HHS Public Access

Author manuscript

Int J Obes (Lond). Author manuscript; available in PMC 2018 January 24.

Published in final edited form as:

Int J Obes (Lond). 2017 November ; 41(11): 1669–1675. doi:10.1038/ijo.2017.167.

Nationally representative equations that include resistance and reactance for the prediction of percent body fat in Americans

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Abstract

Background/Objectives—Resistance and reactance collected by bioelectrical impedance (BIA) can be used in equations to estimate percent body fat at relatively low cost and subject burden. To our knowledge no such equations have been developed in a nationally representative sample.

Subjects/Methods—Dual-energy X-ray absorptiometry (DXA) assessed percent body fat from the 1999–2004 NHANES was the criterion method for development of sex-specific percent body fat equations using up to 6,467 males or 4,888 females 8 to 49 years of age. Candidate variables were studied in multiple mathematical forms and interactions using the Least Absolute Shrinkage and Selection Operator (LASSO). Models were fit in 2/3′s of the data and validated in 1/3 of the data selected at random. Final coefficients, R^2 values and root mean square error (RMSE) were estimated in the full data set.

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Conflict of interest: The authors declare no conflict of interest

Conflict of interest: none declared.

Supplementary information is available at International Journal of Obesity's website.

Results—Models that included age, ethnicity, height, weight, BMI and BIA assessments (resistance, reactance and height^2/resistance) had R^2 values of 0.831 in men and 0.864 in women in the full data set. RMSE measurements were between 2 and 3 body fat percentage points, and all equations showed low bias across groups formed by age, race/ethnicity or body mass index category. The addition of triceps skinfold and waist circumference increased the R^2 to 0.905 in males and 0.883 in females. Adding other anthropometrics (plus menses in females) had little impact on performance. Reactance and resistance alone (in multiple mathematical forms) performed poorly with $R^2 \sim 0.2$.

Conclusions—Equations that included BIA assessments along with demographic and anthropometric variables provided percent body fat assessments that had high generalizability, strong predictive ability and low bias.

Keywords

anthropometry; percent body fat; NHANES; dual-emission X-ray absorptiometry; children; adolescents; adults; bioelectrical impedance

INTRODUCTION

Years of use have shown body mass index (BMI) to be a helpful tool for the evaluation of body size in both public health and clinical environments, but since BMI does not distinguish lean from fat mass, error in the identification and quantification of excess fatness is expected. In circumstances that require precise assessment of body fatness several different types of measurements are available. Among these, dual energy X-ray absorptiometry (DXA) is often selected for use in clinical research settings where scanners and trained personnel are available and exposure of subjects to low level radiation is considered reasonably safe. In settings in which DXA and similarly precise measurements are not considered feasible, the best alternative is often a prediction equation that requires only more easily obtained measurements. We have recently published a series of such equations that use demographic and anthropometric variables to predict percent body fat (1). The equations were built using several mathematical forms that allowed flexible models to be fit in data representative of the United States population and were shown to be unbiased in youth (8–19 years) and adults (20 and older). Our previous research focused on demographic and anthropometric variables and did not include reactance and resistance from bioelectrical impedance analysis (BIA).

BIA is a practical option for measurement of body fatness in many settings because the machinery is portable, relatively inexpensive, and easy to operate and does not involve radiation. BIA measures the body’s resistance to an alternating electrical current that varies depending on the water and electrolyte content of the body (2). The electrical resistance and reactance from BIA together with other measurements can be used in equations to indicate fatfree mass, fat mass and percent body fat. Although all three of these quantities can be useful, in obesity research it is percent body fat that arguably has the most utility, since absolute quantities of mass may not by themselves valid indicators of excess adiposity.

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Reactance, resistance, height, weight and other measures have been used to predict percent body fat or fat mass, fat free mass and total body water (3–6). Percent fat was calculated from the later equations. However, most of these equations were developed in small or moderately sized samples that were limited to a specific and narrowly defined group that was recruited by convenience. Differences in body fat and water distributions, limb lengths, body shape and tissue resistivity between populations impact BIA measurements (7) and make it necessary for investigators to match the characteristics of the sample in which an equation was developed to the individuals to whom it will be applied. Thus equations that have strong generalizability are needed to fully harness the usefulness of BIA. Our objective was to use data from the American National Health and Nutrition Survey (NHANES) to create and describe sex-specific equations that predict percent body fat using reactance, resistance, demographics, and several different sets of anthropometrics.

METHODS

Data for this study were from the 1999–2004 NHANES, which used a complex, multistage, probability sampling design to provide a representative sample of US noninstitutionalized children and adults (8). Participants self-reported their race and ethnicity and were categorized as non-Hispanic Whites, non-Hispanic Blacks, Mexican Americans, other Hispanics or other race/ethnicities. We studied age as a continuous variable and as a dichotomous variable indicating youth (8 to 19) or adult (20 to 49 years). Menarche status (presence or absence) was determined for girls 12 years of age and older based on their selfreported age of first menstrual period. Ten anthropometrics were measured using standardized procedures (8) (height, weight, triceps and subscapular skinfolds, waist, maximal calf, arm and thigh circumferences, and upper arm and upper leg lengths).

Bioelectrical impedance was measured in 8 to 49 year old participants using a HYDRA ECF/ICF Bio-Impedance Spectrum Analyzer (model 4200, Xitron Technologies, San Diego, California). A small alternating current was passed through surface electrodes placed on the right hand and foot. We used the reactance and resistance measured at 50 KHz. DXA measurements were obtained using a Hologic QDR-4500A fan-beam densitometer (Hologic, Inc., Bedford, Massachusetts) and adjusted using the Schoeller et al. (9) method. Participants were excluded from both BIA and DXA measurements if they were pregnant, had amputations other than fingers or toes, or weighed over 300 pounds. Additional exclusions related to BIA assessment were presence of artificial joints, pacemaker, and coronary stents or other metal objects that could not be removed from the body. Participants were excluded from DXA measurement if they had self-reported history of radiographic contrast material use in past 7 days or participation in nuclear medicine studies in the past 3 days, or had a height over 6′5″. Missing DXA measurements were imputed using methods that have been described (10). In the text that follows we call both imputed and measured DXA assessed percent body fat “observed”, for the purpose of differentiating observed values from the values predicted using the equations developed here. There are no public use DXA data available for girls 8–17 years from the 1999–2000 survey due to unresolved IRB issues concerning the reporting of pregnancy test results in females 8 to 17 years of age in 1999.

Analytic sample

There were 13,962 men and women 8 to 49 years in the 1999–2004 NHANES data with a positive survey weight. After exclusions for no measured or imputed DXA (n=1,118), highly variable DXA assessments (n=5), missing or implausible BIA measurements (n=1,276), missing or implausible weight, height, lengths or circumferences (n=208) the analysis sample included 11,355 participants, and of these 5.1% had percent body fat values that were imputed. Among these participants all variables required for the models tested were present, with the exception of skinfolds: 184 were missing only triceps skinfold, 872 were missing only subscapular skinfold and 330 were missing both. The number of participants used in each analysis depended upon whether triceps and subscapular skinfold were in the initial variable list. Details on exclusions are shown in Supplemental information 1.

Analysis plan

All analyses were stratified by gender, took into account the complex survey design and were conducted using SAS (SAS/STAT® 9.3 User's Guide, 2011). The National Center for Health Statistics (NCHS) recommends recalculating the sampling weights if >10% of the sample are excluded (10). We followed this recommendation since 19 to 29% of the participants were excluded in our analysis datasets (details of method are in supplemental information 2).

In this work we differentiate between variables, indices and terms. The variables used were race/ethnicity, age (continuous and dichotomous), menarche status (females only), 10 anthropometric variables, reactance and resistance. Two standard indices studied were BMI (weight in kg/height in m^2) and resistance index (RI: height in cm^2/resistance (5, 11, 12)). Terms used included the linear, squared, cubic, inverse and interactions (see Supplemental information 3 for a detailed description). The maximum number of terms tested was 1,696 for males and 1,816 for females. We conducted model selection for 20 different subsets of candidate variables and indices (models A to T). The candidate variables, indices and terms for models A to N were the same used in our previous work (1), but with the addition of reactance, resistance, RI and corresponding terms. Model O was created using the base demographic variables, height, weight and BMI, plus all the lengths that were measured and the BIA assessments (reactance, resistance and RI). This model was of interest since BIA measures are known to be influenced by lengths (11, 13). Model P included skinfolds instead of lengths. Models Q to T were created using different combinations of demographics, reactance, resistance and RI.

We conducted sensitivity analyses to compare the performance of models that were developed from a list of candidate variables that alternatively included or excluded skinfolds and BIA in a factorial design, models W, X, Y and P). We kept the sample of participants uniform for these analyses i.e., avoided inclusions or exclusions based on missing measurements. In addition, we used the same sample to compare models with the outcome of kg of body fat versus the outcome of percent body fat.

To determine predication equations we followed the same four steps described previously (1), and so they are described only briefly here.

Step 1. Using random assignment create development and validation datasets composed of 2/3 and 1/3 of the data respectively.

Step 2. Generate models in development dataset using the Least Absolute Shrinkage and Selection Operator (LASSO) technique (14). To reduce the possibility of over-fitting, the model that had a standard error (SE) ≥ 1 SE larger than the minimum cross-validation error (CV) and an adjusted R^2 that was ≥ 0.01 smaller than the model with the minimum cross-validation error was selected (15).

Step 3. Evaluate final model equations in the validation data sets. The predicted percent body fat was calculated in the data reserved for validation using the coefficients and terms of the model selected in step 2. The predicted percent body fat was then examined in univariate regression models with percent body fat from DXA as the dependent variable. For each model we generated R^2 and RMSE. We present separate results for non-Hispanic White, nonHispanic Black and Mexican Americans. Other ethnic groups are not shown since the NCHS recommends that researchers do not analyze them separately due to small sample sizes (10), but they are included in overall estimates. Mean signed differences (MSD: equation percent body fat – DXA percent body fat)) were calculated overall and by age, race and weight status subgroups.

Step 4. Produce final equations using full datasets.

To improve the precision of the equations, the coefficients for the final gender-specific equations were estimated from the full analytic datasets (development and validation data combined). We also estimated the R^2 and RMSE of the final equations.

RESULTS

Characteristics of the weighted analysis sample are shown in Table 1, along with the unweighted number of participants on which the estimates were based. The majority of the weighted sample were non-Hispanic Whites, and over two-thirds were overweight or obese. The mean BMI was 25.5 kg/m^2 in males and 25.9 kg/m^2 in females, and the overall mean percent body fat 26.1 and 36.8, respectively.

Supplemental information 4 (males) and 5 (females) shows results from 20 models (A to T) created in the development sample and applied to the validation sample with R^2 and RMSE calculated overall and R^2 within age, race/ethnicity subgroups. For models A to P there was little difference between the R^2 and the RMSE in the development versus the validation samples (data not shown in tables). For those models the average overall R^2 in men was slightly lower (mean difference −0.008, 95% CI −0.015, −0.001) and the RMSE slightly higher (mean difference 0.04, 95% CI −0.03, 0.10) in the validation sample compared to the development sample. In females, the pattern was the opposite (0.003, 95% CI −0.001, 0.008 for mean difference and −0.07, 95% CI −0.12, −0.03 for RMSE).

In both males and females overall, models that included a skinfold measurement tended to perform better than those that did not. Performance tended to be better in boys compared to adult males but similar across race/ethnic groups (supplemental information 4). When applied to the data from males stratified by both race/ethnicity and age category the R^2 values tended to be lower in White and Mexican American men. In females (supplemental information 5), models A to P produced an R^2 over 0.86 in the overall analysis. These models also performed well in females when stratified by age or race ($R^2 > 0.845$). However, when stratified by both age and race, the models performance declined slightly in Mexican American women (R^2 between 0.761 and 0.826) and Black women (R^2 between 0.797 and 0.844).

For model Q the candidate variables included age, race, resistance, reactance, and RI, but no anthropometric variables (other than height which was included in the squared form in RI). That model performed poorly overall in both genders as did models R, S and T, which also included no anthropometric variables (R^2 between 0.066 and 0.234). BMI as a single term (model U) performed better than models Q to T. However, when BMI, height and weight and demographics were included along with BIA (model N), the R^2 was over 0.8 in both genders. RMSE values were <3 percent body fat for models A to P, but were over 5.9 percent body fat for models Q to T and >3.8 for model U.

Tables 2 (males) and 3 (females) show the R^2 and RMSE estimates in the full dataset (development and validation samples combined) for the models selected in the development dataset, but with the coefficients recalculated in the full dataset. As expected, the R^2 and RMSE estimates were similar to those found in the validation data (Supplemental information 4 and 5).

We explored systematic differences in the prediction of percent body fat in subgroups categorized by age, ethnicity and BMI by examining MSD using the validation data. In Figure 1 we show the results from model J as representative of the results for Models A to P. All of those models had low bias as illustrated by MSD within ±1 percentage point of percent body fat within all the subgroups. In contrast, the MSD for models Q and model S had substantial bias by weight status. Models Q and S tended to overestimate percent body fat in underweight and overweight males and females but underestimate percent body fat in normal weight males and females and obese females. Models Q and S also showed moderate bias for some analyses within age and ethnic groups.

Table 4 contrasts models that all included age, race, height, weight and BMI as candidate variables, but varied in regard to skinfold and BIA measurements. Model W included neither skinfolds nor BIA variables (reactance, resistance and RI). In males, the addition of either BIA variables or 2 skinfolds (triceps and subscapular) to models predicting percent body fat produced a similar R^2 (0.813 and 0.819), whereas, in women the R^2 was slightly higher in the equations that included BIA compared to those that included skinfolds (0.801 and 0.844, respectively). In both genders, for the prediction of percent body fat model P that included both BIA and the 2 skinfolds had a larger R^2 and a smaller RMSE than either alone.

Table 4 also show results from models that used kg of fat mass as the outcome versus percent body fat in the same group of individuals. In all 4 models the prediction of fat mass was associated with higher R^2 values and lower RMSE than the prediction of percent body fat. In females for model P the R^2 for prediction of fat mass was exceptionally large at 0.973.

DISCUSSION

We developed equations that use resistance and reactance from BIA and other anthropometric and demographic variables to predict percent body fat in children and adults and demonstrated low bias in the estimates across categories by age, ethnicity and BMI. Comparisons of the diagnostics in the development versus the validation data did not indicate over fitting was a concern. In males 11 equations produced R^2 values > 0.86 and another 5 had R^2 > 0.83, whereas, in females 16 equations produced R^2 values >0.86. In both males and females, the addition of arm length and leg length (model O) to demographics, height, weight, reactance, resistance and RI as candidate variables (model N) made essentially no difference in performance. The variables that improved performance of model N the most were triceps skinfold and waist. As shown in model M, the addition of triceps skinfold to model N resulted in an increase in R^2 from 0.831 to 0.892 in males, and a smaller increase in females (0.864 to 0.879). By also adding waist to this list of variables (model I), the R^2 increased to 0.905 and 0.883 in males and females, respectively. Alone or only with demographics, the BIA assessments (reactance, resistance and RI) performed poorly (models Q to T).

Compared to models shown in the 2016 publication (1) that included demographics and anthropometrics, performance was consistently improved in the current work that added BIA assessments as candidate variables, and the improvement tended to be larger in females than in males. For example, model I with candidate variables age, race, height, weight, BMI triceps, waist, reactance, resistance and RI had an R^2 that was higher by 0.089 in males and 0.086 in females compared to the same model without the BIA assessments. With the addition of BIA, model A, yielded R^2 values 0.044 and 0.081 higher in males and females, respectively. Thus, BIA improved even models with 10 anthropometric measures plus BMI.

In this comparison to published work it is understood that the equations with and without (1) BIA assessments included multiple mathematical terms for multiple candidate variables and indices. Also, the comparisons used data from study samples that were not identical. Our 2016 study used participants from NHANES years 1999–2006, whereas, the current study used only 1999–2004 because BIA data were not collected in 2005–2006. Additionally, BIA was not measured on adults 50 and older and so older adults were excluded here, but were studied previously. Skinfold measurements were sometimes missing in both studies, and this blocked participants from being included in certain models. In addition the number of participants with assessments of other variables needed for different models varied. Here models W, X, Y and P provide comparisons of equations selected and tested in the exact same participants. Similar to the comparisons across different studies and participants, model P showed that addition of both two skinfolds and BIA to an existing model resulted in a greater R^2 than models with either skinfolds (model X) or BIA (model Y). Model Y that substituted BIA assessments for triceps and subscapular skinfolds produced the similar R^2 in males and a higher R^2 in females (by 0.043).

Similar types of comparisons were made by Lohman et al (16) in their study of 98 American Indian youth 8 to 11 years of age who had percent body fat assessed by deuterium dilution. A percent body fat prediction model that included two skinfolds (triceps and suprailiac) and RI and reactance in addition to age, sex and weight produced a higher R^2 (0.843) than similar models with either the skinfold ($R^2 = 0.827$) or the BIA variables ($R^2 = 0.776$). Taken together, the results from the current work, our previous work (1) and the Lohman paper (16) indicate that the addition of BIA to a model that includes anthropometry is likely to increase the R^2, but changes in R^2 when BIA variables are substituted for skinfolds may vary based on the age and gender of the individuals studied, as well as other factors such as the quality of measurement collection.

Several investigators have demonstrated R^2 values over 0.9 for equations that combine the genders and predict fat-free mass (rather than percent body fat) using relatively simple equations that included height^2/resistance. For instance, Deurenberg et al. (17) cited an r of 0.99 (therefore a R^2 of 0.98) for the prediction of fat free mass in boys and girls (combined) with resistance, height and weight the only variables. Schaefer et al. (18) found an R^2 of 0.975 in (combined) boys and girls with resistance, height and age the only variables. In our previous paper (1), we reviewed the impact of combining versus stratifying by gender. Percent body fat levels are so different in males and females that etiologic studies of the causes or consequences of percent body fat are usually performed stratified by gender. Therefore, we and others (19–22) have advocated use of gender stratified models for the prediction of percent body fat.

Another reason for the higher R^2 in the Deurenberg (17) and Schaefer (18) papers than those reported here is that the previous papers predicted body fat mass rather than percent body fat. In this paper we showed some examples in which fat mass was predicted with a higher R^2 than percent body fat when analyzed using the same sex specific sample, methods and candidate terms. It is incorrect to directly apply the R^2 from the prediction of kg of fat mass or fat free mass to percent body fat, even though an estimate of percent body fat can be calculated using total mass and either of those quantities. We think that obesity researchers are more often interested in percent body fat than kg fat mass and consider our focus on that characteristic a strength.

Error in the DXA measurements used to assess percent body fat is a limitation of this study that could not be overcome. Criterion data from a 4 compartment model would have been more precise. Although DXA assessments continue to improve with advances in software, relatively large bias has been detected in the past (9). Here we applied the correctionsuggested by Scholler et al.(9), but more work is critically needed to determine if this correction is appropriate for individuals of different size, fatness and age. Also, the NHANES used a research quality instrument that required placement of electrodes to conduct the BIA assessments. Other bathroom scale type instruments that do not require electrode placement may give different results. Some BIA instruments do not routinely output reactance and resistance, even though the information is (by definition) collected.

It is a strength that these equations are generalizable to individuals over a wide range of age and BMI, and their complexity likely supported this attribute. Nevertheless, this work did not address the accuracy of the equations in athletes with types of body builds that are rare in the overall population, and so they should be applied with caution in that group. A drawback of the complexity of the equations is that they are difficult to compute without the help of a computer.

To assist investigator use of our equations we developed the American Body Composition Calculator (ABCC). The program facilitates the generation of columns of percent body fat estimates for models A to P and is available at (http://ABCC.sph.unc.edu). Thus, the equations for prediction of percent body fat produced in this work are easily available to researchers, and we encourage their wide use to enhance studies on the role of obesity in health and disease.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This work was supported by the National Institute of Diabetes and Digestive and Kidney Diseases (R01-DK097046).

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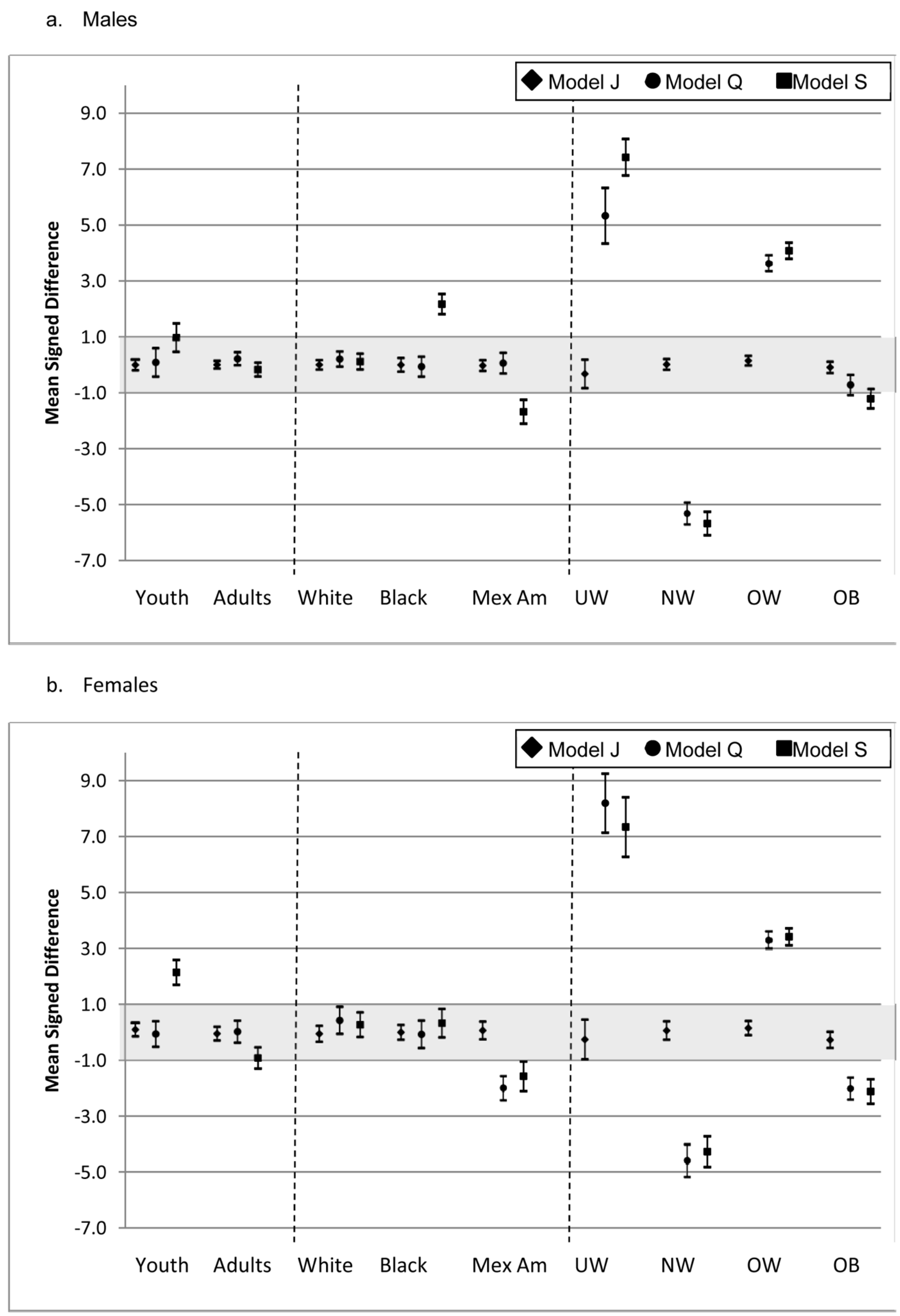

Figure 1.

Mean signed differences (MSD) between percent body fat measured by DXA compared to values predicted using models J, Q and S in the cross-validation data set within subgroups by age, ethnicity and BMI category in males (figure 1a) and females (figure 1b). The candidate variables were: Model J: age, race, resistance, reactance, resistance index, height, weight, BMI, triceps skinfold, waist circumference; Model Q: age, race, resistance, reactance, resistance index; and Models S: resistance, reactance, resistance index. A positive value indicates that the equation overestimated the measured percent body fat and a negative value indicates the equation underestimated the measured percent body fat. NHANES 1999–2004.

Table 1

Description of the weighted analysis sample from 1999–2004 NHANES

	Males			Females		
	N[a]	Mean or %	SE	N[a]	Mean or %	SE
Age (years)	6467	28.3	0.21	4888	29.1	0.29
Youth (%)	6467	29.9	0.64	4888	30.0	0.88
Menses (%)	---	---	---	4888	65.1	1.25
Race/Ethnicity (%)	6467			4888		
Non-Hispanic White		65.7	1.62		66.2	1.95
Non-Hispanic Black		11.8	1.01		13.0	1.20
Mexican American		10.8	1.12		9.0	1.08
Multi-ethnic/other		11.7	1.30		11.8	1.30
Weight (kg)	6467	76.5	0.34	4888	67.5	0.47
Height (cm)	6467	171.6	0.19	4888	160.7	0.21
BMI (kg/m^2)	6467	25.5	0.10	4888	25.9	0.15
BMI Category (%)	6467			4888		
Underweight		2.3	0.24		3.3	0.37
Normal Weight		21.9	0.75		26.8	1.01
Overweight		42.3	0.99		47.2	1.35
Obese		33.6	1.02		22.8	1.03
DXA % Body Fat[b]	6467	26.1	0.11	4888	36.8	0.19
White	2119	26.4	0.13	1773	36.6	0.28
Black	1775	23.8	0.19	1321	37.1	0.29
Mexican	2028	27.5	0.23	1373	38.1	0.29
Youth	3881	25.4	0.26	2607	33.1	0.26
White	994	25.6	0.39	745	33.0	0.39
Black	1239	23.1	0.25	828	32.4	0.23
Mexican	1345	27.6	0.24	818	34.4	0.37
Adults	2586	26.5	0.12	2281	38.4	0.23
White	1125	26.7	0.15	1028	37.9	0.32
Black	536	24.2	0.25	493	39.6	0.35

	Males			Females		
	N[a]	Mean or %	SE	N[a]	Mean or %	SE
Mexican	683	27.5	0.30	555	40.4	0.32
Triceps skin-fold (mm)	6332	13.8	0.12	4509	21.9	0.23
Subscapular skinfold (mm)	5994	16.0	0.18	4159	18.0	0.21
Waist (cm)	6467	89.9	0.26	4888	86.0	0.39
Maximal calf circumference (cm)	6467	37.7	0.08	4888	37.1	0.13
Arm circumference (cm)	6467	31.8	0.09	4888	30.0	0.13
Thigh circumference (cm)	6467	52.3	0.13	4888	51.9	0.19
Upper arm length (cm)	6467	37.6	0.07	4888	35.1	0.07
Upper leg length (cm)	6467	42.2	0.08	4888	39.0	0.10
Resistance (Ohms at 50 KHz)	6467	495.9	1.59	4888	590.4	2.12
Reactance (Ohms at 50 KHz)	6467	61.4	0.18	4888	64.5	0.20

[a] Number in sample without application of sampling weights

[b] Average of 5 imputed values

Table 2

Males: R^2 and RMSE overall and in subgroups in full sample, NHANES 1999–2004

Model[a]	Overall		Age: 8–19 years		Age: 20–49 years		Race/Ethnicity: White		Race/Ethnicity: Black		Race/Ethnicity: Mexican		Age * Race/Ethnicity: White-Boys		White-Men		Black-Boys		Black-Men		Mexican-Boys		Mexican-Men	
	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE
A	0.889	2.09	0.917	2.19	0.866	2.04	0.887	2.05	0.900	2.14	0.886	2.04	0.914	2.17	0.867	2.00	0.915	2.27	0.885	2.05	0.923	2.17	0.844	1.97
B	0.886	2.11	0.915	2.21	0.863	2.06	0.884	2.08	0.898	2.16	0.883	2.06	0.913	2.18	0.863	2.03	0.913	2.29	0.883	2.07	0.921	2.20	0.841	1.99
C	0.864	2.32	0.901	2.40	0.833	2.28	0.860	2.29	0.883	2.33	0.863	2.24	0.896	2.39	0.834	2.25	0.904	2.41	0.862	2.28	0.910	2.36	0.811	2.17
D	0.906	2.22	0.918	2.28	0.870	2.11	0.896	2.15	0.906	2.26	0.902	2.23	0.911	2.24	0.871	2.06	0.910	2.32	0.888	2.08	0.917	2.27	0.835	2.13
E	0.864	2.41	0.896	2.54	0.838	2.36	0.861	2.37	0.879	2.46	0.860	2.38	0.892	2.52	0.839	2.31	0.898	2.55	0.859	2.40	0.901	2.52	0.818	2.30
F	0.880	2.16	0.905	2.34	0.860	2.08	0.878	2.13	0.893	2.21	0.876	2.12	0.903	2.31	0.860	2.06	0.902	2.43	0.884	2.06	0.913	2.30	0.835	2.03
G	0.881	2.15	0.908	2.30	0.859	2.09	0.879	2.12	0.893	2.21	0.878	2.11	0.906	2.27	0.860	2.06	0.905	2.39	0.882	2.08	0.916	2.26	0.835	2.02
H	0.870	2.26	0.906	2.33	0.841	2.22	0.869	2.21	0.877	2.37	0.869	2.18	0.904	2.30	0.844	2.17	0.905	2.39	0.849	2.36	0.913	2.30	0.822	2.10
I	0.905	2.23	0.917	2.30	0.870	2.12	0.895	2.16	0.905	2.27	0.901	2.23	0.910	2.25	0.869	2.07	0.909	2.34	0.887	2.09	0.916	2.28	0.837	2.13
J	0.856	2.48	0.887	2.64	0.831	2.41	0.852	2.44	0.873	2.51	0.856	2.42	0.881	2.63	0.832	2.36	0.891	2.65	0.855	2.43	0.895	2.60	0.815	2.32
K	0.836	2.65	0.880	2.72	0.801	2.61	0.832	2.60	0.848	2.75	0.845	2.50	0.875	2.71	0.802	2.56	0.885	2.71	0.811	2.78	0.890	2.65	0.799	2.42
L	0.855	2.49	0.886	2.65	0.830	2.41	0.852	2.44	0.872	2.53	0.854	2.43	0.881	2.64	0.831	2.37	0.891	2.65	0.853	2.45	0.894	2.62	0.813	2.33
M	0.892	2.38	0.908	2.41	0.844	2.32	0.881	2.30	0.891	2.43	0.891	2.35	0.903	2.34	0.846	2.25	0.900	2.45	0.854	2.38	0.910	2.36	0.814	2.27
N	0.831	2.69	0.872	2.81	0.798	2.63	0.827	2.64	0.842	2.81	0.837	2.57	0.863	2.83	0.802	2.56	0.878	2.80	0.806	2.81	0.885	2.72	0.789	2.48
O	0.833	2.67	0.872	2.81	0.803	2.60	0.831	2.61	0.844	2.79	0.835	2.58	0.865	2.81	0.807	2.53	0.877	2.81	0.811	2.78	0.884	2.73	0.787	2.49
P	0.871	2.24	0.908	2.31	0.841	2.21	0.870	2.20	0.877	2.36	0.873	2.15	0.905	2.28	0.845	2.17	0.907	2.36	0.848	2.36	0.917	2.25	0.826	2.08
Q	0.162	5.98	0.173	7.14	0.145	5.41	0.135	5.91	0.159	6.47	0.153	5.85	0.145	7.07	0.121	5.40	0.166	7.32	0.144	5.91	0.192	7.21	0.124	5.05
R	0.149	6.03	0.143	7.27	0.145	5.41	0.119	5.96	0.153	6.50	0.151	5.86	0.108	7.22	0.119	5.41	0.153	7.38	0.144	5.91	0.175	7.28	0.137	5.01
S	0.086	6.25	0.087	7.50	0.095	5.57	0.075	6.11	0.095	6.72	0.113	5.99	0.077	7.35	0.082	5.52	0.126	7.49	0.095	6.07	0.140	7.44	0.114	5.08
T	0.074	6.29	0.034	7.72	0.098	5.56	0.065	6.14	0.900	6.73	0.098	6.04	0.024	7.56	0.085	5.51	0.074	7.71	0.100	6.06	0.084	7.68	0.121	5.05
U	0.378	4.93	0.292	6.39	0.570	3.65	0.387	4.78	0.390	5.28	0.361	4.82	0.272	6.32	0.591	3.52	0.332	6.34	0.583	3.91	0.363	6.23	0.609	3.12

[a] Candidate variables/indices not retained by the selection process are shown in parentheses

Model A: age, race, resistance, reactance, resistance index, (height), weight, BMI, triceps skinfold, subscapular skinfold, waist, calf circumference, arm circumference, thigh circumference. arm length, (leg length) (n=5938)

Model B: age, race, resistance, reactance, resistance index, (height), weight, BMI, triceps skinfold, subscapular skinfold, waist, calf circumference, arm circumference, thigh circumference (n=5938)

Model C: age, race, resistance, reactance, resistance index, height, weight, BMI, subscapular skinfold, waist circumference, calf circumference, arm circumference, thigh circumference (n=5994)

Model D: age, race, resistance, reactance, resistance index, (height), (weight), BMI, triceps skinfold, waist circumference, calf circumference, (arm circumference), (thigh circumference) (n=6332)

Model E: age, race, resistance, reactance, resistance index, height, weight, BMI, waist circumference, calf circumference, arm circumference, thigh circumference (n=6467)
Model F: age, race, (resistance), reactance, resistance index, (height), weight, BMI, triceps skinfold, subscapular skinfold, waist, calf circumference (n=5938)
Model G: age, race, resistance, reactance, resistance index, (height), weight, BMI, triceps skinfold, subscapular skinfold, waist, arm circumference (n=5938)
Model H: age, race, resistance, reactance, resistance index, (height), weight, BMI, triceps skinfold, subscapular skinfold, arm circumference (n=5938)
Model I: age, race, resistance, reactance, resistance index, (height), (weight), BMI, triceps skinfold, waist circumference (n=6332)
Model J: age, race, resistance, reactance, resistance index, height, weight, BMI, waist circumference, arm circumference (n=6467)
Model K: age, race, resistance, reactance, resistance index, height, weight, BMI, arm circumference (n=6467)
Model L: age, race, resistance, reactance, resistance index, height, weight, BMI, waist circumference (n=6467)
Model M: age, race, resistance, reactance, resistance index, (height), weight, BMI, triceps skinfold (n=6332)
Model N: age, race, resistance, reactance, resistance index, height, weight, BMI (n=6467)
Model O: age, race, resistance, reactance, resistance index, height, weight, BMI, arm length, leg length (n=6467)
Model P: age, race, resistance, reactance, resistance index, (height), weight, BMI, triceps skinfold, subscapular skinfold (n=5938)
Model Q: age, race, resistance, reactance, resistance index (n=6467)
Model R: age, race, resistance, reactance (n=6467)
Model S: (resistance), reactance, resistance index (n=6467)
Model T: (resistance), reactance (n=6467)
Model U: BMI (n=6467)

Table 3

Females: R^2 and RMSE overall and in subgroups in full sample, NHANES 1999–2004

Model[a]	Overall		Age: 8–19 years		Age: 20–49 years		Race/Ethnicity: White		Race/Ethnicity: Black		Race/Ethnicity: Mexican		Age * Race/Ethnicity: White-Girls		White-Women		Black-Girls		Black-Women		Mexican-Girls		Mexican-Women	
	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE
A	0.876	2.41	0.869	2.38	0.855	2.42	0.879	2.42	0.876	2.44	0.869	2.34	0.871	2.33	0.865	2.44	0.872	2.49	0.824	2.41	0.866	2.35	0.817	2.34
B	0.879	2.37	0.876	2.32	0.858	2.39	0.884	2.36	0.876	2.42	0.864	2.35	0.880	2.25	0.869	2.40	0.871	2.49	0.826	2.36	0.869	2.33	0.810	2.35
C	0.874	2.47	0.867	2.46	0.854	2.48	0.877	2.47	0.873	2.55	0.862	2.44	0.874	2.37	0.861	2.51	0.863	2.65	0.827	2.48	0.855	2.51	0.819	2.37
D	0.880	2.46	0.873	2.43	0.851	2.48	0.882	2.42	0.884	2.56	0.867	2.40	0.880	2.32	0.865	2.49	0.871	2.58	0.846	2.50	0.862	2.37	0.808	2.42
E	0.880	2.54	0.870	2.53	0.863	2.54	0.881	2.53	0.890	2.60	0.860	2.56	0.874	2.43	0.868	2.57	0.871	2.79	0.860	2.49	0.857	2.57	0.810	2.53
F	0.874	2.43	0.872	2.36	0.851	2.45	0.878	2.43	0.873	2.45	0.856	2.42	0.875	2.30	0.861	2.47	0.870	2.50	0.819	2.41	0.860	2.40	0.797	2.43
G	0.876	2.40	0.875	2.33	0.854	2.43	0.882	2.39	0.871	2.47	0.862	2.38	0.880	2.25	0.865	2.44	0.868	2.52	0.818	2.42	0.866	2.35	0.805	2.38
H	0.875	2.41	0.874	2.34	0.853	2.44	0.881	2.40	0.870	2.48	0.861	2.38	0.880	2.25	0.864	2.45	0.866	2.54	0.818	2.42	0.863	2.38	0.807	2.37
I	0.883	2.42	0.877	2.40	0.857	2.44	0.888	2.35	0.886	2.55	0.870	2.37	0.888	2.25	0.872	2.43	0.869	2.60	0.858	2.41	0.867	2.32	0.808	2.42
J	0.876	2.58	0.867	2.56	0.858	2.59	0.877	2.58	0.885	2.67	0.858	2.57	0.870	2.47	0.863	2.61	0.871	2.79	0.848	2.60	0.852	2.61	0.811	2.53
K	0.878	2.56	0.869	2.54	0.860	2.57	0.879	2.55	0.884	2.67	0.861	2.55	0.873	2.44	0.866	2.59	0.866	2.85	0.851	2.57	0.854	2.58	0.813	2.52
L	0.871	2.62	0.860	2.63	0.854	2.62	0.872	2.62	0.879	2.73	0.853	2.61	0.864	2.53	0.859	2.65	0.862	2.88	0.843	2.64	0.841	2.70	0.810	2.54
M	0.879	2.47	0.872	2.45	0.851	2.49	0.880	2.43	0.885	2.56	0.866	2.41	0.880	2.32	0.863	2.51	0.868	2.61	0.854	2.43	0.859	2.39	0.807	2.42
N	0.864	2.70	0.849	2.72	0.848	2.68	0.865	2.69	0.874	2.79	0.849	2.65	0.854	2.62	0.852	2.71	0.855	2.96	0.837	2.69	0.832	2.78	0.807	2.55
O	0.870	2.64	0.856	2.66	0.854	2.63	0.871	2.63	0.878	2.74	0.853	2.62	0.861	2.56	0.858	2.66	0.858	2.93	0.844	2.63	0.840	2.71	0.809	2.54
P	0.875	2.41	0.874	2.34	0.853	2.44	0.881	2.40	0.870	2.48	0.861	2.38	0.880	2.25	0.864	2.45	0.866	2.54	0.818	2.42	0.863	2.38	0.807	2.37
Q	0.255	6.32	0.138	6.50	0.177	6.23	0.243	6.38	0.356	6.30	0.312	5.66	0.124	6.42	0.187	6.37	0.220	6.86	0.212	5.91	0.181	6.13	0.167	5.31
R	0.250	6.34	0.139	6.50	0.175	6.24	0.242	6.39	0.344	6.35	0.297	5.72	0.130	6.40	0.185	6.37	0.216	6.88	0.218	5.89	0.177	6.14	0.166	5.32
S	0.207	6.52	0.142	6.49	0.162	6.29	0.205	6.54	0.277	6.67	0.239	5.96	0.133	6.39	0.170	6.43	0.221	6.85	0.201	5.95	0.176	6.15	0.141	5.39
T	0.207	6.52	0.142	6.49	0.162	6.29	0.205	6.54	0.277	6.67	0.239	5.96	0.133	6.39	0.170	6.43	0.221	6.85	0.201	5.95	0.176	6.15	0.141	5.39
U	0.682	3.85	0.633	3.99	0.650	3.75	0.706	3.76	0.690	3.83	0.670	3.67	0.663	3.77	0.685	3.72	0.664	4.02	0.588	3.92	0.629	3.92	0.589	3.45

[a]Candidate variables/indices not retained by the selection process are shown in parentheses

Model A: age, race, resistance, reactance, resistance index, (height), weight, BMI, triceps skinfold, subscapular skinfold, waist, calf circumference, (arm circumference), thigh circumference, (arm length), (leg length), menses (n=4031)

Model B: age, race, resistance, reactance, resistance index, (height), weight, BMI, triceps skinfold, subscapular skinfold, waist, calf circumference, (arm circumference), thigh circumference (n=4031)

Model C: age, race, resistance, reactance, resistance index, (height), weight, BMI, subscapular skinfold, waist circumference, calf circumference, arm circumference, thigh circumference (n=4159)

Model D: age, race, resistance, (reactance), resistance index, (height), (weight), BMI, triceps skinfold, waist circumference, (calf circumference), (arm circumference), thigh circumference (n=4509)

Model E: age, race, resistance, reactance, resistance index, (height), weight, BMI, waist circumference, calf circumference, arm circumference, thigh circumference (n=4888)

Model F: age, race, resistance, (reactance), resistance index, (height), (weight), BMI, triceps skinfold, subscapular skinfold, waist, calf circumference (n=4031)

Model G: age, race, resistance, reactance, resistance index, (height), weight, BMI, triceps skinfold, subscapular skinfold, waist, (arm circumference) (n=4031)

Model H: age, race, resistance, reactance, resistance index, (height), weight, BMI, triceps skinfold, subscapular skinfold, (arm circumference) (n=4031)

Model I: age, race, resistance, reactance, resistance index, (height), weight, BMI, triceps skinfold, waist circumference (n=4509)

Model J: age, race, resistance, reactance, resistance index, (height), weight, BMI, waist circumference, arm circumference (n=4888)

Model K: age, race, resistance, reactance, resistance index, (height), weight, BMI, arm circumference (n=4888)

Model L: age, race, resistance, reactance, resistance index, (height), weight, BMI, waist circumference (n=4888)

Model M: age, race, resistance, reactance, resistance index, (height), weight, BMI, triceps skinfold (n=4509)

Model N: age, race, resistance, (reactance), resistance index, (height), weight, BMI (n=4888)

Model O: age, race, resistance, reactance, resistance index, (height), weight, BMI, (arm length), (leg length) (n=4888)

Model P: age, race, resistance, reactance, resistance index, (height), weight, BMI, triceps skinfold, subscapular skinfold (n=4031)

Model Q: age, (race), resistance, reactance, (resistance index) (n=4888)

Model R: age, (race), resistance, reactance (n=4888)

Model S: resistance, (reactance), (resistance index) (n=4888)

Model T: resistance, (reactance) (n=4888)

Model U: BMI (n=4888)

Table 4

Comparison of four models to predict percent body fat or fat mass, NHANES 1999–2004

	R^2				RMSE			
	Percent Body Fat		Fat Mass		Percent Body Fat		Fat Mass	
Model[a]	Male	Female	Male	Female	Male	Female	Male	Female
W	0.662	0.743	0.890	0.947	3.63	3.46	2.94	2.42
X	0.813	0.801	0.933	0.957	2.70	3.05	2.30	2.19
Y	0.819	0.844	0.940	0.967	2.66	2.69	2.17	1.92
P	0.871	0.875	0.949	0.973	2.24	2.41	2.00	1.72

Model W: age, race, height, weight, BMI (n=5938 for males and n=4031 for females)

Model X: age, race, height, weight, BMI, triceps skinfold, subscapular skinfold (n=5938 for males and n=4031 for females)

Model Y: age, race, resistance, reactance, resistance index, height, weight, BMI (n=5938 for males and n=4031 for females)

Model P: age, race, resistance, reactance, resistance index, height, weight, BMI, triceps skinfold, subscapular skinfold (n=5938 for males and n=4031 for females)