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Obesity Diagnostic/Methodology

Bioelectrical impedance analysis to estimate body composition in children and adolescents: a systematic review and evidence appraisal of validity, responsiveness, reliability and measurement error

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Summary

Bioelectrical impedance analysis (BIA) is a practical method to estimate percentage body fat (%BF). In this systematic review, we aimed to assess validity, responsiveness, reliability and measurement error of BIA methods in estimating %BF in children and adolescents.We searched for relevant studies in Pubmed, Embase and Cochrane through November 2012. Two reviewers independently screened titles and abstracts for inclusion, extracted data and rated methodological quality of the included studies. We performed a best evidence synthesis to synthesize the results, thereby excluding studies of poor quality. We included 50 published studies. Mean differences between BIA and reference methods (gold standard [criterion validity] and convergent measures of body composition [convergent validity]) were considerable and ranged from negative to positive values, resulting in conflicting evidence for criterion validity. We found strong evidence for a good reliability, i.e. (intra-class) correlations ≥0.82. However, test-retest mean differences ranged from 7.5% to 13.4% of total %BF in the included study samples, indicating considerable measurement error. Our systematic review suggests that BIA is a practical method to estimate %BF in children and adolescents. However, validity and measurement error are not satisfactory.

Keywords: BIA, criterion validity, measurement properties, youth.

Abbreviations: %BF, percentage body fat; BIA, bioelectrical impedance analysis; BMI, body mass index; CV, coefficient of variation; DEXA, dual-energy X-ray absorptiometry; FFM, fat free mass; FM, fat mass; ICC, intra-class correlation coefficient; MIC, minimal important change; SEM, standard error of measurement; TBW, total body water; UWW, underwater weighing.

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Introduction

The relationship between obesity and cardiovascular diseases is primarily based on (indicators of) percentage body fat (%BF) (1,2), including anthropometric measures such as body mass index (BMI), waist circumference, hip circumference, waist-to-hip ratio, waist-to-height ratio and skinfold thickness, measured at various body parts such as triceps, biceps, subscapular and suprailiac sites. Of all indicators, BMI, expressed as weight divided by square height, is most widely used, applying age and gender specific cut-offs to classify weight status of children (3). However, BMI cannot distinguish between fat and fat-free components and is therefore not a good predictor of %BF (1,2,4–7).

Widely used reference methods for estimating %BF include dual-energy X-ray absorptiometry (DEXA), isotope dilution (e.g. deuterium ^{18}O) and underwater weighing (UWW). However, although the true gold standard for estimating %BF is cadaver analysis, multicomponent models (e.g. three or four component models) are considered sufficiently accurate for estimating %BF in living humans. Three component (3C) models divide the body into fat mass (FM), water and fat free dry mass. Four component (4C) models additionally divide fat free dry mass into proteins and minerals (8). Although the above described measures are more precise when compared to anthropometric measures, they are rather costly and time-consuming and therefore not very practical in large epidemiological and field studies. An alternative, more practical and child friendly measure of %BF is bioelectrical impedance analysis (BIA). Using body impedance and total body water (TBW) as input variables, %BF, FM and fat free mass (FFM) can be predicted. However, there is a great variety in devices, including hand-to-foot devices (lying supine or standing), hand-to-hand and foot-to-foot devices. Additionally, there is a great variety in (un)known prediction equations used, resulting in differences in estimated %BF, FM and FFM. Therefore, we were only interested in BIA as a predictor of %BF, FM and FFM, e.g. the combination of BIA devices and prediction equations.

To date, a systematic review of the measurement properties of different BIA methods for the estimation of body composition %BF, FM and FFM in children and adolescents is lacking. Essential requirements of BIA methods include criterion validity, responsiveness and reliability. Reliability reflects the degree of which the measurement is free from measurement error, which becomes apparent when repeated measures are performed (e.g. test-retest reliability). Criterion validity refers to the degree to which a (single) score of a measurement instrument is an adequate reflection of a gold standard. Responsiveness refers to the degree to which changes in scores of a measurement are an adequate reflection of changes in a gold standard, i.e. the validity of changes in scores (9). Our aim is to review primary studies examining criterion validity, responsiveness, reliability and measurement error of BIA methods in estimating %BF, FM or FFM in children and adolescents.

Methods

Literature search

We performed a systematic literature search in PubMed, Embase and the Cochrane Library, including published studies through November 2012. The strategy focused on terms related to 'bioelectrical impedance analysis (BIA)' (electric impedance, electric resistance) in AND-combination with terms representing measurement properties (validity, responsiveness, reliability, reproducibility, measurement error), in AND-combination with terms related to %BF (FM, FFM) and in AND-combination with studies that represented children and adolescents. The full search can be obtained upon request. In addition, reference lists were screened for additional studies.

Inclusion criteria

Studies were included if they examined criterion validity, responsiveness, reliability and/or measurement error of BIA to estimate body fat in healthy children and adolescents (aged < 18 years). Validity studies were only included if they (i) compared BIA with a gold standard measure of body fat and (ii) converted BIA outcome (e.g. impedance, total body water) %BF, FM or FFM. Multicomponent (i.e. 3C or 4C) models were considered as gold standards (i.e. criterion validity). However, because other convergent measures are widely used as reference methods, DEXA, isotope dilution (e.g. deuterium, ^{18}O) or UWW were considered as reference methods as well (i.e. convergent validity). Inclusion criteria for studies examining responsiveness were similar to those for validation studies, except for the additional criterion of having a longitudinal design, thereby comparing BIA with a gold standard or convergent measure on at least two time points. Studies examining reliability and/or measurement error were only included when having at least two measurements of BIA. We only included full-text studies that were published in the English language in peer-reviewed journals.

Selection process

First, two reviewers (HT and TA) independently checked all titles and abstracts of studies identified through the search process to establish potential relevant studies. Second, two reviewers independently screened the full text papers to check if they met the inclusion criteria. A third reviewer (BB) checked inconsistencies.

Data extraction

Two reviewers (HT and TA) independently performed the data extraction using a structured form. The following data were extracted (i) characteristics of the study population; (ii) characteristics of the BIA device; (iii) equation to predict body fat; (iv) characteristics of the gold standard or convergent measure of body fat and (v) results for each measurement property. Disagreement between the reviewers with respect to the data extraction was discussed until consensus was reached.

Methodological quality assessment

All included studies were examined using methodological quality criteria for each measurement property adapted from the COSMIN checklist (10,11), using four response options (excellent, good, fair, poor) (see Supporting Information Table S1). An overall methodological quality score per measurement property was obtained by taking the lowest rating of any criterion of the measurement property ('worst score counts') (11). The measurement properties included in the current review are criterion and convergent validity, responsiveness, reliability and measurement error. Three quality criteria were examined for criterion and convergent validity, for responsiveness 6, for reliability 9 and for measurement error 9. Two independent reviewers (HT and TA) performed the quality assessment. A third reviewer (BB) checked inconsistencies.

Data synthesis

To synthesize the results regarding criterion and convergent validity, responsiveness, reliability and measurement error of BIA to assess body fat in children and adolescents, we applied a best evidence synthesis (9). This best evidence synthesis is in accordance with general guidelines of the Cochrane Collaboration, in which the number of studies, the methodological quality of the studies, and the (consistency of the) results are taken into account.

According to the best evidence synthesis, the possible overall rating for a measurement property is 'positive', 'indeterminate' or 'negative', accompanied by a level of evidence

- Strong evidence: consistent findings in multiple (≥2) studies of good methodological quality OR in one study of excellent methodological quality;
- Moderate evidence: consistent findings in multiple (≥2) studies of fair methodological quality OR in one study of good methodological quality;
- Limited evidence: one study of fair methodological quality.
- Conflicting evidence: conflicting findings;
- Unknown: Only studies of poor methodological quality.

For validity and responsiveness, results were reflected by the degree of agreement with the gold standard or convergent measures of body fat. The degree of agreement was reflected by (i) the mean difference between the BIA measure and the gold standard (i.e. criterion measure) or convergent measure of body fat (i.e. convergent validity) and (ii) the magnitude bias, e.g. whether the mean difference was dependent on the amount of body fat (i.e. %BF, FM or FFM) (12). For reliability, results were reflected by correlations (correlation coefficients or intra-class correlation coefficient [ICC]). Results were graded positive when correlations were >0.7. For measurement error, results were reflected by mean difference, standard error of measurement (SEM) and coefficient of variation (CV).

Information on what constitutes a minimal important change (MIC) was needed to conclude on the magnitude of mean differences, SEM and CV. Since this information was not available in children and adolescents, we only described these results without applying a level of evidence.

Importantly, for all measurement properties, studies of poor quality were not considered in the best evidence synthesis. Therefore, these studies were excluded from the summarized results. However, to provide a complete overview, all studies – regardless of their methodological quality – were included in the supplementary tables.

In addition to the results that were extracted from all included studies to apply a best evidence synthesis, we extracted all reported results (e.g. correlations, regressions) to provide a complete overview of all data regarding criterion and convergent validity, responsiveness and reliability (for details see Supplementary Tables).

Results

The literature research yielded a total of 308 hits: 233 in PubMed, 51 in Embase and 24 in Cochrane. After removing doubles and checking inclusion criteria, we included 50 published papers. Figure 1 summarizes the flowchart of included papers. Table 1 shows the sample characteristics of all included papers. Forty-three papers examined validity, two responsiveness, 15 reliability and 16 measurement error. In Supporting Information Table S2, the examined instrument properties are shown, arranged by BIA device.

Population characteristics – summarized for each measurement property

Table 1 shows the population characteristics of all included studies. Sample size ranged from 17 to 948 for validity, 78 to 86 for responsiveness, 10 to 183 for reliability and 4 to 331 for measurement error. Mean age ranged from 5.8 to –17 years for validity, 10.6 to 11.0 years for responsiveness, 5.0 to 14 years for reliability and 5.0 to 18 years for measurement error. Finally, %BF ranged from 9.8 to 45.8% for validity, 24.3 to 24.7% for responsiveness, 13.0 to 45.7% for reliability and 12.0 to 29.6% for measurement error.

For all measurement properties, a large number of studies did not report measurement circumstances prior to BIA measurement. Having fasted for at least 2 h was reported in 23 studies, 11 studies reported bladder voiding and 15 studies reported restrictions on physical activity or exercise prior to BIA measurement (of which five studies at least 8–10 h).

Bioelectrical impedance analysis devices

In total 16 different BIA devices were applied, of which the RJL and Tanita TBF models were examined most

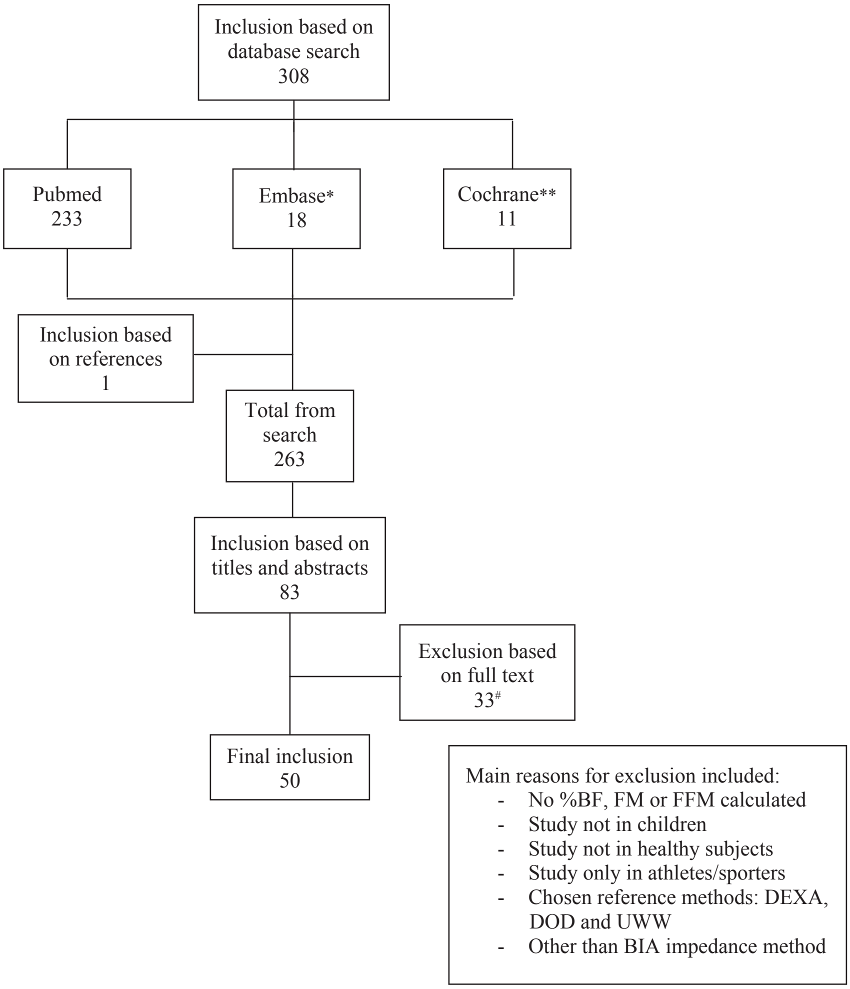

Figure 1 Flowchart of study inclusion. * Indicates not in Pubmed. ** Indicates not in Pubmed and Embase.# Important reasons for exclusion were adult population, children with a disease and validation of (BIA) to estimate total body water (TBW) instead of percentage body fat (%BF). (DEXA, dual-energy X-ray absorptiometry; DOD, deuterium oxide dilution; FFM, fat free mass; FM, fat mass; UWW, underwater weighing.)

frequently (see Supporting Information Table S2). For the majority of BIA devices, adhesive electrodes were used, in a tetrapolar position (electrodes placed on hand, foot, wrist and ankle). Other BIA devices used pressure contacts, in tetrapolar (i.e. foot-to-foot and hand-to-hand devices) and octopolar positions (hand-to-foot devices).

Criterion and convergent validity

Five papers evaluated criterion validity and 38 papers evaluated convergent validity of 18 BIA devices against a gold standard, of which four papers evaluated two BIA devices, one paper included two samples and one paper included two validations (in total 51 studies [e.g. comparisons] were included). The methodological quality was excellent in 16 studies, good in 13 studies, fair in 16 studies and poor in six studies.

Details of criterion and convergent validity results of each BIA method, sorted by methodological quality, study frequency and BIA device, are shown in Supporting Information Tables S3 and S4, respectively. In Supporting Information Table S5, an overview of all prediction equations is shown. Due to the enormous possible combinations between devices and prediction equations, we summarized the results of examined combinations.

Criterion validity

Mean differences between BIA and gold standard of body composition ranged from −12.3 to 13.7% for %BF and from −19.0 to 3.5 kg for FFM. Findings for magnitude biases were not consistent for %BF and ranged from r = −0.56 to r = 0.18. No magnitude biases were reported for FM. Only one study assessed mean difference between BIA and gold standard for FM, which was 1.4 kg. No magnitude bias was found in this study. Since mean differences and magnitude biases ranged from negative to positive, we conclude there is conflicting evidence for criterion validity.

Convergent validity

Mean differences between BIA and convergent measures of body composition ranged from −16.9 to 7.7% for %BF,

Table 1 Population characteristics – sorted by BIA device

Reference	Measurement property *Sample*	*n* (%boys)	Age (years) means ± SD	BF (%)* means ± SD	Measurement circumstances†
BIA 101					
(20)	Validity	30 (43%)	Boys 6.7 [6.3; 7.5]‡ Girls 6.8 [6.0; 7.9]‡	Boys 21.0 [15.0; 27.5]‡ Girls 22.2 [16.5; 29.3]‡	10 min rest
(21)	Reliability/Measurement error	*Inter-observer* 10 (50%)	14	BMI Boys 20.3 ± 2.2 Girls 18.9 ± 2.2	(Not reported)
	Reliability/Measurement error	*Intra-observer* 10 (50%)	14	BMI Boys 19.8 ± 2.4.2 Girls 22.7 ± 2.7	
(22)	Validity/Intrarater, interrater and interday reliability/ Measurement error	84 (54%)	14.5 ± 1.0	FFM 36.7 ± 5.7	Overnight fast, strenuous PA restriction, bladder voiding (30 min)
BIA 2000M					
(23)	Validity	27 (52%) Obese	Boys 12.6 ± 3.3 Girls 13.1 ± 2.4	Boys 38.5 ± 6.3 Girls 40.4 ± 5.4	Overnight fast
BMR 2000					
(24)	Validity	47 (49%)	Boys 12.7 ± 2.7 Girls 11.6 ± 1.6		3 h fast, vigorous exercise restriction
	Reliability	14 (57%)	11.8 ± 1.8		
Bodystat models					
(25)	Validity	30 (40%) Overweight/obese	7.6 ± 1.3		(Not reported)
(26)	Validity	42 (100%)	12.9 ± 1.0		3 h fast
(27)	Cross-validity	94 (56%) Sri Lankan children	Boys 9.6 ± 2.7 Girls 10.1 ± 2.8		3 h fast, 12 h strenuous PA restriction
(28)	Cross-validity	75 (51%)	8.7 ± 1.9		90 min exercise restriction
(29)	Validity	Pune sample 560 (53%) Mysore sample 58 (50%) All Indian children	Pune sample Boys 6.2 [6.2; 6.3]§ Girls 6.2 [6.2; 6.3]§ Mysore sample Boys 8.7 [8.5; 8.9]§ Girls 8.9 [8.5; 9.0]§		5 h fast, bladder voiding
EZ 1800					
(30)	Reliability	30 (not reported)	9–11		(Not reported)
Holtain					
(31)	Measurement error	*Inter-observer* 9 (not reported)	5–15	(Not reported)	No fasting state
	Measurement error	*Intra-observer* 4 (not reported)	5–15	(Not reported)	
Human IM models					
(32)	Validity	102 (0%) Indonesian girls	12.5 ± 0.6	21.4 ± 4.7	Fasting state, exercise restriction, bladder voiding
(33)	Validity	58 (47%)	14.2 ± 1.9	48.2 ± 6.3	(Not reported)
	Cross-validity	61 (44%)	14.0 ± 1.4	37.6 ± 5.7	
Imp™ models					
(34)	Cross-validity	318 (52%) Asian children	(Not reported)	(Not reported)	(Not reported)
(15)	Reliability/Measurement error	68 (62%)	14.8 ± 0.4	BIA %BF (trial 1) Boys 9.7 ± 6.7 Girls 18.6 ± 5.4	PA restriction, normal hydration
(35)	Validity	158 (49%) Lebanese children	9.29 ± 0.77	Boys 26.3 ± 9.6 Girls 26.7 ± 7.1	Overnight fast, bladder voiding
In body models					
(36)	Validity/Measurement error	117 (44%)	10–17	Boys 12.0 ± 5.6 Girls 23.0 ± 8.3	(Not reported)
(37)	Validation	333 (49%)	Boys 9.7 ± 2.0 Girls 9.5 ± 2.1	Boys 20.7 ± 5.4 Girls 24.8 ± 5.4	No fasting state
(38)	Validity	166 (52%)	Boys 11.7 ± 3.2 Girls 11.1 ± 3.0	Boys 16.5 ± 8.3 Girls 19.6 ± 7.4	3 h fast, bladder voiding
OMRON					
(39)	Validity/Reliability	331 (53%)	12–17	Boys 16.3 ± 7.2 Girls 26.2 ± 6.0	(Not reported)
RJL models					
(40)	Validity/Reliability	30 (47%)	Boys 12.5 ± 1.0 Girls 11.6 ± 1.4	13.0 ± 4.0	No fasting state, exercise restriction

Table 1 *Continued*

Reference	Measurement property *Sample*	*n* (%boys)	Age (years) means ± SD	BF (%)* means ± SD	Measurement circumstances†
(41)	Validity	166 (not reported)	7–15	FFM (kg) 7–10 years 23.7 ± 3.7 11–15 years 39.2 ± 8.3	(Not reported)
(42)	Validity	75 (45%) 84% white, 16% Hispanic	5.8 ± 1.2	19.2 ± 7.8	(Not reported)
(13)	Validity/Responsiveness	86 (40%) 67% white, 33% African American	Boys 10.6 ± 2.2 Girls 11.3 ± 2.5	BMI Boys 24.7 ± 6.4 Girls 26.7 ± 7.3	Overnight fast, bladder voiding
(43)	Validity	61 (61%)	12.4 ± 0.9	18.9 ± 9.3	(Not reported)
(44)	Reliability/Measurement error	26 (not reported)	5.0 ± 0.8	Body weight (kg) 20.2 ± 3.0	(Not reported)
(45)	Validity/Reliability/ Measurement error	43 (49%)	Boys 10.3 ± 0.6 Girls 10.3 ± 0.6	Boys 22.1 ± 10.2 Girls 25.8 ± 9.5	(Not reported)
(46)	Validity/Reliability/ Measurement error	94 (56%)	Boys 12.3 ± 1.4 Girls 12.3 ± 1.1	Boys 20.4 ± 9.1 Girls 23.5 ± 6.9	3 h fast, 12 h strenuous PA restriction
(47)	Cross-validity *UAS sample*	25 (not reported)	12.5 ± 1.3	17.9 ± 5.4	3 h fast, 12 h strenuous PA restriction
	Cross-validity *WHNRC sample*	38 (not reported)	15.7 ± 1.6	18.4 ± 7.7	
(37)	Validity	333 (49%)	Boys 9.7 ± 2.0 Girls 9.5 ± 2.1	Boys 24.8 ± 5.4 Girls 20.7 ± 5.4	No fasting state
(48)	Validity *HIPteens*	54 (0%)	13.1 ± 1.4	45.8 ± 7.5	(Not reported)
(24)	Validity	47 (49%)	Boys 12.7 ± 2.7 Girls 11.6 ± 1.6	Boys 16.1 ± 7.6 Girls 20.1 ± 6.2	3 h fast, vigorous exercise restriction
	Reliability	14 (57%)	11.8 ± 1.8	Body weight 45.7 ± 8.7 kg	
SEAC					
(49)	Validity	172 (48%) 32% European, 34% Maori, 34% Pacific Island	Boys 9.3 Girls 9.6	Boys 23 Girls 30	(Not reported)
(50)	Validity/Reliability	30 (53%)	Boys 9.7 ± 1.3 Girls 10.1 ± 1.4	Boys 17.4 ± 5.4 Girls 23.9 ± 7.8	(Not reported)
Selco					
(51)	Cross-validity	57 (100%) Japanese boys	10.9 ± 1.6	20.9 ± 6.4	3–4 h fast PA, restriction, bladder voiding
	Reliability	12 (unknown)	(unknown)	(unknown)	
Stay healthy					
(52)	Validity/Reliability/ Measurement error	115 (44%)	14.9 ± 1.7	18.8 ± 8.3	(Not reported)
Tanita TBF 300 models					
(53)	Validity	17 (35%) Overweight/obese children	10.2 ± 1.2	44.3 ± 5.4	(Not reported)
(54)	Validity	382 (47%) 29% white, 44% Asian, 27% black	13.1–14.0	FM (kg) 11.4–19.3	(Not reported)
(55)	Validity	203 (52%)	Boys 8.9 [8.8; 9.0]¶ Girls 8.9 [8.8; 8.9]¶	Boys 18.6 [16.9; 20.4]¶ Girls 17.7 [16.5; 18.9]¶	10–12 h fast
(56)	Validity/Reliability	183 (0%) African–American girls	9.3 ± 0.8	32.0 ± 13.1	(Not reported)
(57)	Validity	176 (48%)	Boys 11.9 ± 0.2 Girls 11.7 ± 0.2	Boys 9.8 ± 6.1 Girls 12.1 ± 7.7	(Not reported)
(39)	Validity/Reliability	331 (53%)	12–17	Boys 16.3 ± 7.2 Girls 26.2 ± 6.0	(Not reported)
	Between day reliability	79 (59%)	12–17	(Not reported)	
(58)	Validity	66 (55%)	7–10	13.1 ± 6.1	Overnight fast, bladder voiding
Tanita BC 418 models					
(14)	Validity/Responsiveness	78 (38%) Obese	Boys 12.0 ± 3.4 Girls 11.3 ± 3.5	Boys 24.3 ± 10.3 Girls 24.7 ± 8.8	(Not reported)
	Cross-validity	17 (29%) Obese	Boys 10.9 ± 1.7 Girls 11.1 ± 1.5	Boys 20.9 ± 46.6 Girls 30.1 ± 10.7	
(59)	Validity	133 (49%) Rural Gambian	5–16	Boys 12.6 ± 3.8 Girls 19.0 ± 5.2	Overnight fast, exercise restriction
(60)	Validity	46 (52%) Obese	11.0 ± 0.53	44.0 ± 0.92	(Not reported)

Table 1 *Continued*

Reference	Measurement property *Sample*	n (%boys)	Age (years) means ± SD	BF (%)* means ± SD	Measurementcircumstances†
Tanita TBF 400 models					
(61)	Validity	49 (35%) Obese	13.0 ± 3.1	27.3 ± 10.3	2 h fast, bladder voiding
	Reliability/Measurement error	58 (not reported)	(Not reported)	(Not reported)	
Tanita TBF 500 models					
(32)	Validity	102 (0%) Indonesian girls	12.5 ± 0.6	21.4 ± 4.7	Fasting state, exercise restriction, bladder voiding
(26)	Validity	42 (100%)	12.9 ± 1.0	16.4 ± 11.6	3 h fast
(62)	Measurement error	53–74 (not reported)	6–18	(Not reported)	2 h fast, bladder voiding
Tanita TBF 860					
(63)	Validity	30 (100%) Athletic boys	15.8 ± 1.0	13.6 ± 7.6	12 h fast (water *ad libitum*),12 h exercise restriction
Xitron 4000					
(64)	Validity/Measurement error	129 (50%) 50% African Americans, 50% whites	10.8 ± 0.1	26.6 ± 0.9	(Not reported)
(65)	Validity/Measurement error	114 (54%) 52% African Americans, 48% whites	African Americans Boys 12.9 ± 0.1 Girls 12.7 ± 0.1 Whites Boys 12.8 ± 0.1 Girls 12.6 ± 0.1	African Americans Boys 26.1 ± 2.3 Girls 24.7 ± 1.6 Whites Boys 25.7 ± 1.9 Girls 29.6 ± 2.1	(Not reported)
(66)	Validity	31 (100%) 12 control; 19 obese	Controls 8.9 ± 0.5 Obese 8.6 ± 0.3	Controls 21.2 ± 1.8 Obese 40.8 ± 0.9	12 h fast, 24 h heavy exercise restriction
(48)	Validity *BAROC sample*	26 (0%)	12.7 ± 0.7	24.7 ± 8.5	(Not reported)

*Based on gold standard. If %BF was not available, FFM (kg) was reported. If a gold standard was not available, BMI (sds) (kg m^{-2}) or body weight (kg) was reported.
†Measurement circumstances prior to BIA measurement, include having fasted (for at least 2 h), voiding the bladder immediately prior to measurement, restricting strenuous exercise/physical activity (PA) (for at least 8 to 12 h).
‡Values between [ ] indicate range.
§Values between [ ] indicate interquartile range.
¶Values between [ ] indicate 95% confidence interval.
%BF, percentage body fat; BIA, bioelectrical impedance analysis; BMI, body mass index; FFM, fat free mass; PA, physical activity.

from –5.2 to 5.2 kg for FM and from –5.5 to 3.8 kg for FFM. Moreover, findings for magnitude biases, if reported, were not consistent for %BF, FM and FFM. Magnitude biases ranged from $r = -0.69$ to $r = 0.47$ for %BF, from $r = -0.75$ to $r = 2.7$ for FM and from $r = -0.73$ to $r = 0.57$ for FFM. These results indicate that the mean differences were dependent on the level of %BF, FFM and FM. Since mean differences and magnitude biases ranged from negative to positive, we conclude there is conflicting evidence for convergent validity.

Prediction equations

The manufacturer's equation was applied in 27 studies (15 different BIA devices), in 11 studies new equations were developed and in 14 studies an external developed equation was applied (i.e. in total 40 different prediction equations used). Although BIA uses TBW to predict FFM, only three equations – applied in four studies – included an age and gender specific hydration factor.

Responsiveness

Only two studies evaluated the responsiveness of BIA, using different BIA devices and convergent measures of body composition. One study had good methodological quality and one study had poor methodological quality. The study of good methodological quality reported a mean difference of –1.37 (standard deviation [SD] 6.98) for %BF and a negative magnitude bias for the RJL 101 device (13). In addition, this study reported an R^2 of 0.44 and a SEM of 0.074 (13). The study of poor methodological quality reported a mean difference of 0.2 kg (SD 1.8) for FM or FFM, and no magnitude bias for the Tanita BC 418 (14).

Reliability and measurement error

Details of results for reliability and measurement error sorted by methodological quality, study frequency and BIA device, are shown in Supporting Information Table S6. Twenty papers examined reliability and/or measurement error. Of these papers, two papers evaluated reliability and/or measurement error of two BIA devices and one paper evaluated reliability and/or measurement error of three devices (in total 24 studies). Fifteen studies examined reliability of 10 BIA devices and 16 studies examined measurement error of 11 BIA devices (seven studies examined both; for further details see Supporting Information

Table S5). None of the studies had an excellent methodological quality. Methodological quality was good in 12 studies, fair in 11 studies and poor in eight studies. Test-retest procedures were often incomplete, e.g. population characteristics were not always reported, the time interval was not always stated and it was not clear whether (new) electrodes were (re)placed. The time interval between test and retest varied between 90 s and 5 weeks. Five studies reported that electrodes were replaced (in one study new electrodes were used) and one study reported that electrodes were not replaced.

Results for reliability for %BF, FFM and FM were good: ICCs were ≥0.96 and correlations were ≥0.82, except for one study (r = 0.27 for boys and r = 0.38 for girls (15)). We therefore conclude there is strong evidence for good reliability of BIA.

Regarding measurement error, absolute mean differences were –0.90 to 1.61% for %BF, 0.05 kg for FM, 0.15 kg for FFM, 2.6 to 8.2Ω for resistance and 0.8 to 4.07Ω for reactance. CVs varied between 1.7 and 22.2%.

Discussion

In this study, we aimed to summarize the evidence on validity, responsiveness, reliability and measurement error of BIA methods for the estimation of body composition (%BF, FM and FFM) in children and adolescents, examining peer-reviewed literature published through November 2012.

Unfortunately, due to the enormous combinations between BIA devices and prediction equations, we could not conclude what is the most valid and reliable BIA device and prediction equation applied. Similarly, we could not conclude on the most accurate BIA procedure, i.e. whether adhesive electrodes are more accurate than pressure contacts.

Criterion and convergent validity

We conclude conflicting evidence for both criterion and convergent validity. Importantly, only five studies used multicomponent models as a reference method, thereby studying criterion validity. The reference methods used within the convergent validity in the present study are not without limitations. All reference methods are based on assumptions to convert measures of FFM (i.e. water, protein, minerals) into measures of %BF, and constants needed for these calculations varied (e.g. not always age and gender specific). For example, water content of FFM is assumed to be constant, but varies in reality (16). In addition, the relative amounts of muscle and bone change substantially during growth (16), complicating the estimate of %BF. Other technical difficulties include the requirement of radiation for DEXA and of complete submerging under water and assessing residual lung volume for UWW (17,18), which are not very child friendly.

It is important to note that a hydration factor should be applied in order to calculate FFM from TBW. According to Lohman (19), this hydration factor should be age and gender specific when applied to children. Strikingly, only a few prediction equations applied an age and gender specific hydration factor. Moreover, measurement circumstances that may alter hydration (i.e. fasting state, bladder voiding and restricting strenuous exercise) were not always reported. We recommend future studies to elaborate more on these important issues.

Correlations between the measurement of interest and the gold standard are often used to reflect criterion validity. However, since high correlations do not mean that two methods agree (12), we excluded correlations from our data synthesis for criterion validity and convergent validity.

In the present study, populations from mixed ethnic background were included. However, we found no studies examining the cross-cultural validity of BIA devices, indicating that no studies examined the criterion validity of BIA devices and equations in different ethnic populations (i.e. black, white, Asian). Therefore, to check whether different prediction equations should be applied for different ethnic populations, we recommend future studies to evaluate the cross-cultural validity of BIA devices.

Responsiveness

Due to a lack of high methodological quality studies, we conclude that the responsiveness of BIA is unknown and discourage the use of BIA to follow within-person changes in %BF – or FM and FFM.

Reliability and measurement error

Based on high ICCs and correlations, we conclude there is strong evidence for the reliability of BIA. A limitation of using ICCs for determining reliability is that it is influenced to a large extent by the variation between participants. The large variation in %BF of the participants in the included studies (9.8–45.8%) might have induced the high ICCs.

As already mentioned in the methods, we need information on what constitutes a MIC, to conclude on the magnitude of the measurement error. However, to the best of our knowledge, this information is not available in children. Since in children measures of body fatness are dependent on personal characteristics such as age, height and gender, intervention studies report age, height and/or gender dependent z-scores. We found reasonable small absolute mean differences (for example –0.90 to 1.61% for %BF). However, when expressed relative to the %BF of the included population (i.e. 12.0–29.6%), these differences represent rather large under- (3.00–7.5%) or overestimations (5.40–13.4%). In addition, we found a large range of CVs (1.70–22.2%). Therefore, we conclude that BIA is susceptible to considerable measurement error.

An important finding of this review is that important details on the test-retest procedures (i.e. population characteristics, time interval, electrode replacement) were lacking in most studies, leading to a lower methodological quality (see Supporting Information Table S1). We recommend that future studies include detailed test-retest procedures to be able to judge the reliability of the BIA.

Conclusion

BIA is a practical method to assess body fat in children and adolescents. However, our systematic review concludes that, based on conflicting results for criterion and convergent validity and considerable measurement error, BIA cannot accurately assess %BF, FM or FFM. We propose that the most frequently used devices and prediction equations are improved and evaluated in multiple high-quality studies.

Conflicts of interest statement

The authors declare no conflicts of interest.

Supporting information

Additional Supporting Information may be found in the online version of this article, http://dx.doi.org/10.1111/obr.12061

Table S1. Methodological quality criteria (10,11).
Table S2. Instrument properties of examined bioelectrical impedance analysis (BIA) devices.
Table S3. Results for criterion validity sorted by methodological quality, study frequency and bioelectrical impedance analysis (BIA) device.
Table S4. Results for convergent validity sorted by methodological quality, study frequency and bioelectrical impedance analysis (BIA) device.
Table S5. Equations to predict percentage body fat (%BF), fat mass (FM) and fat-free mass (FFM).
Table S6. Results for reliability and measurement error sorted by bioelectrical impedance analysis (BIA) and methodological quality.

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