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Original article

New bioelectrical impedance analysis equations for children and adolescents based on the deuterium dilution technique

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SUMMARY

Background and aims: Body composition in childhood is not only a marker of the prevalence of obesity, but it can also be used to assess associated metabolic complications. Bioelectrical impedance analysis (BIA) shows promise as an easy to use, rapid, and non-invasive tool to evaluate body composition. The objectives of this study were to: (a) develop BIA prediction equations to estimate total body water (TBW) and fat-free mass (FFM) in European children and early adolescents and to validate the analysis with the deuterium dilution as the reference technique and (b) compare our results with previously published paediatric BIA equations.

Methods: The cohort included 266 healthy children and adolescents between 7 and 14 years of age, 46% girls, in five European countries: Bosnia and Herzegovina, Latvia, Montenegro, North Macedonia, and Portugal. TBW and FFM were the target variables in the developed regression models. For model development, the dataset was randomly split into training and test sets, in 70:30 ratio, respectively. Model tuning was performed with 10-fold cross-validation that confirmed the unbiased estimate of its performance. The final regression models were retrained on the whole dataset.

Results: Cross-validated regression models were developed using resistance index, weight, and sex as the optimal predictors. The new prediction equations explained 87% variability in both TBW and FFM. Limits of agreement between BIA and reference values, were within ±17% of the mean, (−3.4, 3.7) and (−4.5, 4.8) kg for TBW and FFM, respectively. BIA FFM and TBW estimates were within one standard deviation for approximately 83% of the children. BIA prediction equations underestimated TBW and FFM by 0.2 kg and 0.1 kg respectively with no proportional bias and comparable accuracy among different BMI-for-age subgroups. Comparison with predictive equations from published studies revealed varying discrepancy rates with the deuterium dilution measurements, with only two being equivalent to the equations developed in this study.

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Conclusions: The small difference between deuterium dilution and BIA measurements validated by Bland–Altman analysis, supports the application of BIA for epidemiological studies in European children using the developed equations.
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1. Introduction

Childhood overweight and obesity is associated with an elevated risk of later development of non-communicable diseases. Excess body fat, rather than the body weight *per se*, is responsible for the metabolic disturbances leading to disease [1]. Body mass index (BMI) is typically used to assess overweight and obesity in population-wide surveys. Although useful, especially in non-clinical settings, it is prone to misleading results as it measures presumed excess weight for a given height, rather than actual body fat and fails to discriminate fat mass from fat-free mass, particularly in childhood [2]. To that end, various techniques have been developed to better evaluate body composition *in vivo* [3]. Deuterium dilution is the reference method for measurement of total body water (TBW) to calculate fat-free mass (FFM) and fat-mass (FM) (2-compartments model) but is not suitable for routine use. Dual energy x-ray absorptiometry (DXA) is often the preferred method in the clinics, yielding accurate values of body fatness over a wide range of body sizes and types [4]. However, it requires high-cost scanners and trained personnel. Deuterium dilution and DXA may be combined in the 4-compartment model of body composition as the acknowledged gold standard assessment [5]. Yet, the deuterium dilution technique is a practical, cost-effective reference method that is suitable in point-of-care testing.

Bioelectrical impedance analysis (BIA) is a well-known technique for the assessment of body composition since it is portable, quick, relatively inexpensive, and non-invasive. Bioelectrical impedance measurements of body composition are based on the principle that impedance (i.e., the inverse of electrical conductivity) of human body is dependent on body water volume and concentrations of charged ions (resistivity of body water). Since FFM contains virtually all the water and conducting electrolytes in the body, FFM and FM can be discriminated based on the body impedance. Although popular, the clinical benefit of BIA has been questioned due to accuracy ambiguities that stem from the inherent limitations of the technique, the confusion between statistically significant and clinically relevant differences, and the lack of standardization of the experimental protocols [6–9].

Validation of BIA prediction equations of TBW and FFM against the deuterium dilution technique has been applied in children of different age, ethnicity, health status, and weight [10–16]. However, body composition differs substantially between children and adults, and it is not straightforward to integrate children's growth patterns into BIA equations [17,18]. Furthermore, concerns still exist that prediction equations are population specific [19] and that body size-to-age sensitivity of impedance vectors can possibly affect the accuracy of TBW predictions [20] suggesting that BIA measurements should be validated for specific ethnicities and populations. In this study, we address these challenges by developing and validating BIA equations for the prediction of TBW and FFM in European children (including early adolescents) using the dilution of deuterium oxide (D_2O) as the reference technique. Furthermore, we contrast our findings with previously published paediatric BIA equations.

2. Materials and methods

2.1. Participants

A total of 290 healthy children and adolescents aged between 7.3 and 14.5 years, participated in the study from five European countries: Bosnia and Herzegovina (BIH), Latvia (LVA), Montenegro (MNE), North Macedonia (MKD), and Portugal (PRT). Twelve participants were excluded from the analysis due to inconsistent TBW measurements validated against BMI-for-age z-score (BMIZ) [21] ($n = 10$ participants excluded with TBW>70% of body weight and a BMIZ > -0.4 and $n = 2$ participants excluded with TBW<40%). Twelve more outliers were identified from the exploratory statistical analysis and by examining the normalised and studentized residuals plots. The final cohort ($n = 266$) consisted of 45 participants from BIH, 18 from LVA, 144 from MNE, 22 from MKD, and 37 from PRT. A methodological/experimental protocol of the study was presented at all recruitment sites. Most of the participants were recruited at schools (65%) while some at health centres (13%), sports clubs (9%), at research institutes (10%) and a small group (3%) at home. Criteria for inclusion were self-reported healthy participants. Their parents or guardians were informed about the protocol of the study and signed a consent form before the enrolment. Ethical committees and relevant authorities within each country approved the common experimental protocol which was discussed and confirmed by experts prior to the experiments, among all countries that participated in the International Atomic Energy Agency (IAEA) funded programme "Applying Nuclear Techniques to Design and Evaluate Interventions to Prevent and Control Obesity in Adolescents in South-Eastern Europe". All measurements were conducted following standardized operating procedures as follows.

2.2. Anthropometric measurements

Weight and height measurements followed international standardized procedures [22] and were taken in triplicate, and the average was considered as the final value. For weight, the participants were barefoot, with light clothes, and values were measured to the nearest 0.1 kg with a calibrated scale. Height was measured in triplicate to the nearest 0.1 cm with a stadiometer. Each country used a different model of scale and stadiometer. The coefficient of variation (CV) of repeated measurements was below 1% for all countries. BMI was calculated as kg/m^2.

2.3. BIA measurements

Resistance (R), reactance (Xc), and impedance (Z) at 50 kHz were measured by: Impedimed DF50 (Impedimed Ltd, San Diego, CA, USA) ($n = 189$ samples from BIH and MNE) and BodyStat 1500MDD (Bodystat Ltd, UK) ($n = 77$ samples from LVA, MKD, and PRT). Participants were asked to be normally hydrated, to refrain from eating and exercise approximately 2 h before the test and to empty their bladder. Instruments were calibrated at the beginning of the day as per manufacturer's instructions. Participants were

barefoot and without wearables on the wrist. Measurements were performed in triplicate (CV < 1%) for 93% of the samples and once for the remaining7%, in the supine position on a non-conducting surface, with hands extended away from the trunk and feet away from each other. Disposable adhesive AgCl gel electrodes were placed on the dorsal sites of ankle, foot, wrist, and hand via guide cables after cleaning the skin with 70% alcohol solution. Specifically, the drive electrodes were positioned at the dorsal surface of the third metacarpal of the hand and the dorsal surface of the third metatarsal of the foot while the voltage sense electrodes were fixed to the dorsal surface of the wrist and between the lateral and medial malleoli of the ankle. All values were reported in Ω.

2.4. Deuterium oxide (D_2O) dilution

Isotope dilution experiments were carried out according to the guidelines of the IAEA [23]. Briefly, participants were asked to empty their bladder and a pre-dose saliva sample was collected from each child using a cotton ball. Then, a weighed amount of approximately 0.1 g D_2O per kg body weight in the form of 10% dilution of D_2O (99.8%, Cambridge Isotope Laboratories, Inc., MA, USA) was given to each participant ensuring that all the amount was ingested by rinsing twice with 50 ml of drinking water. Approximately 3.5 h after dosing a post-dose saliva sample was collected to measure the enrichment of body water with D_2O. All samples were stored at −20 °C. For the analysis, saliva samples were thawed at room temperature, centrifuged, and measured by Fourier transform infrared spectroscopy (FTIR, Agilent 4500 Series) that was specifically calibrated for quantitative D_2O analysis. All spectra were recorded in duplicate. TBW (kg) was calculated from the dilution of the deuterium dose (i.e., dose consumed (mg)/post-dose D_2O enrichment (mg/kg)) divided by 1.041 to adjust for the non-aqueous hydrogen exchange between the deuterated water (HDO) and the body tissues [23]. FFM was derived by assuming constant body hydration and applying an age- and sex-specific hydration factors for water content of FFM [24] ranging from 0.755 to 0.748 in this age group. FM was then determined by subtracting FFM from body weight.

2.5. Statistical analysis

TBW and FFM were designated as target variables due to the functional relationship between resistance and the hydrated lean tissue of the body. Analysis was divided into three parts: (i) data preparation, where data integrity was checked, cross-checked for methodological errors, and outliers were identified, (ii) exploratory data analysis and ordinary least squares (OLS) fitting where linearity between the dependent (TBW or FFM) and independent variables was confirmed in the absence of multicollinearity among the predictors along with homoscedasticity of the errors, and (iii) 10-fold cross-validation with train-test split sets. Data scaling was carried out with the StandardScaler as implemented in Scikit-learn (v0.23) [25] using Python (v3.8), Pycaret [26], and Statsmodels (v0.11) [27]. Model development was carried out using the Recursive Feature Elimination (RFE) method [28]. The potential independent variables included weight, height, impedance, resistance, reactance, height^2/resistance (impedance index, RI), age, and sex. These were consistently checked by regression diagnostics with variable inflation factors (VIFs) below 5, before they were considered further in the model development. A two-independent samples t-test was used to verify no differences between the mean values of resistance analyzed by the two different BIA analyzers and a one-way analysis of variance (ANOVA) to confirm the same response of normalized BIA vectors recorded from different countries ($P < 0.05$ was considered as significant). Model development included data shuffling to avoid any type of bias and a split-group design with random data splitting in 70%:30% classes for the model-development (n = 186, male: 104, female: 82) and the test (n = 80, male: 39, female: 41) sets, respectively. 10-fold cross-validation was performed on the training set to find the optimal set of parameters. Normal distributions of residuals were verified by graphical analysis. Analysis of covariance (ANCOVA) [29] was performed to assess the difference between slopes of measured and predicted values of TBW and FFM. Agreement was assessed by Bland–Altman plots [30]. Lin's concordance correlation coefficient [31] (supplementary, code section) was used to evaluate the degree of precision between reference and predicted values of TBW and FFM by testing if pairs of observations fall on the 45° line through the origin. Two one-sided test, TOST [32], (equivalence test) was used to assess the equivalency between the reference and the published predicted TBW and FFM values based on the 90% confidence interval (CI) ($\alpha = 0.05$) within a equivalence bound Δ of ±0.5 (in Cohen's d_z, representing a medium effect size).

3. Results

Data from a total of 266 children (143 boys, 123 girls) were evaluated in this study. Participant characteristics and raw data, by country, are presented in Table 1. The apparent lower %BF and higher values of impedance and resistance of LVA and MNE compared to the relevant indices of other countries, could not be attributed to methodological reasons but rather to biological variation. Characteristics of the training and test data sets are presented in Table 2. The RFE-CV plot (supplementary, Fig. S1) depicts the optimal number of variables in the model along with their cross-validated test score and variability. Three variables, RI, weight, and sex can adequately describe the data variability. Regression analysis yielded $R^2 = 0.87$ for the training group and 0.87 for the test group for TBW and $R^2 = 0.88$ for the training group and 0.87 for the test group for FFM (supplementary, Figs. S3–S5). After validating the comparable performance of the linear regression on both training and test sets, we confirmed that our model generalizes well for this group of European children. Thus, the final equation was extracted by applying the training fit on all data. The final prediction equations of BIA for the evaluation of TBW and FFM are presented in Table 3.

Neither the intercept nor the slope of the regression lines differs significantly between D_2O and BIA for TBW and FFM ($P_{TBW} = 0.81$, $P_{FFM} = 0.80$) confirming the null hypothesis that the relationship with the covariates is uniform across groups. The limits of agreement analysis (Bland–Altman plots) was used to evaluate the bias between each predictive equation for TBW and FFM as determined by D_2O dilution (Fig. 1a and b). The estimates of body composition measured by BIA showed a mean bias of (0.18 ± 1.80 kg; 95% limits of agreement (LOA): −3.4 to 3.7 kg) for TBW and a mean bias of (0.11 ± 2.38 kg; 95% LOA: −4.5 to 4.8 kg) for FFM compared to those obtained by the D_2O dilution (Table 4). No significant difference was detected between the measured and predicted mean values of TBW ($P = 0.09$) and FFM ($P = 0.44$) using a paired t-test. The concordance correlation coefficient (ρ_c) was calculated to 0.93 for both TBW and FFM (Table 4). To investigate if differences were randomly scattered or specific to certain body compositions, we grouped the cohort according to BMIZ. The prediction equations yielded good agreement within all BMIZ groups as shown by the high value of concordance correlation coefficients (Table 4). No proportional bias was detected (TBW: $R^2 = 0.06$, $r_p = 0.25$, 95% CI: (0.13, 0.35), $P < 0.001$; FFM: $R^2 = 0.06$, $r_p = 0.24$, 95% CI: (0.12, 0.35), $P < 0.001$).

We identified 14 prediction equations for TBW and FFM in the literature from the last 25 years regarding healthy children (Table 5). Those equations were derived based on isotope dilution

Table 1
Participants' (n = 266) characteristics from each county[a].

	Bosnia and Herzegovina (n = 45)	Latvia (n = 18)	Montenegro (n = 144)	North Macedonia (n = 22)	Portugal (n = 37)
Age (years)	9.8 ± 1.3 [7.3–12.0]	9.7 ± 1.3 [7.4–11.7]	10.3 ± 0.6 [9.3–11.8]	11.3 ± 2.2 [7.5–14.5]	9.0 ± 0.7 [8.1–11.7]
Height (cm)	144.7 ± 11.1 [121.9–173.8]	143.5 ± 9.4 [123.0–159.0]	145.2 ± 7.9 [127.7–168.2]	149.9 ± 17.6 [105.3–175.4]	133 ± 6.9 [115.7–145.1]
Weight (kg)	46.3 ± 12.0 [24.2–81.5]	36.4 ± 7.6 [22.2–56.8]	40.0 ± 10.4 [21.4–89.4]	56.4 ± 20.4 [18.7–91.2]	33.1 ± 8.5 [18.9–52.3]
BMI (kg/m^2)	22.1 ± 5.0 [15.0–34.9]	17.5 ± 2.2 [14.7–23.9]	18.8 ± 3.8 [12.0–39.7]	23.5 ± 5.7 [13.4–31.2]	18.5 ± 3.4 [14.1–25.7]
BMI-for-age (BMIZ)	1.7 ± 1.4 [−0.8–4.1]	0.4 ± 0.9 [−1.2–2.1]	0.6 ± 1.3 [−3.8–4.3]	1.7 ± 1.6 [−1.7–3.8]	0.9 ± 1.3 [−1.3–3.5]
TBW (kg)	23.9 ± 4.4 [15.5–35.0]	22.6 ± 3.5 [14.1–28.6]	20.2 ± 4.0 [11.2–35.0]	24.5 ± 7.9 [11.4–41.5]	16.5 ± 3.1 [10.8–24.0]
FFM (kg)	22.1 ± 4.0 [14.1–31.1]	19.4 ± 2.9 [12.2–23.7]	20.6 ± 3.8 [12.1–34.2]	25.0 ± 7.5 [12.1–41.5]	17.1 ± 3.1 [11.0–23.9]
%BF	30.9 ± 11.9 [7.2–55.3]	17.0 ± 7.1 [8.6–34.7]	32.6 ± 9.1 [8.8–52.5]	38.5 ± 10.4 [17.8–53.0]	33.9 ± 7.6 [19.1–51.6]
Impedance (Ω)	639.1 ± 64.4 [505.7–753.4]	696 ± 64.5 [593.0–848.0]	679.0 ± 80.2 [460.9–943.5]	623.6 ± 87.9 [442.7–835.7]	702.9 ± 89.1 [558.0–849.3]
Resistance (Ω)	636.2 ± 60.8 [502.7–750.5]	693.5 ± 64.8 [589.0–846.0]	676.2 ± 80.2 [458.9–943.7]	621.2 ± 87.8 [440.0–833.0]	699.6 ± 89.0 [554.3–890.3]
Reactance (Ω)	60.8 ± 7.0 [43.3–81.7]	60.4 ± 5.3 [50.0–70.8]	61.7 ± 6.1 [42.6–77.1]	57.7 ± 7.0 [44.8–70.6]	68.9 ± 7.9 [53.1–90.0]

[a] Values are means ± SD [range].

Table 2
Participants' characteristics from the training and test datasets used for cross-validation[a].

Variable	Train set (n = 186)	Test set (n = 80)	*P*
Age (months)	120.8 ± 15.2	121.3 ± 11.7	0.78
Height (cm)	144.0 ± 10.5	144.1 ± 10.9	0.92
Weight (kg)	42.0 ± 13.4	40.3 ± 11.8	0.31
BMI (kg/m^2)	19.9 ± 4.6	19.1 ± 4.2	0.16
BMI-for-age (BMIZ)	1.0 ± 1.4	0.8 ± 1.4	0.24
TBW (kg)	21.2 ± 5.2	20.9 ± 5.1	0.71
FFM (kg)	27.7 ± 6.9	27.3 ± 6.8	0.68
%BF	32.1 ± 10.9	30.8 ± 9.4	0.35
Impedance (Ω)	667.6 ± 82.7	678.7 ± 82.1	0.30
Resistance (Ω)	664.7 ± 82.5	675.9 ± 82.3	0.30
Reactance (Ω)	61.8 ± 7.1	62.5 ± 7.3	0.46
Males	104 (56%)	39 (49%)	0.28

[a] Values are means ± SD. p-values were calculated with a two-tailed unpaired t-test for continuous variables and a chi-square test for binary variables.

and DXA as reference techniques. RI was used as a covariate in all cases while weight, sex, age, and height were the other predictors sorted by rank of incidence in the published predictive equations. All studies performed during the last twenty years (Equations 1-12) cross-validated the results. TOST equivalence outcome is presented along with bias and concordance level.

4. Discussion

This study developed and validated prediction equations for TBW and FFM in European children aged 7–14 years. BIA estimates of TBW and FFM depended on resistance index, weight, and sex. The resistance index (RI), rather than simply resistance or impedance, is the preferred predictor in body composition studies carried out with BIA as it is solely based on Ohm's Law relationship and it is directly related to the total volume of water in the body. It is also the most important covariate in our data when ranked by absolute importance, in accordance with published findings that often reported RI as the single most influential predictor of total body water (TBW) [40]. In our study, RI normalized the children's height (supplementary, Fig. S6) which was the most unstable parameter between sexes as it spans a wide range of values. It improved the regression model overall but at the same time weakened the impact of sex. Weight was also a critical parameter of both the TBW and FFM prediction equations, again in line with other similar studies, as water is the most abundant compartment in the body especially for children [41].

Body fat and body composition varies by sex in adults, but it is debatable if such differences are evident in pre-pubertal children and adolescents. Sex-specific changes in body composition mainly concern the FM after puberty, around the age of 12 years [42]. In the present study, sex was the least important predictor variable compared to RI and weight, being the third ranking in feature importance plot (supplementary, Fig. S2). However, its inclusion improves the prediction as the cohort includes adolescents up to 14.5 years of age (Tanner stages II and III). Females typically exhibit higher values of extracellular water to TBW ratio [43]. Thus, RI is higher in females than males for a given FFM and body weight and this difference further justifies the inclusion of sex as a regression covariate.

Limits of agreement between D_2O and BIA methods were within ±17% of the mean. The estimates have high relative variation at the individual level but small average bias. BIA FFM and TBW estimates are highly correlated within one SD for approximately 83% of the children. We also identified 17 participants (6.7%) having residuals which exceeded the 95% confidence. It is frequently argued that such wide limits of agreement negatively impact the application of the prediction equations at the individual level. However, for population-level epidemiological studies of body composition in this age group, this is of lesser importance.

Although no proportional bias was detected in the whole dataset, we observed marginally increased absolute bias within each subgroup, possibly due to fewer measurements and high leverage points of samples at low and high BMIZ (Table 4). Seo *et al.* [44] performed validation of BIA versus DXA in children according to the degree of obesity and found better agreement between DXA and BIA for children with severe obesity than for children with mild to moderate obesity. Conversely, other studies suggested that bias is proportional to the level of body fat as either the adipose tissue or the high relative amount of extracellular water for overweight and

Table 3
BIA prediction equations for TBW and FFM.[a]

Equation	R^2	RMSE[b]
TBW (kg) = 0.44 RI (cm^2/Ω) + 0.12 weight (kg) + 0.33 sex (male = 1, female = 0) + 1.5	0.87	1.81
FFM (kg) = 0.59 RI (cm^2/Ω) + 0.16 wetbl2ight (kg) + 0.71 sex (male = 1, female = 0) + 1.4	0.87	2.37

[a] Further model fit measures are presented in the supplementary file (Tables S1–S4).
[b] Root mean square error.

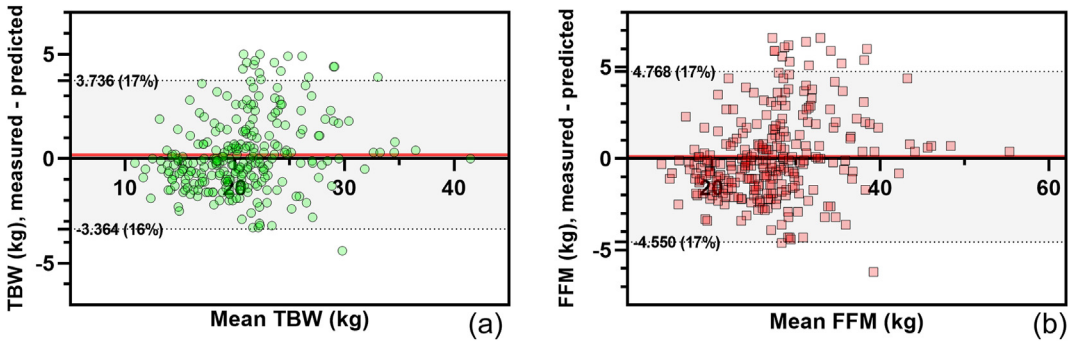

Fig. 1. Bland–Altman plots of the prediction equations (Table 3). Solid red lines illustrate fixed bias (i.e., the mean difference). The dashed black lines (grey area) indicate the LOA (i.e., mean difference ± 1.96 SD) in absolute values and as a percentage of TBW_{D2O} and FFM_{D2O}. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

obese might lower the accuracy of BIA measurements [10]. In the current study, the accuracy of the TBW and FFM equation derived from the cohort after cross-validation with training and test datasets, was comparable to the accuracy for each BMIZ subgroup of underweight, normal weight, overweight, and obese. Even if our results showed relatively wide 95% limits of agreement between predicted and criterion values for TBW and FFM, these were consistent across the subgroups. Comparing the estimated values of FM and %BF with those calculated from measured FFM, we found that FM was overestimated by 2.3 kg and %BF by 6%. This error is similar to that reported by Rush *et al.* [37] (5.1%) in children between 5 and 14 years of age.

4.1. Comparison with published prediction equations

In general, BIA validation studies in children have reported that equations developed for a particular population are not always applied successfully to others [12] possibly to different physiological characteristics between populations or regression overfitting when deriving the original predictor. Evaluation of a representative sample of published equations in the present sample of children revealed a varying degree of agreement. Paired t-test yielded significant differences between the predicted TBW and FFM in all of the previously published equations except the ones developed by Wickramasinghe *et al.* [34] (Eq. 4 and 9). That study included healthy children of 5–15 years of age with a mean value of 10 years which coincides with our study group. However, analyses such as paired t-tests emphasize differences between methods rather than similarities that might be more important in body composition studies [3]. Our predicted equations and equations 4 and 9 (Table 5) are equivalent. For TBW, equations 2 and 5 are within the equivalence bounds but since they do not include a difference of 0, they are characterized as equivalent but different compared to our prediction. Similarly, equations 10, 12 and 13 are within the equivalent interval being equivalent to our equation for FFM but not equal. The inter-rater agreement as measured by the concordance correlation coefficient yielded a significant positive correlation ($\rho_c > 0.90$) for equations 2, 4, 5, 8, 9, and 10. The agreement of our BIA equations with [34], possibly suggest, that unlike in adults [45], ethnicity does not seem to play a key role in the BIA prediction equations for children at this age. Equations developed for Mexican children from different regions and ethnic backgrounds [15] (Eq. 6) showed that ethnicity did not significantly contribute to the BIA prediction power. Likewise, a cross-sectional study performed in a cohort of New Zealand European, Maori and Pacific Island children aged 5–14 [37] years (Eq. 11) showed that ethnicity was not a significant predictor of FFM. The developed BIA equation for that cohort was similar to that developed for children up to 14 years of white ethnicity in USA [46] although no equivalence test was performed. However, Morrison *et al.* [47] found that BIA prediction equations in a sample of black and white females (6–17 years) were ethnicity- but not age-specific. Furthermore, validation of leg–leg BIA in adolescents from different ethnic groups (black, Asian, and white adolescents aged 11–15 years) demonstrated ethnicity as an

Table 4
Measured (D_2O) vs predicted (BIA) values of TBW and FFM grouped by BMIZ.[a]

	TBW_{D2O} (kg)	TBW_{BIA} (kg)	Difference ρ_c[b]; bias ± SD 95% LOA (kg)	FFM_{D2O} (kg)	FFM_{BIA} (kg)	Difference ρ_c[b]; bias ± SD 95% LOA (kg)
All participants [n = 266]	20.8 ± 5.0 [10.8–41.5]	20.7 ± 4.5 [11.0–41.5]	0.93; 0.2 ± 1.8 (−3.4, 3.7)	27.3 ± 6.7 [13.9–55.5]	27.2 ± 6.1 [14.2–55.1]	0.93; 0.1 ± 2.4 (−4.5, 4.8)
Underweight BMIZ < −1 [n = 8]	14.4 ± 2.1 [11.2–17.0]	14.9 ± 2.0 [12.1–17.4]	0.91; −0.5 ± 0.6 (−1.8, 0.7)	18.7 ± 2.7 [14.5–22.1]	19.4 ± 2.7 [15.6–22.7]	0.91; −0.7 ± 0.8 (−2.4, 0.9)
Normal weight −1 ≤ BMIZ < +1 [n = 136]	19.3 ± 4.2 [10.8–29.9]	18.9 ± 3.4 [11.0–29.5]	0.89; 0.5 ± 1.1 (−3.1, 4.0)	25.3 ± 5.6 [13.9–39.6]	24.8 ± 4.6 [14.2–39.1]	0.90; 0.6 ± 2.4 (−4.1, 5.2)
Overweight +1 ≤ BMIZ < +2 [n = 37]	21.4 ± 3.8 [14.7–32.8]	21.7 ± 3.3 [16.2–32.5]	0.89; −0.3 ± 1.6 (−3.5, 2.9)	28.0 ± 5.1 [19.1–43.9]	28.6 ± 4.4 [21.1–43.1]	0.89; −0.6 ± 2.1 (−4.7, 3.6)
Obese BMIZ > + 2 [n = 85]	23.6 ± 5.3 [15.0–41.5]	23.6 ± 4.9 [15.6–41.5]	0.93; −0.02 ± 1.9 (−3.8, 3.7)	30.9 ± 7.1 [19.4–55.5]	31.1 ± 6.6 [20.3–55.1]	0.93; −0.2 ± 2.5 (−5.1, 4.6)

[a] Values are means ± SD [range].
[b] Concordance correlation coefficient.

Table 5
Comparison of published BIA prediction equations in children applied to the reference D_2O data of this study.

Eq.	Source (first author; date)	Sample size, age, origin	Reference method	Equations	TOST ±Δ[b], 90% CI [Lower, Upper]	Bias ± SD 95% LOA[c]	ρ_c[d]
TBW							
	This study	266 (M: 143, F: 123) 7.3–14.5 y; Bosnia and Herzegovina, Latvia, Montenegro, North Macedonia, Portugal	Isotope dilution, D_2O	0.44 RI + 0.12 weight + 0.46 sex + 1.5	0.54 [−0.01, 0.37]	0.2 ± 1.8 [−3.4, 3.7]	0.93
1	de Beer, 2011 [11]	56 (M: 20, μ = 5.7, F: 36, μ = 5.6); Netherlands	Isotope dilution, D_2O	0.59 RI + 0.065 weight + 0.04	0.67 [1.58, 2.03]	1.8 ± 2.2 [−2.5, −6.2]	0.79
2	Liu, 2011 [10]	948 (M: 492, F: 456) 8–10 y; China, Lebanon, Malaysia, Philippines, Thailand	Isotope dilution, D_2O	0.231 RI + 0.066 height + 0.188 weight + 0.128 age + 0.5 sex − 4.574	0.55 [−0.84, −0.48]	−0.7 ± 1.8 [−4.2, 2.9]	0.91
3	Haroun, 2010[a] [33]	382 (M: 181, F: 201) 11–15 y; Different ethnic groups (black, Asian, white), UK	Isotope dilution, D_2O	Females: 0.125 + 0.647 height^2/Z Males: −1.822 + 0665 height^2/Z	0.64 [0.72, 1.14]	0.9 ± 2.1 [−3.2, 5.1]	0.88
4	Wickramasinghe, 2008 [34]	282 (M: 158, μ = 9.5, F: 124, μ = 10.1); Sri Lanka	Isotope dilution, D_2O	0.40 RI + 0.18 weight + 1.44 sex − 0.03	0.57 [−0.35, 0.03]	−0.16 ± 1.9 [−3.9, 3.5]	0.93
5	Horlick, 2002 [35]	1170 (M:664 F: 627) 4–18 y; USA	DXA	0.725 + 0.475 RI + 0.140 weight	0.55 [−0.87, −0.49]	−0.7 ± 1.8 [−4.3, 2.9]	0.93
FFM							
	This study	266 (M: 143, F: 123) 7.3–14.5 y; Bosnia and Herzegovina Latvia, Montenegro, North Macedonia, Portugal	Isotope dilution, D_2O	0.59 RI + 0.16 weight + 0.71 sex + 1.4	1.19 [−0.13, 0.35]	0.1 ± 2.4 [−4.5, 4.8]	0.93
6	Ramirez, 2012 [15]	336 (M: 203, F: 163) 6–15 y; Mexico	Isotope dilution, D_2O	0.661 RI + 0.200 weight - 0.320	1.26 [−1.82, −1.31]	−1.6 ± 2.5 [−6.5, 3.4]	0.91
7	Khan, 2012 [13]	200 (M: 102, F: 98) 4–10 y; Bangladesh	Isotope dilution, D_2O	2.34 + 050 weight − 0.52 sex + 0.18 age + 0.21 height^2/Z	1.78 [−4.14, −3.42]	−3.8 ± 3.6 [−10.8, 3.2] >	0.77
8	Liu, 2011 [10]	948 (M: 492, F: 456) 8–10 y; China, Lebanon, Malaysia, Philippines, Thailand	Isotope dilution, D_2O	0.299 RI + 0.086 height + 0.245 weight + 0.260 age + 0.901 sex − 6.952	1.19 [−1.01, −0.53]	−0.8 ± 2.4 [−5.4, 3.9]	0.92
9	Wickramasinghe, 2008 [34]	282 (M: 158, F: 124) 5–15 y; Sri Lanka	Isotope dilution, D_2O	0.56 RI + 0.23 weight + 2.1 sex − 0.8	1.24 [−0.40, 0.10]	−0.15 ± 2.5 [−5.0, 4.7]	0.93
10	Nielsen, 2007 [36]	248 (M:140 F: 108) 9–11 y; Sweden	DXA	−5.11 + 0.54 RI + 0.05 Xc + 0.06 height + 0.09 weight + 0.97 sex	1.25 [−0.93, −0.43]	−0.68 ± 2.5 [−5.5, 4.2]	0.91
11	Rush, 2003 [37]	172 (M:83 F: 89) 5–14 y; New Zealand	Isotope dilution, D_2O	0.622 RI + 0.234 weight + 1.166	1.30 [−3.48, −2.95]	−3.2 ± 2.6 [−8.3, 1.9]	0.84
12	Horlick, 2002 [35]	1170 (M:664 F: 627) 4–18 y; USA	DXA	(3.474 + 0.459 RI + 0.064 weight)/ (0.769–0.009 age − 0.016 sex)	1.23 [−3.90, −3.40]	−3.7 ± 2.5 [-8.5, 1.2]	0.80
13	Lewy, 1999 [38]	34 (M: 19, μ = 11.4, F: 15, μ = 10.2); African-American, USA	DXA	0.84 RI + 1.10	1.32 [−0.72, −0.17]	−0.45 ± 2.6 [−5.6, 4.7]	0.91
14	Suprasongsin, 1995 [39]	34 (M: 16, F: 18) 8–26 y; White-American, USA	Isotope dilution, $H_2^{18}O$	0.632 RI + 0.289 weight + 1.445	1.82 [−6.42, −5.68]	−6.0 ± 3.6 [−13.2, 1.1]	0.68

M: males, F: females, μ = mean age (in years, y).
[a] Only the model for the white ethnicity was considered.
[b] Raw Δ with Cohen dz = ± 0.5.
[c] Bland–Altman test (measured (D2O)-predicted (BIA)).
[d] Concordance correlation coefficient.

independent variable for the prediction of TBW, albeit within-Asian population variability among the various subgroups [33] (Eq. 3). Asian population partial variability was also demonstrated by Liu *et al*. [10] (Eq. 2) who validated BIA predicted equations of TBW and FFM in children 8–10 years from China, Lebanon, Malaysia, Philippines, and Thailand. Thai children were better described by separate equations while all other populations shared the same ones.

5. Conclusion

We developed and validated BIA equations for the estimation of TBW and FFM for European children aged 7–14 years across a wide range of BMI. Bland–Altman plots showed good agreement between values obtained by D_2O and BIA with minimal bias that justify their use in epidemiological studies. The wide confidence intervals of the error when estimating individual results, possibly restrict the clinical applicability of individual BIA measurements. Comparison with predictive equations from published studies through concordance analysis, revealed varying limits of agreement with the current deuterium dilution measurements with only two being equivalent to the equations developed in this study. The main strength of this study is that it included a large sample of children and adolescents, with a broad range of age and BMI, across five European countries. Results indicate that any variation associated with age or country of origin does not interfere with the outcomes. It was our intention to replicate real-world measurements where such variations do exist, and we gave emphasis on the fact that within these variations all assessments followed a common agreed protocol. Comparable accuracy of TBW and FFM was shown for subgroups of different BMIZ, indicating that the prediction equations for the whole sample work consistently well. However, due to the small number ($n = 8$) of the very lean children, we expect low statistical power for that specific group. Conversely, we presented robust results within the overweight/obese range which could aid the management of childhood obesity in Europe.

Author contributions

Conceptualization and data curation: all authors, Formal Analysis: NK, Original draft preparation: NK, Review and Editing: LCW, PK. All authors read and approved the final manuscript.

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Informed consent statement

Parental informed consent was obtained from all subjects involved in the study.

Institutional review board statement

Ethical approvals

- Bosnia and Herzegovina: Ethical Board of Public Health Institute of Republic of Srpska. Reference number: 500-4666-3/17; 15.09.2017.
- Latvia: Research Ethical Board for Institute of Food Safety, Animal Health and Environment BIOR. Conclusion number: 3/11/1/2018; 11.01.2018.
- Montenegro: Ethical Board of Institute of Public Health of Montenegro. Reference number: 01–686/17; 01.02.2017.
- North Macedonia: Ethical commission for research conducted on people, Faculty of Medicine, Ss. Cyril and Methodius University – Skopje. Approval decision No. 03–3152/16; 24.07.2018.
- Portugal: Ethical Board for Health of the National Institute of Health Dr. Ricardo Jorge – In PT: Comissão de Ética para a Saúde do Instituto Nacional de Saúde Dr. Ricardo Jorge (CES INSA). Reference number: CES_INSA_IM01_02; 18.06.2019.

Data availability statement

Data are available on specific request to the corresponding author.

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Declaration of competing interest

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Appendix A. Supplementary data

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References

[1] Wells JCK, Shirley MK. Body composition and the monitoring of non-communicable chronic disease risk. Glob Health Epidemiol 2016;1:e18.
[2] Demerath EW. Do changes in body mass index percentile reflect changes in body composition in children? Data from the fels longitudinal study. Pediatrics 2006 Mar 1;117(3):e487–95.
[3] Ward LC. Human body composition: yesterday, today, and tomorrow. Eur J Clin Nutr 2018 Sep;72(9):1201–7.

[4] Shepherd JA, Ng BK, Sommer MJ, Heymsfield SB. Body composition by DXA. Bone 2017 Nov;104:101–5.
[5] Wilson JP, Strauss BJ, Fan B, Duewer FW, Shepherd JA. Improved 4-compartment body-composition model for a clinically accessible measure of total body protein. Am J Clin Nutr 2013 Mar 1;97(3):497–504.
[6] Ward LC. Bioelectrical impedance analysis for body composition assessment: reflections on accuracy, clinical utility, and standardisation. Eur J Clin Nutr 2019 Feb;73(2):194–9.
[7] Lyons-Reid J, Ward LC, Kenealy T, Cutfield W. Bioelectrical impedance analysis—an easy tool for quantifying body composition in infancy? Nutrients 2020 Mar 27;12(4):920.
[8] Brantlov S, Ward LC, Jødal L, Rittig S, Lange A. Critical factors and their impact on bioelectrical impedance analysis in children: a review. J Med Eng Technol 2017 Jan 2;41(1):22–35.
[9] Lyons-Reid J, Derraik JGB, Ward LC, Tint M, Kenealy T, Cutfield WS. Bioelectrical impedance analysis for assessment of body composition in infants and young children-A systematic literature review [Internet] Clin Obes 2021 Feb 9. Available from: https://onlinelibrary.wiley.com/doi/10.1111/cob.12441.
[10] Liu A, Byrne NM, Ma G, Nasreddine L, Trinidad TP, Kijboonchoo K, et al. Validation of bioelectrical impedance analysis for total body water assessment against the deuterium dilution technique in Asian children. Eur J Clin Nutr 2011 Dec;65(12):1321–7.
[11] de Beer M, Timmers T, Weijs PJM, Gemke RJBJ. Validation of total body water analysis by bioelectrical impedance analysis with deuterium dilution in (pre) school children. e-SPEN, Eur e-J Clin Nutr Metab 2011 Oct;6(5):e223–6.
[12] Prins M, Hawkesworth S, Wright A, Fulford AJC, Jarjou LMA, Prentice AM, et al. Use of bioelectrical impedance analysis to assess body composition in rural Gambian children. Eur J Clin Nutr 2008 Sep;62(9):1065–74.
[13] Khan AI, Hawkesworth S, Hawlader MDH, Arifeen SE, Moore S, Hills AP, et al. Body composition of Bangladeshi children: comparison and development of leg-to-leg bioelectrical impedance equation. J Health Popul Nutr 2012 Oct 20;30(3):281–90.
[14] Martinez EE, Smallwood CD, Quinn NL, Ariagno K, Bechard LJ, Duggan CP, et al. Body composition in children with chronic illness: accuracy of bedside assessment techniques. J Pediatr 2017 Nov;190:56–62.
[15] Ramírez E, Valencia ME, Bourges H, Espinosa T, Moya-Camarena SY, Salazar G, et al. Body composition prediction equations based on deuterium oxide dilution method in Mexican children: a national study. Eur J Clin Nutr 2012 Oct;66(10):1099–103.
[16] Aglago KE, Menchawy IE, Kari KE, Hamdouchi AE, Barkat A, Bengueddour R, et al. Development and validation of bioelectrical impedance analysis equations for predicting total body water and fat-free mass in North-African adults. Eur J Clin Nutr 2013 Oct;67(10):1081–6.
[17] Kyle UG, Earthman CP, Pichard C, Coss-Bu JA. Body composition during growth in children: limitations and perspectives of bioelectrical impedance analysis. Eur J Clin Nutr 2015 Dec;69(12):1298–305.
[18] Wells JCK. Measuring body composition. Arch Dis Child 2005 Jun 14;91(7):612–7.
[19] Dehghan M, Merchant AT. Is bioelectrical impedance accurate for use in large epidemiological studies? Nutr J 2008 Dec;7(1):26.
[20] Bosy-Westphal A, Danielzik S, Dörhöfer R-P, Piccoli A, Müller MJ. Patterns of bioelectrical impedance vector distribution by body mass index and age: implications for body-composition analysis. Am J Clin Nutr 2005 Jul 1;82(1):60–8.
[21] World Health Organization. Growth reference 5-19 years [internet]. Available from: https://www.who.int/growthref/who2007_bmi_for_age/en/; 2007.
[22] World Health Organization. WHO European childhood obesity surveillance initiative. Protocol, October 2016 [Internet]. 2016 [cited 2020 Sep 20]. Available from: https://www.euro.who.int/__data/assets/pdf_file/0018/333900/COSI-protocol-en.pdf.
[23] International Atomic Energy Agency. Introduction to body composition assessment using the deuterium dilution technique with analysis of saliva samples by Fourier transform infrared spectrometry. Vienna: International Atomic Energy Agency; 2010 (IAEA Human Health Series No 12).
[24] Wells JC, Williams JE, Chomtho S, Darch T, Grijalva-Eternod C, Kennedy K, et al. Pediatric reference data for lean tissue properties: density and hydration from age 5 to 20 y. Am J Clin Nutr 2010 Mar 1;91(3):610–8.
[25] Pedregosa F, Varoquaux G, Gramfort A, Michel V, Thirion B, Grisel O, et al. Scikit-learn: machine learning in Python. J Mach Learn Res 2011;12:2825–30.
[26] Ali M. PyCaret: an open source, low-code machine learning library in Python [Internet]. 2020. Available from: https://www.pycaret.org.
[27] Seabold S, Perktold J. Statsmodels: econometric and statistical modeling with Python. In: Austin, Texas; 2010 [cited 2020 Sep 27]. pp. 92–6. Available from: https://conference.scipy.org/proceedings/scipy2010/seabold.html.
[28] Li F, Yang Y. Analysis of recursive feature elimination methods. In: Proceedings of the 28th annual international ACM SIGIR conference on research and development in information retrieval [internet]. New York, NY, USA: Association for Computing Machinery; 2005. p. 633–4. https://doi.org/10.1145/1076034.1076164 (SIGIR '05). Available from:.
[29] Jerrold H. Zar. Biostatistical analysis. Pearson; 2010. p. 292–305.
[30] Martin Bland J, Altman DouglasG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986 Feb 8;327(8476):307–10.
[31] Lin LI-K. A concordance correlation coefficient to evaluate reproducibility. Biometrics 1989 Mar;45(1):255.
[32] Schuirmann DJ. A comparison of the two one-sided tests procedure and the power approach for assessing the equivalence of average bioavailability. J Pharmacokinet Biopharm 1987 Dec 1;15(6):657–80.
[33] Haroun D, Taylor SJC, Viner RM, Hayward RS, Darch TS, Eaton S, et al. Validation of bioelectrical impedance analysis in adolescents across different ethnic groups. Obesity 2010 Jun;18(6):1252–9.
[34] Wickramasinghe VP, Lamabadusuriya SP, Cleghorn GJ, Davies PSW. Assessment of body composition in Sri Lankan children: validation of a bioelectrical impedance prediction equation. Eur J Clin Nutr 2008 Oct;62(10):1170–7.
[35] Horlick M, Arpadi SM, Bethel J, Wang J, Moye J, Cuff P, et al. Bioelectrical impedance analysis models for prediction of total body water and fat-free mass in healthy and HIV-infected children and adolescents. Am J Clin Nutr 2002 Nov 1;76(5):991–9.
[36] Nielsen BM, Dencker M, Ward L, Linden C, Thorsson O, Karlsson MK, et al. Prediction of fat-free body mass from bioelectrical impedance among 9- to 11-year-old Swedish children. Diabetes Obes Metabol 2007 Jul;9(4):521–39.
[37] Rush EC, Puniani K, Valencia ME, Davies PSW, Plank LD. Estimation of body fatness from body mass index and bioelectrical impedance: comparison of New Zealand European, Maori and Pacific Island children. Eur J Clin Nutr 2003 Nov;57(11):1394–401.
[38] Lewy VD, Danadian K, Arslanian S. Determination of body composition in african-American children: validation of bioelectrical impedence with dual energy X-ray absorptiometry [Internet] J Pediatr Endocrinol Metabol 1999 Jan;12(3):443–8 [cited 2020 Oct 10];12(3). Available from: https://www.degruyter.com/view/j/jpem.1999.12.3/jpem.1999.12.3.443/jpem.1999.12.3.443.xml.
[39] Suprasongsin C, Kalhan S, Arslanian S. Determination of body composition in children and adolescents: validation of bioelectrical impedance with isotope dilution technique [Internet] J Pediatr Endocrinol Metabol 1995 Jan;8(2):103–9 [cited 2020 Oct 10];8(2). Available from: https://www.degruyter.com/view/j/jpem.1995.8.2/jpem.1995.8.2.103/jpem.1995.8.2.103.xml.
[40] Kushner R, Schoeller DA, Fjeld CR, Danford L. Is the Impedance index (ht2/R) significant in predicting total body water? Am J Clin Nutr 1992 Nov 1;56(5):835–9.
[41] Friis-Hansen BJ, Holiday M, Stapleton T, Wallace WM. Total body water in children. Pediatrics 1951 Mar 1;7(3):321.
[42] Weber DR, Leonard MB, Zemel BS. Body composition analysis in the pediatric population. Pediatr Endocrinol Rev 2012 Nov;10(1):130–9.
[43] Tagliabue A, Cena H, Deurenberg P. Comparative study of the relationship between multi-frequency impedance and body water compartments in two European populations. Br J Nutr 1996 Jan;75(1):11–9.
[44] Seo Y-G, Kim JH, Kim Y, Lim H, Ju Y-S, Kang MJ, et al. Validation of body composition using bioelectrical impedance analysis in children according to the degree of obesity. Scand J Med Sci Sports 2018 Oct;28(10):2207–15.
[45] Ward LC, Heitmann BL, Craig P, Stroud D, Azinge EC, Jebb S, et al. Association between ethnicity, body mass index, and bioelectrical impedance: implications for the population specificity of prediction equations. Ann N Y Acad Sci 2006 Jan 25;904(1):199–202.
[46] Houtkooper LB, Going SB, Lohman TG, Roche AF, Van Loan M. Bioelectrical impedance estimation of fat-free body mass in children and youth: a cross-validation study. J Appl Physiol 1992 Jan 1;72(1):366–73.
[47] Morrison JA, Guo SS, Specker B, Chumlea WMC, Yanovski SZ, Yanovski JA. Assessing the body composition of 6–17-year-old black and white girls in field studies. Am J Hum Biol 2001 Feb 1;13(2):249–54.