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Investigating predictors of eating: is resting metabolic rate really the strongest proxy of energy intake?

Jessica McNeil,[1] Gilles Lamothe,[2] Jameason D Cameron,[4] Marie-Ève Riou,[3] Sébastien Cadieux,[3] Jacynthe Lafrenière,[5] Gary Goldfield,[4] Stephanie Willbond,[3] Denis Prud'homme,[3,6] and Éric Doucet[3]

[1]Cancer Epidemiology and Prevention Research, Alberta Health Services, Calgary, Alberta, Canada; [2]Department of Mathematics and Statistics and [3]Behavioral and Metabolic Research Unit, School of Human Kinetics, Faculty of Health Sciences, University of Ottawa, Ottawa, Ontario, Canada; [4]Healthy Active Living and Obesity Research Group, Children's Hospital of Eastern Ontario Research Institute, Ottawa, Ontario, Canada; [5]Institute of Nutrition and Functional Food, Laval University, Quebec, Quebec, Canada; and [6]Institut de recherche de l'Hôpital Montfort, Ottawa, Ontario, Canada

ABSTRACT

Background: Evidence suggests that fat-free mass and resting metabolic rate (RMR), but not fat mass, are strong predictors of energy intake (EI). However, body composition and RMR do not explain the entire variance in EI, suggesting that other factors may contribute to this variance.

Objective: We aimed to investigate the associations between body mass index (in kg/m^2), fat mass, fat-free mass, and RMR with acute (1 meal) and daily (24-h) EI and between fasting appetite ratings and certain eating behavior traits with daily EI. We also evaluated whether RMR is a predictor of the error variance in acute and daily EI.

Design: Data collected during the control condition of 7 studies conducted in Ottawa, Ontario, Canada, were included in these analyses (n = 191 and 55 for acute and daily EI, respectively). These data include RMR (indirect calorimetry), body composition (dual-energy X-ray absorptiometry), fasting appetite ratings (visual analog scales), eating behavior traits (Three-Factor Eating Questionnaire), and EI (food buffet or menu).

Results: Fat-free mass was the best predictor of acute EI (R^2 = 0.46; $P < 0.0001$). The combination of fasting prospective food consumption ratings and RMR was the best predictor of daily EI (R^2 = 0.44; $P < 0.0001$). RMR was a statistically significant positive predictor of the error variance for acute (R^2 = 0.20; $P < 0.0001$) and daily (R^2 = 0.23; $P < 0.0001$) EI. RMR did, however, remain a statistically significant predictor of acute (R^2 = 0.32; $P < 0.0001$) and daily (R^2 = 0.30; $P < 0.0001$) EI after controlling for this error variance.

Conclusions: Our findings suggest that combined measurements of appetite ratings and RMR could be used to estimate EI in weight-stable individuals. However, greater error variance in acute and daily EI with increasing RMR values was observed. Future studies are needed to identify whether greater fluctuations in daily EI over time occur with increasing RMR values. This trial was registered at clinicaltrials.gov as NCT02653378. *Am J Clin Nutr* 2017;106:1206–12.

Keywords: appetite, eating behavior traits, energy intake, error variance, resting metabolic rate

INTRODUCTION

Edholm et al. (1) were among the first to suggest that energy intake (EI) is driven by the body's energy demands. However, these investigators did not observe a statistically significant relation between total energy expenditure (EE) and EI within a single day (1). More recently, Blundell et al. (2) demonstrated that fat-free mass, but not BMI (in kg/m^2) or fat mass, was positively associated with objectively assessed acute (1 meal) and daily (24-h) EI before and after a 12-wk exercise intervention in overweight and obese participants. Considering that resting metabolic rate (RMR) is the largest component of total EE and is strongly influenced by fat-free mass (including lean body mass) (3), it is plausible that RMR could show similar associations with EI as does fat-free mass. RMR is closely linked to fat-free mass, which accounts for ~60–70% of the variance in RMR, whereas fat mass, age, and sex account for a combined 7–9% of the variance in RMR (4, 5). Accordingly, Blundell et al. (2) demonstrated a strong correlation between fat-free mass and RMR (r = 0.51–0.85; $P < 0.0001$). A subsequent study by Caudwell et al. (4) reported that RMR was a statistically significant predictor of acute (1 meal) and daily (24-h) EI and fasting and postmeal hunger ratings before and after a 12-wk exercise intervention in the same cohort of participants. Furthermore, a secondary analysis of 23 randomized controlled studies (n = 529 participants) reported that hunger ratings explained an additional 6% of the variance in EI when added to regression models along with age, sex, body weight, and estimated RMR (6). Finally, Hopkins et al. (7) reported that the effects of fat-free mass and fat mass on EI were fully mediated by RMR. It has thus been suggested that RMR can be used as a strong predictor of EI (2, 4, 7, 8).

We conducted secondary data analyses to evaluate the contributions of fat mass, fat-free mass, BMI, and RMR to the

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Supplemental Table 1 is available from the "Online Supporting Material" link in the online posting of the article and from the same link in the online table of contents at http://ajcn.nutrition.org.

Address correspondence to ÉD (e-mail: edoucet@uottawa.ca).

Abbreviations used: EE, energy expenditure; EI, energy intake; RMR, resting metabolic rate.

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variance in acute (1 meal) EI. In addition, we added 4 fasting appetite ratings (desire to eat, hunger, fullness, and prospective food consumption) and certain eating behavior traits (dietary restraint, dietary disinhibition, and susceptibility to hunger) to the regression models with daily (24-h) EI as an outcome. These outcomes represent 3 constructs of appetite control: energy need (body composition and resting EE), a proxy of peripheral signaling (fasting appetite ratings), and behavioral control and attitudes toward food. As an attempt to explain additional variance in EI, we conducted an exploratory analysis to evaluate whether RMR was a predictor of the degree of error variance and dispersion in acute and daily EI within a statistical regression model. We first hypothesized that fat-free mass and RMR, but not fat mass, would be associated with acute and daily EI. Second, we hypothesized that appetite ratings and cognitive eating behavior traits would explain additional variances in daily EI. Finally, we hypothesized that RMR would be associated with the degree of error variance and dispersion in acute and daily EI.

METHODS

Participants

Seven studies using the same methods were conducted at the Behavioral and Metabolic Research Unit of the University of Ottawa in Ottawa, Canada, between 2004 and 2014 to assess acute EI (n = 191). Three of these studies also included data on daily EI (n = 55). All participants recruited for these studies were free of cardiovascular or metabolic diseases, were nonsmokers, and were weight stable ($\pm$2 kg) for $\geq$6 mo before recruitment. Further details on the design, recruitment process, and methods for each of these studies are provided elsewhere (9–15). The University of Ottawa ethics committee approved all secondary data analyses presented herein and all procedures involving human participants. Written informed consent was obtained from all participants before their involvement in each study.

Design and procedure

Data collected at baseline for longitudinal studies and during the control session for randomized crossover trials were included in these analyses. Premenopausal women were always tested between days 1 and 8 of the menstrual cycle. All outcomes were assessed at the same time of day during each study. For each session, participants arrived at the laboratory after a 12-h overnight fast and were instructed not to consume alcohol or engage in structured physical activity (e.g., playing sports or training) for $\geq$24 h before the start of each session.

Anthropometric measurements

Participants in all studies were weighed to the nearest 0.1 kg with a BWB-800AS digital scale (Tanita Corporation). Their standing height without shoes was measured to the nearest centimeter using a wall stadiometer (Tanita HR-100 height rod; Tanita Corporation of America Inc.). Body composition was assessed with dual-energy X-ray absorptiometry (Lunar Prodigy; General Electric).

RMR

RMR was measured in all studies with indirect calorimetry for 30 min (5-min acclimatization period and 25 min of measurements) while the participants were fasting. CO_2 and O_2 were measured using the ventilated hood technique with either a Deltatrac II metabolic cart (Sensor Medics Corporation) or a Vmax Encore 29N metabolic cart (Sensor Medics Corporation). The correlation coefficients (r) between the 2 indirect calorimeters calculated with 12 participants in our laboratory were 0.99, 0.99 and 0.97 for RMR, VO_2, and VCO_2 values, respectively.

Fasting appetite ratings and eating behavior traits

The participants' fasting appetite sensations were recorded with visual analog scales before the consumption of a standard breakfast. Participants were asked to answer 4 specific questions that quantify subjective appetite sensations using 100-mm visual analog scales presented on a computer screen (16). These questions measured the participants' desire to eat ("How strong is your desire to eat?"), hunger ("How hungry do you feel?"), fullness ("How full do you feel?"), and prospective food consumption ("How much food do you think you could eat?"). The Three-Factor Eating Questionnaire (17) was used to evaluate eating behavior traits. More specifically, this 51-item questionnaire measured the degree of cognitive dietary restraint (score range: 1–21), dietary disinhibition (score range: 1–16), and susceptibility to hunger (score range: 1–14). Higher scores indicate a greater presence of an eating behavior trait. Only 27 participants had all measures of fasting appetite ratings, eating behavior traits, and acute EI, but not daily EI. Hence, fasting appetite ratings and eating behavior trait variables were only added as predictors to the regression models with daily EI as an outcome.

Acute and daily EI

Acute EI was measured with either a test meal selected from a validated food menu (18) or a buffet (19) in all 7 studies. This test meal was administered 3 h after the consumption of a standard breakfast in all studies. Briefly, the food menu contained a total of 62 meal, snack, and beverage items from which the participants were able to choose what they wanted to consume at that moment. The items were then prepared and served to the participants in ad libitum quantities. For the buffet, all food items were prepared in advance and served to the participants in ad libitum quantities. In both cases, participants had 30 min to consume "as much or as little as you want" from these test meals. All food items were weighed to the nearest gram before and after the participants consumed the test meal.

After this test meal in 3 studies, participants were asked to select the items from the menu that they wanted to consume later that day. The selected food items were then prepared, weighed, and packed into separate containers for the participants to take home. Daily EI was calculated based on participants' intake during the standard breakfast, their intake during the ad libitum test meal inside the laboratory, and their intake from containers that were taken home for the remainder of that day. The participants brought back the containers the following day, at which time all remaining food items were weighed to the nearest gram. Finally, acute and daily EI were calculated with the Food Processor

SQL program (version 10.8; ESHA Research) using the 2007 Canadian Nutrient Data File.

Statistical analyses

Statistical analyses were performed with SPSS (version 17.0; SPSS Inc.). Partial correlations controlling for age and sex were computed between fat mass, fat-free mass, BMI, and RMR with acute and daily EI. Partial correlations controlling for age and sex were also computed between fasting appetite ratings and eating behavior traits with daily EI. The variables that were significantly correlated with measures of EI ($P < 0.05$) were then entered into a forward stepwise linear regression model to determine the contribution of each of these variables to explaining the variance in acute and daily EI (variables that met the entry criteria of $P \leq 0.05$).

To determine the strength of the associations between RMR and the degree of error variance in EI, we computed an estimate of the error variance and dispersion from the median in acute and daily EI fit into a linear regression model with RMR as a predictor. First, a modification of the Brown-Forsythe test was adapted to assess the homogeneity of variance in acute and daily EI in response to RMR values for a linear model (20) by computing the squared value of EI residuals from the regression model with RMR as a predictor. Second, we aimed to describe the degree of dispersion in acute and daily EI as a continuous function of RMR by fitting these values into a normal dispersion model and computing the difference in residual values from the median value (21). These variables were then entered into a linear regression model as dependent variables, along with RMR as the predictor. We computed a final linear regression analysis with acute or daily EI as the outcome and RMR as the predictor, combined with a weighted least-squares calculation [i.e., 1/(estimated EI SD)^2], which takes into consideration the increasing degree of error variance in EI according to increasing RMR values. Effects were considered statistically significant at $P < 0.05$ and data are presented as means ± SDs.

RESULTS

Table 1 presents the characteristics of the participants included in the acute ($n = 7$ studies) and daily ($n = 3$ studies) EI analyses. Partial correlation results between the study predictors can be found in **Supplemental Table 1**. The r value for the strength of the association between acute and daily EI was 0.79 ($P < 0.0001$) in the 55 participants with data for acute and daily EI, suggesting that both outcome measurements are closely related.

Table 2 presents the partial correlations between acute and daily EI with BMI, fat mass, fat-free mass, and RMR. The partial correlations between daily EI with all fasting appetite ratings and eating behavior traits are also presented in Table 2. Acute EI was positively correlated with BMI, fat-free mass, and RMR. Daily EI was positively correlated with RMR, fasting prospective food consumption ratings, and susceptibility to hunger scores. **Table 3** presents results from the forward stepwise linear regression analyses. BMI, fat-free mass, and RMR were added as predictors to the stepwise linear regression model with acute EI as an outcome. Only fat-free mass remained as a statistically significant predictor of acute EI. RMR, fasting prospective food consumption ratings, and susceptibility to hunger were added as predictors to the stepwise linear regression model with daily EI as an outcome. The combination of fasting prospective food consumption ratings and RMR was the best predictor of daily EI.

TABLE 1
Participant characteristics for acute ($n = 7$ studies) and daily ($n = 3$ studies) energy intake analyses[1]

Variable	Value
Acute energy intake analysis ($n = 191$)	
Male	25 (13)
Female	166 (87)
Age, y	37 ± 14
BMI, kg/m^2	25 ± 5
Fat mass, kg	22 ± 11
Fat-free mass, kg	44 ± 10
Resting metabolic rate, kcal/d	1381 ± 269
Acute energy intake,[2] kcal/d	700 ± 434
Daily energy intake analysis ($n = 55$)	
Male	8 (15)
Female	47 (85)
Age, y	25 ± 8
BMI, kg/m^2	28 ± 7
Fat mass, kg	30 ± 16
Fat-free mass, kg	48 ± 10
Resting metabolic rate, kcal/d	1517 ± 280
Fasting desire to eat appetite ratings, mm	53 ± 19
Fasting hunger appetite ratings, mm	53 ± 21
Fasting fullness appetite ratings, mm	14 ± 15
Fasting prospective food consumption ratings, mm	51 ± 19
Dietary restraint score of 1–21	8 ± 3
Dietary disinhibition score of 1–16	7 ± 3
Susceptibility to hunger score of 1–14	7 ± 3
Daily energy intake,[3] kcal/d	2827 ± 1147

[1] Values are n (%) or means ± SDs.
[2] Acute energy intake was measured over 1 meal (lunch).
[3] Daily energy intake was measured over a 24-h period.

TABLE 2
Partial correlations between anthropometric measurements, resting metabolic rate, fasting appetite measurements, and eating behavior traits with acute or daily energy intake[1]

Outcome	r	P value
Acute energy intake ($n = 191$)		
BMI	0.18	0.02
Fat mass	0.12	0.10
Fat-free mass	0.21	0.004
Resting metabolic rate	0.22	0.003
Daily energy intake ($n = 55$)		
BMI	0.16	0.24
Fat mass	0.14	0.30
Fat-free mass	0.27	0.06
Resting metabolic rate	0.35	0.01
Fasting desire to eat appetite ratings	0.26	0.06
Fasting hunger appetite ratings	0.20	0.16
Fasting fullness appetite ratings	−0.06	0.67
Fasting prospective food consumption ratings	0.31	0.03
Dietary restraint	0.13	0.36
Dietary disinhibition	0.09	0.52
Susceptibility to hunger	0.34	0.01

[1] Age and sex were added as covariates in these correlations.

TABLE 3
The amount of variance (R^2) and the standardized regression coefficients (β) for the significant predictors of acute and daily energy intake[1]

Outcome variable	*n*	Model	Significant predictor(s)	R^2	β	*P* value	95% CIs for β
Acute energy intake	191	1	Fat-free mass	0.46	30.6	<0.0001	25.8, 35.4
Daily energy intake	55	1	Fasting prospective food consumption appetite ratings	0.32	22.9	<0.0001	13.6, 32.2
		2	Fasting prospective food consumption appetite ratings	0.44	17.5	<0.0001	8.4, 26.5
			Plus resting metabolic rate		1.6	0.001	0.7, 2.5

[1] Forward stepwise linear regression model statistical analysis.

RMR was a statistically significant predictor of the error variance (i.e., squared values of EI residuals) for acute and daily EI (**Table 4**). Similarly, RMR was a statistically significant predictor of the degree of dispersion in EI residuals from the median for both acute and daily EI (Table 4). When we visually inspected the association between RMR and EI, increases in EI residuals, or the degree of error variance, with RMR values could be observed (**Figure 1**). However, when we controlled for this degree of error variance by adding a weighted least-squares calculation of the predicted SD for each RMR value into the regression model, RMR remained a statistically significant predictor of acute and daily EI (**Table 5**).

DISCUSSION

The primary aim of our study was to evaluate the contributions of BMI, body composition, and RMR to explaining the variance in acute (1 meal) and daily (24-h) EI and the contributions of fasting appetite ratings and eating behavior traits to daily EI. To our knowledge, this is the first study to investigate some of the unexplained variance in EI by examining the strength of the association between RMR and the statistical degree of error variance in EI. Our results corroborate our first hypothesis and previously published findings (2, 4, 7, 22, 23), showing that fat-free mass and RMR are consistent and strong predictors of EI. Blundell et al. (2) demonstrated that fat-free mass, but not BMI or fat mass, was positively associated with objectively assessed daily EI before and after an exercise intervention. Blundell et al. (8) also proposed that RMR is the strongest predictor of EI because it helps ensure that a sufficient amount of kilocalories are consumed to maintain basic metabolic processes and a stable lean body mass. In addition, Dulloo et al. (24) re-evaluated data from the Minnesota semistarvation study and reported that chronic hyperphagia continued beyond the restoration of baseline fat mass levels, lasting until baseline levels of fat-free mass were regained (25). Cameron et al. (23) also demonstrated statistically significant positive associations between fat-free mass and skeletal muscle mass with daily EI in 304 adolescents. Studies have provided support for the contribution of RMR or daily EE to EI, independently of fat-free mass. More specifically, Piaggi et al. (26) reported that the association between fat-free mass and daily EI was reduced by 80% and became nonstatistically significant after accounting for 24-h EE. In addition, Hopkins et al. (7) recently confirmed that the effects of fat-free mass and fat mass on EI were fully mediated by RMR.

In our study, fasting prospective food consumption ratings explained 32% of the variance in daily EI, with RMR accounting for an additional 12% of the variance when added to the regression model. These results add to previous studies that showed significant correlations between appetite ratings and EI (6, 27–30). However, results are conflicting when the strongest predictor of EI is investigated among different measures of appetite sensation. More specifically, Flint et al. (29) reported statistically significant associations between all pre- and postmeal appetite ratings with acute EI, whereas Barkeling et al. (30) noted that only desire to eat and prospective food consumption ratings were significantly associated with subsequent EI. Drapeau et al. (27) noted that fullness ratings were most strongly associated with daily EI, and Sadoul et al. (6) reported that hunger was the single appetite rating that best integrated all other appetite measurements following a principal component

TABLE 4
The amount of variance (R^2) and the standardized regression coefficients (β) for resting metabolic rate as a predictor of the error variance and dispersion in acute and daily energy intake residuals[1]

Outcome variable	*n*	R^2	β for resting metabolic rate	*P* value	95% CIs for β
Error variance for acute energy intake[2]	191	0.20	349.9	<0.0001	249.7, 450.0
Dispersion in acute energy intake residuals from the median[3]	191	0.16	0.3	<0.0001	0.2, 0.4
Error variance for daily energy intake[2]	55	0.23	2965.2	<0.0001	1450.9, 4479.4
Dispersion in daily energy intake residuals from the median[3]	55	0.19	1.1	0.001	0.5, 1.8

[1] Linear regression model statistical analysis.
[2] The error variance in acute and daily energy intake is defined as the squared values of energy intake residuals when resting metabolic rate is added as a predictor to the linear regression model.
[3] The dispersion in acute and daily energy intake residuals from the median value when the resting metabolic rate is added as a predictor to the linear regression model.

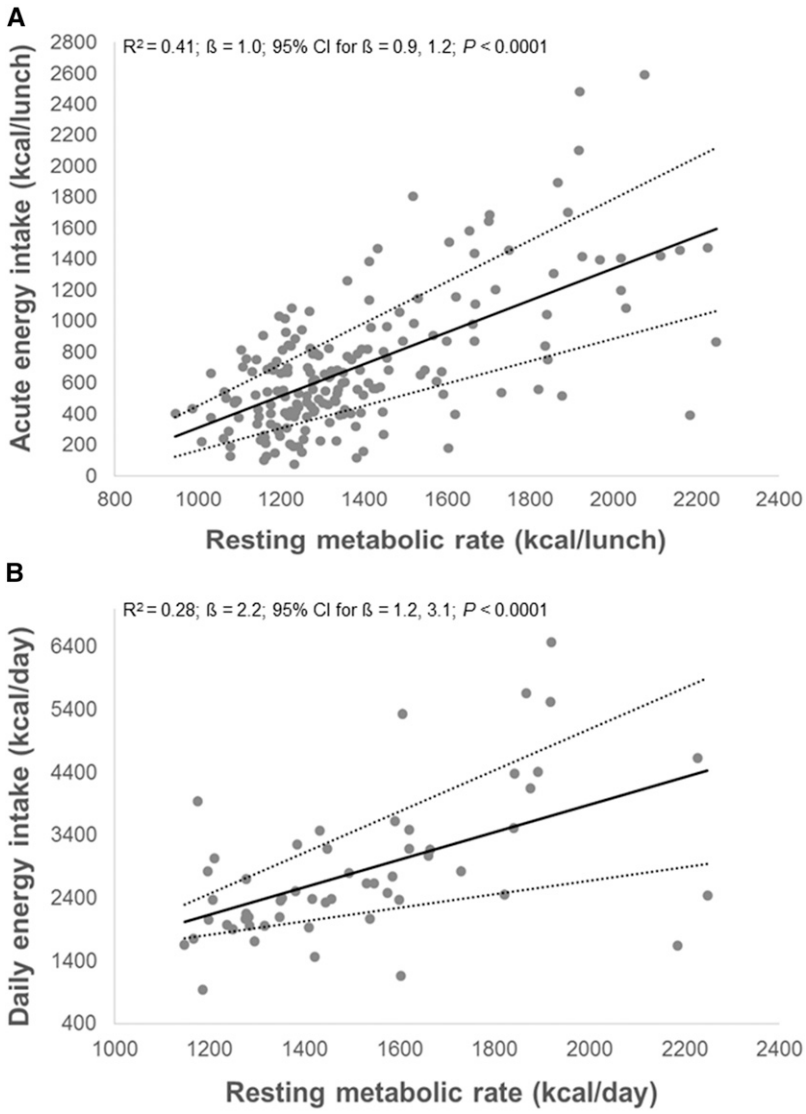

FIGURE 1 The strength of the association between acute (A) and daily (B) energy intake and resting metabolic rate. The degree of error variance is represented by a line of best fit placed at the equivalent of ±1 SD, as determined by the linear regression model equation. A linear regression model with acute (1 meal) or daily (24-h) energy intake as the outcome and resting metabolic rate as the predictor was computed. This linear regression model for acute and daily energy intake included 191 and 55 participants, respectively.

analysis. This discrepancy in findings may in part be related to the frequency and timing of appetite and EI measurements (e.g., fasting and postmeal appetite ratings, acute and daily EI) and to the statistical analyses conducted. Despite these differences, Drapeau et al. (27) reported that postmeal appetite ratings were associated with daily EI assessed 2 wk later, suggesting that measurements of appetite sensations on one occasion are related to EI measured at a later time and may be seen as a stable predictor of daily EI. Furthermore, linear regression models conducted by Sadoul et al. (6) with data from 23 randomized controlled studies suggested that the combination of age, sex, body weight, estimated RMR, and hunger ratings explained 25% of the variance in EI and that increases in hunger ratings and RMR predicted increases in EI. These results corroborate our findings of combined RMR and appetite ratings (more specifically, fasting prospective food consumption ratings) as the best predictor of daily EI. However, ∼45–55% of the variance in EI remained unexplained. Delayed compensatory responses to environmental exposures that took place over the previous days (26, 31, 32) may have altered EI in a way that cannot entirely be captured by more stable measures of eating behavior traits and body composition or RMR. For instance, spontaneous physical activity participation measured in a metabolic chamber was positively associated with 3-d ad libitum EI after adjusting for 24-h energy balance in 107 healthy men and women (26). Variations in day-to-day exposures to food and its rewarding properties (e.g., food reinforcement) may also impact EI (33–35) and undermine the effect of more stable predictors of EI that were included in our statistical regression model.

As an attempt to explain the additional variance in EI noted in this study, we plotted the association between RMR and EI (Figure 1) and evaluated the strength of the associations between RMR with the error variance and degree of dispersion in EI residuals. A visual inspection of the association between RMR

TABLE 5
The amount of variance (R^2) and the standardized regression coefficients (β) for resting metabolic rate as a predictor of acute and daily energy intake[1]

Outcome variable	n	Model	R^2	β for resting metabolic rate	P value	95% CIs for β
Acute energy intake	191	Unadjusted	0.41	1.0	<0.0001	0.9, 1.2
	191	Adjusted[2]	0.32	1.0	<0.0001	0.8, 1.2
Daily energy intake	55	Unadjusted	0.28	2.2	<0.0001	1.2, 3.1
	55	Adjusted[2]	0.30	2.3	<0.0001	1.3, 3.3

[1] Linear regression model statistical analysis.
[2] Adjustment for the error variance in acute or daily energy intake (weighted least-squares calculation of the predicted SD for each resting metabolic rate value).

and EI in Figure 1 indicates that EI residuals, or the degree of error variance, increase with RMR values. Linear regression analysis further supports this observation by identifying RMR as a positive statistically significant predictor of the error variance and the degree of dispersion in EI residuals. These results confirm that EI residuals increase with RMR values, which may shed some light on some of the unexplained variance in EI reported in this study and in other studies (2, 4–7). However, we did not observe changes in the regression model results with RMR as a predictor and acute or daily EI as an outcome when we controlled for this error variance by adding a weighted least-squares value to the model. Future studies are needed to corroborate these findings.

An important strength of this study is the inclusion of objectively measured body composition (dual-energy X-ray absorptiometry), RMR (indirect calorimetry), and EI (food menu and buffet) data collected under controlled laboratory conditions in ~200 and 50 participants for acute and daily EI, respectively. However, there are important limitations to this study that must be highlighted. First, we only assessed acute and daily EI at one given time point for each participant, which does not take into consideration day-to-day variations in this outcome or the impact of changes in the measured predictors on changes in EI. The partial correlations and linear regression analyses conducted do not allow us to infer causality. In addition, physical activity EE, characteristics of EI (e.g., macronutrient intake, the timing of food intake for daily EI data), and other environmental factors and personality traits (e.g., food reward, impulsivity) that may impact EI were not taken into consideration. Although we noted a high degree of correlation between the two brands of metabolic carts used within this study (r = 0.97–0.99), small differences in RMR values due to the use of different metabolic cart brands are possible. Finally, only 82 participants with acute EI data also had complete data for all fasting appetite ratings and eating behavior traits, which includes the 55 participants with daily EI results. Therefore, we were only able to add fasting appetite ratings and eating behavior traits as predictors to the regression model with daily EI as an outcome.

In summary, our results demonstrate that fat-free mass was the best predictor of acute EI, and the combination of fasting prospective food consumption ratings and RMR was the best predictor of daily EI. The combined measurement of subjective appetite ratings and RMR could therefore be used to estimate EI in weight-stable individuals. However, despite our inclusion of EI measurements in weight-stable individuals only, greater fluctuations around the mean in acute and daily EI with increasing RMR values were observed. Future studies are needed to investigate changes in daily EI over time in weight-stable individuals to identify whether greater day-to-day fluctuations in daily EI occur with increasing RMR values.

The authors' responsibilities were as follows—JM, JDC, M-ÈR, SC, JL, GG, SW, DP, and ÉD: were involved in the design, conceptualization, or data collection of one or more studies from which the data were used to conduct the secondary analyses for the manuscript presented herein; JM and ÉD: conceptualized the research questions and wrote the manuscript; JM and GL: conducted the data analyses; and all authors: critically revised the paper and read and approved the final manuscript. None of the authors reported a conflict of interest related to the study.

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