New fat free mass - fat mass model for use in physiological energy balance equations

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Abstract

Background: The Forbes equation relating fat-free mass (FFM) to fat mass (FM) has been used to predict longitudinal changes in FFM during weight change but has important limitations when paired with a one dimensional energy balance differential equation. Direct use of the Forbes model within a one dimensional energy balance differential equation requires calibration of a translate parameter for the specific population under study. Comparison of translates to a representative sample of the US population indicate that this parameter is a reflection of age, height, race and gender effects.

Results: We developed a class of fourth order polynomial equations relating FFM to FM that consider age, height, race and gender as covariates eliminating the need to calibrate a parameter to baseline subject data while providing meaningful individual estimates of FFM. Moreover, the intercepts of these polynomial equations are nonnegative and are consistent with observations of very low FM measured during a severe Somali famine. The models preserve the predictive power of the Forbes model for changes in body composition when compared to results from several longitudinal weight change studies.

Conclusions: The newly developed FFM-FM models provide new opportunities to compare individuals undergoing weight change to subjects in energy balance, analyze body composition for individual parameters, and predict body composition during weight change when pairing with energy balance differential equations.

Background

Modeling body weight regulation, and thus energy balance, involves quantifying appropriate system inputs, outputs, and balances. Mathematical models based on the energy balance equation provide descriptions of the impact of physiological changes and quantitative predictions of body mass during weight change. The development of energy balance models can have two approaches: 1. descriptions of the impact of physiological changes 2. quantitative predictions of body mass during weight change applying minimal individual baseline information.

The Hall model [1] is developed around the first approach where a system of five differential equations is carefully determined to reflect the specific flow of macronutrient energy during weight change. Although the model is physically descriptive, simulations require information of the macronutrient composition of individual baseline (zero energy balance) and target energy intake (change in energy intake by caloric restriction or overfeeding) along with numerous parameter estimates.

On the other hand, several models have been developed which require less baseline and parameter estimation [2-8]. The simplified models share several characteristics which reduce the number of state variables and equations. The first major simplification assumes glucose/glycogen mass is modeled by a time averaged constant, thereby eliminating the carbohydrate balance equation and its associated parameters and baseline inputs [3].

The second major simplification assumes that fat-free mass (FFM) can be written as a pre-defined function of fat mass (FM), eliminating the protein balance equation and the FFM state equation. The choice of function varies depending on the selected model, however, most functions are linear functions of FM [2,4-8]. Recently, the Forbes model was successfully incorporated into a two dimensional differential equation with satisfactory results.

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A reduced one dimensional equation was consequently derived (Equation 25 in [3]).

The cross-sectional Forbes model was developed using group mean data of 167 women (Equation 1, Table 1). A key feature of Forbes model is that the developed cross-sectional function is concave and this observation supports a long-held view that longitudinal changes in body mass at the lower biological range are associated with very large changes in FFM while fat loss at the upper range has only minimal FFM effects. Forbes and others subsequently collected various study data to test his model in a longitudinal context and the results appeared satisfactory in predicting FFM changes for any given change in FM [9-12]. These satisfactory results provide an attractive choice for a one dimensional energy balance differential equation model (Equation 2, Table 1), where $c_f$ and $c_l$ are the energy conversion constants for one kg of FFM and FM, respectively, and $E$ represents the rate of energy expended in kcal/d and is a function of FM and FFM [3]. Because the Forbes model is not valid for low FM we propose a new FFM - FM model which corresponds to experimental data on low FM while still preserving the predictive properties of the Forbes model.

A second consideration in applying the Forbes model within a one dimensional differential equation is that longitudinal body composition data does not actually "travel" down the Forbes curve. Body composition travels down a parallel translation of the original Forbes curve [12]. This does not affect estimates of ΔFFM as the slope of two parallel curves is identical. As past applications of the Forbes model were only concerned with estimating ΔFFM, identifying which translate of the Forbes model longitudinal body composition data traveled was not a concern. Because, in the one dimensional model, the rate of energy expenditures is dependent on the precise quantity of FFM at any given time during weight change, the specific translate of the Forbes curve must be derived. As a result, each individual simulation of the differential equation requires recalculation of a calibration parameter, D [3] (Equation 3, Table 1).

We formulate a new class of fourth order polynomial models using the newly released National Health and Nutrition Examination Survey (NHANES) data ($n = 11$, 186). We show that the intercepts of these polynomial equations reflects real-life body composition through comparison to data from the recent severe famine in Somalia [13]. We also show that longitudinal data travels the trend set by NHANES and that the new models predict the changes in FFM with equal accuracy to the Forbes model, thereby preserving the most descriptive conclusions derived from the Forbes model. The developed NHANES FFM-FM models provide new opportunities to compare individuals undergoing weight change to subjects in energy balance, analyze body composition for individual parameters, and predict body composition during weight change by pairing with energy balance differential equations.

### Methods

#### Experimental Design and Rationale

An existing large database reflective of the United States non-institutionalized population was used to determine cross-sectional relationships between FFM and FM considering age, height, race and gender as additional covariates. We used the cross-sectional models to answer three main questions related to pairing a FM model to an energy balance equation: Do the cross-sectional models preserve the accuracy of predictions provided by the Forbes model for changes in FFM during weight change? Do the cross-sectional models have a non-negative intercept that reflects observed data? How do the cross-sectional models vary with age, height, gender and race? To answer these questions we analyzed two existing cross-sectional body composition databases consisting of athletes and subjects with anorexia nervosa and five existing weight change databases which reflect changes in body composition due to caloric restriction, caloric restriction...

### Table 1: List of Formulas

| Number | Formula Reference and Citation | Equation |
|--------|--------------------------------|----------|
| 1      | Forbes Equation (Females) [10]  | $FFM = 10.4 \ln(FM) + 14.2$ |
| 2      | Differential Equation Energy Balance Model [3] | $c_f \frac{dFFM}{dt} + c_l \frac{dFM}{dt} = I - E(FM, FFM)$ |
| 3      | Generalized Forbes Equation [3] Females [10] | $FFM = 10.4 \ln(FM = D)$ |
| 4      | Forbes Equation (Males)         | $FFM = 13.8 \ln(FM) + 16.9$ |
combined with exercise, gastric bypass surgery, laparo-
scoptic adjustable gastric band surgery, and overfeeding.

Subjects and Measurements
All of the following studies were approved by respective
Institutional Review Boards and subjects provided writ-
ten informed consent prior to participation.

Cross Sectional Data
NHANES is a program designed to assess the health and
nutritional status of adults and children in the United
States. NHANES performs a continuous, nationally re-
presentative health survey of the civilian, non-institution-
alized United States population, collecting data on about
5000 persons each year from interviews, physical exami-
nations, and medical tests including bone densitometry.
In 1999 NHANES began performing dual-energy x-ray
absorptiometry whole body measurements on survey
subjects 8 years old and older in three mobile examina-
tion centers. Our study focus is on the adult age, gender,
height and ethnicity-specific DXA body composition ref-
ence database developed from the NHANES survey
data collected from 1999 to 2004. We expressed FFM and
FM as indices to height (i.e., FFM and fat/height² (kg/m²))
as reported by [14-16], referred to as FFMI and FMI,
respectively (Table 2).

Cross sectional body composition data for women with
anorexia nervosa between the ages of 18 and 45 years was
obtained from the study described in [17]. Subjects were
patients receiving treatment at the Eating Disorder
Research Unit at the New York State Psychiatric Institute
(NYSPI), Columbia University Medical Center (CUMC).
Several different types of body composition methods
were applied in [17] and we focus our report on the DXA
measurements (Table 2).

Cross sectional DXA body composition data was col-
lected at the New York Obesity Research Center on 124
healthy adults actively participating in exercise training
programs including body building, cycling, and long dis-
tance running. Subjects participated in these activities for
a minimum of five hours per week for six months. Sub-
jects were evaluated as part of a larger long-term body
composition study as described in [18] (Table 2).

Longitudinal Data
Phase I of the Comprehensive Assessment of Long-term
Effects of Reducing Intake of Energy (CALERIE) trial
tested the effects of calorie restriction on biomarkers of
age-related disease [19]. Our study uses the reference
database of age, height, weight, gender, and DXA body
composition measurements developed from the CAL-
ERIE data at baseline, 3 months and 6 months from the
Pennington Biomedical Research Center site. Twelve of
the CALERIE subjects were placed on a very low-calorie
diet (890 kcal/d), twelve were placed on a low-calorie diet
(25% below baseline energy requirements), and twelve
were prescribed a combination of caloric restriction
(12.5% below baseline energy requirements) and exercise
(physical activity increased to 12.5% above baseline total
energy expenditures). Thirty of the subjects were over-
weight and six of the subjects had a baseline BMI (kg/m²)
classifying them as obese. The average change in weight
for the sixth month period was -8.8 kg.

DXA body composition measurements for seventeen
female bariatric surgery patients were recorded for a two
year period after surgery in [20,21]. We developed a re-
ference database consisting of age, height, weight and body
composition developed from the study in [20,21]. Mea-
urements were obtained at baseline, 6 months, one year
and two years following the surgery. The two year average
change in weight for the surgery patients was -21.2 kg.

Twenty-four severely obese female gastric bypass
patients were followed for a period of one year in the
study described in [22]. The Siri 3-compartment model,
a measurement that has been validated for use in extremely
obese subjects, was used to estimate percentage body fat
at baseline and follow-up. We used age, height, weight
and body composition measurements at baseline and one
year from this study. The average amount of weight loss
for the gastric bypass subjects was -48.4 kg.

The subjects in the Minnesota Starvation Experiment
(16) consisted of thirty-six white males, ages 22 to 33
years old, which were carefully selected from 400 volun-
teers in the Civilian Public Service for the ability to with-
stand long-term caloric restriction [23]. The experiment
was set up into a period where baseline expenditures
were determined, followed by a 24 week period of calorie
reduction to approximately 1800 kcal/d. Underwater
weighing body composition measurements were obtained
at baseline, 12, and 24 weeks. Our reference
database uses height, weight, and body composition at all
three points in time. The Minnesota Starvation Experi-
ment consists of lean individuals who lost on average 16.8
kg over the 24 week period.

The longitudinal effects of overfeeding on body compo-
sition for 22 subjects were examined in [24,25]. DXA
measurements of body composition were obtained for 22
subjects, 12 of which had a BMI over 25 kg/m² and 10
who were of normal range BMI. Subjects were overfed
1000 kcal/d over baseline energy requirements for a
period of 8 weeks. Average body mass gain over the 8
week period was 3.7 kg.

Statistical and Mathematical Methods
Because any continuous function can be approximated by
a polynomial, we determined the best fit polynomial with
FM as the independent variable. We tested for statisti-
cally significant effects of powers of FM, A, H, race, gen-
der, and interactions between these variables. Races
considered were, white non-Hispanic, Hispanic, African
## Table 2: Baseline Characteristics of Study Cohorts

| Study                           | n   | Age (yrs) | Height (cm) | Total Body Mass (kg) | Fat Mass (kg) | FFM (kg) |
|---------------------------------|-----|-----------|-------------|----------------------|---------------|----------|
|                                 | M   | F         | M           | F                    | M             | F        |
| NHANES [14,15]                  | 5617| 5566      | 46.5 ± 20.0 | 47.5 ± 20.1          | 174.3 ± 7.9   | 160.6 ± 7.2 |
| Anorexia [17]                   | --  | 38        | --          | 26.0 ± 5.8           | --            | 162.7 ± 6.0 |
| Athletes [18]                   | 62  | 62        | 31.9 ± 10.5 | 35.7 ± 10.6          | 177 ± 7.3     | 164.8 ± 6.3 |
| Bariatric Surgery [20,21]       | --  | 17        | 41.7 ± 7.4  | --                   | 165.2 ± 6.3   |
| CALERIE [19]                    | 15  | 20        | 38.0 ± 7.0  | 37.6 ± 5.5           | 178.1 ± 7.0   | 165.7 ± 6.6 |
| Gastric Bypass Surgery [22]     | --  | 24        | 38.7 ± 9.4  | --                   | 163.0 ± 7.0   |
| Overfeeding [24,25]             | 10  | 12        | 34.9 ± 8.1  | 40.8 ± 6.7           | 177.0 ± 3.9   | 164.6 ± 6.0 |
| Minnesota [23]                  | 30  | --        | --          | --                   | 179.4 ± 5.4   | --       |

Group values are mean ± SD.
American, and Asian. JMP (Release 8; SAS Inc, Cary, NC) was used for data description, statistical analysis, and analysis of variance which included paired t-tests and linear regression analysis. Analysis of variance was used to test for the effects of fat and its corresponding powers, age, height, gender and race. Numerical solutions to algebraic equations were conducted using Maple computer algebra system software (Release 12; Waterloo, CANADA) combined with Microsoft Excel (Release 2007; Seattle, WA) by using the Maple add-in feature in Excel.

Results
Cross Sectional NHANES and Longitudinal Weight Change Data
The cross-sectional FFMI-FMI relationship generated by the NHANES data is shown in Figure 1 and Figure 2. The NHANES male data with overlays of the data from the overfeeding study conducted by Levine [24,25] and the Minnesota Starvation Experiment ([23]), are shown in Figure 1A. Longitudinal data for females from CALERIE [19], overlay the NHANES cross-sectional FFMI-FMI plot of Figure 1B. Figure 2B consists of overlays of the anorexia nervosa patients in [17] and the athletic subjects [18] and the Figure 2A depicts gastric bypass subjects baseline and longitudinal body composition data [22].

New FFM Models
Several iterations of the statistical model that considered all possible interactions between race, gender, age, height, and powers of FM were performed to obtain a parsimonious final model. The final model was derived by preserving higher values of the regression coefficient ($R^2 > 0.86$) while considering a reduced set of variables with statistically significant parameter estimates $P < 0.001$, yielding the class of fourth order polynomials in Table 3.

Separate indicator variables for the non-African American (NAA) and non-white ethnic group were not found to be statistically significant. Hence, the non-African American (NAA) group includes all ethnic groups other than African American subjects. As a result, in the final model reduced to two separate race indicator variables, NAA and African American (AA).

Variation in NHANES band
The class of models in Table 3 generates different FFM-FM curves reflecting the variation observed in the NHANES band. Thus, fixing age, height, gender and race will yield a specific FFM-FM relationship. Figure 3 depicts plots of two sample curves; Figure 3A for non-African American males, age 30, height 170 cm and Figure 3B for non-African American females, age 30, height 163 cm. The variance due to age, height and race captures almost the entire width of the band as seen in Figure 4A. The Forbes curve acts as an averaging curve, slicing through the NHANES band. Three translates of Forbes original curve are shown in Figure 4B for females by varying the value of $D$ in Equation 2. The translates of the Forbes curve indicate how the value of $D$ relates to position within the NHANES band.

Of particular interest is how longitudinal data may encompass the NHANES band in the case of large weight loss. The transition from baseline to longitudinal body composition of the gastric bypass surgery patients can be observed in Figure 2A which is an overlay of the data from [22] and the NHANES FFM-FMI relationship. The plot shows the trend of body composition for the most part follows the NHANES band. There are several conjectures of why some subjects move to the outer edges of the band which we pose in the Discussion section.

Zero Fat
The set of NHANES generated polynomials have a non-zero intercept and can be used to estimate the lowest theoretical BMI as a function of height. Figure 5 is a plot of level curves for males (Figure 5A) and females (Figure 5B) of BMI versus height while holding age fixed for zero fat.
Table 3: Class of polynomials [13].

Mean BMI data of surviving subjects of the 1992-93 famine in Somalia with mild edema are plotted alongside the NHANES generated subjects (see Supplemental Material). Mean BMI data of surviving subjects of the 1992-93 famine in Somalia with mild edema are plotted alongside the NHANES generated subjects.

Table 4 provides the mean error between measured and predicted FM at baseline, final time, and total change in FM. The Forbes model was used to successfully estimate longitudinal changes in FFM during weight change for numerous data sets [12]. We can generate analogous estimates using the NHANES polynomial equations. These estimates are obtained by using the selected model to estimate baseline and final body composition using measured baseline weight and magnitude of weight change, thereby being able to quantify changes by subtraction of end values from baseline values. In the case of the NHANES polynomial equations, we would require age, height, gender, and race information also.

For example, if an African American female age 34, height 165 cm with baseline total body mass of 75 kg loses 10 kg of total body mass we can estimate baseline \( FM \) by setting total mass equal to 75 and using the relationship that total body mass is equal to the sum of \( FM \) and \( FFM; \) \( 75 = FM + FFM \). We then substitute the NHANES expression for an African American female, age 34, height 165 cm for \( FFM \):

\[
75 = FM + 37.6 + 0.2FM + 0.007FM^2 + 3.5 \times 10^{-7} FM^4 - 0.00008FM^5
\]

where the bracketed portion is \( FFM \) given by the NHANES polynomial. This leaves only one unknown variable, which is \( FM \). We can solve for \( FM \) algebraically using Maple software which yields \( FM = 27.75 \) kg. A similar calculation with the left hand side of the equation set as 75 kg of total body mass will give us the \( FM \) as predicted by the NHANES polynomial equation at the changed weight; \( FM = 20.74 \) kg. \( FFM \) is obtained either from substituting the \( FM \) values into the polynomial or by subtracting \( FM \) from body mass. In this manner, we can determine the longitudinal change in \( FFM \). In the above example the change in \( FFM \) would be -2.99 kg.

Table 4 provides the mean error between measured and predicted \( FM \) at baseline, final time, and total change in
FFM over the period of the study for the NHANES and Forbes models. For a male version of a Forbes model, we generated a log linear fit to men of average stature in the NHANES dataset. Specifically, average height was found to be 174.3 ± 7.9 cm. Thus we selected all males in the data set with height ranging from 172 - 176 cm and fit a log linear curve through the data arriving at a male Forbes model (Equation 4, Table 1).

Earlier studies have established that the Forbes model provides a good estimate of FFM change during weight change [12], even though the Forbes model may not accurately predict body composition. The reason behind this discrepancy is that although the baseline and final body composition value may not necessarily be located on the original Forbes curve, they are points on a parallel Forbes curve (Figure 6). The slope of the secant line between the points is equal to the slope of the secant line between the points on the original Forbes curve and as a result can be used to estimate the change in FFM effectively.

**Discussion**

The class of derived FFM - FM polynomials account for most of the variation observed in the NHANES data by considering age, height, gender and race as additional factors.
covariates allowing for immediate use of individualized FFM curves within a one dimensional differential equation model. This allows for generation of separate curves due to individual parameters as opposed to fitting the value of \( D \) to specific populations in order to translate the Forbes curve.

In addition to providing a class of models that can be paired to a one dimensional energy balance differential equations, there are several interesting observations produced by the NHANES polynomials. One application of the NHANES generated models is determination of the width of the band for specific \( FM \) values. For example, we applied the NHANES models to determine BMI as a function of height for zero fat (Figure 5). Theoretically, these values estimate the lowest possible BMI and are supported by the close correlation to mean data collected during the 1992-93 Somalia famine in [13] also plotted in Figure 5. For the two data points, the mean age for males was 32 and the mean age for females was 35. Out of the 261 subjects in the famine study, 51 had severe edema which impacted their BMI. However, we can compare the subjects from [13] who had severe edema to the 24 week data from the Minnesota Starvation Experiment some of whom also experienced edema. The mean BMI for the famine subjects with edema was 15.4 at a height of 167 cm and the mean BMI of the Minnesota subjects at 24 weeks was 16.4 with a mean height of 179.5 cm [13,23]. Although these results are confounded by edema, it provides experimental support for the conclusion that BMI at zero fat is an increasing function of height. The polynomial regression models have several limitations. The effect of physical activity was not incorporated as a covariate. However, as observed with the placement of the athletes within the NHANES band (Figure 2B), physical activity does affect the position of the \( FFM-FM \) value on the band. Moreover, increased free-living physical activity was observed during weight gain in [24,25] and therefore can also be a factor for longitudinal body composition during weight change. It also appears that for the case of gastric bypass, changes in \( FFM \) for a cohort of subjects are less than estimated by the NHANES band and their resulting regression models (Figure 2A). This may be due to available active tissue within \( FFM \) or increased physical activity as a result of weight loss and remains to be investigated although we point out that this observation does not apply to energy balance equations that model weight change as a function of changes in energy intake and activity.

Through access of several sources of longitudinal data, we confirm the conclusions made in [12] that the original Forbes model in Equation 1 and the similarly generated male Forbes model in Equation 2, estimate the change in \( FFM \) during weight change with a high degree of accuracy. The Forbes model was generated as a cross-sectional fit of the relationship between \( FFM \) and \( FM \), however, it would be incorrect to consider this as an individual curve on which baseline data begins and travels down during weight change. The Forbes model is actually a family curves where baseline and longitudinal data for an individual study are located on a translation of the

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**Figure 5** Plots of \( FFM \) versus height at zero \( FM \). Plots of BMI (kg/m\(^2\)) versus height (cm) for A. males and B. females generated using the model in Table 3 after substituting \( FM \) equal to zero and race set to NAA. Age was set at 20 (dash-dot), 30 (dot) and 40 (dash). Circles represent mean BMI data against mean height for surviving subjects with mild edema [13].
original Forbes model [9] as observed in Figure 6. Because the translated curve and the original curve are parallel, the slope of the secant line between the baseline and final points on the curves are identical. Thus, the Forbes model is not a model that identifies location of a baseline point and final point during weight change, but a model that primarily quantifies the change in \( \text{FFM} \) as confirmed by the results in Table 4.

Discrepancies between placement of weight change subjects and normal subjects within the NHANES band is discovered by the NHANES models as observed in the massive weight loss of the gastric bypass surgery patients. The higher mean error in prediction of body composition at the changed weight and the placement of a cohort of subjects over the top of the NHANES band immediately points out that there is a distinction between subjects with the quantities of \( \text{FM} \) in the weight stable population and the weight change subjects (Figure 2A, Table 4). There are three possible reasons for this difference. The body composition measurements for the gastric bypass subjects were not made by DXA and thus may deviate slightly from the DXA measurements of NHANES. The second possibility is that once individuals lose great amounts of weight, they may become more active and thus increase their \( \text{FFM} \). A final possibility is that the body composition of the weight changed subjects is simply different than the individuals who are already in the NHANES band. Understanding reasons behind these discrepancies will lead to improved decisions within the context of weight loss and weight re-gain.

**Conclusions**

In conclusion, the relationship between \( \text{FFM} \) and \( \text{FM} \) is an integral component for differential equation energy balance models. By examining correlations of \( \text{FFM} \) with \( \text{FM} \) through the cross-sectional NHANES data and longitudinal data from calorie restriction, calorie restriction combined with exercise, bariatric surgery, gastric bypass surgery, and overfeeding studies, we established that the trend set by NHANES is traveled during weight change.

**Table 4: Model predictions of \( \Delta \text{FFM} \)**

|                      | NHANES       |          | Forbes     |          | NHANES ΔFFM | Forbes ΔFFM |
|----------------------|--------------|----------|------------|----------|-------------|-------------|
|                      | Baseline     | Final    | Baseline   | Final    |             |             |
| Anorexia [17]        | 1.5 ± 3.1    | --       | 2.5 ± 2.8  | --       | --          | --          |
| Athletes Males [18]  | 8.0 ± 4.5    | --       | 9.3 ± 5.3  | --       | --          | --          |
| Athletes Females [18]| 6.1 ± 2.9    | --       | 3.7 ± 3.7  | --       | --          | --          |
| Bariatric Surgery    | -3.8 ± 3.2   | -5.7 ± 3.2| 1.4 ± 3.2  | 4.7 ± 3.3| -2.3 ± 3.0  | -1.0 ± 3.2  |
| Bariatric Surgery    | -1.6 ± 3.2   | 1.2 ± 3.0| -2.0 ± 2.7  | 0.9 ± 2.5| -0.4 ± 1.1  | -0.3 ± 1.2  |
| CALERIE 6 Month      | 4.4 ± 3.2    | 5.7 ± 4.7| 4.9 ± 3.1  | 6.1 ± 4.4| -0.5 ± 1.2  | -0.4 ± 1.2  |
| Males [19]           |             |          |            |          |             |             |
| FemaleCALERIE 6 Month| 2.8 ± 3.9    | -2.0 ± 7.2| -5.0 ± 4.5  | -2.3 ± 5.2| -7.7 ± 4.7  | -0.3 ± 5.5  |
| Overfeeding Males    | -2.2 ± 6.1   | -0.5 ± 5.4| -2.2 ± 6.6  | -0.3 ± 5.5| 0.1 ± 1.5   | -0.1 ± 1.6  |
| [24,25]              | 0.2 ± 3.3    | -2.0 ± 3.1| -0.6 ± 3.8  | -2.7 ± 3.4| 0.8 ± 1.1   | 0.7 ± 1.3   |
| Overfeeding Females  | 2.9 ± 3.3    | 5.2 ± 3.0| 0.6 ± 2.8  | 4.6 ± 2.2| 2.2 ± 2.0   | 0.6 ± 2.1   |

Mean error between measured and predicted \( \text{FM} \) at baseline and at the end of the weight change study along with the mean error in the \( \Delta \text{FFM} \). The NHANES model is comparable to the Forbes model except in the case of the gastric bypass subjects.
except in certain subjects with massive weight loss during surgery (Figure 2). Our central focus was to supply a FFM function of FM that preserves the predictive properties of the Forbes model for the change in FFM during weight loss, has a non-negative physically realistic intercept, and also accounts for individual variability due to age, height, race and gender. Since the development of the FFM formula, we have applied the new FFM formula within an energy balance equation with satisfactory results [26].

The resulting class of formulas satisfactorily model the large variation observed in the NHANES data and predict longitudinal data with a comparable level of accuracy to the Forbes model while also preserving non-negativity for FFM as FM tends to zero. The models predict conclusions of low fat mass data observed during famines [13] reflecting a biologically meaningful intercept. The NHANES models provide individualized estimates of baseline and longitudinal changes in body composition along with the potential to identify deviations of weight change data from the weight stable population.

These findings have implications for the future of dynamic models of human body weight change and policy regarding prescriptions for weight management.

Competing interests
The authors declare that they have no competing interests.

Authors’ contributions
DT carried out the mathematical analysis of the data, ran the numerical simulations, and drafted the manuscript. SD supplied data and analyzed the numerical results, JAK supplied data and analyzed the numerical results, CKM supplied data and analyzed the numerical results, LM supplied data and analyzed the numerical results, SBH conceived of the study and participated in the design and performed the statistical analysis, BJS supplied data and analyzed the numerical results, and the Mayo Foundation. All authors read and approved the final manuscript.

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