ORIGINAL ARTICLE

Anthropometric predictors of body fat in a large population of 9-year-old school-aged children

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Summary

Objective

To develop and cross-validate predictive models for percentage body fat (%BF) from anthropometric measurements [including BMI z-score (zBMI) and calf circumference (CC)] excluding skinfold thickness.

Methods

A descriptive study was carried out in 3,084 pre-pubertal children. Regression models and neural network were developed with %BF measured by Bioelectrical Impedance Analysis (BIA) as the dependent variables and age, sex and anthropometric measurements as independent predictors.

Results

All %BF grade predictive models presented a good global accuracy (≥91.3%) for obesity discrimination. Both overfat/obese and obese prediction models presented respectively good sensitivity (78.6% and 71.0%), specificity (98.0% and 99.2%) and reliability for positive or negative test results (≥82% and ≥96%). For boys, the order of parameters, by relative weight in the predictive model, was zBMI, height, waist-circumference-to-height-ratio (WHtR) squared variable (_Q), age, weight, CC_Q and hip circumference (HC)_Q (adjusted $r^2 = 0.847$ and RMSE = 2.852); for girls it was zBMI, WHtR_Q, height, age, HC_Q and CC_Q (adjusted $r^2 = 0.872$ and RMSE = 2.171).

Conclusion

%BF can be graded and predicted with relative accuracy from anthropometric measurements excluding skinfold thickness. Fitness and cross-validation results showed that our multivariable regression model performed better in this population than did some previously published models.

Keywords: Anthropometry, body fat grade models, prediction equations, children.

Introduction

Childhood obesity is a worldwide epidemic and World Health Organization European Region studies indicate Portugal as the country with the highest rate of overweight among 7 to 9-year-old children (1).

There is evidence supporting improved outcomes for interventions aiming at early detection and correction of overweight (2,3). Frequently, Body Mass Index (BMI) [weight (kg) / height (m)^2] is used as a screening tool of obesity. However, as all methods based on weight and height, the major limitation is its inability to distinguish weight status from adiposity (4,5).

Ideally, the definition of childhood obesity should accurately reflect body fat and have cut-off points to predict adverse health effects (6,7). Because children are constantly growing, this task becomes more difficult than in adults and any measure of excess weight need to be adjusted to age (6,7).

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Accurate methods to assess adiposity [e.g, densitometry, dual-energy x-ray absorptiometry (DXA), computed tomography] are not suitable for use as a screening tool (8). As an alternative, anthropometric measurements, such as BMI, waist circumference (WC), hip circumference (HC), mid-upper arm circumference (MUAC), calf circumference (CC) and subcutaneous skinfold thickness [triceps (TSF) and subscapular (SSF)] can be performed easily, quickly, inexpensively, reliably and can be used in epidemiologic studies (8). However, there is no general consensus on the reliance, use and application of single anthropometric indices as identifiers of adiposity in children (6). Therefore, specific predictive equations of %BF from several anthropometric measurements have been developed in children (9–13). However Goran *et al.* (10) failed in validating Slaughter equation, reason why they derived a new one. Dezenberg *et al.* (11) also found that both Goran (10) and Slaughter (13) equations did not accurately predict fat mass in a heterogeneous group of children. Furthermore, these cross-validated equations are skinfold dependent, which has many disadvantages such as not being recommended for children of the same age and sex with BMI >95th percentile (14,15).

Therefore, the present study's main objective is to develop new, sex-specific, %BF predictive models derived from simple anthropometric measurements excluding skinfold thickness. Prior to the determination of %BF, all children were also assessed for overweight (as defined by BMI) (16,17) and overfatness (as defined by bioimpedance estimates of body fatness) (18) with specifically developed %BF grade prediction models. Using %BF cut-offs, children were categorized into four grades ('underfat', 'normal', 'overfat' and 'obese') (18) or only into two grades ('overfat/obese' and 'others' or only 'obese' and 'others'). Such models were built for obesity screening purposes using simple anthropometric measurements. Finally, the predictive model was cross-validated and compared with previously published models.

Methods

Study design and participants

The descriptive and the multivariable regression analysis here reported are part of a Project titled 'Nutritional, Biochemical and Genetic Study of an Overweight and Obese Children Population in the Southern Region', approved by the Directorate General of Health, the Ministry of Science and Education and also by the Ethics Committee of the Hospital Garcia de Orta, according to Helsinki Declaration. The project was carried out from January of 2009 to June 2013 in a population of prepubertal children (based on Tanner stage) recruited from 87 public schools of Lisbon and Tagus Valley urban region and included anthropometric, BIA, biochemical and genetic analysis.

To be included in the study, the children should have completed 9 years of age during the ongoing school year, with the exact chronologic ages calculated in days, as the date of examination minus birth date. This assumption reduced the initial population of 5,989 to 5,577 children. The age criteria was applied because it is a late enough age for obesity rebound and because, at this age, there is less possibility of spontaneous regularization of corpulence (19).

Children transferred to another school, missing the minimal required measurements or whose parents abandoned participation were also excluded, leaving 5,514 children. All children's parents were required to give informed consent to participate in the study. Because of lack of consent for some of the procedures, especially venous blood draws (out of the scope of this specific study), the number of children enrolled was reduced to 3,084 (Figure 1).

Anthropometric and bioelectrical impedance analysis

Clinical procedures were carried out at school under the guidance of two pediatric specialists, which had previously been assessed for the equivalence of their measuring performance. All anthropometric measurements were taken with participants dressed in lightweight clothing and without shoes.

Height was measured to the nearest 0.1 cm at the end of a deep inspiration (20) (stadiometer – Seca 217, Hamburg, Deutschland). Weight was measured to the nearest 0.1 kg (digital calibrated scale – Seca 899). zBMI was determined using the least mean squares method (21) and was used to categorize subjects as 'thin' (grades 1, 2 and 3), 'normal weight', 'overweight' or 'obese' according to World Obesity/Policy and Prevention (International Obesity Task Force – IOTF) cut-offs (16,17).

The following circumference measurements, also taken, to the nearest 0.1 cm, with the tape snug but not compressing the skin, were made using a flexible and inextensible tape (Seca 203)

MUAC was measured on the upper left arm, flexed at 90°, at the midpoint between the acromion and the olecranon (20). CC was measured at the point of the widest diameter of the calf (20). Both measurements were taken while participants were sitting. WC and HC were measured in the standing position, with the first at umbilicus level (22) at the end of normal expiration and
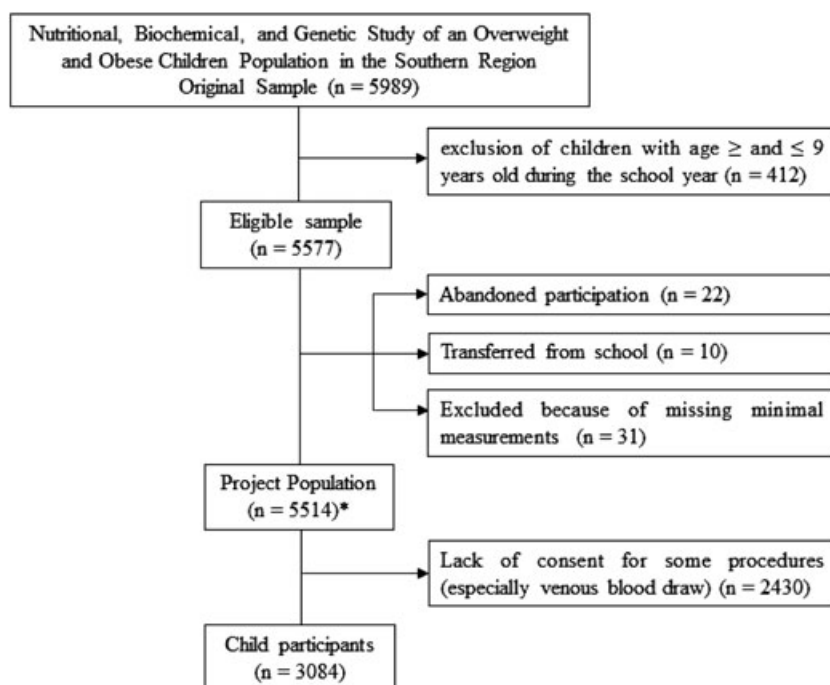
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Figure 1 Flowchart of child participation in the study. *Project population sample was used to characterize the nutritional status of the population.

the second at the widest part of the hip at the level of the great trochanter (20). Waist–hip ratio (WHR) was defined as WC/HC. WHtR was defined as WC/height.

Skinfold thickness was measured with a Harpender Skinfold Caliper (West Sussex, UK) at two sites (TSF and SSF), was read twice and the mean value was recorded. Whenever the two values differed greatly, a third measurement was made. Measurements were recorded by one observer for the left side of the body (20) to the precision of ±0.5 mm. For the measurement of TSF, the midpoint of the back of the upper arm between the tips of the olecranon and the acromion processes was determined with the arm flexed at 90° (20). The SSF was measured at immediately below the inferior angle of the scapula (20). Centrality index was defined as SSF/TSF.

Tetrapolar whole-body BIA (measured with Omron BF 511 – 500 mÅ, 50 KHz, Kyoto, Japan) was used to evaluate %BF, percentage of skeletal muscle (%SM) and resting metabolic rate (RMR), all of which have been validated previously in children against Magnetic Resonance Imaging findings (23). Children were measured 2 h or more after breakfast according to the manufacturer instructions. For the assessment of adiposity, based on bioimpedance, four grades ('underfat', 'normal', 'overfat' and 'obese') were defined using McCarthy body fat reference curves for children and adolescents (18).

Statistical analysis

Descriptive statistic, group comparison tests, modeling and associated plots were performed using SPSS 23.0 (IBM corp., Armonk, NY, US). Missing data were ignored and outliers were included in the statistics.

Because parametric assumptions were not met across all groups, Spearman correlations evaluated the relationship between the anthropometric measures and both BMI z-score and %BF, and Kruskal–Wallis ANOVA, Mann–Whitney ranks and Mood's median tests were used for group comparisons. A Mann–Whitney multi-comparison test was applied in groups with a case size above 20. For smaller groups, differences were evaluated through Hedge's g effect size.

Next, and for cross-validation purposes, the sample was split, for each model, into two different sets with %BF stratification: 70% of the sample was randomly selected from %BF strata and allocated to a model-training sample set, while the remaining 30% was allocated to a validation sample set. Anthropometric features, measured %BF and other characteristics of each set were compared through Mann–Whitney test to check for homogeneity between the two groups. Models for %BF grade classification and for %BF value prediction were built and evaluated.

Percentage BF grade predictors were developed using the measured anthropometric variable's training data

through multinomial/binomial logistic regression and neural network (NN) analysis and the outcomes were further evaluated through Bayesian analysis. The global working sample size was dependent on the selected variables and is reported in Table 2 for each obesity grade predictor. Finally, to build a %BF predictive model the best candidate parameter was pre-selected through a stepwise forward, based on the Akaike information criterion across 1,000 bootstrap regression models. This bagging procedure required no missing values for all the candidate variables reducing the available sample to 2,201 children. This sample were split in two different sets: 70% were randomly assigned from %BF strata to a model-training set, while the remaining 30% were allocated to a cross-validation set. To build a linear regression, a model training set was used, choosing the final model parameters through stepwise forward. Model fitness was evaluated through root mean square error (RMSE) and adjusted r^2. Root mean square prediction error (RMSPE) and the measured *versus* predicted adjusted r^2 were used as cross-validation performance indexes to validate each model development step.

Furthermore, our %BF measurements were compared with %BF values calculated from previously published %BF prediction equations. Most of these equations required skinfold thickness data, reducing the working sample to 603 children. Cross-validation indexes such as the mean predicted %BF, the measured *versus* predicted adjusted r^2 as well as the RMSPE were calculated. Significant differences between the predicted and measured %BF were screened by the paired Student's *t* test. Statistical significance was considered when $p < 0.05$. The equations that were used in the comparison were Slaughter *et al.* (13), Goran *et al.* (10), Dezenberg *et al.* (11) and Marrodán *et al.* (24), because their parameters are included in those used in this study.

Results

A population sample of 5,514 schoolchildren (2,772 boys and 2,742 girls) with mean age 9.75 ± 0.57 years was characterized anthropometrically. Results showed that according to IOTF definition, 6.2% were 'underweight' (thinness grades 1, 2 or 3), 66.1% were 'normal weight', 27.6% were 'overweight' including 6.9% 'obese' (Table S1).

Mean values of anthropometric characteristics, with the exception of BMI, zBMI, WHR and %SM, were significantly higher in girls than in boys (Mann–Whitney, $p < 0.05$) (Tables 1 and S1).

The ethnic composition of the sample subjects was 87.4% Caucasian, 11.3% Afro-Portuguese and 1.3% other ethnicities. Differences between ethnicities were found in WC, HC, WHR, %BF and %SM (Kruskal–Wallis, $p < 0.05$), with Afro-Portuguese children having lower values, but being higher than Caucasian children (Mann–Whitney, $p < 0.05$) (Table 1).

Like zBMI, %BF was also categorized by adiposity grades. Differences were noticed for height (between 'underfat', 'normal' and 'overfat' and also between 'overfat' and 'obese' groups), WHR and SSF (both between 'underfat' and 'normal' groups) (Table S2). Figure 2 illustrates how sample size was dependent on the selected variables.

There were different strengths in the association between %BF and the measured anthropometric variables. Results indicates that all parameters, except WHR ($r = 0.307$) and %SM ($r = 0.462$), showed a strong correlation with %BF. Nevertheless, zBMI ($r = 0.935$), BMI ($r = 0.902$) and WHtR ($r = 0.838$) presented the highest values (Table S3). Scatter plots between %BF and anthropometric parameters (Figure S1) were constructed to further explore these relationships. Because most scatter plots demonstrate a slight upward curve, just like the one present in the association between %BF and zBMI (Figure 3), four non-linear models (quadratic, cubic, logarithmic and exponential) were compared. The linear, quadratic and cubic presented the highest squared correlation values (Table S4). Because no meaningful difference was found and for simplicity, quadratic models were selected.

For the creation of screening models, all anthropometric measurements (including quadratic functions of the parameters) as well as age and sex were taken into account. However, only the variables that contributed most to the classification model, and the associated cross-validation performance results, are presented in Table 2. Results indicate that the NN model failed to classify children who were in the 'underfat' grade (18.8% correctly predicted) and, in less extension, those in the 'overfat' grade (56.7% correctly predicted). In contrast to the previous model, the multinomial logistic model (MLM) approach showed a higher accuracy in classifying 'underfat' grade children. The global cross-validation results of the two models show that both are very strong obesity grade predictors: 91.3% for NN *versus* 91.4% for MLM. Individual analyses of each group demonstrate that NN is a better classification predictor for 'normal' and 'obese' grades. Most significant differences are found in the 'underfat' and 'overfat' grade groups (18.8% and 56.7% for NN, 43.1% and 58.7% for MLM, respectively).

For the creation of only two grades screening models ('overfat/obese' or exclusively 'obese' child grades), a binomial logistic regression was built. The results indicate that when BMI *z*-score, WHtR, WC, weight, height and sex parameters were used, 95.1% of children belonging

Table 1 Descriptive characteristics (by sex and ethnicity) of the study sample

| | Sex | | | | Ethnicity | | | | | | | | |
| | Male | | Female | | Caucasian | | Afro-Portuguese | | Others | |
Characteristic	n	Mean ± SD	n	Mean ± SD	n	Mean ± SD	n	Mean ± SD	n	Mean ± SD
Age[¥]	1,487	9.78 ± 0.58*	1,597	$9.73 \pm 0{,}56$*	2,560	$9.71 \pm 0.57_a$	331	$9.88 \pm 0.65_a$	37	$9.69 \pm 0.55_a$
Weight (kg)	1,487	$35.26 \pm 8{,}45$**	1,597	35.57 ± 8.35**	2,560	$35.31 \pm 8.47_a$	331	$36.15 \pm 8.32_a$	37	$34.56 \pm 7.75_a$
Height (cm)	1,487	138.3 ± 6.99*	1,597	138.2 ± 7.33*	2,560	$137.9 \pm 7.12_a$	331	$140.8 \pm 7.27_b$	37	$137.1 \pm 7.64_a$
BMI (kg/m(2))	1,487	18.44 ± 3.18**	1,597	18.24 ± 3.19**	2,560	$18.37 \pm 3.21_a$	331	$18.08 \pm 3.09_a$	37	$18.23 \pm 3.01_a$
BMI z-score	1,487	0.60 ± 1.08**	1,597	0.66 ± 1.06**	2,560	$0.64 \pm 1.07_a$	331	$0.50 \pm 1.12_a$	37	$0.63 \pm 0.98_a$
WC (cm)	1,368	64.75 ± 8.84**	1,444	65.68 ± 9.25**	2,382	$65.33 \pm 9.15_a$	294	$63.76 \pm 8.27_b$	34	$64.51 \pm 9.0_{a,b}$
HC (cm)	1,078	71.03 ± 7.81**	1,158	72.53 ± 8.00**	1,955	$71.8 \pm 7.89_a$	235	$72.2 \pm 8.45_a$	27	$68.9 \pm 7.0_a$
WHR (WC/HC)	1,078	0.90 ± 0.05**	1,158	0.89 ± 0.06**	1,955	$0.90 \pm 0.06_a$	235	$0.88 \pm 0.05_b$	27	$0.90 \pm 0.04_a$
WHtR (WC/height)	1,368	0.47 ± 0.05**	1,444	0.48 ± 0.06**	2,385	$0.47 \pm 0.57_a$	294	$0.45 \pm 0.05_b$	34	$0.47 \pm 0.05_a$
MUAC (cm)	1,368	$20.94 \pm 2{,}94$**	1,444	21.32 ± 2.74**	2,385	$21.2 \pm 2.85_a$	294	$21.3 \pm 2.80_a$	34	$20.4 \pm 2.43_a$
CC (cm)	1,368	29.08 ± 3.25*	1,444	29.09 ± 3.27*	2,385	$29.1 \pm 3.29_a$	294	$28.9 \pm 3.14_a$	34	$28.4 \pm 3.15_a$
TSF (mm)	284	12.65 ± 6.47**	319	13.99 ± 5.51**	522	$13.53 \pm 5.95_a$	63	$12.21 \pm 6.54_a$	14	$12.7 \pm 6.43_a$
SSF (mm)	284	9.53 ± 6.68**	319	11.13 ± 6.70**	522	$10.42 \pm 6.75_a$	63	$10.51 \pm 7.22_a$	14	$8.92 \pm 4.40_a$
BF (%)	1,368	21.22 ± 7.34**	1,457	22.34 ± 7.88**	2,380	$22.03 \pm 7.62_a$	295	$20.31 \pm 7.90_b$	35	$21.72 \pm 6.83_a$
SM (%)	1,368	32.56 ± 2.79**	1,457	31.41 ± 2.52**	2,380	$31.84 \pm 2.71_a$	295	$32.89 \pm 2.63_b$	35	$31.36 \pm 2.54_a$
RMR (Kcal/day)	1,368	$1{,}237 \pm 120.96$**	1,457	$1{,}185 \pm 95.42$**	2,380	$1{,}209 \pm 112.85_a$	295	$1{,}223 \pm 103.29_b$	35	$1{,}185 \pm 110.94_a$

[¥]Age in days were converted in years for a better comparison between groups.

*Distribution (mean ranks) and medians are the same between groups – Mann–Whitney ($p > 0.05$) and Mood's median test ($p > 0.05$).

**Distributions are different between groups – Mann–Whitney ($p < 0.05$) and mean test ($p < 0.05$). Distribution (mean ranks) are different between groups with different letters: a, b [Mann–Whitney ($p < 0.05$)]. The test of significance adjustments was made using Dunn–Bonferroni correction. BF (body fat), BMI (body mass index), CC (calf circumference), HC (hip circumference), MUAC (mid upper arm circumference), RMR (resting metabolic rate), SM (skeletal muscle), SSF (subscapular skinfold thickness), TSF (triceps skinfold thickness), WC (waist circumference), WHR (waist–hip ratio) and WHtR (waist circumference-to-height-ratio).
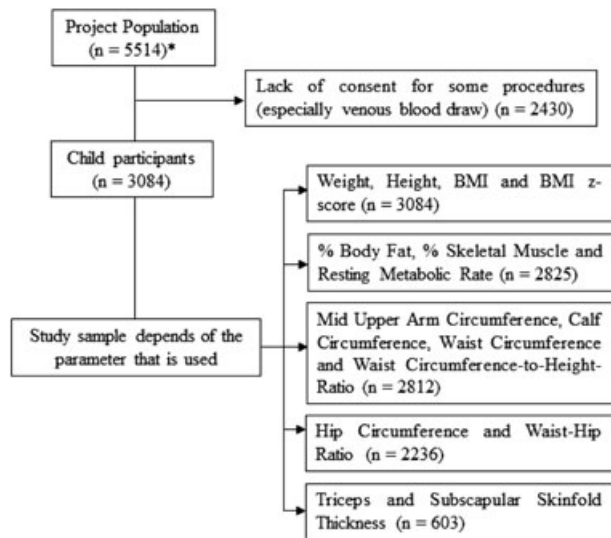
Figure 2 Flowchart of child participation in the study according to the anthropometric and BIA parameters that were selected. *Project population sample was used to characterize the nutritional status of the population.

to the 'overfat/obese' grade were correctly classified. This model presented a posterior probability of correct positive and negative test results of 87% (95% confidence interval [CI]: 83%–91%) and 96% (95% CI: 96%–97%), respectively. On the other hand, to accurately classify 97.9% of the children as belonging to the 'obese' grade, only the BMI z-score, WC, WHR, weight and height parameters were required (Table 2). These latter screening model results showed that 82% (95% CI: 73%–88%) of the children with a positive result were effectively into the 'obese' grade and 99% (95% CI: 98%–99%) that presented a negative result were not.

Finally, a %BF predictive model was developed and validated using simple anthropometric variables. In the
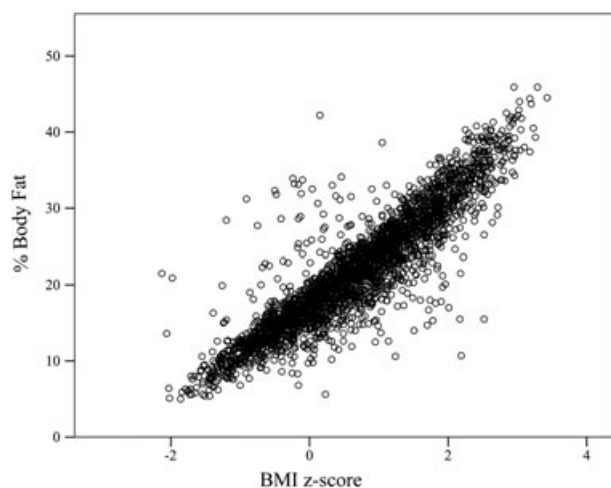

Figure 3 Scatter plots between %BF and BMI z-score.

resulted set of bootstrap models zBMI, WHtR and WHtR_Q (importance: 0.114, 0.0842 and 0.0807, respectively) were globally the best predictors, with SSF and TSF (importance: 0.0516 and 0.0500, respectively) presenting a relatively smaller predictive power (Table S5). The %BF predictive models for both sexes and the stepwise cross-validation of the %BF predictive equations are shown in Table 3. The training and validation subsamples did not differ significantly in %BF and anthropometric measurements (Kruskal–Wallis, $p > 0.05$ for every parameter; data not shown).

The results indicate that, for boys, BMI z-score, height, squared WHtR, age, weight, squared CC and squared HC are the variables that most contributed to the adjusted r^2 positive alterations (Table 3). The final step predictive equation is, therefore: $22.589 + (3.776 \times$ BMI z-score$) - (0.426 \times$ height$) + (12.038 \times$ waist circumference-to-height-ratio_Q$) + (0.001 \times$ age$) + (0.482 \times$ weight$) - (0.043 \times$ calf circumference_Q$) + (2.229 \times$ calf circumference$) + (0.001 \times$ hip circumference_Q$)$; adjusted $r^2 = 0.847$, RMSE = 2.852.

For girls, the preferred model includes BMI z-score, waist circumference-to-height-ratio_Q, height, age, hip_Q and calf_Q circumferences (Table 4). The final step predictive equation is: $23.628 + (6.195 \times$ BMI z-score$) + (19.689 \times$ waist circumference-to-height-ratio_Q$) - (0.180 \times$ height$) + (0.004 \times$ age$) + (0.001 \times$ hip circumference_Q$) + (0.03 \times$ calf circumference_Q$)$; adjusted $r^2 = 0.872$, RMSE = 2.717.

The predictive parameters for the equations account for 84.7% and 87.2% of the %BF variance (adjusted r^2) in the training sample set for boys and girls, respectively. Figure 4 shows the predicted and measured %BF values for boys and girls in the validation subsample using the predictive models showed in Table 4. In addition, this table compares cross-validation results obtained with our equation, with those from previously published predictive equations (10,11,13,24). In contrast to our equation, most of these previous equations have in common the use of skinfold thickness and none of their predictions fitted very well our data, with RMSE/RMSPE below 3%. Only ours and Slaughter's equation (13) presented estimated mean values not significantly different from the measured %BF mean. However, our equation shows a better identity fit (adjusted $r^2 = 0.947$) with smaller prediction errors (RMSE = 1.989 and RMSPE = 2.915) than all tested previous published equations.

Discussion

Our study demonstrates that, based on a relatively large sample of pre-pubertal children, predictive models for %

Table 2 %BF obesity grade prediction models

	Accuracy (%)*		Accuracy (%)*; Specificity (%)*; Sensitivity (%)*	
%BF grade	Neural networks (*n* = 2,202)	Multinomial logistic regression (*n* = 2,759)	Binomial logistic regression (overfat/obese) (*n* = 2,216)	Binomial logistic regression (obese) (*n* = 2,216)
Underfat	18.8	43.1	—	—
Normal	98.0	97.7	—	—
Overfat	56.7	58.7	95.1; 98.0; 78.6	—
Obese	74.2	73.2	—	97.9; 99.2; 71.0
Global	91.3	91.4	—	—
Selected variable	1, 2, 3, 4, 5, 6, 7, 8, 9	1, 3, 6, 7, 10, 11	1, 2, 3, 6, 8, 12	1, 2, 3, 6, 8

Selected variables: (1) weight, (2) height (cm), (3) BMI *z*-score, (4) hip circumference (cm), (5) calf circumference (cm), (6) waist circumference-to-height-ratio, (7) age (in days), (8) waist circumference (cm), (9) mid upper arm circumference (cm), (10) squared BMI *z*-score and (11) squared waist circumference-to-height-ratio, 12 (sex).
*Shown results are related to the performance of each model in the validation sample set. BMI (body mass index).

Table 3 Stepwise cross-validation of %BF predictive equation from anthropometric measurements with measured *versus* predicted data

	Training set		Validation set	
Stepwise model predictors	Adjusted *r*²	RMSE (%)	Adjusted *r*²	RMSPE (%)
Boys (*n* = 759 in the training set and 301 in validation subsample)				
BMI *z*-score	0.807	3.209	0.762	3.612
BMI *z*-score, height	0.828	3.033	0.806	3.248
BMI *z*-score, height, waist circumference-to-height-ratio_Q	0.837	2.947	0.817	3.162
BMI *z*-score, height, waist circumference-to-height-ratio_Q, age	0.840	2.918	0.821	3.134
BMI *z*-score, height, waist circumference-to-height-ratio_Q, age, weight	0.842	2.907	0.823	3.120
BMI *z*-score, height, waist circumference-to-height-ratio_Q, age, weight, calf circumference_Q	0.844	2.886	0.823	3.121
BMI *z*-score, height, waist circumference-to-height-ratio_Q, age, weight, calf_Q and calf circumferences	0.846	2.870	0.823	3.117
BMI *z*-score, height, waist circumference-to-height-ratio_Q, age, weight, calf_Q, calf and hip_Q circumferences	0.847	2.852	0.823	3.110
Girls (*n* = 778 in the training set and 363 in validation subsample)				
BMI *z*-score	0.831	3.117	0.832	3.226
BMI *z*-score, waist circumference-to-height-ratio_Q	0.852	2.915	0.856	2.996
BMI *z*-score, waist circumference-to-height-ratio_Q, height	0.860	2.832	0.861	2.929
BMI *z*-score, waist circumference-to-height-ratio_Q, height, age	0.869	2.747	0.865	2.902
BMI *z*-score, waist circumference-to-height-ratio_Q, height, age, hip circumference_Q	0.870	2.731	0.868	2.868
BMI *z*-score, waist circumference-to-height-ratio_Q, height, age, Hip_Q and calf_Q circumferences	0.872	2.717	0.869	2.867

r (correlation coefficient), RMSE (root mean square error), RMSPE (root mean square prediction error), _Q (squared variable). Candidate predictors included age (in days), BMI *z*-score [body mass index (kg/m²)], height (in cm), calf and hip waist circumferences (in cm), waist circumference-to-height-ratio and weight (in kg).

BF can be developed from anthropometric measurements excluding skinfold thickness.

The data shows that both zBMI (*r* = 0.935) and BMI (*r* = 0.902) have the strongest correlation with %BF, which

Table 4 Comparison of current study model and previously published equations performances to predict %BF

(n = 603)	Predicted %BF	Adjusted r^2	RMSE (%)	RMSPE (%)
Current model [§]	21.588 ± 7.326	0.947	1.765	2.915
Goran *et al.* (10)	20.430 ± 5.219[¥]	0.675	4.358	5.427
Dezenberg *et al.* (11)	25.559 ± 5.865[¥]	0.592	4.875	6.673
Slaughter *et al.* (13)	21.027 ± 8.680	0.704	4.156	5.406
Marrodán *et al.* (24)	24.235 ± 6.098[¥]	0.634	4.625	5.744

[§]This predicted versus measured regression was built using the same sample (n = 603) that was used for the previously published equations cross-validation. *r* (measured versus estimated %BF identity regression Spearman coefficient correlation), RMSE (root mean square error), RMSPE (root mean square prediction error), SD (standard deviation), [¥] significantly different from measured %BF mean (21.370 ± 7.642).

is consistent with Pecoraro *et al.* (25) (*r* = 0.92 for BMI); however, Boeke *et al.* (26) (*r* = 0.81 for BMI and zBMI) and Gutin *et al.* (*r* = 0.82 for BMI) (27) presented lower correlation results. This may be because of the fact that these authors have studied small sample sizes or because they used bipolar impedance (28).

Recent studies have also tried to determine which measure – WC, HC, WHC or WHtR – is better suited for the diagnosis of overfatness; however, until now, there has been no general agreement (14,29–31). The study here reported shows that all these variables, with the exception of WHR, are strongly correlated with %BF, with WHtR presenting the highest correlation. Watts *et al.* (15) found strong correlations between DEXA total body fat and BMI (*r* = 0.86), WC (*r* = 0.81) and HC (*r* = 0.88). Bigorna *et al.* (32) showed that BMI and WC had a high correlation and similar accuracies as predictors of adiposity. However, Aeberli *et al.* showed that WC performed slightly better than BMI in predicting %BF (29). On the

contrary, to Brambilla *et al.* (30), WHtR is a better predictor of adiposity than WC or BMI.

One of the main results of our study, to the best of our knowledge, is the first validated body fat grade predictor model that can be used as a screening tool for obesity.

Both, NNs and multinomial logistic regression models, were shown to be very strong obesity grade predictors (global accuracy ≥ 91.3%). However, the later model showed 2.29 times more sensitivity in classifying children in the 'underfat' grade (presenting similar accuracy in the other grade categories) and has the advantage of only requiring weight, height, WC and age. In contrast, NNs require the same parameters, plus CC, HC and MUAC.

Binomial logistic regression indices have also demonstrated a very good global accuracy, with a high specificity and sensitivity. To classify children into the 'overfat/obese' grade, or exclusively into the 'obese' grade, only three direct measurements are needed: weight, height and WC. The obese screening model also requires sex as a parameter.

Another major contribution of this work is the development of a cross-validated %BF predictive equation that, to the best of our knowledge, is the first developed in children that includes zBMI and CC as predictors and excludes the use of skinfold thickness. There are advantages in this exclusion because skinfold thickness has several problems: (i) it has higher errors at higher levels of adiposity (14,15); (ii) it lacks high-quality calibrated calipers (15); (iii) it requires highly trained anthropometrists (15); and (iiii) as demonstrated by our study, it has relatively small %BF predictive power. Furthermore, the results of this study suggest the need of sex-specific equations only requiring, for both sexes, small and simple anthropometric measurements (height, weight, WC, HC and CC), as well as age (in days).
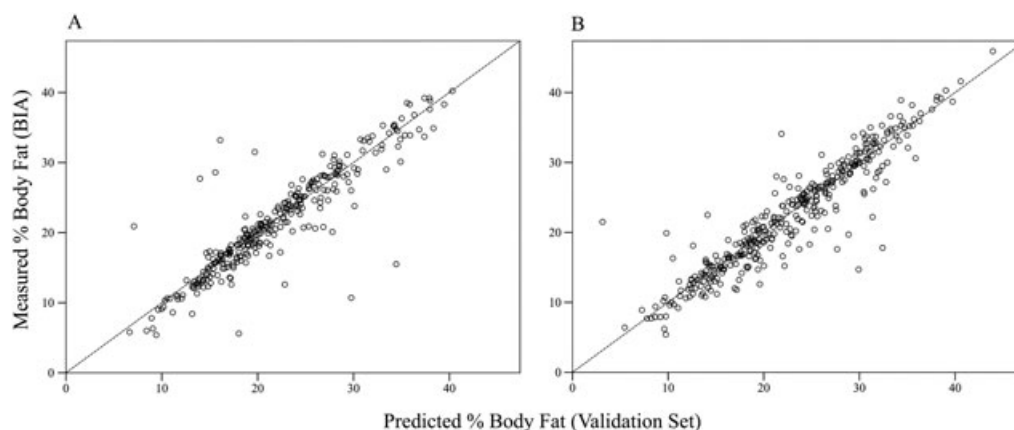

Figure 4 Scatter plot between %BF measured by BIA and validation set predicted %BF [A, male model (cross-validation *n* = 301); B, female model (cross-validation *n* = 363)]. Dotted line shows the identity regression (Y = X).

The equations developed by Slaughter et al. (13), Goran et al. (10), Dezenberg et al. (11) and Marrodán et al. (24) were also applied in the present study. This last equation was selected because of being exclusively based on WHtR. However, the predictor's choice was based on previous studies' findings, which have no general consensus between authors, and was not cross-validated.

The results of this study also show that ours and Slaughter's equations (13) have both a significant agreement between predicted and measured %BF. The remaining equations underestimate or overestimate %BF (Table 4). Furthermore, our equation presented a higher fitness than Slaughter's, as demonstrated by the better respective adjusted r^2, RMSE and RMSPE, when applied to the cross-validation sample subset.

Several other studies have also explored the validation of these equations in their own populations. Hussain et al. (33) in 99 Pakistani children (9–19 years old) concluded that Slaughter's equation (13) presented a reasonable correlation with DXA measured %BF, while Goran's (10) and Dezenberg's (11) equations underestimate and overestimate, respectively, %BF. L'Abbée et al. (34) also reported an overestimation of %BF in a sample of 30 Dutch children (6–7 years old) by the Dezenberg equation (11) compared to the isotope dilution technique. However, for Nasredinne et al. (12), these three predictive equations underestimated %BF in pre-pubertal Lebanese children. Huang et al. (35) also indicated that the Dezenberg predictive equation (11) is not appropriate in predicting total body fat in Latin children.

Differences in lifestyles, cultural background and environmental living conditions between populations may be the reason for the above described poor fitness of prior developed models to different populations. Although our models were cross-validated (which is not the case in the others), for the same reasons, it may also result in its sub-optimal generalization. Therefore, they will also need to be validated in other populations before extrapolations are warranted.

In conclusion, %BF can be graded and predicted with reasonable accuracy, in children with characteristics similar to the ones from our sample, from anthropometric measurements even excluding skinfold thickness. Fitness and cross-validation results showed that our multivariable regression models performed better in this population than did previously published models.

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Disclosure

The authors declared no conflict of interest.

Author contributions

SA, JMF and FF designed the study; SA, FPF, MEF and LRS conducted anthropometric and BIA measurements; PM performed statistical analysis; SA and JMF wrote the manuscript under the guidance of FPF; JCF, MM and MV critical reviewed the preliminary draft of this manuscript. All authors read and approved the final manuscript.

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Supporting Information

Supplementary Table 1. Anthropometric characteristics and sex distribution of the project population (n = 5,514).
Supplementary Table 2. Physical characteristics distributed by adiposity grades.
Supplementary Table 3. Anthropometric correlations with obesity indices.
Supplementary Table 4. Anthropometric fitting models of %BF.
Supplementary Table 5. Importance of predictors for %BF.
Supplementary Figure 1. Scatter plots correlating %BF and anthropometric parameters