costs,28 which our analyses suggest is untrue. It will therefore
be important when prescribing personalized exercise plans for
controlling or reducing weight, and managing patient ex-
pectations, to know if the degree of long-term energy compen-
sation changes with age and other demographic variables such
as sex. It is well known that older individuals are more at risk of
obesity than are younger individuals. To test if older people,
and potentially one sex more than the other, exhibit greater en-
ergy compensation, we took advantage of the information on
sex, age, and body composition (measured by isotope dilution)
included in our dataset, which consisted of 692 men and 1,062
women aged 18 to 96 years, with FFM ranging from 24.3 to
97.1 (median: 47.64 kg) and body mass index (BMI) ranging
from 12.5 to 61.7 (median: 25.2 kg/m²). To test if the slope


Exercise, where measured or inferred energy compensation has been documented on several occasions, 16–18 or instead whether it is the default model of energy expenditure in humans living typical lives, where activity and energy intake are naturally adjusted over time.

Therefore, variation in BEE should add up to variation in TEE, with predictions about the slope (\(b\)) of the relationship between TEE and BEE and between AEE and BEE; example individual data points have been included to illustrate the predicted relationship in addition to some unexplained variation. The additive model assumes that AEE and BEE are independent and thus uncorrelated.

Figure 1. Energy budgets and competing hypotheses

(A) Representation of the total energy expenditure (TEE) of endothermic animals as the sum of the energy invested in activity, reproduction, growth, thermoregulation, digestion (thermic effect of food; TEF), and basal energy expenditure (BEE; the minimum amount of energy required for the functioning [e.g., breathing] and the maintenance [e.g., tissue turnover] of vital systems). Proportions are somewhat arbitrary but recognize that in vertebrates BEE is typically a minor element of TEE. Any source of energy expenditure above BEE (except TEF) is apportioned as activity energy expenditure (AEE), which includes the costs of thermoregulation, reproduction, and growth when present.

(B) Representation of the TEE of most non-reproductive adult humans, in which there are no energy costs of growth or reproduction, and the cost of thermoregulation is assumed to be negligible. In this simplified energy budget, the proportions recognize that in adult humans ~60% of energy is spent on BEE and BEE is categorized into proportions based loosely on Müller et al.\(^9\), and most of the AEE component is indeed represented by physical activity, including locomotion, posture, and “fidgeting.”\(^10\)

(C) Illustration of the various models that have been proposed to describe how humans and other animals manage their energy budget,\(^1–8, 11–15\) and their associated predictions about the slope (\(b\)) of the relationship between TEE and BEE and between AEE and BEE. The left stack bar shows a simplified baseline version of TEE as the sum of BEE and AEE. Comparing the left versus right stacks shows the mean effect of an increase in AEE on BEE and TEE. The regression lines in the panels to the right show the predicted relationships between TEE and BEE and between AEE and BEE; example individual data points have been included to illustrate the predicted relationship in addition to some unexplained variation. The additive model assumes that AEE and BEE are independent and thus uncorrelated. Therefore, variation in BEE should add up to variation in TEE, with \(b = 1\) due to part-whole correlation. In other words, the additive model predicts that additional calories burned by undertaking extra activity results in an equivalent increase in TEE. By contrast, the performance model assumes that a greater “metabolic machinery” is needed to support higher AEE due to increased assimilation of energy, and thus \(b > 1\) for the relationship between TEE and BEE. That is, the performance model predicts that the resultant total calories burned due to activity will be higher than just the calories expended during the activity because of additional energy spent on subsequent physical recovery and maintenance of a more expensive metabolic machinery to support this behavior. Alternatively, both humans and animals may respond to greater energy being expended on activity over the long term by reducing the energy expended on other processes, a phenomenon captured by the compensation model. The compensation model assumes that energy budgets are somewhat constrained, which forces trade-offs between energy invested into AEE and BEE, thus predicting a negative relationship between AEE and BEE and therefore \(b < 1\) for the relationship between TEE and BEE. It is currently unknown whether energy compensation in humans occurs only under extreme conditions, or at least only during periods of prescribed exercise, where measured or inferred energy compensation has been documented on several occasions,\(^16–18\) or instead whether it is the default model of energy expenditure in humans living typical lives, where activity and energy intake are naturally adjusted over time.
of the TEE-BEE and AEE-BEE relationships changes according to sex, age, and body composition, we added the interaction terms between BEE and each of these factors to the multiple regression model (in addition to other two-way interactions between sex, age, and body composition that control for sex differences and age-related changes in body composition; Table S1B). Overall, energy compensation was not different in men versus women and did not vary with age (i.e., BEE × sex and BEE × age interactions; Table S1B). Hence, energy compensation seems to be a general phenomenon that applies equally to men and women, young and old. Note that FFM and FM were derived from isotope dilution, assuming a constant ratio for FFM hydration (73.2%), but according to published literature, FFM hydration may not be constant with adult age. However, any variation is probably small, and indeed unpublished analyses on data for over 1,000 adults with ages ranging from 20 to over 70 indicate that the ratio of total body weight to FFM hardly changes (S. Heymsfield, personal communication).

Interestingly, the BEE × FM interaction was significant with a negative estimate (Table S1B), indicating that the slope of the TEE-BEE and AEE-BEE relationships decreases as FM increases. In other words, controlling for sex, age, and FFM, compensation increases with FM. People that are at the 10th percentile of the BMI distribution compensate 27.7% of activity calories, whereas people at the 90th percentile compensate 49.2% of activity calories (Figure 3). It appears then that individuals with greater fat levels are predisposed to increased adiposity either because they are stronger energy compensators or because they become stronger compensators as they get fatter. If the former, then two people can be equally active, yet one puts on fat mass while the other stays lean. If the latter, then such a positive feedback loop may imply that using exercise as a strategy to escape high adiposity becomes less and less effective. Resolving the causality of this relationship between fat mass and energy compensation might be key to better deploying exercise in the fight against the growing obesity pandemic.

The energy compensation detected in the aforementioned analysis can be the result of processes occurring at two distinct levels of covariation: between individuals and within individuals. Energy compensation at the between-individual level would indicate that people with higher-than-average AEE tend to have a lower-than-average BEE—a covariance due to genetic and/or permanent environmental factors that would cause the between-individual TEE-BEE slope (between) to be <1. By contrast, energy compensation at the within-individual level would indicate that, for a given individual, reversible increases in AEE are accompanied by decreases in BEE, and vice versa, which would cause the...
within-individual TEE-BEE slope ($b_{\text{within}}$) to be <1. To partition the relationship between TEE and BEE at the between- and within-individual levels, we re-analyzed data representing paired measurements of 36 men and 32 women aged between 70 and 90 years sampled 7 years apart within the context of a longitudinal study. This dataset provides the opportunity to estimate the extent of energy compensation occurring both between and within individuals. Using a bivariate mixed model, we partitioned the slope of the TEE-BEE relationship (while accounting for sex, age, FFM, FM, and sex- and age-related differences in FFM and FM) at the between- and within-individual levels (Table S2A). This analysis clearly reveals that energy compensation occurs only at the within-individual level (Figure 4A). While the between-individual slope was $b_{\text{between}} \pm \text{SE} = 1.86 \pm 1.05$, the within-individual slope was $b_{\text{within}} \pm \text{SE} = 0.15 \pm 0.17$.

To further illustrate the compensation occurring at the within-individual level, we ran a second bivariate mixed model with AEE and BEE as the dependent variables. In this model, the within-individual covariance was significantly negative (Table S2B). The within-individual correlation ($\pm \text{SE}$) between AEE and BEE was $r = -0.58 \pm 0.08$ (Figure 4B). Hence, during extended periods when the studied cohort expended more energy on activity, they compensated by reducing energy expended on basal processes (but individuals with higher-than-average AEE do not necessarily have a lower-than-average BEE). The within-individual slope in these people indicates particularly strong energy compensation between AEE and BEE (Figure 4B). That is, in this sample of people, the calories they burn during bouts of activity are almost entirely compensated for by reducing energy expended on other processes such that variation in activity had little impact on TEE.

Measurements of BEE and TEE provide invaluable insights into energy management; the next step is to elucidate the proximate and ultimate mechanisms driving these observed patterns of energy compensation. One possible factor is energy intake. For example, if obese people tend to increase their food consumption in response to increased AEE less than other demographics, they have fewer resources for other functions, and this could encourage the body to energy compensate, reducing BEE. Another possible factor involved in energy compensation, which is relatively hard to measure and not available in our dataset, is fidgeting, or non-exercise activity thermogenesis (NEAT). In principle, NEAT can decrease in response to increases in AEE, although few studies have directly measured it, and reviews of the literature to determine whether NEAT in humans decreases to compensate or partially compensate for increases in AEE conclude that there is no evidence overall that NEAT systematically changes, e.g., Fedewa et al.35 If energy compensation has an underlying genetic basis, in the future it might be possible to screen individuals to ascertain whether exercise would be a valuable fat loss intervention because they are “weak compensators” or a fruitless fat loss intervention because they are strong compensators (while recognizing other benefits to exercise including protecting against weight regain36,37). Moreover, we need to understand whether there are costs to reducing BEE. If there are, such as, for example, a compromised immune system or slowed recovery from injury38,39, then for some individuals the point at which exercise reaches a detrimental level will be considerably lower than for others.

The ever growing and diversifying range of fat loss plans and fads available to the public reflects the reality, well known to researchers, that prescribed exercise programs for weight reduction rarely result in substantive or long-term changes in body mass. The few national guidelines that have been published converge on the recommendation of a 500–600 kcal/day deficit through exercising and dieting to instigate fat loss. These guidelines are general for the population and do not factor in the variation in energy compensation exhibited by people with different levels of fat mass, as demonstrated in the current study. Public health strategies for fat loss should be revised to recognize energy compensation as our understanding progresses about which individuals compensate and by how much. In this vein, more research is needed on the potentially substantial diversity of energy compensation between sub-populations. In the future, personalized exercise plans targeting fat loss might be developed partly based on an individual’s genetic propensity for energy compensation.

**STAR METHODS**

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SUPPLEMENTAL INFORMATION
Supplemental information can be found online at https://doi.org/10.1016/j.cub.2021.08.016.

ACKNOWLEDGMENTS
The DLW database, which can be found at https://doubly-labelled-water-database.iaea.org/home, is hosted by the IAEA and generously supported by Taiyo Nippon Sanso and SERCON. We are grateful to the IAEA and these companies for their support and especially to Takashi Oono for his tremendous efforts at fundraising on our behalf. The authors also gratefully acknowledge funding from the Chinese Academy of Sciences (CAS 153E11YKYSB20190045) to J.R.S. and the US National Science Foundation (BCS-1824466) awarded to H.P. The funders played no role in the content of this manuscript. We are grateful for the data submission of David Ludwig and Cara Ebbeling, and for the analysis by Steve Heymsfield of his own data indicating no change in FFM hydration with age in adults.

AUTHOR CONTRIBUTIONS
V.C. and L.G.H. suggested the idea of testing for energy compensation in the available dataset, undertook analyses, and led on the manuscript writing. J.R.S. contributed to manuscript writing. All authors apart from L.G.H. and V.C. provided DLW data to the database that was used in the analyses, read the manuscript, and commented if they wished. J.R.S., C.L., A.H.L., A.J.M.-A., H.P., J.R., D.A.S., H.S., K.R.W., W.W.W., and Y.Y. assembled and managed the database.

DECLARATION OF INTERESTS
The authors have no conflicts of interest to declare.

Please cite this article in press as: Careau et al., Energy compensation and adiposity in humans, Current Biology (2021), https://doi.org/10.1016/j.cub.2021.08.016.


STAR METHODS

KEY RESOURCES TABLE

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RESOURCE AVAILABILITY

Lead Contact
Further information and requests should be directed to and will be fulfilled by the lead contact, Lewis Halsey (l.halsey@roehampton.ac.uk).

Materials availability
All the data used in this study have already been published and are available in the public domain; the current manuscript presents a secondary analysis.

Data and code availability
- The data reported in this study cannot be deposited in a public repository because they are held by the management group of the IAEA DLW database. To request access, follow the instructions available at https://doubly-labelled-water-database.iaea.org/dataAnalysisInstructions.
- The code used for all statistical analyses and the production of data figures has been deposited at Figshare and is publicly available as of the date of publication. The DOI is listed in the key resources table.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

EXPERIMENTAL MODEL AND SUBJECT DETAILS

The International Atomic Energy Agency DLW database (v 3.1.2) is a world-wide collection of total energy expenditure (TEE) measurements. All TEE measurements were made using the stable isotope method of doubly-labeled water analysis, and are based on recalculation of the original data using the latest DLW equations. Although the entire database includes over 6,500 DLW measurements between 1981 and 2017, for the purpose of this study the database was restricted to TEE measures accompanied by measurements of BEE via indirect calorimetry. The database was also restricted to adult subjects (> 18 y old) and we excluded subjects undergoing intense physical activity including professional sports training, and those who were pregnant, lactating, or diseased. Fat free (lean) mass (FFM) was derived from isotope dilution and fat mass (FM) was calculated by subtracting FFM from total body weight. Note that using total body weight and height-normalized indices of FFM and FM yielded similar results to using FFM and FM. Activity energy expenditure (AEE) was calculated as 0.9*TEE – BEE, assuming that the thermic effect of food accounts for 10% of the total energy budget. The average (±SD) physical activity level (PAL = TEE/BEE) of the analyzed database was 1.74 ± 0.27 (range: 0.76 – 3.30) and 90% of observations were between 1.35 and 2.18 PAL (5th and 95th quartiles).

METHOD DETAILS

To test the mutually exclusive predictions arising from the energy management models (Figure 1C), we used multiple linear regressions with TEE as the dependent variable and sex, age, FFM, FM, and BEE as independent variables, on some or all of a dataset on 1754 adults. FFM and FM were square-root transformed to reduce the influence of some potentially influential observations at the extreme upper end of the distribution (e.g., 6 observations with > 80 kg fat mass).
QUANTIFICATION AND STATISTICAL ANALYSIS

All analyses were conducted in R using bespoke code. Details of the results of those analyses are found in the Results and discussion section, and the Tables S1 and S2, with visualization provided in Figures 2, 3, and 4. Confidence intervals are provided for all regression slope estimates. Results were interpreted as statistically significant when associated with p < 0.05. The first multiple regression model was run on the entire dataset to get an overall estimate of the TEE-BEE and AEE-BEE relationships after accounting for sex, age, FFM, and FM (Table S1A). We were then interested to test if the TEE-BEE and AEE-BEE relationships varied by sex, age, and body composition. To do so, we introduced two-way interactions between BEE and sex, age, FFM, and FM (Table S1B). To control for possible sex- and age-related changes in the effects of FFM and FM, we also included two-way interactions between body composition variables (FFM and FM) and sex and age (Table S1B). All independent variables (including sex) were centered prior to analysis, such that significance of main effects are estimated at the average values despite significant interactions in the model.40 We used the visreg function41 to plot the partial residuals and illustrate the TEE-BEE and AEE-BEE slopes (Figure 2) and the interaction between BEE and FM (Figure 3). For these models, the residuals had homogeneity of variance and were normally distributed, and there were suitably low variance inflation factors for all covariates indicating limited linear covariance between the predictor variables.42

Bivariate mixed model analysis
The Health, Aging, and Body Composition (Health ABC) study has produced repeated paired measurements of TEE and BEE in elderly men and women.43 The first set of measurements were taken between 1998 and 2000 on subjects in their 8th decade of life. A second set of measurements was carried out in 2006, approximately 7 years after the first.30 We used bivariate mixed models in ASReml-R44 to partition the relationship between TEE and BEE at the between- versus within-individual levels in men and women separately. Both TEE and BEE were fitted as response variables in a model that included (anonymous) individual identity as a random effect. This enabled modeling of the between-individual variances ($V_{between}$) in TEE and BEE as well as the between-individual covariance ($COV_{between}$) between the two. The residuals were also modeled as an unstructured variance-covariance matrix, effectively capturing the within-individual variances ($V_{within}$) in TEE and BEE as well as the within-individual covariance ($COV_{within}$). The between-individual slope ($b_{between}$) between TEE and BEE was calculated as $COV_{between}$ divided by $V_{between}$ in BEE, while the within-individual slope ($b_{within}$) was calculated as $COV_{within}$ divided by $V_{within}$ in BEE. Note that the bivariate mixed model included age, FFM, and FM as fixed effects fitted to both TEE and BEE, and as such the slope estimates are conditioned on these variables. Moreover, interactions between age and FFM and age and FM were included to control for potential age-related changes in body composition. To better illustrate the relationship between AEE and BEE, we ran a second bivariate mixed model that was identical to the above except that TEE was replaced by AEE. For each model, assessment of the residuals indicated homogeneity of variance and normality, and suitably low variance inflation factors for all covariates.