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REVIEW

Equations based on anthropometric measurements for adipose tissue, body fat, or body density prediction in children and adolescents: a scoping review

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Abstract

Purpose Assessing the body composition of children and adolescents is important to monitor their health status. Anthropometric measurements are feasible and less-expensive than other techniques for body composition assessment. This study aimed to systematically map anthropometric equations to predict adipose tissue, body fat, or density in children and adolescents, and to analyze methodological aspects of the development of anthropometric equations using skinfolds.

Methods A scoping review was carried out following the PRISMA-ScR criteria. The search was carried out in eight databases. The methodological structure protocol of this scoping review was retrospectively registered in the Open Science Framework (https://osf.io/35uhc/).

Results We included 78 reports and 593 anthropometric equations. The samples consisted of healthy individuals, people with different diseases or disabilities, and athletes from different sports. Dual-energy X-ray absorptiometry (DXA) was the reference method most commonly used in developing equations. Triceps and subscapular skinfolds were the anthropometric measurements most frequently used as predictors in the equations. Age, stage of sexual maturation, and peak height velocity were used as complementary variables in the equations.

Conclusion Our scoping review identified equations proposed for children and adolescents with a great diversity of characteristics. In many of the reports, important methodological aspects were not addressed, a factor that may be associated with equation bias.

Level IV Evidence obtained from multiple time series analysis such as case studies. (NB: dramatic results in uncontrolled trials might also be regarded as this type of evidence).

Keywords Scoping review · Obesity · Children · Adolescents · Anthropometric measurements · Anthropometric equations

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Introduction

The prevalence of overweight among children and adolescents aged 5 to 19 years has increased worldwide. In 2016, an estimated 213 million boys and girls were overweight and 125 million were obese [1], and the number of children and adolescents living with obesity is predicted to rise to 206 million by 2025 and to 254 million by 2030 [2]. In the United States, surveys conducted in 2015–2016 showed that 35.1% of children and adolescents were overweight, with a continuous increase in obesity and severe obesity [3].

Obesity in childhood and adolescence contributes to the long-term development of severe comorbidities, which can lead to elevated blood pressure or even to premature death in adulthood [4]. The deleterious effects of obesity can already be observed during childhood and adolescence, with increased total fat and central fat being directly associated with several cardiovascular and metabolic risk factors [5–7].

Body composition assessment in children and adolescents is important to detect not only obesity but also low weight and malnutrition, which, in 2016, were estimated to affect 192 million boys and girls worldwide [1]. Body composition is one of the health-related components of physical fitness tests used for children and adolescents, such as FITNESSGRAM® [8], or for young athletes, being associated with growth, maturation, and sports performance [9].

At a broader level, body composition can be assessed in vivo or in vitro. While in vitro methods include the analysis of cadavers or tissue biopsy, in vivo methods are indirect—that is, they do not provide a direct assessment of body composition [10]. Because cadaver dissection is a complex procedure, studies of this type are rare, and the best-known one is 'The Brussels Cadaver Analysis Study,' conducted in the 1970s and 1980s [11]. Cadaver dissection can be used to validate adipose tissue estimates obtained by other methods used for body composition assessment, such as nuclear magnetic resonance [11, 12] and anthropometry [13].

In vivo methods can be divided into type I (descriptive models) and type II (mechanistic models) [10]. Type II models usually have an underlying physical or biological basis and use well-established ratios or proportions to relate the unknown component to the measurable property or known component [10]. These models are often used as a reference method to develop and validate descriptive equations. Although accurate, type II models have certain limitations, such as high cost and low practicality. Type I models share in common a type of mathematical function derived by statistical analysis of quantitative measurements and require a reference method to quantify the unknown component. These models are more practical, simple, fast, and low-cost, and examples include bioelectrical impedance analysis and anthropometry [10].

Type I models (descriptive methods) are often developed and validated using regression equations and a reference method. Over the decades, many anthropometric studies have been conducted to develop equations for predicting body fat (BF) [14, 15]. Equations are specific to the characteristics of the group from which they were derived, such as athletes from different sports [16] and people with diseases [17] or disabilities [18], but they can be applied to the general population if they are adjusted to match its characteristics, such as sexual maturation, ethnicity, and sex, which are factors associated with changes in body composition [19–25].

Despite a large number of anthropometric studies, many of the prediction equations are not widely known. Therefore, mapping and cataloging them would help clinicians select the most appropriate equations to use in each particular population. In addition, skinfolds are the most commonly used anthropometric measurements in BF prediction equations, and they are strongly correlated with adiposity [18, 26, 27]. Skinfolds require a more detailed methodological guidance for the consistent application of these equations in practice. In this respect, analyzing the methodology used to develop the equations that include skinfolds would allow us to identify the knowledge gaps and limitations on this topic.

In this context, this scoping review had two main objectives: (1) to systematically map anthropometric equations to predict adipose tissue, BF, or body density in children and adolescents using in vitro or in vivo techniques as a reference method; and (2) to analyze the methodological aspects described for the development of anthropometric equations using skinfolds.

Methods

Preliminary search

In December 2019, we conducted a preliminary search using the MEDLINE (PubMed), Cochrane Library, and Open Science Framework (OSF) databases to assess the state of the art on the topic and the Joanna Briggs Institute (JBI) database of systematic reviews and implementation reports to identify scoping or systematic reviews that have mapped anthropometric equations in children and adolescents. We found only one review [15], which aimed to identify equations to estimate both fat and lean mass by anthropometry and bioelectrical impedance analysis, but it was limited to the reference methods three-component (3C) and four-component (4C) models. The review limited the search for studies published from 1985 to 2012 in English.

Review questions

The present review aimed to compile and disseminate scientific information on the topic, based on the following questions: Which equations for predicting adipose tissue, BF, or body density, based on existing anthropometric measurements, are specific to children and adolescents? What methodological details are described for the development of anthropometric equations using skinfolds? This information is crucial to minimize methodological errors in the application of anthropometric equations for estimating body composition, especially in children and adolescents.

Protocol and checklist

We developed this scoping review according to the JBI guidelines [28] and the Preferred Reporting Items for Systematic reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) guidelines [29] (Table S1). The entire methodological structure of this scoping review, including objectives, inclusion criteria, and methods, was specified in advance and documented in a protocol registered with OSF (https://osf.io/35uhc/).

Inclusion criteria

Participants

Children or adolescents aged 5 to 19 years. Reports in which the participants were beyond these age limits were included if (1) the mean age of the participants was within the age range of 5–19 years and (2) the number of years within the age range of 5–19 years was greater than or equal to the number of years outside this age range. If the article reported only the participants' mean age or age range, it was included if the information provided met the two previously mentioned criteria. The age range adopted in the present review (5–19 years) followed the standards adopted by the World Health Organization for school-age children and adolescents [30].

Concept

This review included articles with original anthropometric equations for estimating adipose tissue, BF, or body density that were validated using one of the following reference methods: multicomponent model, dual-energy X-ray absorptiometry (DXA), ADP, HW, isotopic dilution, total body potassium, computed tomography, magnetic resonance imaging, neutron activation, or cadaver dissection.

We excluded articles that only proposed adjustments to preexisting equations, articles that included other existing anthropometric methods in the equation (e.g., body mass index and waist-to-height ratio), and those using methods other than anthropometric measurements to estimate body composition as predictor variables (e.g., bioelectrical impedance analysis).

Context

There were no restrictions on the context. We included reports regardless of geographic location, ethnicity, sex, health condition, disability, level of physical activity, or body composition.

Types of evidence sources

We included the following types of reports: clinical trials, quasi-experimental studies, prospective and retrospective cohort studies, case–control studies, cross-sectional studies, case reports, and conference abstracts.

Search strategy

Initially, we searched MEDLINE using medical subject headings (MeSH) to identify the descriptors and their respective entry terms for the inclusion criteria, combining them with Boolean operators ("AND" and "OR"). We included terms related to child, adolescent, anthropometry, body composition, and reference methods for body composition assessment. We ran this initial search in the Cochrane Library and MEDLINE (PubMed) databases to verify search sensitivity. We analyzed the title, abstract, and keywords of the first 100 articles retrieved from these two databases to identify other related terms that could be added to the search strategy. We then included the terms identified as relevant in the search strategy and applied the final version to eight electronic databases: MEDLINE (PubMed), Cochrane Library, SPORTDiscus (through EBSCO), Cumulative Index to Nursing and Allied Health Literature (CINAHL) (through EBSCO), Web of Science, Scopus, LILACS, and EMBASE. Because the LILACS and EMBASE databases have their own health science descriptors and Emtree terms, respectively, we tailored the search terms to each one of these databases. We defined descriptors in English, Portuguese, and Spanish in the LILACS database due to its particular features, while in the other databases, we used only descriptors in English. The search strategies for each database are available as supplementary information (Table S2). We performed additional sensitive searches in the search platforms and in other systematic reviews not to miss any important publications [31–34].

We searched the gray literature by checking the Bank of Theses and Dissertations of the Coordination for the Improvement of Higher Education Personnel (*Coordenação de Aperfeiçoamento de Pessoal de Nível Superior*—CAPES), which is a federal agency linked to the Brazilian Ministry of Education and responsible for the assessment of the quality of the national and international scientific production. We hand-searched the American Journal of Clinical Nutrition, which is the journal that yielded the largest number of publications after the initial search in all databases to identify any studies that may not have been detected due to limitations of the database search algorithm. We also hand-searched the reference lists of all articles selected in the final stage of the review and included those that met the inclusion criteria.

Source of screening and selection of evidence

We exported the search results from each database to Mendeley reference management software version 1.17.13 (Elsevier), where duplicates were removed and a file was generated with a unified database. We imported this file into Rayyan, a web application developed to assist in the screening of articles for reviews [35]. Using Rayyan, two researchers (MSC and IGAE) independently screened the articles by first evaluating the titles and abstracts and then reading the full text of all publications identified as potentially relevant. Disagreements in the inclusion of articles between the two researchers were resolved by consensus or by the analysis of a third reviewer (PHRFA).

Data extraction

We developed, tested, and adjusted a form to meet the requirements for the extraction of relevant information for reviews. We used Google Forms to create an online form and exported the responses to an Excel® file (Microsoft Corp. Redmond, WA) to compare and identify possible differences in data tabulation between the researchers. We conducted a pilot study to familiarize the reviewers with the instrument and to ensure that the information was extracted in a standardized and appropriate manner. Two independent reviewers (MSC and IGAE) extracted data from the included articles, and disagreements were resolved by consensus or discussion with a third reviewer (PHRFA).

Analysis and presentation of results

For organization purposes, we first grouped the data by reference (author and year), country, population (sample characteristics, size, and age group), reference method, statistical analysis (coefficient of determination [R^2], standard error of the estimate [SEE], and correlation coefficient [r]), and description of the equation. Then, we pooled data on the methodological details of equations involving skinfold measurements. We extracted information on skinfold caliper model and calibration method, evaluator training and error rate, acceptable measurement error limits, anthropometric references, body side, and number of measurements. Using these data, we plotted a graph showing the models of skinfold calipers used, the continent in which they were used, and the number of reports per continent.

We tabulated the equations exactly as they had been defined in the reports. We observed a lack of standardization in the nomenclature and location of anthropometric measurements, which sometimes occurs due to different names and descriptions assigned by the authors to the same measurement. To provide more detailed information, we created a table in which we included the nomenclature of the measurements and their respective description (extracted only from the reports that described the measurements), without considering the reference cited in the report.

We used the measurement units as they had been described in the reports: body mass in kg, skinfolds in mm, and stature, girth, length, bone breadth, and height in cm. In cases where other measurement units were used, we described the unit within the equation.

We calculated that a sample size of 10–15 participants per predictor variable included in the analysis was suitable for the development of multiple regression analyses [36]. In statistical analysis, an $R^2 \geq 0.64$ and $r \geq 0.80$ were considered to have a strong effect [37]. For percent BF (%BF), SEE ≤ 3.5% was considered good for the proposed equation [38].

To provide additional details on some variables, we created a map highlighting the countries of origin of the proposed equations with the respective number of reports. We plotted a graph (bubble plot) showing the reference methods used and the number of reports per decade.

As recommended by PRISMA-ScR guidelines, which have been followed in the previous scoping reviews [39–41], we did not assess the methodological quality of the included reports.

Results

Search

The initial search in the eight databases resulted in 15,218 reports after removing duplicates. We excluded most full-text reports due to a lack of adequate study design (Table S3). The complementary search identified 12 studies that referred to 12 reports. At the end, 78 studies were included, referring to 78 reports [16–19, 25–27, 42–112] (**Fig. 1**).

Characteristics of reports

The reports included a great diversity of sample characteristics, and we were able to find the description of 593 equations. This topic has been researched for almost 6 decades

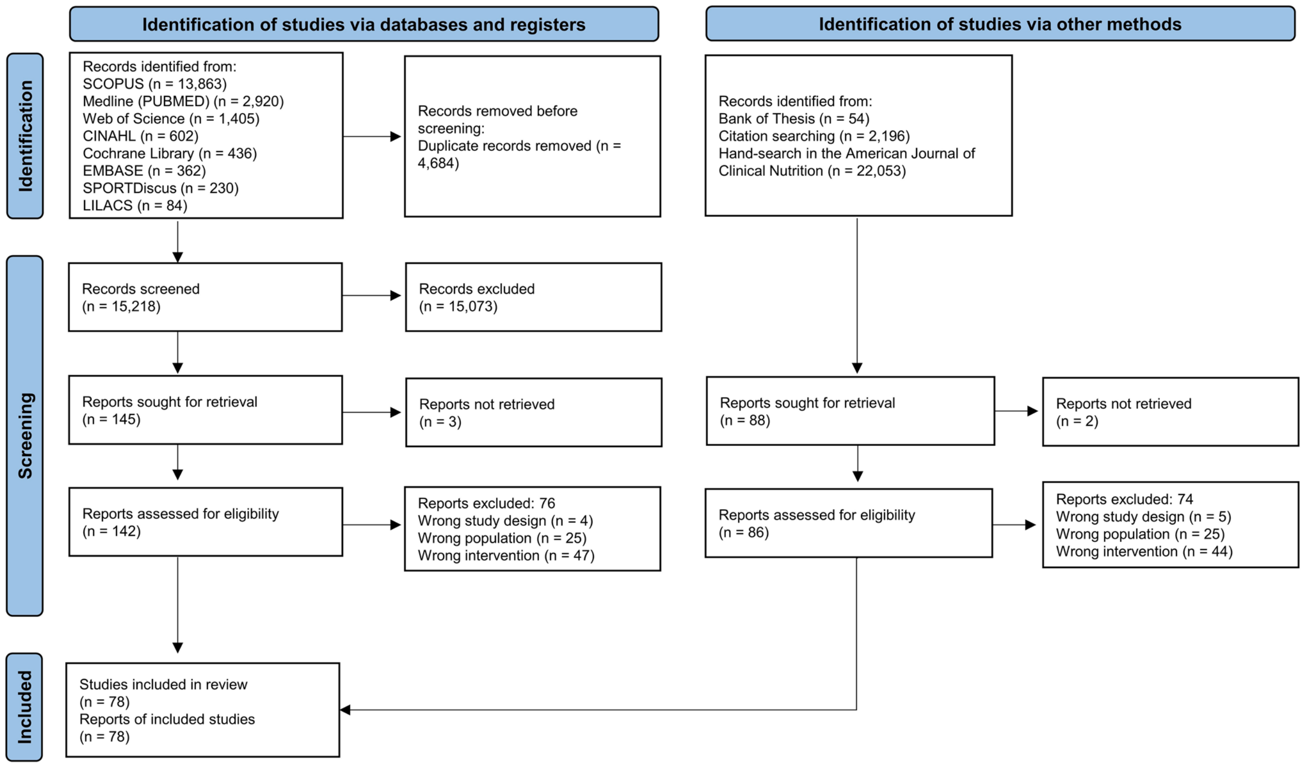

Fig. 1 Flowchart of study selection and inclusion process in the scoping review. The figure represents the process of identification, screening, and final inclusion of 78 studies (phase 1, phase 2, and phase 3 of the review)

(1961–2019), and the first study identified on the topic was conducted by Parízková and published in 1961 [42]. Twenty-nine studies were published in the last decade, and most of them (10 studies) were published in 2017 (Table S4).

Equations were identified in 22 countries across all continents. The continent with the largest number of reports was North America (28 reports) [25, 27, 43, 45–47, 50, 54, 56–59, 61, 62, 67–69, 72–76, 80, 93, 96, 100, 104, 105], followed by Europe with 17 reports [16, 18, 42, 44, 48, 49, 52, 53, 64, 70, 83, 88, 91, 99, 110–112]. Although no study was developed directly in Central America, Huang et al. [80] conducted a study in the United States of Latin American descendants; most of them from Central American countries (Fig. 2).

Characteristics of the populations

The samples were heterogeneous in terms of age. Some studies used samples of limited age groups [47], with age group divisions every 0.5 years, while others used samples of broad age groups, ranging from 8 to 31 years [99], including young people at all stages of sexual maturation. Although the reported equations, for the most part, were developed for healthy individuals, many of them considered other sample characteristics (Table S4).

Sample size of reports

Sample size for the derivation of equations varied widely. The study by Johnston et al. [62] had the smallest sample size, with only six participants, while the study by Stevens et al. [96] had the largest sample size, with 3334 participants. Most studies conducted in the 1960s and 1970s had small sample sizes, and the study by Frerichs et al. [54] was the only one with a sample size of more than 100 participants divided by sex, age, or other characteristics (Table S4).

Of the 77 studies that reported sample size, 35 (45.5%) met the criterion of a sample size of ten participants per predictor variable [19, 26, 54, 55, 60–62, 64–66, 68, 69, 72–75, 78, 84, 85, 88–90, 92, 93, 96, 99, 100, 102–106, 109, 111, 112]. When considering 15 participants per predictor variable, 19 studies (24.4%) met this criterion [60, 62, 65, 66, 68, 69, 78, 84, 88, 92, 93, 96, 99, 100, 102, 104–106, 111] (Table S4).

Fig. 2 Map of countries of origin and number of studies of anthropometric equations. The figure represents the nationality of the individuals evaluated in the 78 studies included in the scoping review, which were identified in the equations to predict body fat or body density in children and adolescents in 22 countries across all continents. USA: United States of America; Countries not reported; studies that did not report the location where subjects were evaluated

Validation procedures

Of all 78 reports, 19 (24.4%) [16, 19, 25, 58, 59, 65, 72, 73, 80, 81, 90, 93, 96, 100, 102–105, 111] performed a cross-validation of the equation, with a higher cross-validation rate in studies conducted in the last decade (11 of 29 reports, 37.9%). Alternative cross-validation techniques included the predicted residual error sum of squares (PRESS), performed in three studies [26, 84, 108], the jackknife method in one study [70], and the leave-one-out method in one study [74] (Table S4).

Reference methods

The HW technique was predominantly used in the first 3 decades. Then, we can observe a transition to other reference methods, reaching a point of equilibrium between HW and DXA in the 1990s; the latter began to predominate from 2000 onward (Fig. 3).

Anthropometric measurements

Anthropometric measurements were grouped into six categories: basic (body mass, stature, sitting height, and arm span), skinfolds, girths, lengths, breadths, and heights. Of

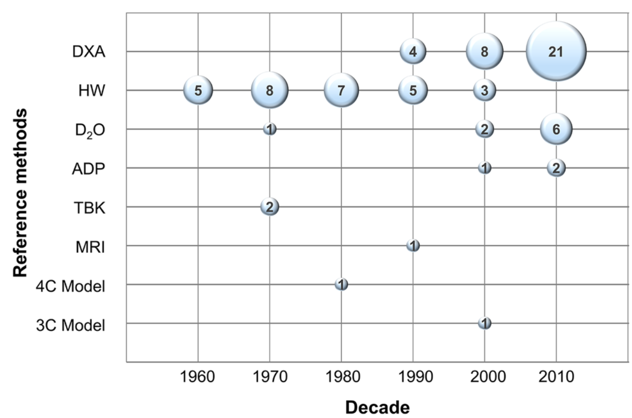

Fig. 3 Bubble plot of the frequency with which reference methods are cited by decade. The y-axis represents the reference models used to develop the anthropometric equations. The x-axis represents the decades in which the studies were published. The size of the bubble is proportional to the number of studies published in the decade. *3C Model* three-component model, *4C Model* four-component model, *ADP* air displacement plethysmography, *D_2O* isotope dilution, *DXA* dual-energy X-ray absorptiometry, *HW* hydrostatic weighing, *MRI* magnetic resonance imaging, *TBK* total body potassium

the 78 reports, 16 (20.5%) used four or more measurement categories [18, 26, 27, 43, 44, 50, 56–59, 76, 83, 86, 100, 104, 108] (Table S4). An interesting aspect in the analysis of skinfolds was that the set of four skinfold measurements made at the biceps, triceps, subscapular, and suprailiac sites was present in 20 of 73 reports.

Anthropometric measurements varied considerably among the reports in both nomenclature and description. An example of the divergent nomenclature in describing the same measurement is the use of suprailiac skinfold [56] and iliac crest skinfold [95], both of which refer to the skinfold thickness measured immediately above the iliac crest. As for different descriptions using the same nomenclature, the most extreme example is waist girth, which had nine different descriptions (Table S5), including measurements at the narrowest part of the torso [89], the midpoint between the lowest rib and the iliac crest [106], and the area of the greatest girth of the abdomen [113].

Statistical analyses

Of 593 equations, only 281 showed an R^2 value, ranging from 0.00 to 1.00. Of these 281 equations, 215 (76.5%) had an $R^2 \geq 0.64$. The r value was showed in 200 equations, ranged from 0.03 to 0.98, of which 105 (52.5%) had an $r \geq 0.80$. In the models for %BF estimation, 137 reported SEE results. Of these, 46 (33.6%) had an error up to 3.5%, indicating optimal SEE results (Table S4).

Equations

Of 593 equations, %BF was used as a dependent variable in 264 (44.5%), body density in 175 (29.5%), and fat mass (FM) (kg) in 148 (25.0%). Regarding sex, almost half of the equations were derived only for males ($n = 284$; 47.9%) (Table 1). Skinfolds were the main measurements used in the equations ($n = 535$; 90.2%), and 423 of them (71.3%) were developed using only skinfold measurements (Table S4).

Table 1 summarizes the anthropometric measurements most commonly used in the equations, divided by groups of measurements. Because length and height measurements were uncommon (less than five occurrences), they were not included in the table. Skinfolds had a similar relative frequency in both males and females, with triceps skinfold being the most commonly used measurement, followed by subscapular skinfold. In the category of basic measurements, stature was more frequently used than body mass only for boys; for girls and for both sexes, body mass was most frequently used. Bone breadths and girths were more frequent in the equations for boys than for girls or for both sexes (Table 1).

Skinfold calipers

Nine skinfold caliper models were identified, and six of them were cited one to four times [17, 26, 47, 49, 51, 65, 90, 97, 101, 102, 108], but they were limited to the same country, indicating that the models follow national standards. Harpenden [19, 44, 47–49, 52, 53, 56, 57, 61, 62, 66, 79, 83, 84, 88, 89, 91, 95, 98, 104, 107, 109, 112], Lange [27, 43, 45, 46, 50, 52–54, 59, 72–76, 80, 103], and Holtain [16,

Table 1 Anthropometric measurements most commonly used in equations, by group of measurements. Absolute values and percentages. n (%)

	Skinfolds						
	Tr	SS	Bi	SI	Ab	Ca	Th
All (593)	356 (60)	272 (46)	202 (34)	144 (24)	76 (13)	49 (8)	48 (8)
M (284)	180 (63)	139 (49)	87 (31)	68 (24)	45 (16)	22 (8)	17 (6)
F (180)	113 (63)	92 (51)	60 (33)	51 (28)	23 (13)	19 (11)	13 (7)
M and F (125)	60 (48)	40 (32)	54 (43)	23 (18)	8 (6)	9 (7)	18 (14)

Other groups of measurements

	Basic		Girth				Breadth	
	BM	St	Wa	Ar	Ca	Th	Wr	BA
All (593)	83 (14)	75 (13)	22 (4)	11 (2)	10 (2)	14 (2)	6 (1)	7 (1)
M (284)	24 (8)	41 (14)	15 (5)	7 (2)	8 (3)	14 (5)	6 (2)	6 (2)
F (180)	27 (15)	22 (12)	5 (3)	3 (2)	0	0	0	1 (1)
M and F (125)	24 (19)	10 (8)	5 (4)	1 (1)	2 (2)	0	0	0

Four equations are from reports that did not report sex

Ab abdominal, *Ar* arm, *BA* biacromial, *BM* body mass, *Bi* biceps, *Wr* wrist, *Ca* calf, *F* female, *Wa* waist, *M* male, *M and F* equations for both sexes, *SI* suprailiac, *Tr* triceps, *SS* subscapular, *St* stature, *Th* thigh

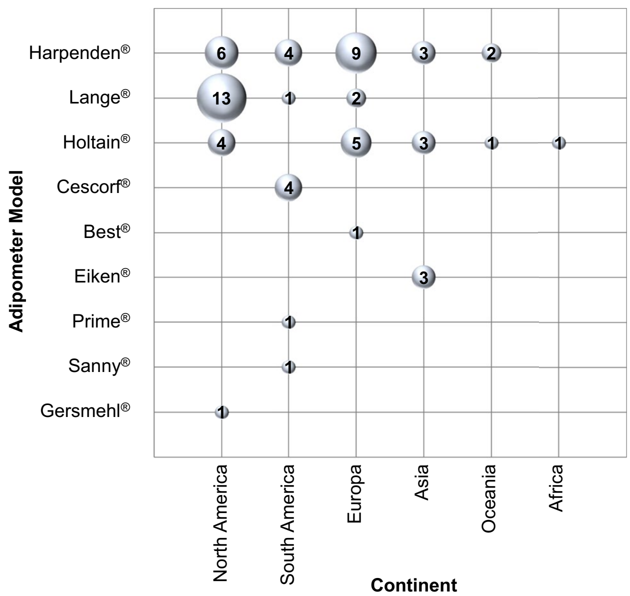

Fig. 4 Bubble plot of the frequency with which models of skinfold calipers are cited in studies by continent. The *y*-axis represents the models of skinfold calipers cited in the studies. The *x*-axis represents the continents on which the studies were carried out. The size of the bubble is proportional to the number of studies published on the continent

18, 49, 58, 70, 71, 81, 82, 85, 93, 94, 96, 99, 105] skinfold calipers were cited more than ten times each in different countries and continents, indicating that these models follow international standards (Fig. 4).

One study reported the use of a new skinfold caliper [83]. Only six studies reported the calibration method used [43, 45, 79, 97, 99, 107], and one of them showed jaw pressure variations when holding the calipers at different openings [45] (Table S6).

Evaluator training and error rate

Of the 73 studies that measured skinfolds, only 30 (41.1%) reported any type of training or the expertise of the evaluator [16–18, 27, 54, 67, 70–73, 79–81, 83, 86, 88, 90, 91, 93–96, 98, 101, 102, 104, 105, 107, 109, 110] (Table S6). In addition, 23 studies (31.5%) [16–18, 26, 54, 57, 59, 73, 76, 77, 81, 86, 88, 91, 93–95, 102, 105, 107–110] reported some method for estimating data collection error (Table S6).

Anthropometric references

In the analysis of anthropometric references cited in the articles, we found 66 citations that accounted for 33 references. Of these, 31 were cited one-to-three times and two were cited more than ten times each: the Anthropometric Standardization Reference Manual [19, 26, 67, 72, 74, 76, 80, 84, 85, 88, 90, 99, 104, 108] by Lohman et al. [114] and several updates of the International Society for the Advancement of Kinanthropometry (ISAK) [16, 18, 26, 79, 86, 94, 95, 98, 102, 107–110] [115–118] (Table S6).

Body side for measurements

Of the 34 studies that reported the body side used for measurement, 21 (61.8%) used the right side [42, 44, 45, 47, 50, 52, 54, 56, 57, 59, 61, 62, 65, 73, 76, 79, 93, 94, 102, 103, 109], seven (21.6%) used the left side [58, 66, 70, 84, 91, 99, 112], one (2.9%) used the non-dominant side [82], three (8.9%) used both sides [19, 53, 83], and one (2.9%) measured both sides independently [49] (Table S6). The left side was most frequently used in studies conducted in Asia and Europe, whereas the right side was most commonly used in those conducted in North America, South America, and Oceania.

Measurement error

Only nine studies (12.3%) reported some form of measurement error [74, 76, 86, 91, 93, 95, 102, 103, 110], all published from 2000 onward (Table S6).

Number of measurements and recording (mean or median)

Of 39 studies reporting the number of measurements, 26 (66.7%) obtained the measurements in triplicate [17, 19, 45, 54, 56, 61, 62, 66, 67, 70–72, 74, 80, 81, 85, 88, 91, 93, 97, 99, 101, 103–105, 112], six (15.4%) in duplicate [59, 75, 79, 82, 94, 98], one (2.6%) made three-to-five measurements [50], one (2.6%) made six measurements (three on each side) [83], and four (10.4%) used the mean of two measurements or, if the difference was greater than the established standard, a third measurement was performed [76, 95, 102, 110]. No study reported having performed only one measurement. Twenty-nine reports used the mean value of the measurements [17, 19, 45, 50, 54, 56, 59, 61, 62, 66, 70, 71, 74, 76, 81, 83, 85, 88, 91, 93, 94, 97, 101–105, 119], one used the median value [80], and one used the mean of two measurements or, if the difference was greater than 5%, a third measurement was performed and the median value was recorded [95] (Table S6).

Discussion

Characteristics of the populations

In equations developed for both males and females, we should take sexual dimorphism into account. Although less common during childhood, it can lead to marked sex differences during puberty, highlighting very distinct anthropometric profiles [120]. Therefore, in the context of sexual dimorphism, including adolescent males and females in the same body composition equation can lead to outcome bias, thus undermining the validity of the equation.

Age and the stage of sexual maturation have an influence on the relationship between anthropometric measurements and body composition [121]. This explains the need to propose specific equations for different age groups in childhood and adolescence. Because the use of samples covering a wide age range may impair the relationship between anthropometric measurements and body composition, equations derived from heterogeneous samples are not recommended for children and adolescents. Equations developed in samples consisting of both adolescents and adults, based on the argument of analyzing individuals with very specific characteristics, such as cystic fibrosis [99], should be viewed with caution, as the predictive ability of the equation may be compromised. In this context, some studies have divided young people into sexual maturation groups to make the equations more specific, as in the studies conducted by Slaughter et al. [61] and Deurenberg et al. [112].

Not only age but also the stage of development is associated with body composition, being reported for assessing sexual maturation, the scale proposed by Tanner, and the method of assessing the peak height velocity proposed by Mirwald et al. [122]. Characteristics of the sample from which the equation was derived must be observed when choosing an equation to use in clinical practice. If there are no suitable equations for the population to be evaluated, it is necessary to propose a new equation or to validate an existing one for this new population [10].

Sample size of reports

Few studies met the sample size criteria in relation to the number of participants per predictor variable, a factor that can compromise the ability to predict the dependent variable with statistical effects. Larger sample sizes may yield more accurate prediction equations with greater statistical power [123], which underscores the need for researchers to develop equations that meet the quality criteria. Our results show that most studies with large sample sizes used DXA as the reference method, which may indicate an advantage of this method over other reference methods as it is practical, fast, and does not require additional examination costs, thus making studies with larger sample sizes feasible.

Validation procedures

Regarding predictive ability, the results of regression models are valid only for the sample for which the model was derived. However, to achieve generalization, the model needs to be tested in a different sample, a process known as cross-validation [36]. This strategy was described by Pollock and Jackson [124], who made a reference to a study from 1968 that, already in that year, recommended performing a cross-validation using an independent subsample of the original group that has not been used in the development of the equations. Another way to check the cross-validation results is using statistical methods, such as the PRESS and jackknife procedures, which can indicate the predictive ability of a regression model and are conceptually equivalent to data-splitting methods, where, for example, an independent sample is randomly selected from the original sample that derived the equation and used for cross-validation [123].

Although important, cross-validation procedures are not commonly performed. They have become more frequent in the last decade, but still account for less than 50% of the studies. This methodological action is recommended for all studies to confirm that the regression models developed are not only valid for the sample used to derive the models (internal validity), but that they can be generalized to other samples (external validity). These procedures should be used in all future studies conducted to develop equations.

Reference methods

DXA was the reference method most commonly cited in the reports. It is a multicomponent method (it divides body weight into FM, mineral bone, and fat- and bone-free mass) that has the potential to diagnose nutritional status and body composition changes, with the advantage of being a practical, fast, low-radiation technique with high precision, accuracy, and availability, thus making it more attractive for use in the pediatric population [125–127].

Our findings show that HW was predominantly used in the 1960s and 1980s. ADP, which seemed to be a promising method to replace HW, did not reach the expected popularity in the field of body composition assessment and was used as a reference method in only three reports. Because BF can be explained as a component located at the molecular level of body composition [128], it is not surprising that most of the equations used densitometric (HW or ADP), hydrometric (dilution techniques for total body water measurement), or total body potassium techniques, which are considered 2C models. These models are based on assumptions that may compromise the accuracy of BF determination in children, as the constants for fat-free mass density (1.1 g/cc) and hydration (73.2% of water is found within the fat-free mass) are a cornerstone of 2C models [129].

Only one report used a multicomponent molecular model, such as the 4C model, which is considered the "gold standard" for BF determination at the molecular level of body composition [130]. The multicomponent method not only validates the equations but also measures overall body composition in children and adolescents, but it has been limited to a few reports since 1990 [131]. Although the 4C model is considered the “gold standard”, the equipment required in this model is expensive and only a few research centers can afford it. To overcome these shortcomings, recent reports have attempted to develop more practical and less-expensive multicomponent models. One proposal is the use of DXA, instead of HW or ADP, to determine body volume and bone mineral content, along with multifrequency bioelectrical impedance analysis to replace isotope dilution for total body water measurement, greatly reducing equipment costs and time [132–134]. Although this approach using DXA as the multicomponent method needs further development and validation, the model seems feasible [130].

As an exception among studies using the most common molecular-based reference methods to develop BF equations, the study by Chan et al. [71] used magnetic resonance imaging, a tissue-level method, to develop an equation for %BF estimation. In fact, the authors should have considered percent adipose tissue rather than FM. Adipose tissue includes molecular components such as lipids (commonly used as FM), proteins, and water, and it should not be used interchangeably with FM.

Computed tomography and neutron activation were not used in any report, which can be explained by the high cost of imaging equipment and tests and the high level of radiation exposure [130]. Although there is a report of an anthropometric equation validated by cadaver dissection in the literature [13], no specific equation was found for children and adolescents, which illustrates the complexity of performing investigations using this method due to time, cost, and ethical barriers [135].

Anthropometric measurements

Some reports used several sets of anthropometric measurements, which demonstrates that studies are not limited to the measurement of skinfolds or body girths to estimate BF. Body mass and stature have been most frequently measured, largely because they are basic measurements used to characterize study samples. The results of the correlation analysis between anthropometric measurements and BF or body density indicate that skinfolds and girths have the strongest correlations, whereas breadths, lengths, and heights have weaker correlations, sometimes without statistical significance [26, 43]. It is probably because of these weak relationships that breadth, length, and height measurements have been poorly explored.

Body girths have also been frequently measured, mainly waist, arm, calf, and thigh, which represent central and peripheral body regions associated with different profiles of BF accumulation, thus contributing to improving the predictive ability of anthropometric equations. After body mass and stature, skinfolds were the most common measurements, as the relationship between these measurements and BF is well established in the literature [136, 137]. Triceps and subscapular skinfold measurements were the most common ones, and this is consistent with their frequent use in population-based studies assessing the nutritional status of children and adolescents in several countries for decades [138–140].

Regarding the set of four skinfold measurements (at the biceps, triceps, subscapular, and suprailiac sites) described in 20 reports, this seems unusual considering the large number of possible combinations among the skinfolds that have been cataloged so far. We analyzed the first study to use this set of measurements [44], but could not find an explanation for this choice, although a reference was made to the study by Edwards et al. [141]. These authors provided no specific reason for their choice, but they recommended that the choice of sites be based on the purpose of the measurement and that, as a next requirement, the criteria for the choice of skinfold site should be based on experimental data. However, that study does not suggest the adoption of these four sites as a standard set of measurements and even makes a critical analysis of the biceps skinfold measurement as the one with the highest technical error rate, so its use should be viewed with caution. It seems that this set of four skinfold measurements has been reproduced by researchers without an adequate understanding of its sources and critical analysis, apparently leading to the reproduction of a questionable model.

To measure the impact of the lack of a standard anatomical location for anthropometric measurements, one report compared measurements made in the abdominal region at four different sites in adult men, and the results ranged from 86.2 to 91.3 cm (a difference of 5.9%) [142]. A lack of standardized anatomical measurement sites can significantly affect the body composition results of anthropometric equations, highlighting the importance of standardized measurements.

Statistical analyses

Many of the hundreds of equations cataloged so far have generated only a linear regression model, regardless of whether the predictor variable predicts the dependent variable. Therefore, it is important to identify the equations with good predictive power based on the statistical results. The correlation results of some equations showed little or no association with BF, and these equations should be interpreted with caution. Although reference SEE values were presented only for %BF estimation, in general, the results should be interpreted as the lower the SEE, the better the regression model.

Two important gaps in the reports were the absence of important information from statistical analysis and the lack of proposed cut-off points for the analyses. These statistical results must be observed as important criteria when choosing an equation to use in clinical practice.

Equations

Body density, measured by HW, although widely reported, was last used in 2000, as this reference method is falling into disuse. Our results confirm that most equations for predicting BF are more frequently based on percentages than on absolute values [111]. There was no broader discussion of the reasons or advantages of using BF prediction based on absolute values (kg) or percentages (%). Conflicting results have been reported on the correlation of anthropometric measurements with FM (kg) and %BF. In male and female children, anthropometric measurements were more strongly correlated with FM (kg) than %BF, leading to the use of FM as the dependent variable in the equation [67]. The opposite result was observed in male adolescents, with better correlation between anthropometric measurements and %BF, based on which %BF was defined as the dependent variable in the equation [102].

FM is described as a less complex variable than %BF [19, 72], thereby increasing the accuracy and predictive power of the equation [67]. However, a lack of consensus on results and a lack of an acceptable theoretical explanation indicate the need for further studies to develop a theoretical model to elucidate this issue.

Our results demonstrate the importance of skinfolds as the main anthropometric measurements for estimating BF. The first study to publish equations for children and adolescents mentioned, back in the 1960s, that the triceps and subscapular skinfolds were the most commonly used anthropometric measurements [42]. This statement was confirmed by a report in the 1980s [56]. The study by Slaughter et al. [56, 61], which probably generated the most popular equation for children and adolescents, also used the sum of the triceps and subscapular skinfolds in the equations, a factor that confirmed and contributed to consolidating these skinfolds as the most popular ones to estimate %BF.

Girths and bone breadths were not frequently used in equations, with an almost negligible occurrence in girls. Regarding the use of girths, we expected that hip girth would be one of the most common measurements in the equations, since it has been reported in some studies as having one of the highest correlation coefficients with body density or BF [18, 45, 50]. Michael and Katch [45], using skinfold and girth measurements, concluded that the inclusion of girth measurements did not improve the equation. Conversely, some studies analyzing anthropometric measurements reported that girths have a similarly high [17, 26, 27, 50] or even higher [60] correlation with fat or body density than skinfolds, showing the potential of girth measurements as predictors of BF.

Length and height measurements were only rarely used in the equations. This suggests that, for the proposed equation models, these measurements are of little importance in estimating BF or body density.

Skinfold calipers

A description of the type of skinfold caliper used represents important information, as it allows the replication of the method with the same equipment. The Harpenden and Holtain calipers were widely used in different countries, being used in five continents. In a review published in 2000, Wang et al. [143] reported that the Lange caliper was the most commonly used one for skinfold measurements, which was confirmed in the present review considering the studies published until 2000, after which there was a change in this trend toward the use of the Harpenden caliper in scientific reports, surpassing the total number of studies conducted with the Lange caliper, with the lowest number of citations in the last two decades.

Skinfold caliper models may vary in format, graduation, and measurement width, but they must have a static jaw pressure of 10 g/mm^2 in any reading range [115]. However, contradictory results have been reported when comparing skinfold measurements made with different brands of calipers. While some studies have reported no differences between skinfold caliper brands [119, 144], others have found significant differences between the measurements [145–148]. In one report, although no significant differences were observed, the authors developed specific equations according to the skinfold caliper model [49]. A detailed description of the equipment should always be provided, including calibration procedures to ensure the reliability of the measurements [149], since the use of poorly calibrated equipment can introduce bias and invalidate the equation [150].

A study comparing calipers after 4 years of use (30,000 measurements) showed a systematic bias, with a mean difference of approximately 5% higher values; the same caliper, but with new springs, showed the same results as the brand-new caliper [151]. The springs of calipers with heavy use lose their compression capacity, while no maintenance or lubrication increases the caliper stiffness, thus increasing its static jaw pressure [150]. These factors highlight the importance of constant maintenance and calibration of the calipers to ensure their accuracy and to avoid the technical error of measurement [152], which may compromise the accuracy of equations.

Evaluator training

Skinfold measurement is the method with the lowest level of precision in anthropometry [115], and the lack of experience or training of the anthropometrist has an important impact on the precision and accuracy of measurements. A comparison between experienced and inexperienced evaluators showed no significant differences in the sum of four skinfold measurements at previously marked anatomical sites, but when each anthropometrist marked the sites on the participant, inexperienced evaluators obtained a mean of 2-mm higher values than experienced ones [153]. Also, a significant difference was found between skinfold measurements made at the exact site location and at different sites located only 1 cm [154] or 2.5 cm [155] away from the exact location. Therefore, evaluator training is important to improve the quality of measurements and to obtain more reliable results. Oppliger et al. [156] confirmed the effectiveness of certification training for evaluators before making skinfold measurements in wrestlers, producing consistent, reproducible, and valid results.

Evaluator error rate

Intra-evaluator error is assessed when more than one measurement is made by the same evaluator, indicating the quality of measurements in terms of precision. This can be assessed by calculating the total or percentage technical error of measurement, intraclass correlation coefficient, or coefficient of reliability [152]. Determining this type of error is important to confirm the quality of measurements, since the lower the evaluator error rate, the lower the risk of bias. Reports should provide information on inter- and intra-evaluator error values compared with reference values, which should be calculated before data collection. Of the 23 studies that reported this type of error, 15 (65%) were published after 2010, which reflects a more current concern with ensuring the quality of measurements.

Given the low precision levels among inexperienced or untrained evaluators, training using a standard protocol is recommended, with repeated measurements in a subsample of the study group to assess measurement precision. Low-precision measurements should be repeated until satisfactory results are obtained [152]. Particularly for inexperienced evaluators, it is recommended to determine reproducibility before starting measurements for research or other purposes [149]. Previous accreditation of the anthropometrist is highly recommended to ensure high-quality anthropometric measurements. The ISAK accreditation scheme for skinfold measurements ensures an intra-evaluator level of 10% for level 1 and 7.5% for level 2 anthropometrists, and an inter-evaluator level compared with a certified anthropometrist (criterion) of 12.5% and 10% for level 1 and level 2 anthropometrists, respectively [157].

Anthropometric references

References from different authors show variations in the anatomical sites that may lead to different results for the same measurement, which is a limitation of anthropometric measurements [143]. The need to standardize measurement procedures has been discussed for decades [158] to ensure high standards and consistency [124]. Lohman et al. [131] reported their concern about the Anthropometric Standardization Reference Manual, which was published in 1988 but has not been reissued since 2000. However, at the same time, ISAK redefined the set of standardized anthropometric measurements and developed a certification training program, which has been operating over the past 20 years. The authors also highlight that future efforts are needed to develop a standardized training program for body composition (132). In this respect, since 1996, ISAK offers a certification program in more than 80 countries [115], with more than 30,000 anthropometrists trained so far in this program [159]. ISAK also has a reference manual that has been frequently updated (in 2001, 2006, 2011, and 2019), thus emerging as a real possibility of achieving standardized anthropometric measurements and becoming an international reference.

The results of a survey of body composition assessment practice, distributed among the members of international sports organizations from 33 countries, showed that the method most commonly used to assess body composition in athletes was skinfold measurement following the ISAK methodology [160], which reinforces the importance of ISAK in the field of anthropometry.

Body side for measurements

Our results showed that the choice of body side for measurements differed across regions, with the left side being more commonly used in Europe (British school) and the right side in North America [161, 162]. The lack of standardization in the measurements precludes the comparison of reports at a global level.

Studies using bilateral skinfold measurements have yielded conflicting results. In adults, a study found a significant difference for the triceps skinfold, but not for the subscapular skinfold [162]. Another study using the triceps skinfold found no significant differences between body sides [148]. A third study found significant differences for some skinfolds, but not for all skinfolds [119]. In children, two reports found significant differences for some, but not all, skinfolds [49, 161].

In all cases, there was no pattern of side predominance for measurements. Given the relevance of this factor, one study proposed equations specific to each body side and suggested that, due to possible bilateral differences, standardization should define a side for anthropometric measurement [49, 161]. The two main anthropometric reference manuals recommend that the right side be used for measurements, regardless of the dominant side [114, 159], using the left side only in cases of injury on the right side [159].

Measurement error

Establishing acceptable error limits for repeated measurements is important to determine reproducibility and ensure the quality of measurements. The studies established different acceptable measurement error limits, both in percentages (5% or 20%) and in absolute values (1 or 2 mm). Regarding skinfold measurements, for a 10-mm skinfold thickness, an error value of 1 mm represents a 10% variation, while for a 40-mm skinfold thickness, it represents an acceptable error margin of only 2.5%. In this respect, determining the errors in percentages promotes the equalization of acceptable error limits, regardless of skinfold thickness. It should be noted that the reported margin of error of 20% mentioned in one report, which resulted from the difference between the highest and lowest of three measurements, appears to be very wide. As an example, if a skinfold has three measurements of 10, 11, and 12 mm (a difference of 20% between the highest and the lowest value), the final mean value will be recorded as 11 mm. However, if the correct value is 10 mm, the final mean value of 11 mm will represent a 10% difference in relation to the correct measurement value. Considering that this value will be used in an equation in which skinfolds are the only variables for predicting BF, this difference may represent an error of approximately 10% in the final result when applying the equation.

Number of measurements

Repeated measurements aim to avoid the measurement bias that can occur with a single measurement, which can result in a large effect on the final BF estimation. In addition, repeated measurements allow the calculation of measurement error, thus providing information on the quality of measurements in terms of precision. Katch and Katch [149] suggested that different skinfolds should be measured in succession, at least twice and preferably five times. Evidently, the use of a single measurement should be discarded, as it may result in significant errors. A minimum of two measurements seems reasonable and feasible in a dynamic laboratory environment.

Some authors used the average of the three measurements as the final skinfold value in the equation [114], while others used the median value, which corresponds to the central value of the three measurements [159]. These are different approaches that can alter the final result. Therefore, it is recommended that the procedure adopted be clearly described in the methods section of the report.

Strength and limits

The strengths of our scoping review include the use of a tested search strategy, which was sensitive enough to present the knowledge gaps and limitations on the topic. Although we used a sensitive search, it is possible that some studies were missed. Another limitation of this study was that the exclusion criteria adopted left out relevant studies, for example, systematic reviews or studies with equations derived from other indices, such as the body mass index.

What is already known on this subject?

There are several equations for predicting body fat in children and adolescents. This study is important to map the existing equations, analyze the methodological aspects to, from the results, and identify knowledge gaps.

What this study adds?

The present review included studies with different methodologies, which allowed us to gather studies from around the world and in different settings and, thus, to identify areas for improvement in future research. Thereafter, it should be noted that these features were better addressed in reports published in the last decade, which reflects a more current concern of researchers with improving the quality of the models developed.

For future studies, we created a table (Table S7) with methodological recommendations to be considered to guarantee the quality of the developed equations. In addition, other scoping reviews in different age groups would greatly contribute to a better understanding of the topic. In addition, it is necessary to develop specific equations for conditions that can impact body composition, such as diseases or disabilities, as well as for athletes, especially in modalities where body composition affects sports performance. Another area that needs further investigation is the statistical analysis used to validate the equations developed, so that they can be validated objectively and accurately.

This scoping review presented equations for a large sample diversity. Therefore, we propose a decision table (Table S8) to help clinicians decide which equation is most suitable for use in clinical practice according to the characteristics of the target population.

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Declarations

Conflict of interest The authors declare no conflicts of interest.

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