Prediction of Fatness by Standing 8-Electrode Bioimpedance: A Multiethnic Adolescent Population

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The objective of this study was to validate an 8-electrode bioimpedance analysis (BIA_8) device (BC-418; Tanita, Tokyo, Japan) for use in populations of European, Maori, Pacific Island, and Asian adolescents. Healthy adolescents (215 M, 216 F; 129 Pacific Island, 120 Asian, 91 Maori, and 91 European; age range 12–19 years) were recruited by purposive sampling of high schools in Auckland, New Zealand. Weight, height, sitting height, leg length, waist circumference, and whole-body impedance were measured. Fat mass (FM) and fat-free mass (FFM) derived from the BIA_8 manufacturer's equations were compared with measurements by dual-energy X-ray absorptiometry (DXA). DXA-measured FFM was used as the reference to develop prediction equations based on impedance. A double cross-validation technique was applied. BIA_8 underestimated FM by 2.06 kg ($P < 0.0001$) and percent body fat (%BF) by 2.84% ($P < 0.0001$), on average. However, BIA_8 tended to overestimate FM and %BF in lean and underestimate FM and %BF in fat individuals. Sex-specific equations developed showed acceptable accuracy on cross-validation. In the total sample, the best prediction equations were, for boys: FFM (kg) = 0.607 height (cm)^2/impedance (Ω) + 1.542 age (y) + 0.220 height (cm) + 0.096 weight (kg) + 1.836 ethnicity (0 = European or Asian, 1 = Maori or Pacific) – 47.547, R^2 = 0.93, standard error of estimate (SEE) = 3.09 kg; and, for girls: FFM (kg) = 0.531 height (cm)^2/impedance (Ω) + 0.182 height (cm) + 0.096 weight (kg) + 1.562 ethnicity (0 = non-Pacific, 1 = Pacific) – 15.782, R^2 = 0.91, SEE = 2.19 kg. In conclusion, equations for fatness estimation using BIA_8 developed for our sample perform better than reliance on the manufacturer's estimates. The relationship between BIA and body composition in adolescents is ethnicity dependent.

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INTRODUCTION

The prevalence of obesity and overweight has increased in Westernized countries in the last few decades, and is continuing to rise (1–3). BMI is in popular use internationally to measure overweight and obesity in epidemiological studies. A limitation of BMI is that it does not distinguish between fat mass (FM) and non-FM. Thus, a very high BMI may be due to high body fat or high lean mass as a proportion of body weight. Because the relationship between BMI and fatness varies from one ethnic group to another, it is difficult to compare fatness across ethnic groups using BMI alone. For example, it has been shown that BMI overestimates body fat in Maori and Pacific Island girls (4) and underestimates body fat in Asians (5–7). Thus, there is a need to develop simple methods that more accurately monitor obesity levels in populations.

Bioimpedance analysis (BIA) allows body fat to be measured quickly and easily and is suitable for field use. The BIA equations for estimating fatness tend to be specific for the population in which they were developed and, therefore, need to be validated in the populations in which they are to be applied. A recently developed hand-to-foot BIA device is an 8-electrode BIA system (BIA_8) (8) that estimates body composition in the standing position, and provides both whole-body and segmental estimates of fatness. Thus, it is an attractive and convenient device that addresses the shortcomings of 4-electrode foot-to-foot BIA instruments which also allow measurements in the standing position but utilize a current pathway that bypasses the arms and trunk (9,10). The validity of BIA_8 has been investigated in Finnish adults (11) and white obese women (12,13) and these studies showed that the BIA_8 instrument underestimated FM (11,12) and percent body fat (%BF) (11–13) when compared with dual-energy X-ray absorptiometry (DXA). In a small study of US subjects with a wide range of BMI and age (6–64 years) (8), BIA_8, compared with DXA, showed good agreement but tended to overestimate %BF in the low %BF range and underestimate this measure at high %BF. More recently, a study of relatively lean (%BF<24%) West African children found that BIA_8 overestimated %BF determined by deuterium dilution (14).

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Few studies have assessed whether ethnicity influences the relationship between bioimpedance and body composition in adolescents (15,16). The validity of BIA_8 in a multiethnic adolescent sample, which includes the main ethnic groups of adolescents living in New Zealand (European, Maori, Pacific Island, and Asian), is unknown. Our objectives were to assess the validity of the BIA_8 estimates of FM in these populations against DXA as a reference and develop bioimpedance prediction equations for fat-free mass (FFM) that are applicable to these populations.

METHODS AND PROCEDURES

Subjects

Participants were recruited, either through school assemblies or with the help of student health groups, from local schools with a high percentage of Pacific Island students. Most were participating in the Pacific Obesity Prevention In Communities study (17). A nonrandom purposive sampling approach was carried out aimed at recruiting participants with a wide range of weight and height with participant numbers uniformly distributed across school-year, ethnic group (European, Maori, Pacific Island, and Asian), and gender. The only exclusion criteria were pregnancy and medication (such as growth hormone therapy) which could affect body composition. No participants indicated they were on diet treatment and none were excluded on the basis of their physical activity level. Ethnicity was defined by self-identification. Written consent was obtained from each participant. Ethical approval was obtained from the Regional Ethics Committee. A total sample size of at least 390 was required in order to detect ($\alpha = 0.05$, power = 80%) a 2% increment in the squared multiple correlation coefficient (R^2) (18).

Measurements

All measurements were performed by a single investigator (J.D.S.) at the Body Composition Laboratory in the Department of Surgery. Height (±0.1 cm) was measured with a stadiometer and waist circumference (±0.1 cm) with a standard, nonstretch tape at the level of the umbilicus. Body weight (±0.1 kg) in light clothing (estimated to nearest 0.05 kg) was measured using a BC-418 8-contact electrode BIA device (Tanita, Tokyo, Japan) and net body weight (body weight less clothing weight) was used for the analyses. The BIA device provided measurements of impedance (±1 Ω) and estimates of %BF (±0.1%), FM (±0.1 kg), and FFM (±0.1 kg). These measurements were carried out in a sequential order and then repeated in the same order. The average of each pair of measurements was used for the analyses. BIA measurements were carried out at a frequency of 50 kHz.

DXA whole-body scans were carried out using a pencil-beam scanner (model DPX+, software version 3.6y; GE Lunar, Madison, WI). Scan images were analyzed for total body FM, fat-free soft tissue mass, and bone mineral content (BMC). DXA FFM was calculated as the sum of fat-free soft tissue mass and BMC. %BF was calculated from the DXA measurements as 100 × FM/(FM + FFM).

Leg length was calculated as the sum of the lengths of the femur and tibia bones measured on the right side using the pixeled DXA image. Femur bone length was measured from the top of the greater trochanter to the middle patellar surface, and tibia bone length was measured from the superior intercondylar eminence to the inferior surface of the medial malleolus. Sitting height was measured as the vertical distance from the apex of the cranium to the top of the greater trochanter. Dimensions were measured in pixels and converted to centimeters based on a DXA scan of a standard ruler.

Statistical analysis

Data were analyzed using SAS version 9.1 (SAS Institute, Cary, NC). Descriptive statistics were produced for age, height, sitting height, leg length, weight, BMI, FFM, FM, %BF, BMC and waist circumference, and are expressed as mean ± s.d. Differences between ethnic groups for each sex were examined by pairwise comparisons using Tukey's test.

Stepwise linear regression and "all-possible subsets" regression procedures were used to develop prediction equations. The potential predictor variables that were used to develop the equations were weight, height (H), sitting height (SH), leg length (LL), age, impedance (Z), impedance index based on height (H^2/Z), sitting height (SH^2/Z) and leg length (LL^2/Z), sex (0 = boys, 1 = girls), ethnicity (coded as three dummy variables for Maori, Pacific, and Asian with European as the reference category), and waist circumference. Potential interactions between ethnicity and the other variables and between age and height were examined. Mallow's Cp statistic (Cp) (19) and the Schwarz-Bayesian criterion (20) were used as measures of the appropriate number of predictors. High adjusted R^2 values, small standard errors of estimate (SEEs), Cp values close to the number of predictors in the model, and minimum Schwarz-Bayesian criterion indicated optimal models. These equations were examined for the significance of the regression coefficients. A variance inflation factor was calculated to assess the stability of each estimated coefficient in the prediction equations. Large variance inflation factor values (>10) imply considerable inter-relationships (collinearity) among the independent variables and such equations tend to be sample specific. Residual analysis was used to check the assumptions of linear regression analysis.

A double cross-validation was carried out in which the total sample (stratified for sex) was randomly divided into two equal-sized groups (groups 1 and 2), an equation was developed in each group, and the other group was used to cross-validate each equation. Equality of the regression slopes for boys and girls was tested for statistical significance by testing the addition of an interaction term consisting of the product of sex and the independent variable. Separate equations were developed for each sex if the slopes were found to differ. If the equations were similar in the two groups with comparable cross-validation performance, a single equation was developed. Covariance analysis was used to compare the regression models in the two groups. Pure error, calculated as the square root of the mean of the squared differences between the measured and predicted FFM, was used to examine the accuracy of the predictive equations on cross-validation. This error should be similar to the value of the SEE for the same equation for the group from which it was developed.

The performance of equations was assessed based on the correlation between measured and predicted values (Pearson correlation coefficient), the concordance between these (concordance correlation coefficient (21)), their difference (bias, expressed as mean ± s.d., tested against zero using paired *t*-tests), the limits of agreement (expressed as 2 s.d. above and below the bias) and the dependence of the bias on the mean of measured and predicted values (both assessed on Bland–Altman plots (22)), and the pure error. Statistical significance was set at $P < 0.05$.

RESULTS

A total of 432 participants were measured. One Maori boy was not able to be accommodated within the DXA scanning area and a dual-scanning approach was attempted. Because this resulted in a large difference (>3 kg) between scale weight and DXA weight (sum of FM, fat-free soft tissue mass, and BMC), he was excluded from further analysis. The ethnic composition of the final sample (215 male, 216 female) was 91 European (37 male), 91 Maori (45 male), 129 Pacific Island (73 male), and 120 Asian (61 male). The Asian group comprised 90 Indians (49 male), 8 Vietnamese (4 male), 5 Cambodians (3 male), 4 Chinese (1 male), 4 Filipinos (2 male), 2 Laotians (1 male), 2 Pakistani females, 2 Afghan females, 1 South Korean male, 1 Thai female, and 1 Malaysian female.

The mean difference between scale weight and DXA weight was 0.00 ± 0.59 (s.d.) kg (a histogram of the differences is provided in the **Supplementary Figure S1** online). Physical characteristics and DXA body composition results are detailed in

Table 1. Compared to European boys, Pacific boys were heavier, had a higher BMI, and had more FFM and BMC. Asian boys were shorter with lower sitting height and FFM than European boys and, compared to Maori and Pacific boys, were shorter, lighter, had lower sitting height, BMI, FFM, and BMC, and a smaller waist circumference. Maori and Pacific girls had a higher BMI, and higher BMC than European girls. Pacific girls were also heavier, had higher FFM, and a larger waist circumference than European girls. Asian girls were shorter, lighter, and had a lower sitting height, FFM, and BMC than all other girls. Asian girls also had a lower BMI, lower FM, and a smaller waist circumference compared to Maori and Pacific girls, a smaller leg length than Pacific girls, and less %BF than Maori girls.

The manufacturer's estimates and DXA measurements of FM, %BF, and FFM were strongly correlated (r = 0.97, 0.92, and 0.96, respectively). The concordance correlation coefficients for these respective comparisons were 0.93, 0.85, and 0.94. Bland–Altman analysis (Figure 1) showed that, on average, the manufacturer's predictions underestimated FM by 2.06 ± 3.57 kg (P < 0.0001) and tended to overestimate FM at low FM values and underestimate at high FM values. The differences between the manufacturer's estimates and the DXA measurements of FM (BIA_8 − DXA) were negatively correlated with the average of these two measures (r = −0.62, P < 0.0001). On average, the manufacturer's predictions underestimated %BF by 2.84 ± 4.70% (P < 0.0001) and tended to overestimate %BF at low %BF values and underestimate at high %BF values (r = −0.59, P < 0.0001, Figure 1). The manufacturer's predictions overestimated FFM by 2.61 ± 3.46 kg (P < 0.0001), on average. These patterns were seen in each sex/ethnicity subgroup.

After data splitting, equations were developed for each sex because the regression coefficients of the best-fitting lines differed significantly between boys and girls. FFM prediction equations developed in groups 1 and 2 for each sex are shown in Table 2 and, for each sex, the same predictors entered into both equations. The predictors for boys were: H^2/Z, weight, height, age, and ethnicity (0 = European or Asian, 1 = Maori or Pacific); and, for girls: H^2/Z, weight, height, and ethnicity (0 = non-Pacific, 1 = Pacific). For boys, waist circumference was a significant predictor but had very high collinearity with weight. Z, LL^2/Z, SH^2/Z, LL, and SH did not add significantly to the equation. For girls, Z, LL^2/Z, SH^2/Z, LL, SH, age, waist circumference, and other ethnicity variables were not significant. The regression models developed in group 2 were used to predict FFM in group 1. In group 1, there was no significant difference between the predicted FFM and the measured FFM in boys (54.12 ± 10.64 and 53.87 ± 11.07 kg, respectively; P = 0.41, limits of agreement for this difference: −5.94 and +6.44 kg) and girls (41.31 ± 7.27 and 41.52 ± 7.70 kg, respectively; P = 0.34, limits of agreement for this difference: −4.34 and +4.76 kg). Similarly, the equations developed in group 1 were used to predict FFM in group 2. In group 2, the predicted FFM did not

Table 1 Physical characteristics and body composition of participants by ethnic group

	Boys				Girls			
	European (n = 37)	Maori (n = 44)	Pacific (n = 73)	Asian (n = 61)	European (n = 54)	Maori (n = 47)	Pacific (n = 56)	Asian (n = 59)
Age (years)	15.4 ± 1.2 (13.4–18.1)	15.7 ± 1.6 (13.2–18.3)	15.9 ± 1.3 (13.2–18.5)	15.6 ± 1.3 (13.4–17.9)	15.5 ± 1.4 (12.9–18.4)	15.9 ± 1.4 (13.2–18.1)	15.8 ± 1.4 (13.3–19.1)	16.0 ± 1.5 (13.4–19.5)
Height (cm)	173.5 ± 9.0 (140.7–188.1)	173.5 ± 8.3 (156.7–191.3)	174.2 ± 6.8 (154.6–192.4)	167.8 ± 8.2[a–c] (148.0–186.9)	164.4 ± 6.3 (147.7–176.3)	164.2 ± 8.5 (137.7–179.5)	165.6 ± 7.1 (150.7–186.3)	157.9 ± 5.3[a–c] (145.1–170.4)
Leg length (cm)	83.9 ± 5.1 (69.3–94.6)	82.9 ± 4.5 (73.9–92.2)	83.8 ± 3.7 (74.1–91.8)	82.0 ± 4.8 (70.1–92.2)	78.6 ± 4.0 (69.2–87.5)	78.0 ± 5.1 (63.4–89.8)	79.1 ± 4.2 (71.0–90.4)	76.6 ± 4.8[c] (62.9–91.6)
Sitting height (cm)	83.1 ± 4.4 (67.2–92.2)	83.9 ± 4.0 (74.9–95.0)	83.7 ± 3.6 (72.0–90.2)	79.5 ± 4.2[a–c] (68.2–86.4)	80.1 ± 3.2 (73.0–87.3)	80.5 ± 4.5 (66.2–87.4)	81.0 ± 3.6 (73.0–90.2)	76.2 ± 2.7[a–c] (68.2–83.4)
Weight (kg)	69.5 ± 19.2 (41.8–110.4)	76.3 ± 19.0 (43.6–126.2)	80.6 ± 18.3[a] (44.2–141.2)	60.8 ± 17.5[b,c] (32.4–116.6)	62.8 ± 15.6 (36.9–101.8)	70.2 ± 18.7 (47.3–124.3)	72.2 ± 14.4[a] (48.4–118.6)	52.4 ± 10.6[a–c] (36.3–90.0)
BMI (kg/m^2)	22.9 ± 5.1 (16.7–35.3)	25.2 ± 5.3 (17.8–36.5)	26.4 ± 4.9[a] (18.0–41.8)	21.4 ± 5.1[b,c] (13.9–34.5)	23.1 ± 5.0 (15.2–34.4)	25.8 ± 5.4[a] (18.3–41.6)	26.3 ± 4.8[a] (18.5–42.2)	21.0 ± 3.8[b,c] (15.0–32.4)
Fat-free mass (kg)	52.0 ± 8.6 (29.5–68.7)	56.9 ± 10.2 (37.6–81.9)	61.1 ± 10.5[a] (34.8–83.9)	45.8 ± 8.8[a–c] (26.1–72.6)	40.1 ± 5.2 (29.2–51.2)	42.9 ± 7.3 (25.6–59.2)	45.6 ± 6.0[a] (31.8–69.0)	34.7 ± 4.4[a–c] (27.5–46.7)
Fat mass (kg)	17.7 ± 13.2 (3.8–46.5)	19.7 ± 12.1 (5.3–46.8)	19.9 ± 11.3 (6.9–56.2)	15.0 ± 12.1 (2.4–54.0)	22.4 ± 11.7 (4.9–50.0)	27.1 ± 13.1 (12.7–66.6)	26.4 ± 10.4 (9.1–54.7)	17.4 ± 7.7[b,c] (6.3–45.4)
Body fat (%)	23.0 ± 11.1 (7.1–43.2)	23.8 ± 10.1 (9.6–48.1)	23.3 ± 8.7 (11.5–48.9)	22.3 ± 12.1 (6.6–52.4)	33.8 ± 9.7 (13.5–51.3)	37.1 ± 8.5 (22.0–54.4)	35.5 ± 7.5 (18.7–53.8)	32.1 ± 8.2[b] (16.2–51.4)
Bone mineral content (kg)	2.7 ± 0.5 (1.6–3.6)	3.0 ± 0.6 (1.8–4.5)	3.3 ± 0.6[a] (1.6–4.6)	2.4 ± 0.5[b,c] (1.1–3.6)	2.3 ± 0.4 (1.5–2.9)	2.6 ± 0.5[a] (1.5–4.0)	2.8 ± 0.4[a] (1.9–3.8)	2.0 ± 0.3[a–c] (1.4–2.8)
Waist circumference (cm)	82.4 ± 13.7 (63.7–114.5)	84.5 ± 14.3 (64.7–118.9)	84.5 ± 12.2 (66.4–128.6)	77.1 ± 14.2[b,c] (56.9–119.0)	79.7 ± 13.2 (60.8–113.7)	84.4 ± 14.9 (65.4–129.3)	85.9 ± 12.4[a] (64.7–122.3)	73.8 ± 9.3[b,c] (58.9–103.8)

Mean ± s.d., range in parentheses.
[a]P < 0.05 vs. European of same sex; [b]P < 0.05 vs. Maori of same sex; [c]P < 0.05 vs. Pacific Island of same sex.

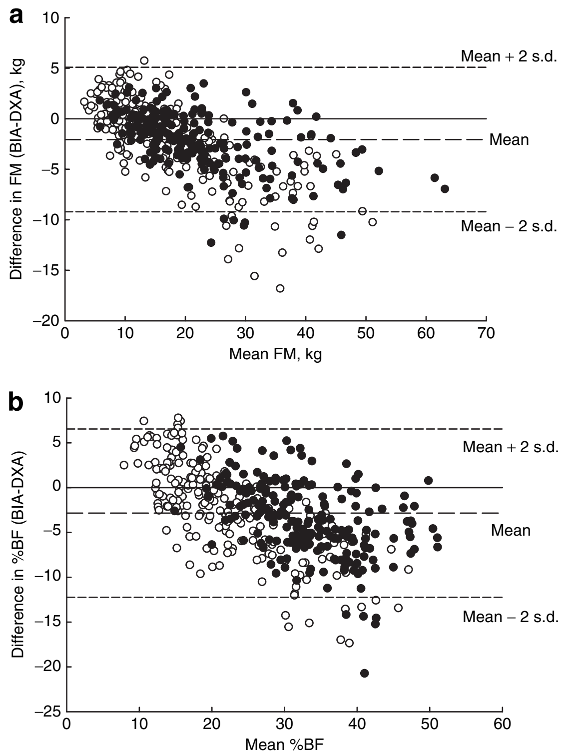

Figure 1 Differences in (**a**) fat mass (FM) and (**b**) percent body fat (%BF) measured by dual-energy X-ray absorptiometry (DXA) and estimated by bioimpedance analysis (BIA, Tanita BC-418) in 215 boys (open circles) and 216 girls (filled circles).

differ significantly from the measured FFM in boys (54.47 ± 11.35 kg vs. 54.76 ± 11.81 kg, respectively; $P = 0.33$, limits of agreement for this difference: −6.42 and +5.84 kg) and girls (40.07 ± 5.98 kg vs. 39.84 ± 6.26 kg, respectively; $P = 0.25$, limits of agreement for this difference: −4.36 and +3.90 kg).

Table 2 summarizes the cross-validation results and it is apparent that, for each sex, the R^2, SEE, and pure error values are similar between the two groups. For each sex, regressions of predicted FFM on measured FFM developed for each group were almost identical with similar deviations from the line of identity (boys: slope = 0.92 for group 1 and slope = 0.93 for group 2; girls: slope = 0.91 for group 1 and slope = 0.89 for group 2). Therefore, single equations using all 215 boys and 216 girls were developed (**Table 2**). Regression analysis with FFM as the dependent variable and the predictors as the independent variables (H^2/Z, age, height, weight, and Maori/Pacific ethnicity for boys; H^2/Z, height, weight, and Pacific ethnicity for girls) in the two combined groups, using group as a dummy variable, showed no group effect in the relation ($P = 0.53$ for boys and $P = 0.47$ for girls). The equation for boys explained 93% of the variance in FFM and H^2/Z alone explained 86% of the variability. The equation for girls explained 91% of the variability in FFM and H^2/Z alone accounted for 87%. The concordance correlation coefficients for predicted vs. measured FFM, FM, and %BF were, respectively, 0.96, 0.96, 0.90 (boys) and 0.95, 0.98, 0.91 (girls). There was no difference between predicted and measured FFM for boys (limits of agreement: −6.11 to +6.11 kg) and girls (limits of agreement: −4.33 to +4.33 kg). Further, there was no difference between measured and

Table 2 Prediction equations based on BIA

	Boys	Girls
Group 1	$n = 108$	$n = 108$
Measured FFM (kg)	53.87 ± 11.07	41.52 ± 7.70
FFM prediction equation	$0.608\ H^2/Z + 1.670\ A + 0.202\ H + 0.092\ W + 2.043\ E_b - 46.476$ $R^2 = 0.92$, SEE = 3.14 kg, CV = 5.8%	$0.542\ H^2/Z + 0.190\ H + 0.090\ W + 1.507\ E_g - 16.966$ $R^2 = 0.91$, SEE = 2.31 kg, CV = 5.6%
Predicted FFM (kg)	53.87 ± 10.63	41.52 ± 7.36
Cross-validation using group 2 participants' FFM	54.12 ± 10.64 kg, pure error = 3.09 kg, CV = 5.7%	41.31 ± 7.27 kg, pure error = 2.27 kg, CV = 5.5%
Group 2	$n = 107$	$n = 108$
Measured FFM (kg)	54.76 ± 11.81	39.84 ± 6.26
FFM prediction equation	$0.594\ H^2/Z + 1.410\ A + 0.233\ H + 0.105\ W + 1.710\ E_b - 47.511$ $R^2 = 0.93$, SEE = 3.11 kg, CV = 5.7%	$0.517\ H^2/Z + 0.174\ H + 0.102\ W + 1.554\ E_g - 14.435$ $R^2 = 0.89$, SEE = 2.10 kg, CV = 5.3%
Predicted FFM (kg)	54.76 ± 11.42	39.84 ± 5.91
Cross-validation using group 1 participants' FFM	54.47 ± 11.35 kg, pure error = 3.06 kg, CV = 5.6%	40.07 ± 5.98 kg, pure error = 2.07 kg, CV = 5.2%
Groups 1 & 2 combined	$n = 215$	$n = 216$
Measured FFM (kg)	54.31 ± 11.43	40.68 ± 7.05
FFM prediction equation	$0.607\ H^2/Z + 1.542\ A + 0.220\ H + 0.096\ W + 1.836\ E_b - 47.547$ $R^2 = 0.93$, SEE = 3.09 kg, CV = 5.7%	$0.531\ H^2/Z + 0.182\ H + 0.096\ W + 1.562\ E_g - 15.782$ $R^2 = 0.91$, SEE = 2.19 kg, CV = 5.4%
Predicted FFM (kg)	54.31 ± 11.01	40.68 ± 6.71

A, age (years); CV, coefficient of variation; E_b: 0 = European or Asian, 1 = Maori or Pacific; E_g: 0 = non-Pacific, 1 = Pacific; FFM, fat-free mass (kg); H, height (cm); SEE, standard error of estimate; W, weight (kg); Z, impedance (Ω).

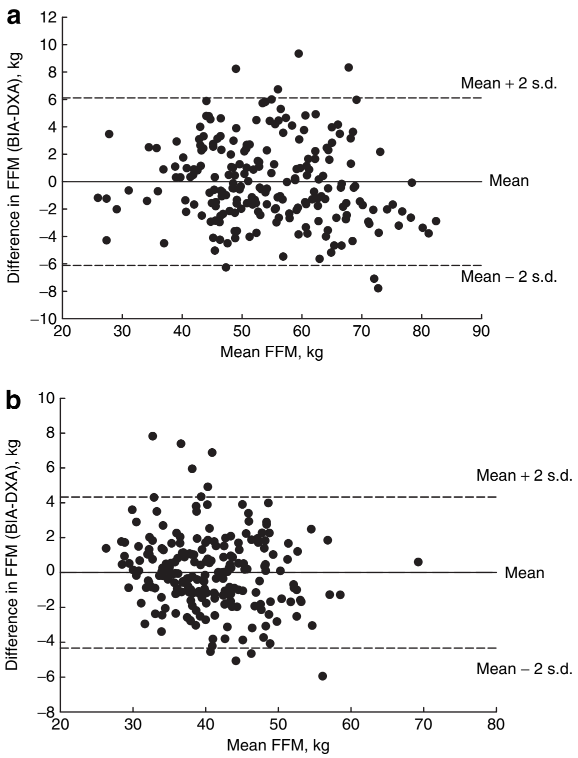

Figure 2 Differences in fat-free mass (FFM) measured by dual-energy X-ray absorptiometry (DXA) and estimated by bioimpedance analysis (BIA) using new equations developed in 215 boys (**a**) and 216 girls (**b**).

predicted FFM in each sex/ethnicity subgroup. For both boys and girls, absolute differences between measured and predicted FFM were randomly distributed around the mean difference (**Figure 2**). Bland–Altman plots assessing agreement for FM and %BF also showed good agreement between measured and predicted values (data not shown).

DISCUSSION

The BIA_8 instrument provides hand-to-foot bioimpedance measurements for subjects in the standing position and is therefore a practical field method for estimating body composition. We found that the manufacturer's equations were not valid for the estimation of body fat in European, Maori, Pacific Island, and Asian adolescents. The manufacturer's equations tended to overestimate FM (both absolute and percent) at low body fatness and underestimate this parameter at high fatness levels. On average, BIA_8 underestimated FM and %BF and overestimated FFM.

To our knowledge this is the first study to examine the validity of BIA_8 in a multiethnic group of adolescents. Our study extends other work on the applicability of the BIA_8 instrument which showed that this machine underestimated FM (12) and %BF (12,13) in obese adult females. These results are consistent with our findings and those of Pietrobelli *et al.* (8) in a study of males and females aged 6–64 years in which BIA_8 tended to overestimate %BF in leaner subjects and underestimate in fatter subjects. A larger study of 133 Gambian children (5–17 years) showed that BIA_8 overestimated %BF (derived by isotope dilution) toward the lower end of %BF (14). In our multiethnic sample we found that this dependence of the BIA_8 measurement bias on fatness level also applied within each sex and ethnic group. A recent study in both normal- and overweight adults showed that the BIA_8 instrument underestimated %BF (11).

Apart from the study that used isotope dilution (14), these published studies and our own used DXA as the reference body composition method. Although DXA, regarded as a gold standard for bone measurement, is not without limitations for body fat estimation (23), it is widely available and more easily applied and acceptable to volunteers than other reference methods such as those based on hydrodensitometry or isotope dilution. The four-compartment model (24), as the preferred reference technique, has rarely been applied in children and adolescents for the development of equations based on BIA (25). DXA and isotope dilution have been widely used as is evident from the summary provided by Nielsen *et al.* (26). The latter approach, however, requires consideration of the variation in hydration of the FFM with maturation (27) and with adiposity (28) whereas DXA provides estimates of FM which are relatively independent of hydration (28). Bray *et al.* (28), in their children's study, have compared performance of several equations developed from BIA measurements in children with their body composition results based on multiple techniques including DXA, isotope dilution, skinfold anthropometry, and the four-compartment model.

BIA technology is designed to estimate total body water and provides only an indirect measure of FFM. FFM composition is affected by maturational stage (29) and rate of maturation may differ between ethnic groups. We did not measure pubertal status, which may have improved predictive accuracy. However, we are not aware of any published studies in healthy adolescents that have included pubertal status in BIA prediction equations with the exception of Horlick *et al.* (30), where Tanner stage was included in the model for a multiethnic group of 4–18–year olds.

FFM was our outcome variable rather than FM or %BF, because of the functional relationship between bioimpedance and the hydrated lean tissue of the body. Using body weight, our equations can easily be used to calculate FM and %BF. Although our equations were developed across a wide %BF range, their predictions of FM and %BF showed good agreement with measurements by DXA. To the best of our knowledge, fatness-specific equations have not been developed for adolescents.

In both of our equations, H^2/Z explained a high proportion of the variability in FFM (86% for boys, 87% for girls). As there may be differences in relative leg lengths between populations (31) and differences in body geometry may affect the electrical properties of the body (32), we measured leg length and sitting height and found that, consistent with previous work (4), they did not add significantly to the models developed. Age was a significant predictor for our equation for boys but not for girls. In both sexes, Pacific Islanders (and Maori boys) had more FFM than Europeans and Asians (and Maori girls), after controlling for all other predictors. This ethnic effect is not surprising, as previous work suggests that, compared to Europeans, Pacific Island children enter puberty or mature earlier (33–35) and are leaner for a given body size (4). In adults, for the same BMI, Maori (36,37) and Pacific Islanders (36–39) have less FM or %BF than Europeans or Asian Indians. A multiethnic (black, white, and other races) sample of adolescent girls was also studied by Phillips *et al.* (15) and the equations they developed based on BIA prediction of FFM (derived by isotope dilution) were similar to those of the current study. In both premenarcheal and postmenarcheal girls the best predictors found by Phillips *et al.* (15) were height^2/resistance, weight, height, black race, and other race. In our study, for the same impedance index, height, and weight, Pacific Island girls have 1.6 kg more FFM than European, Maori, and Asian girls. This result is similar to that found in the study of girls aged 10–15 years by Going *et al.* (16), in which prediction equations for adolescent girls from different ethnic groups (black, Hispanic, white, and other races) were developed (with pubertal status not accounted for) and for the same age, weight, and height^2/resistance, black girls had ~1.6 kg more FFM compared to non-black girls.

One recent study of abdominally obese women (40) showed that BIA_8 was not superior to either a 4-electrode BIA system, BMI or waist circumference in detecting metabolic risk factors. However, in participants in that study (40), BIA_8 did not provide valid estimates of FM and %BF (12). Our equations may have a role in epidemiological studies designed to predict health risk from fatness; however, cohort studies are required that demonstrate that %BF is a better predictor of obesity-related morbidity than BMI.

In conclusion, we have developed, using a double cross-validation procedure, robust equations for body fat estimation using an 8-electrode BIA device that are applicable to European, Maori, Pacific Island, and Asian adolescents in the 12–19-year age range. Our equations perform better than reliance on the manufacturer's estimates and show that ethnicity is important in BIA prediction of body fat in adolescents. As BMI does not differentiate between fat and lean mass and is not an equivalent measure of fatness across ethnic groups (4–7, 36–39), these equations have particular value for multiethnic adolescent populations (17), where a more accurate assessment of fatness is needed. Longitudinal studies are required to show if, in adolescents, our equations can accurately determine individual changes in body composition.

SUPPLEMENTARY MATERIAL

Supplementary material is linked to the online version of the paper at http://www.nature.com/oby

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DISCLOSURE

The authors declared no conflict of interest.

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