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Bioelectrical impedance analysis versus reference methods in the assessment of body composition in athletes

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1	Bioelectrical Impedance Analysis versus Reference Methods in the Assessment of Body Composition in Athletes A
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32 Abstract

The present systematic review aimed to compare the accuracy of Bioelectrical Impedance Analysis (BIA) and Bioelectrical Impedance Vector Analysis (BIVA) vs. reference methods for the assessment of body composition in athletes. Studies were identified based on a systematic search of internationally electronic databases (PubMed and Scopus) and hand searching of the reference lists of the included studies. In total, 42 studies published between 1988 and 2021 were included. The methodological quality was assessed using the Quality Assessment Tool for Observational Cohort and Cross-sectional Studies as recommended by the National Institute of Health. Twenty-three studies had an overall good rating in terms of quality, while 13 were rated as fair and six as poor, resulting in a low to moderate risk of bias. Fat mass was inconsistently determined using BIA vs. the reference methods, regardless of the BIA-technology. When using the foot to hand technology with predictive equations for athletes, a good agreement between BIA and the reference methods was observed for fat-free mass, total body, intra and extra cellular water. However, an underestimation in fatfree mass and body fluids was found when using generalized predictive equations. Classic and *Specific* BIVA represented a valid approach for assessing body fluids (Classic BIVA) and percentage of fat mass (*Specific* BIVA). The present systematic review suggests that BIA and BIVA can be used for assessing body composition in athletes, provided that foot-to-hand technology, predictive equations, and BIVA references for athletes are used.

Keywords: Bioimpedance vector analysis; Classic BIVA; *Specific* BIVA; Phase angle; Tolerance ellipses; Resistance training; Nutrition

63	Abbrew	iations
1 ∕ ₀ 4	BIA	Bioelectrical impedance analysis
3 4 65	BIVA	Bioelectrical impedance vector analysis
666	BIS	Bioelectrical spectroscopy analysis
67 67	DXA	Dual-energy X-ray absorptiometry
9 1 68	ECW	Extracellular water
12 69	FM	Fat mass
14 70	FFM	Fat free mass
1 7 1	ICW	Intracellular water
18 72	LST	Lean soft tissue
20 73	R	Resistance
21 2 274	Xc	Reactance
23 2 475 25	TBW	Total body water
2 676	UWW	Underwater weighting
28 77 28 77	4C	Four compartment model
30 78		
32 79		
34 80 35		
3 81 37		
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63 64 65 Body composition describes the amount of the various components of the human body, such as fat (FM) and muscle mass or body fluids (Heymsfield et al. 2005). However, the assessment of body composition through direct procedures is not possible in humans (Heymsfield et al. 2005). For this reason, a number of indirect methods have been developed and implemented over the years, allowing to assess a wide range of body composition parameters (Heymsfield et al. 2005). Among these methods, some are considered as the gold standard for certain parameters, such as the dilution techniques for the body fluids assessment (Heymsfield et al. 2005). Other methods including energy X-ray absorptiometry (DXA), underwater weighing (UWW), air displacement plethysmography, magnetic resonance, and computed tomography are also classified as indirect approaches and used as reference methods in the body composition evaluation (Heymsfield et al. 2005).

However, most of the aforementioned techniques are expensive and require long procedures and highly specialized personnel (Campa et al. 2021b). For this reason, double-indirect methods have been implemented for obtaining estimations derived from indirect methods such as DXA, UWW or dilution techniques through validated regression equations. Over the recent years, the bioelectrical impedance analysis (BIA) has been identified as a possible alternative for assessing body composition. Although BIA is classified as a double-indirect approach, being noninvasive, portable, relatively low-cost, and technologically friendly, its use has gained attention in clinical and practical, as well as in research contexts (Lukaski and Raymond-Pope 2021). BIA is based on the different impedance of fat and lean tissues when a weak electric current flows through the body and several technologies have been designed and commercialized to date. These technologies include hand to hand, leg to leg, foot to hand direct or segmental approach, implying profound differences in both testing procedures (e.g., body position and electrodes placement) and final outcomes (Dellinger et al. 2021; Stratton et al. 2021). The hand to hand technology measures the upper body impedance, the foot to foot measures the lower body impedance, and the foot to hand measures the right hemisoma impedance, all estimating the remaining body sections through dedicated algorithms; on the contrary, the direct segmental technology measures the whole-body impedance (Campa et al. 2021b). Based on these four technologies, many devices have been produced by the manufacturers, working at a wide range of sampling frequency (from 1 to 1000 kHz), albeit the 50 kHz frequency has been identified as the most appropriate for measuring bioimpedance in humans (Kyle et al. 2004a, b).

The traditional BIA approach allows the quantification of both absolute (kg or L) or relative amount (%) of a number of body composition parameters through predictive equations, thanks to the different conductance properties of each

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biological tissue. In fact, FM shows poor conductive proprieties, while fat-free mass (FFM), including the lean soft tissue (LST) and body fluids, is a good electrical conductor (Lukaski and Piccoli 2012). Following the procedures, the devices may either provide the quantitative estimation of body composition parameters using predictive equations set by the manufacturer or provide the raw resistance (R) and reactance (Xc) to be inserted into specific formulas up to the operator (Campa et al. 2021b). In this regard, most of the formulas have been developed for non-athletic populations, and formulas for athletes have been designed recently (Campa et al. 2021b). This may have an impact on the final outcomes, as shown in athletes samples (Pichard et al. 1997; Houtkoopr et al. 2001; Matias et al. 2016a,b; Deminice et al. 2016; Shiose et al. 2020; Coratella et al. 2021). However, these studies examined the difference in body composition parameter (e.g., FM and FFM or body fluids) in athletes. Notwithstanding, many studies have compared the BIA vs. reference methods in athletes using different BIA-technologies, predictive equations, and devices. All these studies have not been systematically reviewed so far, in order to provide a comprehensive overview of the literature.

A further approach when using bioimpedance parameters is the bioelectrical impedance vector analysis (BIVA), proposed by Piccoli et al. (Piccoli et al. 1994) in 1994 and modified by Buffa et al. (Buffa et al. 2013) in 2013. The initial approach (Classic BIVA) consists of the simultaneous evaluation of R and Xc adjusted for the stature, plotting them as a vector within a graph (Piccoli et al. 1994). The later approach (Specific BIVA), consists of the concurrent adjustment of R and Xc for the stature and for the cross-sectional area of the arm, waist, and calf (Buffa et al. 2013). Classic and Specific BIVA were developed with the aim to determine total body water (TBW) and %FM, respectively. The change in vector length reflects the change in TBW (Classic BIVA) or %FM (Specific BIVA), while the lateral displacement of the vector reflects the bioelectrical phase angle for both BIVA approaches, graphically represented as the angle between the vector and the x-axis (Stahn et al. 2012). Particularly, the phase angle has been proposed as an indicator of cellular health, cell membrane integrity (Stahn et al. 2012; Lukaski and Raymond-Pope 2021) and faithfully reflects the intracellular/extracellular water (ICW/ECW) ratio (Marini et al. 2020; Campa et al. 2021b). As such, BIVA allows a qualitative assessment of body composition, avoiding the use of prediction equations to estimate the different parameters. Additionally, although BIVA does not quantify each component, the vector position can be evaluated within tolerance ellipses drawn for each population, representing their percentile within that population distribution (Campa et al. 2019). The use of BIVA in athletes has been implemented quite recently, and a few studies have assessed body composition in athletes using both BIVA and reference methods. Some authors have systematically reviewed the use of BIVA in sports practice (Castizo-Olier et al. 2018), albeit they did not focus on the comparison of BIVA vs. reference methods. In this regard, this was not possible at that time, given that the first studies comparing BIVA vs. reference method in athletes 156 was only published in 2020 (Campa et al. 2020; Marini et al. 2020). Figure 1 depicts the key concepts of BIA and the application of BIVA.

Insert Figure 1 next here

Therefore, the main purposes of the present systematic review were to summarize the results of studies that compared i) BIA vs. reference methods in the estimation of body composition parameters in athletes and ii) BIVA vs. reference methods in the qualitative assessment of body composition parameters in athletes. Furthermore, we aimed to provide appropriate strategies to assess body composition in athletes using BIA or BIVA, considering the different technologies and predictive equations.

Methods

Search strategy and eligibility criteria

The present study was carried out following the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines (Page et al. 2021). The bibliographic search was performed on August 15th, 2021, using Scopus and PubMed online databases. The search query was applied to the source title, abstract, and keywords, and included combinations of at least one of the terms identifying body composition, with at least one of the terms identifying the bioimpedance techniques applied, a term on the reference technique, and a term on the field of application. The resulting search query was:

("body composition" OR "fat mass" OR "fat free mass" OR "muscle mass" OR "lean mass" OR "total body water" OR "extracellular water" OR "intracellular water" OR FM OR FFM OR TBW OR ECW OR ICW) AND (BIA OR bioimpedance OR "bioelectrical impedance" OR BIVA OR "bioelectrical impedance vector analysis" OR "vector analysis" OR biavector) AND (DXA OR DEXA OR densitometry OR imaging OR CT OR tomography OR MRI OR MRT OR magnetic OR RMT OR RM OR "dilution techniques" OR "deuterium dilution" OR "isotope dilution" OR UWW OR hydrodensitometry OR "underwater weight" OR "BOD POD" OR ADP OR "air-displacement plethysmography" OR "criterion method" OR "standard technique" OR "direct technique" OR "reference technique") AND (sport OR athletes). To identify additional relevant papers, hand searching of the reference lists of the included papers was performed.

The inclusion criteria were:

 Peer-reviewed articles that assessed body composition in athletes involved in individual or team sports using BIA or BIVA and reference techniques.

• Accessible in English full text.

• Individuals aged above 16 years, and with no chronic diseases or health problems.

The exclusion criteria were:

- Reviews and case studies.
- Articles aimed to develop predictive equations without a cross-validation group.

Study selection and data processing

Based on the initial titles retrieved, duplicates were removed. Abstracts identified from the literature searches were screened for potential inclusion by two authors (F.C. and G.C.) and a third author (L.G.) when there was a disagreement between the first two. Data extraction included information about each article, such as: authors, year, study design, participants' information (sex, age), type of sports code, bioimpedance methodology and devices, reference technique, outcome measures and main results.

Quality assessment

Methodological quality was assessed using the Quality Assessment Tool for Observational Cohort and Cross-sectional Studies in observational studies (NIH 2014) recommended by the National Institute of Health, U.S. Department of Health and Human Services. The tool consists of 14 criteria that are used to assess quality, including whether the population studied was clearly specified and defined, whether the outcome assessors were blinded, and an assessment of the participation rate. The criteria were classified as "yes", "no", "unclear", or "not applicable". Quality rates were good, fair, or poor as judged by two independent observers (F.C. and L.G.) following the instructions given by the National Institute of and Human Services.

Results

Search outcomes

The literature search resulted in 554 articles. After removal of duplicates (n=242) and abstract screening, 43 studies were considered relevant. After the full text screening, 11 were further excluded, so that a total of 32 studies fully met the eligibility criteria. Ten additional studies were included after a hand searching of the reference lists of the included articles.

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The PRISMA flow chart is shown in Figure 1. Finally, 42 studies published between 1988 and 2021 were considered. Out of these 42 articles, 37 presented a cross-sectional and five a longitudinal study design.

Insert Figure 2 next here

Participants

A total of 2978 subjects (1962 men and 1016 women) participated in the selected studies. Regarding sports code, N=534 participants were involved in team sports, N=339 in individual sports, while the exact number of subjects for each sport modality was not reported for N=2105 participants.

Risk of bias

The risk of bias resulted as low to moderate, as summarized in Supplementary Table 1. Measurement procedures (e.g., electrodes placement, hydration status, food and fluid intake before the test or time from the last exercise) of BIA were sometimes not completely described. Furthermore, the predictive equations used to estimate body composition parameters were not always reported. Twenty-three studies had an overall good rating in terms of quality, while 13 were rated as fair and 6 as poor (Table S1).

Bioelectrical devices and technologies

The selected articles included different devices and technologies as shown in Figure 2. Considering the four different technologies, 4 articles used the hand to hand (Esco et al. 2011; Loenneke et al. 2013; Graybeal et al. 2020; Syed-Abdul et al. 2021), 6 the leg to leg (Civar et al. 2003, 2006; Dixon et al. 2005; Loenneke et al. 2013; Domingos et al. 2019; Graybeal et al. 2020), 29 the foot to hand (Birzniece et al. 2015; Colville et al. 1989; Lukaski et al. 1990; Kirkendall et al. 1991; Hortobágyi et al. 1992; Pichard et al. 1997; Williams and Bale 1998; Fornetti et al. 1999; De Lorenzo et al. 2000; Houtkoopr et al. 2016; Krzykała et al. 2004; Svantesson et al. 2008; Company and Ball 2010; Matias et al. 2016a, b, 2021; Deminice et al. 2016; Krzykała et al. 2016; Arias Téllez et al. 2019; Campa et al. 2020, 2021; Marini et al. 2020; Graybeal et al. 2020; Silva et al. 2020; Sardinha et al. 2020; Shiose et al. 2012, 2013; Esco et al. 2015; Krzykała et al. 2019; Hartmann Nunes et al. 2012, 2013; Esco et al. 2015; Lee et al. 2021). Particularly, more than one technology was used in some studies and for each technology, different devices were used. Considering the dependent variables, 30 articles (Birzniece et al. 2015; Colville et al. 1989; Lukaski et al. 1990; Kirkendall et al. 1991; Hortobágyi et al. 1992; Pichard et al. 1997; Williams and Bale 1998; Fornetti et al. 1999; De Lorenzo et al. 2021).

2000; Houtkoopr et al. 2001; Civar et al. 2003, 2006; Andreoli et al. 2004; Dixon et al. 2005; Svantesson et al. 2008;
249 Company and Ball 2010; Esco et al. 2011, 2015; Loenneke et al. 2012, 2013; Krzykała et al. 2016; Raymond et al. 2018;
3250 Arias Téllez et al. 2019; Domingos et al. 2019; Brewer et al. 2019; Hartmann Nunes et al. 2020; Graybeal et al. 2020;
3261 Sardinha et al. 2020; Lee et al. 2021; Matias et al. 2021; Syed-Abdul et al. 2021) assessed FM and FFM comparing BIA with reference methods, although seven additional studies used more than one technology, resulting in 37 comparisons.
3262 A total of 7 studies (Birzniece et al. 2015; Matias et al. 2016b, a; Deminice et al. 2016; Shiose et al. 2020; Coratella et al. 2021; Francisco et al. 2021) assessed body fluids comparing BIA with reference methods, using the foot to hand technology. A total of 5 articles (Campa et al. 2020, 2021a; Marini et al. 2020; Silva et al. 2020; Stagi et al. 2021) assessed body composition comparing BIVA with reference methods, using the foot to hand technology.

Insert Figure 3 next here

BIA vs. reference methods: FM and FFM

Table 1 shows the study design, demographic information, bioimpedance methodology, reference methods, and the main results for each study. Considering the 16 studies that used a foot to hand technology for assessing FM, eight (Colville et al. 1989; Hortobágyi et al. 1992; Pichard et al. 1997; Williams and Bale 1998; Boileau and Horswill 2000; Houtkoopr et al. 2001; Andreoli et al. 2004; Company and Ball 2010) showed an overestimation of the %FM obtained by BIA, five studies an underestimation of %FM (Lukaski et al. 1990; De Lorenzo et al. 2000; Arias Téllez et al. 2019) and FM (Svantesson et al. 2008; Birzniece et al. 2015), while three studies showed an agreement in the estimated %FM (Pichard et al. 1997; Krzykała et al. 2016) and FM (Graybeal et al. 2020). Birzniece et al. (Birzniece et al. 2015) observed both a cross-sectional and longitudinal underestimation of %FM obtained by BIA. Of these studies, only seven (Colville et al. 1989; Lukaski et al. 1990; Pichard et al. 1997; De Lorenzo et al. 2000; Houtkoopr et al. 2001; Andreoli et al. 2004; Company and Ball 2010) reported the predictive equations used. Considering the 10 studies that used a foot to hand technology for assessing FFM, four studies showed a good agreement between BIA and reference methods (Lukaski et al. 1990; Fornetti et al. 1999; Graybeal et al. 2020; Matias et al. 2021), three studies showed an underestimation (Colville et al. 1989; Hortobágyi et al. 1992; Pichard et al. 1997) and three studies showed an overestimation of FFM (De Lorenzo et al. 2000; Svantesson et al. 2008; Birzniece et al. 2015). Birzniece et al. (Birzniece et al. 2015) observed both a crosssectional and longitudinal overestimation of FFM obtained by BIA. Of these studies, only seven (Colville et al. 1989; Lukaski et al. 1990; Pichard et al. 1997; Fornetti et al. 1999; De Lorenzo et al. 2000; Houtkoopr et al. 2001; Matias et al. 2021) reported the predictive equations used. LST of the arm and legs was estimated by only one study (Sardinha et al.

2020), which showed an excellent agreement between BIA and the reference method and reported the predictiveequations.

Nine studies used a direct segmental technology for assessing FM, albeit Lee et al. (Lee et al. 2021) utilized three different devices for a total of 11 comparisons. Six studies reported an overestimation of FM (Brewer et al. 2019; Hartmann Nunes et al. 2020; Graybeal et al. 2020; Lee et al. 2021) and %FM (Loenneke et al. 2013; Lee et al. 2021). Of these six studies, one used a regional approach for investigating the legs FM (Brewer et al. 2019), and one assessed the visceral FM (Hartmann Nunes et al. 2020). Three studies (Esco et al. 2015; Krzykała et al. 2016; Raymond et al. 2018) showed an underestimation of %FM, and one of them used a regional approach measuring the arms and legs FM (Raymond et al. 2018), three studies (Raymond et al. 2018; Brewer et al. 2019; Graybeal et al. 2020) showed no difference between BIA and the reference methods. The study by Graybeal et al. (Graybeal et al. 2020) found higher %FM only in men, while they reported a good agreement in women. None of these nine studies using the direct segmental technique reported the equations. Five studies used a direct segmental technology for assessing FFM. Four studies showed an underestimation compared with the reference method. Of these four studies, Graybeal et al. (Graybeal et al. 2020) found this result only in men, while Raymond et al. (Raymond et al. 2018) referred to arms and Brewer et al. (Brewer et al. 2019) to arms and legs FFM. Two studies reported an overestimation in FFM (Loenneke et al. 2012; Esco et al. 2015), and two studies reported no difference in the FFM, but only when measuring women (Graybeal et al. 2020) or the trunk FFM (Raymond et al. 2018). None of these five studies using the direct segmental technique reported the equations. Esco et al. (Esco et al. 2015) was the only study that using a regional approach for assessing arm, leg, and trunk LST, reported a good agreement between the methods.

Six studies used a leg to leg technology for assessing FM, albeit Loenneke et al. (Loenneke et al. 2013) utilized two different predictive equations, as reported in Table 1, for a total of seven comparisons. Three of them reported an underestimation in %FM (Civar et al. 2003; Loenneke et al. 2013) and FM (Dixon et al. 2005), two studies an overestimation in FM (Domingos et al. 2019; Graybeal et al. 2020), while three studied showed no difference (Civar et al. 2006; Loenneke et al. 2013; Graybeal et al. 2020). Considering the Graybeal et al. (Graybeal et al. 2020) study, higher FM was found only in men, while no difference was reported for women. In the Loenneke et al. (Loenneke et al. 2013) study, no difference was found when the device was set on the "non-athlete" mode, while FM was underestimated using the "athletes" modality. Only Graybeal et al. (Graybeal et al. 2020) assessed FFM and reported a good agreement with the reference method for women and an underestimation for men. No study involving leg to leg BIA-technologies reported the predictive equations used.

Four studies used a hand to hand technology and reported an underestimation in %FM (Esco et al. 2011; Loenneke et al. 2013; Graybeal et al. 2020; Syed-Abdul et al. 2021), albeit Loenneke et al. (Loenneke et al. 2013) and Syed-Abdul et al. (Syed-Abdul et al. 2021) utilized different predictive equations, as reported in Table 1, for a total of eight comparisons. Of these four studies, Loenneke et al. (Loenneke et al. 2013) and Syed-Abdul et al. 2021) reported lower %FM when the devices were set on the "athlete" modality, and a good agreement when the devices were set on the "non-athlete" modality. Graybeal et al. (Graybeal et al. 2020) overestimated %FM in men, while no difference for women was found; additionaly, FFM was underestimated in men and a good agreement for women was found. No studies involving hand to hand BIA technologies reported the predictive equations used.

Insert Table 1 next here

BIA vs. reference methods: Body fluids estimations

Table 2 shows the study design, demographic information, bioimpedance methodology, reference methods, and the main results for each study. All seven studies assessing TBW were performed using the foot to hand technology, albeit different devices (Matias et al. 2016a) and procedures (Matias et al. 2016b; Deminice et al. 2016; Shiose et al. 2020; Coratella et al. 2021) for a total of 31 comparisons. Five studies reported no difference in TBW assessed by BIA vs. reference methods (Matias et al. 2016b, a; Shiose et al. 2020; Coratella et al. 2021; Francisco et al. 2021), four studies an underestimation (Matias et al. 2016a, b; Deminice et al. 2016; Coratella et al. 2021), and one study an overestimation (Matias et al. 2016a, b; Coratella et al. 2021) for a total of 12 comparisons. Five studies reported no difference in ECW assessed by BIA vs. reference methods (Birzniece et al. 2015; Matias et al. 2016a, b; Coratella et al. 2021) for a total of 12 comparisons. Five studies reported no difference in ECW assessed by BIA vs. reference methods (Birzniece et al. 2015; Matias et al. 2016a, b; Coratella et al. 2021), four studies an underestimation (Birzniece et al. 2015; Matias et al. 2016a, b; Coratella et al. 2021), and no study reported an overestimation. Three studies (Matias et al. 2016a, b; Coratella et al. 2021), and no study reported an overestimation. Three studies (Matias et al. 2016a, b; Francisco et al. 2021) used the foot to hand technology to assess ICW, albeit different devices (Matias et al. 2016a, b; Coratella et al. 2021), and no study reported an overestimation. Three studies (Matias et al. 2016a, b; Francisco et al. 2021) used the foot to hand technology to assess ICW, albeit different devices (Matias et al. 2016a, b; Coratella et al. 2021) used the foot to hand technology to assess ICW, albeit different devices (Matias et al. 2016a, b; Coratella et al. 2021) used the foot to hand technology to assess ICW, albeit different devices (Matias et al. 2016a, b; Deminice et al. 2016; Shiose et al. 2020; Cora

Insert Table 2 next here

341 BIVA vs. reference methods

Five studies compared the BIVA's outcomes with body composition measurements obtained from reference methods, as shown in Table 3. All the analyzed studies were conducted using a foot to hand technology. Two studies were conducted with a cross-sectional design (Marini et al. 2020; Stagi et al. 2021), and showed that the *specific* vector length was correlated positively with %FM and the classic vector negatively with TBW, both at the whole body (Marini et al. 2020) and the segmental level (Stagi et al. 2021). These findings were also confirmed in three longitudinal studies (Campa et al. 2020, 2021a; Silva et al. 2020), which highlighted the effectiveness of BIVA in assessing changes in body composition over time. In addition to the vector length evaluation, its position along the minor axis of the BIVA ellipses, that is mainly due to phase angle variations, has been associated with the ICW/ECW ratio (Campa et al. 2020, 2021a; Marini et al. 2020).

Insert Table 3 next here

Discussion

The present systematic review aimed to compare i) BIA vs. reference methods in the estimation of body composition parameters in athletes and ii) BIVA vs. reference methods in the qualitative assessment of body composition parameters in athletes. Forty-two studies were included in the review, for a total of 2978 athletes involved in team or individual sports. Overall, most of the studies included used the foot to hand technology, allowing to draw a detailed picture of the BIA or BIVA vs. reference methods for FM FFM and body fluids, quantitative and qualitative assessment, respectively. The remaining hand to hand, leg to leg, and direct segmental technologies were used in few studies, and none of these assessed body fluids, so that the comparison is incomplete.

BIA vs. reference methods: FM and FFM

The studies that assessed FM and FFM using BIA vs. reference methods resulted in inconsistent findings. Concerning the FM, BIA showed poor accuracy vs. the reference methods, regardless of the technology used. However, while in some studies the authors used a direct formula to determine %FM (Colville et al. 1989; Pichard et al. 1997), in other studies FM was indirectly derived as the difference between the body mass and FFM (De Lorenzo et al. 2000; Houtkoopr et al. 2001; Andreoli et al. 2004; Company and Ball 2010). In addition, although the same predictive equations were used (Oppliger et al. 1991), different reference methods were chosen to determine %FM, such as 4C (Andreoli et al. 2004) or

DXA (De Lorenzo et al. 2000). However, a lack of agreement between 4C and DXA was later observed when assessing
%FM in athletes (Santos et al. 2010), making the comparison between BIA and the reference methods challenging. To
further entangle this picture, several studies that used the foot to hand (Kirkendall et al. 1991; Hortobágyi et al. 1992;
Williams and Bale 1998; Houtkoopr et al. 2001; Svantesson et al. 2008; Birzniece et al. 2015; Krzykała et al. 2016; Arias
Téllez et al. 2019; Graybeal et al. 2020), and all the studies that used the hand to hand, the leg to leg and the direct
segmental technology, did not report the predictive equations used for determining %FM. Interestingly, two studies
(Loenneke et al. 2013; Syed-Abdul et al. 2021) that used hand to hand devices found no difference between BIA and the
reference methods when the device was set on the "non-athlete" mode, while an underestimation in %FM was observed
when the "athlete" mode was set. According to the manufacturer of the device used by Loenneke et al. (Loenneke et al. 2013), the "athletic" mode is utilized for individuals who have exercised at least 10 hours a week consistently for at least
6 months, or who have a resting heart rate of 60 bpm or less. These factors may not exclude that an athlete may have
different characteristics. In this regard, an actual definition of athlete is advocated, so to define clearly when a specific or
generalized equation or modality should be used.

Using the foot to hand technology coupled with predictive equations developed for athletes, BIA showed no difference with reference methods for estimating FFM (Lukaski et al. 1990; Fornetti et al. 1999; Graybeal et al. 2020; Matias et al. 2021) and its LST component (Sardinha et al. 2020). On the contrary, when generalized equations were used, inconclusive findings were observed. Regarding the direct segmental technology, BIA showed an underestimation of FFM compared to the reference methods. Only one study assessed FFM using the leg to leg and hand to hand technology, reporting underestimation in men and good agreement in women for both technologies (Graybeal et al. 2020). In conclusion, the present state of the art needs to be implemented with procedures including the gold standard procedure for determining %FM and FFM (4C) and predictive equations for athletes, reported in the protocol. Considering that the Matias et al. (Matias et al. 2021) equation is the only one developed with 4C, its use should be preferred when assessing FFM in athletes.

BIA vs. reference methods: body fluids estimations

All the studies comparing BIA vs. reference methods to assess body fluids were conducted using the foot to hand technology and the dilution techniques as the reference method. Such a consistency allows more robust outcomes when summarizing the results. Considering all the studies, the use of predictive equations for athletes (Matias et al. 2016b) resulted in good agreement with the dilution techniques. Notably, the Matias' equations (Matias et al. 2016b) were

developed for the foot to hand technology at a 50 kHz frequency, and are to date the only available ones. In contrast, the 4<u>0</u>4 use of generalized predictive equations (Kushner and Schoeller 1986; Van Loan and Mayclin 1987; Lukaski and ³405 406 7 407 9 408 Bolonchuk 1988; Kushner et al. 1992; Sergi et al. 1994; Schoeller and Luke 2000; Morgenstern et al. 2002; Sun et al. 2003) led to an overall underestimation of the body fluids. Lastly, BIA was also shown to be a valid method for assessing body fluids in person with varying hydration status (Francisco et al. 2021). <u>4</u>09 BIVA vs. reference methods. <u>144</u>0 **4**611 1481.2 2401.3 24214 2441.5 241216 2481_7 3401.8 34219 **34**⊉0 **3421** 37

BIVA is an alternative method to qualitatively assess body composition in athletes. It allows the analysis of the ICW/ECW ratio and the amount of TBW (Classic BIVA) or %FM (Specific BIVA) (Campa et al. 2021b). Since these techniques are based on raw data, BIVA does not require the use of predictive equations, avoiding possible errors due to their improper application. On the other hand, BIVA does not provide estimates of volume or mass, but a classification (e.g., more or less body fluids or %FM) and ranking (e.g., better or worse after treatment or intervention) tool (Lukaski and Raymond-Pope 2021). In this regard, a rightward or leftward displacement of the BIVA vector is interpreted as a decrease or increase in the ICW/ECW ratio, respectively; moreover, longer vectors corresponds to lower TBW (Classic BIVA) or higher %FM (Specific BIVA) and vice versa (Campa et al. 2021b). All the selected studies agree in suggesting BIVA as a valid method for assessing body composition in athletes compared to the reference methods. Specifically, the standard reference methods were 4C (Marini et al. 2020), dilution techniques (Marini et al. 2020; Campa et al. 2020; Silva et al. 2020) and DXA (Marini et al. 2020; Stagi et al. 2021; Campa et al. 2021a). Notably, BIVA was derived from the foot to hand technology only. This leads to some considerations. In first instance, the reference tolerance ellipses for athletes have been designed for the foot to hand technology, so that different technology should not be used due to the lack of agreement between the technologies (Silva et al. 2019; Dellinger et al. 2021; Stratton et al. 2021). Secondly, when the aim of the research is to compare an athlete with his peers, the tolerance ellipses have been designed for some athletic populations, such as soccer (Micheli et al. 2014; Bongiovanni et al. 2020), volleyball (Campa and Toselli 2018), cycling (Giorgi et al. 2018), or endurance, sports team or power/velocity (Campa et al. 2019) athletes. All other sports should be redirected to the tolerance ellipses for generic athletic population (Campa et al. 2019).

Limitations of the review and future perspectives

A few limitations to this review should be acknowledged. Firstly, we classified the results according to the BIA technology used in the selected studies. However, even within the same technology, there could be confounding factors. For example, the positioning of the electrodes used in the foot to hand technologies and their typology could lead to different outcomes, increasing the variability within the results. In this regard, recent guidelines have been proposed to

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avoid inconsistent procedures (Campa et al. 2021b). Secondly, several devices have been considered, which could have different characteristics that may represent a further confounding factor, such as the amperage and their reliability.
Furthermore, regardless of the BIA-devices and technologies used, the athlete's evaluation must consider numerous factors such as the hours since last exercise and the nutrition prior to the test (Lukaski et al. 1990). A number of future perspectives also arise from these results. For example, future longitudinal studies are warrantied, assessing the responsiveness of different BIA technologies in comparison with the reference methods. Moreover, further studies are needed to understand which factors (e.g., amperage, body segments measured, experimental conditions) other than technologies increase the between-device variability. Lastly, authors are encouraged to provide raw bioelectrical data to a more transparent assessment of body composition through BIA and BIVA.

Conclusions

Regardless of the BIA-technology, the assessment of FM% results in lack of agreement with the reference methods. When estimating FFM using predictive equations developed for athletes and the foot to hand technology, a good agreement with the reference methods has been observed. Generalized equations lead to an underestimation of FFM. Similarly, body fluids are accurately estimated using predictive equations for athletes and the foot to hand technology, while overall underestimated using generalized equations. Regarding BIVA, Classic and *Specific* approaches represented two valid methods for assessing body fluids (Classic BIVA) and percentage of fat mass (*Specific* BIVA). The present systematic review suggests that BIA and BIVA could be used for assessing body composition in athletes, provided that equations and BIVA references developed for athletes are used. Figure 4 summarizes the main finding of the present systematic review.

Insert Figure 4 next here

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669 37	Figure captions
670 39	Figure 1. Key concepts of bioelectrical impedance analysis.
671 41	Figure 2. PRISMA Flow chart of the studies' selection.
672 43	Figure 3. Bioelectrical devices and technologies involved in the selected studies.
673 45	Figure 4. Bioelectrical impedance analysis (BIA) vs. reference methods in athletes.
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Authors	Study	Participants	Bioimpedance	Sampling	Analytical procedure	Reference	Main results
	design		device / method	frequency		method	
				(kHz) /			
				Current (µA)			
(Colville	Cross-	21 bodybuilders (men: n	103, RJL Systems,	50 / 800	RJL Systems equation for	Hydrostatic	BIA overestimated %FM (difference mean value: 7.5 %) and
et al.	sectional	$=$ 9, age 27.8 \pm 5.7 y and	Detroit, MI / BIA		men: $\%$ FM = [(Wt -	weighing	underestimated FFM (difference mean value: -4.8) in athletes
1989)		women: n = 12, age 28.7	using a foot to hand		FFM/Wt] * 100, with $FFM =$		considered as an entire group
		± 7.2 y)	technology at single		$1.1554 - 0.0841*(Wt*R)/S^2$		
			frequency		and for women: $\%$ FM = [(Wt		
					- FFM)/Wt] * 100, with FFM		
					$= 1.113 - 0.00556^{*}(Wt^{*}R)/S^{2}$		
(Lukaski	Cross-	104 athletes (men: $n = 58$,	101, RJL Systems,	50 / 800	(Lukaski and Bolonchuk	Hydrostatic	BIA showed no difference for the FFM estimation in controlled
et al.	sectional	age 20.7 ± 0.3 y and	Detroit, MI / BIA		1987): FFM = $0.734 * S^2/R +$	weighing	(difference mean value: 0.2 kg) and uncontrolled condition
1990)		women: n = 46, age 19.8	using a foot to hand		0.116*Wt + 0.096*Xc +		groups (difference mean value: 2.2 kg)
		\pm 0.2 y) involved in	technology at single		0.876*Sex - 4.03, where 0 if		
		different sports and	frequency		female and 1 if male		BIA underestimated %FM in controlled (difference mean
		divided into controlled					value: 0.2 %) and uncontrolled condition groups (difference
		and uncontrolled			FM = Wt - FFM		mean value: 3.0 %)
		condition groups					
(Kirkenda	Cross-	29 male football players	Valhalla 1990B,	50 / 500	Equations owned by	Hydrostatic	BIA overestimated %FM (difference mean value: 5.0 %)
ll et al.	sectional	(age 27.0 \pm 2.6 y)	Valhalla, San		manufacturer	weighing	
1991)			Diego, CA/ BIA				
			using a foot to hand				
			technology at single				
			frequency				
(Hortobág	Cross-	90 men American football	Spectrum II System,	50 / 800	Equations owned by	Hydrostatic	BIA overestimated %FM (blacks: difference mean value: 5.4
yi et al.	sectional	players: 55 blacks (age	RJL Systems,		manufactures	weighing	%; whites: difference mean value: 3.2 %) and underestimated
1992)		19.4 ± 1.2 y) and whites	Detroit, MI / BIA				FFM (blacks: difference mean value: 5.0 kg; whites: difference
		(age 19.7 ± 1.5 y)	using a foot to hand				mean value: 3.3 kg)

Table 1. Articles comparing bioimpedance outcomes with fat and fat-free mass and lean soft tissue derived using a reference method.

			technology at single				
			frequency				
(Pichard	Cross-	17 female runners (age	BIO-Z, Eugédia,	50 / 800	RJL Systems: $\%$ FM = 1 -	DXA	RJL Systems equation overestimated %FM (difference mean
et al.	sectional	26.5 ± 1.4 y)	Paris, France / BIA		$(0.3981*S^2/R + 0.3068*Wt +$		value: 3.1 %)
1997)			using a foot to hand		0.095299) *(S – 100) +		
			technology at single		0.7414/Wt) *100		RJL Systems equation underestimated FFM (difference mean
			frequency				value: -0.8 kg)
					RJL Systems: FFM = 5.091 +		
					$0.6483 * S^2 / R + 0.1699 * Wt$		Lukaski's equation (Lukaski et al. 1985) underestimated FFM
							(difference mean value: -2.4 kg)
					(Lukaski et al. 1985): FFM =		
					$3.04 + 0.85 * S^2/R$		Lukaski et al. equation (Lukaski et al. 1986) underestimated
							FFM (difference mean value: -1.9 kg)
					(Lukaski et al. 1986): FFM =		
					$4.917 + 0.821 * S^2/R$		Lukaski and Bolonchuk (Lukaski and Bolonchuk 1987)
							equation underestimated FFM (difference mean value: -1.9 kg)
					(Lukaski and Bolonchuk		
					1987): FFM = $0.734 * S^2/R +$		Van Loan and Mayclin (Van Loan and Mayclin 1987) equation
					0.116*Wt + 0.096*Xc +		underestimated FFM (difference mean value: -2.8)
					0.876*Sex – 4.03, where 0 if		
					female and 1 if male		Segal et al. (Segal et al. 1988) equation underestimated FFM
							(difference mean value: -2.8 kg)
					(Van Loan and Mayclin		
					1987): FFM = 17.7868 +		Graves et al. (Graves et al. 1989) equation underestimated FFM
					$0.00098~(S^2) + 0.3736^*Wt - \\$		(difference mean value: -1.8 kg)
					0.0238* R – 4.2921*Sex –		
					0.1531*Age, where 0 if		Heitmann's equation (Heitmann 1990) underestimated FFM
					female and 1 if male		(difference mean value: -2.0 kg)
							Deurenberg et al. (Deurenberg et al. 1991) equation
							underestimated FFM (difference mean value: -4.9 kg)

(Segal et al. 1988): FFM = 10.4349 + 0.000646*(S²) - 0.01397*R + 0.42087*Wt

(Graves et al. 1989): FFM = $5.49 + 0.475 * S^2/R + 0.295 * Wt$

(Heitmann 1990): FFM = total body water/0.72*100, with TBW = 11.03 + $0.266*S^2/R + 0.186*Wt +$ 4.702*Sex - 0.081*Age, where 0 if female and 1 if male

(Deurenberg et al. 1991): $FFM = S^2/R*0.34 + 0.1534*S$ + 0.273*Wt - 0.127*Age + 4.56*Sex - 12.44, where 0 if female and 1 if male

(Hannan et al. 1993): %FM = + 7.32 - 0.572*S²/R + 0.664*Wt

 $(Stolarczyk et al. 1994): FFM = 0.0012454*S^2 - 0.09404*R + 0.1555*Wt + 0.1417*Xc - 0.0833*Age + 20.05$

Hannan et al. (Hannan et al. 1993) equation showed no difference in the %FM estimation (difference mean value: 0.6 %).

Stolarczyk et al. (Stolarczyk et al. 1994) equation underestimated FFM (difference mean value: -3.6 kg)

(Williams and Bale 1998) (Fornetti	Cross- sectional Cross-	232 athletes (men: $n =$ 117, age 21.2 ± 1.2 y and women: $n =$ 115, age 21.1 ± 1.3 y) involved in different sports 132 female athletes (age	 101, RJL Systems, Detroit, MI / BIA using a foot to hand technology at single frequency 101, RJL Systems, 	50 / 800 50 / 800	Equations owned by manufacturer FFM = (0.282*S) +	Hydrostatic weighing DXA	 BIA overestimated %FM in men (difference mean value: 0.9 %; LoA: -6.2 to 3.8) and women (difference mean value: 1.2 %; LoA: -3.2 to 4.8) BIA's equation showed no difference in the FFM estimation
et al. 1999)	sectional	20.4 ± 1.5 y) involved in different sports	Detroit, MI / BIA using a foot to hand technology at single frequency		(0.415*Wt) – (0.037*R) + (0.096*Xc) – 9.734		(difference mean value: -0.1 kg)
(De Lorenzo et al. 2000)	Cross- sectional	43 male athletes (19 water polo, 9 judo, 15 karate) aged 18 -34 y	101 Anniversary, AKERN Systems; Florence, Italy / BIA using a foot to hand technology at single frequency	50 / 400	(Oppliger et al. 1991): %FM = [(Wt – FFM)/Wt] * 100, with FFM = 1.949 + (0.701*Wt) + 0.186* (S ² /R)	DXA	BIA underestimated %FM (difference mean value: -2.5 %; LoA: -8.0 to 3.0) and overestimated FFM (difference mean value: 2.4 kg; LoA: -4.5 to 9.0)
(Houtkoo pr et al. 2001)	Cross- sectional	19 female heptathletes (age 25.5 ± 3.5 y)	Valhalla 1990B, Valhalla, San Diego, CA/ BIA using a foot to hand technology at single frequency	50 / 800	(Lohman 1992): %FM = [(Wt - FFM)/Wt] * 100, with FFM = $[0.73*(S^2/R)] + (0.16*Wt)$ + 2.0 (Lohman 1992): %FM = [(Wt - FFM)/Wt] * 100, with FFM = $[0.666 (S^2/R)] +$ (0.217*Xc) + (0.164*Wt) – 8.78 Equation owned by Valhalla Impedance Analyzer Corp.	DXA	Lohman's (Lohman 1992) equation overestimated %FM (difference mean value: 2.1 %) Lohman's (Lohman 1992) equation overestimated %FM (difference mean value: 1.8 %) Equation owned by Valhalla Impedance Analyzer Corp. overestimated %FM (difference mean value: 5.5 %) Lukaski and Bolonchuk (Lukaski and Bolonchuk 1987) equation overestimated %FM (difference mean value: 4.4 %)

					(Lukaski and Bolonchuk 1987): %FM = [(Wt – FFM)/Wt] * 100, with FFM = $0.734*S^2/R + 0.116*Wt +$ 0.096*Xc + 0.876*Sex - 4.03, where 0 if female and 1 if male		
(Civar et	Cross-	99 male (age 21.87 ± 2.04	Tanita 310, Tanita	N/A / N/A	Equations owned by	Hydrostatic	BIA underestimated %FM (difference mean value: 3.2 %)
al. 2003)	sectional	y) athletes involved in	Inc., Tokyo, Japan /		manufactures	weighing	
		different sports	BIA using a leg to				
			leg technology at				
	-		multifrequency				
(Andreoli	Cross-	10 male (age 21.0 ± 4.3 y)	Xitron 4000b,	50 / 500	(Oppliger et al. 1991): %FM	4C	BIS overestimated %FM (difference mean value: 12.1 %)
	sectional	water polo athletes.	Xitron technologies,		= [(Wt - FFM)/Wt] * 100,	according to	
2004)			San Diego, CA /		with FFM = $1.949 +$	the witners	
			hand technology at		$(0.701^{\circ} \text{ Wt}) + 0.180^{\circ} (3^{\circ} \text{K})$	equation	
			multifrequency			equation	
(Dixon et	Cross-	25 male wrestlers (age	TBF-300A, Tanita	N/A / N/A	"Athletic" equation owned by	Hydrostatic	BIA underestimated FM (difference mean value: - 2.2 kg; LoA:
al. 2005)	sectional	19.2 ± 1.2 y)	Corp., Arlington		manufactures	weighing	-5.0 to 9.4)
			Heights, IL / BIA				
			using a leg to leg				
			technology at				
			multifrequency				
(Civar et	Cross-	60 female (age 20.70 \pm	Tanita 310, Tanita	N/A / N/A	Equations owned by	Hydrostatic	BIA showed no difference in the FM estimation (difference
al. 2006)	sectional	1.43 y) athletes involved	Inc., Tokyo, Japan /		manufactures	weighing	mean value: 0.2 kg)
		in different sports	BIA using a leg to				
			leg technology at				
			multifrequency				

(Svantess on et al. 2008)	Cross- sectional	33 male athletes: 16 ice hockey players (age 15.6 \pm 6.1 y) and 17 soccer players (age 24.1 \pm 3.8 y)	Hydra 4200, Xitron technologies, San Diego, CA / BIS using a foot to hand technology at multifrequency	5 - 1000 / 800	Equations owned by manufactures	DXA	BIS underestimated FM (difference mean value: - 2.8 kg) and overestimated FFM (difference mean value: 2.0 kg)
(Company and Ball 2010)	Cross- sectional	80 male athletes: 40 endurance athletes (age 30.4 ± 1.3 y) and 40 short distance runners (age $23.1^{\circ} \pm 0.7$ y)	DF50, ImpediMed, San Diego, CA / BIA using a foot to hand technology at single frequency	50 / 200	(Lukaski et al. 1986): %FM = [(Wt – FFM)/Wt] * 100, with FFM = 4.917 + 0.821*S ² /R	DXA	BIA overestimated %FM (difference mean value: 6.4 %)
(Esco et al. 2011)	Cross- sectional	40 female athletes (21.1 ± 2.3) involved in different sports	HBF-300, Omron Helthcare, Kyot, Japan / BIA using a hand to hand technology at multifrequency	N/A / N/A	Equations owned by manufacturer	DXA	BIA underestimated %FM (difference mean value: -5.1 %, LoA: -2.2 to 12.3) and overestimated FFM (difference mean value: 3.4 kg, LoA: -2.4 to 8.4)
(Loenneke et al. 2012)	Cross- sectional	33 male (age 20.0 ± 1.0 y) baseball players and 16 female (age 20.0 ± 1.0 y) gymnasts	HBF-500, Omron Helthcare, Kyoto, Japan / BIA using a direct segmental technology at multifrequency	N/A / N/A	FFM index = FFM/S ² , with FFM estimated using an equation owned by manufactures	DXA	BIA underestimated FFM index in men (difference mean value: 0.5 kg/m ²) and women (difference mean value: 1.2 kg/m ²)
(Loenneke et al. 2013)	Cross- sectional	35 male (age $20.1 \pm 1.0 \text{ y}$) baseball players	i) TBF-350, Tanita Corp., Arlington Heights, IL / BIA using a leg to leg technology at multifrequency	i) N/A / N/A ii) N/A / N/A iii) N/A / N/A	Two predictive equations provided by the manufacturer ("athletes" and "non- athletes") Two predictive equations provided by the manufacturer	DXA	Leg to leg BIA with the "athletes" equation underestimated %FM (difference mean value: -5.5 %), while no difference was found using the "non-athletes" equation (difference mean value: 0.2 %) Hand to hand BIA with the "athletes" equation underestimated %EM (difference mean value: -5.7 %), while no difference was

			ii) HBF-306, Omron Helthcare, Kyoto, Japan / BIA using a hand to hand technology at multifrequency		("athletes" and "non- athletes") Equation owned by the manufacturer		found using the "non-athletes" equation (difference mean value: 0.6 %) Direct segmental BIA overestimated %FM (difference mean value: 2.0 %)
			ii) HBF-500, Omron Helthcare, Kyoto, Japan / BIA using a direct segmental technology at multifrequency				
(Birzniece et al. 2015)	Longitudi nal	71 athletes (men: $n = 43$, age 27.1 \pm 0.8 y and women: $n = 28$, age 29.4 \pm 1.2 y) involved in different sports	SFB7, ImpediMed, Brisbane, Australia / BIS using a foot to hand technology at multifrequency	4 – 1000 / 200	FFM = total body water/0.732, with TBW estimated using an equation owned by the manufacturer FM = Wt – FFM	DXA	 BIS underestimated FM (difference mean value: -3.9 kg, LoA: -2.5 to 15.0) and overestimated FFM (difference mean value: 7.2 kg, LoA: -17.0 to 0.1) at baseline considering the athletes as an entire group BIS underestimated change in FM (difference mean value: -1.2)
							kg, LoA: -4.5 to 11.0) and overestimated change in FFM (difference mean value: 1.0 kg, LoA: -11.0 to 4.0) considering the athletes as an entire group
(Esco et al. 2015)	Cross- sectional	biss- 45 female athletes (age 21.2 ± 2.0 y) involved in different sports.	InBody 770, $5-500 / N/$ Biospace, Co, Seoul. Korea / BIA	5 – 500 / N/A	Equations owned by manufacturers	DXA	BIA underestimated %FM (difference mean value: -3.3 %, LoA: 2.3 to -8.9) and overestimated FFM (difference mean value: 2.2 kg, LoA: -1.6 to -0.1)
			segmental technology at multifrequency				BIA showed no difference in the arms (difference mean value: 0.1 kg, LoA: 0.7 to -0.8), legs (difference mean value: 0.3 kg, LoA: 2.2 to -3.0), trunk (difference mean value: 0.1 kg, LoA: 3.3 to -3.0), and total LST (difference mean value: 0.2 kg, LoA: 4.0 to -4.4) estimation.

(Krzykała	Cross-	31 female field hockey	i) 101 Anniversary,	i) 50 / 400	Equations owned by	DXA	Foot to hand BIA showed no difference in the %FM estimation
et al.	sectional	players (age 19.5 ± 3.6 y)	AKERN Systems;		manufacturers		(difference mean value: 0.1 %, LoA: 8.0 to -8.5)
2016)			Florence, Italy /	ii) N/A / N/A			
			BIA using a foot to				Direct segmental BIA underestimated %FM (difference mean
			hand technology at				value: -4.9 %, LoA: 2.0 to -11.0).
			single frequency				
			ii) BC418, Tanita				
			Corp., Arlington				
			Heights, IL / BIA				
			using a direct				
			segmental				
			technology at				
			multifrequency				
(Raymond	Cross-	44 male (age 19.0 ± 1.0 y)	InBody 770,	1 – 1000 / N/A	Equations owned by	DXA	BIA underestimated arms FM (difference mean value: -0.4 kg,
et al.	sectional	American football athletes	Biospace, Co,		manufactures		LoA: -1.1 to 1.8), arms %FM (difference mean value: -1.9 %,
2018)			Seoul. Korea / BIA				LoA: -7.9 to 11.9), and arms FFM (difference mean value: -1.4
			using a direct				kg, LoA: -0.4 to 3.2)
			segmental				
			technology at				BIA underestimated legs FM (difference mean value: -2.8 kg,
			multifrequency				LoA: 3.3 to 11.3), legs %FM (difference mean value: -3.9 %,
							LoA: -1.0 to 6.7), and legs FFM (difference mean value: -5.4
							kg, LoA: 0.7 to 9.9)
							BIA showed no difference in FM (difference mean value: 0.2
							kg, LoA: -6.2 to 5.7) and FFM (difference mean value: -0.4 kg,
							LoA: -4.3 to 5.1) and in %FM estimation (difference mean
							value: 0.9 %, LoA: -10.0 to 8.7) of the trunk
							BIA underestimated FM (difference mean value: -3.0 kg, LoA:
							-4.4 to 10.4) and %FM (difference mean value: -2.5 %, LoA: -

							7.9 to 12.9), and overestimated FFM (difference mean value:
							2.5 kg, LoA: -11.3 to 6.4)
(Brewer et	Cross-	160 athletes involved in	InBody 770,	N/A / N/A	Equations owned by	DXA	BIA underestimated legs (men: difference mean value: -6.6 kg;
al. 2019)	sectional	different sports: 44 men	Biospace, Co,		manufacturer		LoA: -15.3 to 3.2; women: difference mean value: -2.7 kg;
		and 116 women (aged	Seoul. Korea / BIA				LoA: -5.9 to 0.4) FM, while showed no difference in arms FM
		from 18 to 23 y)	using a direct				(men: difference mean value: 0.6 kg; LoA: -2.4 to 3.5; women:
			segmental				difference mean value: -0.1 kg; LoA: -0.9 to 0.8)
			technology at				
			multifrequency				BIA underestimated arms (men: difference mean value: -1.3
							kg; LoA: -3.1 to 0.5; women: difference mean value: -0.4 kg;
							LoA: -1.4 to 0.5) and legs (men: difference mean value: -6.6
							kg; LoA: -15.3 to 3.2; women: difference mean value: -2.7 kg;
							LoA: -5.9 to 0.4) FFM
(Domingo	Cross-	29 male (age 23.1 ± 3.4 y)	TBF-310 Tanita,	N/A / N/A	Equation owned by	4C	BIA overestimated FM (difference mean value: 1.2 kg, LoA: -
s et al.	sectional	judo athletes	Tanita Corp.,		manufactures	according to	6.7 to 7.0)
2019)			Tokyo, Japan / BIA			the Withers	
			using a leg to leg			et al. (1998)	
			technology at			equation	
			multifrequency				
(Arias	Cross-	30 male climbers (age	QuadScan 4000,	N/A / N/A	Two predictive equations	DXA	The "athletes" equation underestimated %FM (difference mean
Téllez et	sectional	26.1 ± 4.9 y)	Bodystat, Douglas,		owned by the manufacturer		value: -6. %2, LoA: -11.8 to -0.7). The "non-athletes" equation
al. 2019)			UK / BIA using a		("athletes" and "non-		underestimated %FM (difference mean value: -9.2 %, LoA: -
			foot to hand		athletes")		13.6 to -4.74)
			technology at				
			multifrequency				
(Graybeal	Cross-	27 bodybuilders (men: n	i) SFB7,	i) 3 - 1000 / 200	Equations owned by	4C	BIS showed no difference in the FM (men: difference mean
et al.	sectional	= 17, age 26.0 \pm 6.5 y and	ImpediMed,		manufacturers	according to	value: -0.9 kg; women: difference mean value: -0.8) and FFM
2020)		women: n = 10, age 25.8	Carlsbad, CA, USA	ii) N/A / N/A		the Wang et	estimation (men: difference mean value: -0.4 kg; women:
		± 5.4 y).	/ BIS using a foot to			al. (2002)	difference mean value: 1.3)
			hand technology at	iii) N/A / N/A		equation	

			multifrequency ii) mBCA 514/515, Seca, Hamburg, Germany / BIA using a direct segmental	iv) N/A / N/A			Direct segmental BIA overestimated FM (difference mean value: 4.3 kg) in men and showed no difference for women (difference mean value: 0.6 kg). Direct segmental BIA underestimated FFM (difference mean value: -4.3 kg) in men and showed no difference for women (difference mean value: -0.6 kg).
			technology at Le multifrequency kg		Leg to leg BIA overestimated FM (difference mean value: 5.1 kg) in men and showed no difference for women (difference mean value: 2.2 kg) Leg to leg BIA undergatimated FFM		
			iii) TBF-300A Tanita, Tanita Corp., Tokyo, Japan				(difference mean value: -4.3 kg) in men and showed no difference for women (difference mean value: -1.8 kg).
			/ BIA using a leg to leg technology at multifrequency				Hand to hand BIA overestimated FM (difference mean value: 3.3 kg) in men and showed no difference for women (difference mean value: 0.2 kg). Hand to hand BIA
			iv) HBF-306, Omron, Kyota, Japan / BIA using a				underestimated FFM (difference mean value: -3.3 kg) in men and showed no difference for women (difference mean value: 0.7 kg).
			hand to hand technology at multifrequency				
(Hartman	Cross-	19 male rugby players	InBody 720,	N/A / N/A	Equations owned by	ADP	BIA overestimated FM (difference mean value: -0.8 kg; LoA: -
n Nunes et se al. 2020)	sectional	(age 25.2 ± 3.6 y)	Seoul. Korea / BIA using a direct		manufacturer	DXA	- 0.9 kg; LoA: -13.7 to 11.7) compared to ADP
			segmental technology at multifrequency				BIA overestimated FM (difference mean value: 4.3 kg; LoA: - 2.8 to 11.7) and underestimated FFM (difference mean value: - 8.1 kg; LoA: -16.4 to 0.3) compared to DXA

(Sardinha et al. 2020)	Cross- sectional	88 athletes (men: $n = 56$, age 22.3 ± 4.3 y and women: $n = 32$, age 22.9 ± 5.2 y) involved in different sports	101 Anniversary, AKERN Systems; Florence, Italy / BIA using a foot to hand technology at single frequency	50 / 400	Arms LST = 0.940 *Sex + 0.042*Wt + 0.080 *S ² /R + 0.024*Xc - 3.927 , where Sex is 1 if female or 0 if male Legs LST = 1.983 *Sex + 0.154*Wt + 0.127 *S ² /R - 1.147 , where Sex is 1 if female or 0 if male	DXA	BIA's equations showed no difference in the arms (difference mean value: 0.1 kg, LoA: -1.1 to 1.3) and legs (difference mean value: 0.1 kg, LoA: -3.8 to 3.9) LST estimation
(Lee et al.	Cross-	95 athletes (men: $n = 50$,	i) IOI353, Jawon	i) 5 - 250 / 250	Equations owned by	DXA	Two direct segmental devices overestimated %FM (IOI353:
2021)	sectional	age 23.0 ± 1.6 y and	Medical,		manufacturer		difference mean value: 0.6 %, LoA: -2.9 to 4.3; InBody 230:
		women: n = 45, age 24.0	Gyeongsan, Korea /	ii) 20 -100 / 330		Computed	difference mean value: -0.7 %, LoA: -3.2 to 3.8) compared to
		\pm 3.6 y) involved in	BIA using a direct			tomography	DXA in men
		different sports	segmental	iii) 1 -1000 / 80			
			technology at				All the direct segmental devices overestimated %FM (IOI353:
			multifrequency				difference mean value: 2.2 %, LoA: -7.5 to 3.2; InBody 230:
							difference mean value: -1.6 %, LoA: -5.6.0 to 2.6; InBody 770:
			ii) InBody 230,				difference mean value: 2.4 %, LoA: -6.4 to -2.0) compared to
			Biospace, Co,				DXA in women
			Seoul. Korea / BIA				
			using a direct				All the direct segmental devices overestimated absolute
			segmental				visceral body fat compared to computed tomography in men
			technology at				(IOI353: difference mean value: 21.0 kg, LoA: -20.6 to 62.6;
			multifrequency				InBody 230: difference mean value: 10.1 kg, LoA: -29.6 to
							49.7; InBody 770: difference mean value: 9.2 kg, LoA: -33.4 to
			iii) InBody 770,				55.0) and in women (IOI353: difference mean value: 9.9 kg,
			Biospace, Co,				LoA: -20.6 to 62.6; InBody 230: difference mean value: 23.4
			Seoul. Korea / BIA				kg, LoA: -29.6 to 49.7; InBody 770: difference mean value:
			using a direct				31.2 kg, LoA: -33.4 to 55.0)
			segmental				

			technology at				
			multifrequency				
(Matias et	Cross-	47 athletes (men: $n = 33$,	101 Anniversary,	50 / 400	$FFM = -2.261 + 0.327 * S^2 / R$	4C	BIA's equations showed no difference in the FFM estimation
al. 2021)	sectional	age 21.9 ± 4.7 and	AKERN Systems;		+ 0.525*Wt + 5.462*Sex,	according to	(difference mean value: -1.5 kg, LoA: -7.8 to 4.7)
		women: n = 14, age 24.9	Florence, Italy /		where Sex is 1 if female or 0	the Wang et	
		\pm 6.0) involved in	BIA using a foot to		if male.	al. (2002)	
		different sports	hand technology at			equation	
			single frequency				
(Syed-	Cross-	104 male American	HBF-306, Omron,	N/A / N/A	Two predictive equations	DXA	The "athletes" equation underestimated %FM (difference mean
Abdul et	sectional	football players (age 19.6	Kyota, Japan / BIA		owned by the manufacturer		value: -4.7 %, LoA: -14.1 to 4.7)
al. 2021)		± 1.5 y)	using a hand to		("athletes" and "non-		
			hand technology at		athletes")		The "non-athletes" equation showed no difference in the %FM
			multifrequency				estimation (difference mean value: -0.4 %, LoA: -8.5 to 7.7)

Note: Data are shown as mean ± standard deviation. BIA: bioimpedance analysis; BIS: bioimpedance spectroscopy; N/A: not available; LoA: limits of agreements; DXA: Dual-energy X-ray Absorptiometry; ADP: Air displacement plethysmography; R: resistance; Xc: reactance; LST: lean soft tissue; FFM: fat-free mass; FM: fat mass; TBW: total body water; Wt: weight in kilograms; S: stature in meters; 4C: four-component model.

Authors	Study	Participants	Bioimpedance device	Sampling	Analytical procedure	Reference	Main results
	design		/ method	frequency (kHz) /		method	
				Current (µA)			
(Birzniece	Longitudi	71 athletes (men: n	SFB7, ImpediMed,	4 – 1000 / N/A	Equation owned by the	Bromide	BIS underestimated ECW (difference mean value: -3.5 L, LoA:
et al.	nal	$= 34$, age 27.1 ± 0.8	Brisbane, Australia /		manufacturer	dilution	-3.5 to 3.0) considering the athletes as an entire group
2015)		y and women: n =	BIS using a foot to				
		37, age 29.4 \pm 1.2	hand technology at				BIS showed no difference in the estimation of ECW change
		y) involved in	multifrequency				considering the athletes as an entire group
		different sports					
(Deminice	Longitudi	13 male soccer	310E, Biodynamics,	50 / N/A	(Lukaski and Bolonchuk	Deuterium	Lukaski and Bolonchuk (Lukaski and Bolonchuk 1988)
et al.	nal	players (age 18.2 \pm	Seattle, USA / BIA		1988): TBW = $0.372 \text{*}S^2/\text{R} + $	dilution	equation underestimated change in TBW in control (difference
2016)		0.8 y) divided into	using a foot to hand		3.05*Sex + 0.142*Wt -		mean value: -1.2 L) and creatine supplementation groups
		creatine	technology at single		0.069*Age, where Sex is 1 if		(difference mean value: -1.1 L)
		supplementation	frequency		men and 0 if female*		
		and placebo groups					Kushner and Schoeller (Kushner and Schoeller 1986) equation
					(Kushner and Schoeller		underestimated change in TBW in control (difference mean
					1986): TBW = 8.399 +		value: -1.0 L) and creatine supplementation groups (difference
					$0.396*S^2/R + 0.143*Wt$		mean value: -1.1 L)
					(Kushner et al. 1992): TBW =		Kushner et al. (Kushner et al. 1992) equation underestimated
					0.59* S/R + 0.065* Wt + 0.04		change in TBW in control (difference mean value: -1.2 L) and
							creatine supplementation groups (difference mean value: -0.9
					(Deurenberg et al. 1990):		L)
					TBW = 6.53 +		Deurenberg et al. (Deurenberg et al. 1990) equation
					0.36740*S ² /impedance +		underestimated change in TBW in control (difference mean
					0.17531*Wt - 0.11 + Age +		value: -1.3 L) and creatine supplementation groups (difference
					2.83*Sex, where Sex is 1 if		mean value: -1.1 L)
					men and 0 if female*		

Table 2. Articles comparing bioimpedance outcomes with total body, extra and intra cellular water derived using a reference method.

(Morgenstern et al. 2002): $TBW = 0.0758*0.84^{[if female]}$ *(S*Wt)^{0.69}

(Sun et al. 2003): TBW = $1.20 + 0.45 * S^2/R + 0.18 * Wt$

and bromide BodygramPRO3.0 (Akern Systems, Italy) predictive equations for the TBW, ECW, and ICW estimations

Equation used by BIA:

Deuterium

dilution

(Kushner and Schoeller 1986): TBW = 8.399 + $0.396*S^2/R + 0.143*Wt$

(Van Loan and Mayclin 1987): TBW = 9.9868 +0.000724*S² + 0.2822*Wt -0.0153*R - 2.3313*Sex -0.1319*Age

(Lukaski and Bolonchuk 1988): TBW = $0.377 \times S^2/R +$ 0.14*Wt - 0.08*age + 2.9*Sex+4.65, where Sex is 0 if female and 1 if male; ECW

Morgenstern et al. (Morgenstern et al. 2002) equation underestimated change in TBW in control (difference mean value: -0.2 L) and creatine supplementation groups (difference mean value: -1.9 L)

Sun et al. (Sun et al. 2003) equation underestimated change in TBW in control (difference mean value: -1.0 L) and creatine supplementation groups (difference mean value: -1.1 L) BodygramPRO3.0 predictive equations showed no difference for the TBW (difference mean value: 0.1 L, LoA: -3.7 to 3.9), ECW (difference mean value: -0.3 L, LoA: -3.0 to 2.4), and ICW (difference mean value: 0.6 L, LoA: -3.4 to 4.7) estimations in women, while underestimated TBW (difference mean value: -1.2 L, LoA: -5.9 to 3.4), ECW (difference mean value: -0.4 L, LoA: -3.9 to 3.0), and ICW (difference mean value: -0.7 L, LoA: -6.2 to 4.7) in men

Kushner and Schoeller (Kushner and Schoeller 1986) equation overestimated TBW in women (difference mean value: 1.7 L, LoA: -2.2 to 5.7), while showed no difference for the TBW estimation in men (difference mean value: 0.4 L, LoA: -5.2 to 5.9)

Van Loan and Mayclin (Van Loan and Mayclin 1987) equation overestimated TBW in women (difference mean value: 2.6 L, LoA: 2.3 to 7.6), while underestimated TBW in men (difference mean value: -5.3 L, LoA: -11.5 to 0.8)

Lukaski and Bolonchuk (Lukaski and Bolonchuk 1988) equation underestimated TBW in women (difference mean value: -3.4 L, LoA: -7.3 to -0.5) and men (difference mean

(Matias et Cross-

al. 2016a) sectional = 127, age 16 -38 y AKERN Systems; and women: n = 57, Florence, Italy / BIA age 16 – 35 y) using a foot to hand involved in different technology at single

frequency

184 athletes (men: n i) 101 Anniversary,

sports

i) 50 / 400

ii) 50 / 800

ii) Hydra 4200, Xitron Technologies, San Diego, CA / BIS using a foot to hand technology at multifrequency

$= 0.189*(S^2/R) + 0.052*Wt - 0.0002*(S^2/Xc) + 1.03$

(Kushner et al. 1992): TBW = 0.59* S/R + 0.065*Wt + 0.04

(Schoeller and Luke 2000): TBW = $0.499*S^2/R + 0.080*Wt + 2.9$

(Sun et al. 2003): TBW = $1.20 + 0.45 * S^2/R + 0.18 * Wt$ for men and TBW = $3.75 + 0.45 * S^2/R + 0.11 * Wt$ for women

(Sergi et al. 1994) :ECW = $-5.22 + 0.2*S^2/R + 0.005/Xc + 0.08*Wt + 1.9 + 1.86*Sex$, where Sex is 0 if female and 1 if male

Equations used by BIS: Equations owned by manufacturer for the TBW, ECW, and ICW estimations value: -5.1 L, LoA: -9.9 to -0.1). Lukaski and Bolonchuk (1988) equation underestimated ECW in women (difference mean value: -0.7 L, LoA: -3.0 to -1.6) and men (difference mean value: -0.4 L, LoA: -3.3 to 2.4)

Kushner et al. (Kushner et al. 1992) equation showed no difference in the TBW estimation in women (difference mean value: -0.1 L, LoA: -4.2 to 3.9), while underestimated TBW in men (difference mean value: -1.2 L, LoA: -7.0 to 4.6).

Schoeller and Luke (Schoeller and Luke 2000) equation underestimated TBW in women (difference mean value: -1.0 L, LoA: -4.8 to 2.0) and men (difference mean value: -3.7 L, LoA: -9.0 to 1.5).

Sun et al. (Sun et al. 2003) equation underestimated TBW in women (difference mean value: -0.8 L, LoA: -4.6 to 2.9) and men (difference mean value: -1.4 L, LoA: -6.2 to 3.5)

Sergi et al. (Sergi et al. 1994) equation underestimated ECW in women (difference mean value: -2.7 L, LoA: -5.0 to 0.1), while showed no difference in men (difference mean value: 0.0 L, LoA: -4.0 to 3.9)

BIS underestimated TBW in women (difference mean value: -0.3 L, LoA: -2.0 to 1.4) while showed no difference in men. BIS underestimated ECW in women (difference mean value: -0.6 L, LoA: -2.7 to 1.5) while showed no difference in men. BIS showed no difference in the ICW estimation in men and women.

(Matias et Cross-

al. 2016b) sectional 69 athletes (men: n = 46, age 22.5 ± 5.3

> y and women: n = 23, age 20.8 ± 5.4 y) involved in

different sports

101 Anniversary, 50/400 AKERN Systems; Florence, Italy / BIA using a foot to hand technology at single frequency

(Matias et al. 2016b): TBW = $0.286 + 0.195 * S^2/R +$ 0.385*Wt + 5.086*Sex, where Sex is 0 if female and 1 if male: ECW = 1.579 + $0.055* S^2/R + 0.127*Wt +$ $0.006* S^2/Xc + 0.932*Sex.$ where Sex is 0 if female and 1 if male; ICW = TBW - ECW(Kushner and Schoeller 1986): TBW = 8.399 + $0.396*S^2/R + 0.143*Wt$ (Van Loan and Mayclin 1987): TBW = 9.9868 + $0.000724 * S^2 + 0.2822 * Wt -$ 0.0153*R - 2.3313*Sex -0.1319*Age (Lukaski and Bolonchuk 1988): TBW = $0.377 \times S^2/R +$ 0.14*Wt - 0.08*age + 2.9*Sex+ 4.65, where Sex is 0 if female and 1 if male: ECW $= 0.189*(S^2/R) + 0.052*Wt -$

 $0.0002*(S^2/Xc) + 1.03$

Deuterium and bromide dilution

Matias et al. (Matias et al. 2016b) equation showed no difference in the TBW (difference mean value: -0.0 L, LoA: -5.6 to 5.6), ECW (difference mean value: 0.2 L, LoA: -3.6 to 4.0), and ICW (difference mean value: -0.2 L, LoA: -6.5 to 6.1) estimations

Kushner and Schoeller (Kushner and Schoeller 1986) equation showed no difference in the TBW estimation (difference mean value: 0.3 L, LoA: -5.8 to 6.3)

Van Loan & Mayclin (Van Loan and Mayclin 1987) equation underestimated TBW (difference mean value: -3.1 l, LoA: -13.1 to 7.0)

Lukaski and Bolonchuk (Lukaski and Bolonchuk 1988) equation underestimated TBW (difference mean value: -3.6 L, LoA: -8.5 to 13.0) and ECW (difference mean value: -0.8 L, LoA: -4.7 to 3.0)

Kushner et al. (Kushner et al. 1992) equation underestimated TBW (difference mean value: -1.5 L, LoA: -7.7 to 4.7)

Schoeller and Luke (Schoeller and Luke 2000) equation underestimated TBW (difference mean value: -3.5 L, LoA: -9.9 to 3.0)

Sun et al. (Sun et al. 2003) equation underestimated TBW (difference mean value: -1.6 L, LoA: -6.9 to 3.8)

					(Kushner et al. 1992): TBW = 0.59* S/R + 0.065*Wt + 0.04		Sergi et al. (Sergi et al. 1994) equation underestimated TBW (difference mean value: -0.9 L, LoA: -4.6 to 3.1)
					(Schoeller and Luke 2000)TBW = 0.499*S ² /R + 0.080*Wt + 2.9		
					(Sun et al. 2003): TBW = $1.20 + 0.45 * S^2/R + 0.18 * Wt$ for men and TBW = $3.75 + 0.45 * S^2/R + 0.11 * Wt$ for women		
					(Sergi et al. 1994): ECW = $-5.22 + 0.2$ *S ² /R + 0.005/Xc + 0.08*Wt + 1.9 + 1.86*Sex, where Sex is 0 if female and 1 if male		
(Shiose et al. 2020)	Cross- sectional	18 male wrestler (age 21.0 ± 1.0 y)	SFB7, ImpediMed, Pinkenba, Australia / BIS using a foot to hand technology at multifrequency	3 – 1000 / 200	(De Lorenzo et al. 1997): TBW = ECW + ICW, with ECW = $1/1000*[(4.3^{2}*40.5^{2})/(1.05\%1$ $0^{-3})]^{1/3}*[(\sqrt{Wt}*S^{2})/extracellular})^{2/3}$ and ICW = 1 + (ICF ^{bis} /ECW) ^{5/2} = [(extracellularR + intracellularR)/extracellularR)*[1 + (273.9/40.5)*(ICF ^{bis} /ECW)]	Deuterium dilution	De Lorenzo et al. (De Lorenzo et al. 1997) equation showed no difference in the TBW estimation (difference mean value: 0.3 L, LoA: -1.1 to 1.7) Moissl et al. (Moissl et al. 2006) equation showed no difference for the TBW estimation (difference mean value: 0.2 L, LoA: - 1.0 to 1.4)
					(Moissl et al. 2006): TBW = $ECW + ICW$, with $ECW =$		

					$\label{eq:states} \begin{split} & [(0.188/BMI) + \\ & 0.2883]*[(S^{2*}Wt^{1/2})^{/extracellular} \\ & R)^{2/3} \text{ and ICW} = \\ & [(0.58758/BMI) + \\ & 0.4194]*[(S^{2*}Wt^{1/2})^{/intracellular} \\ & R)^{2/3} \end{split}$		
(Francisco et al. 2021)	Cross- sectional	201 athletes (134 men, 67 women) with mean age 21.4 ± 5.1y divided into well-hydrated, euhydrated and dehydrated groups	Hydra 4200, Xitron Technologies, San Diego, CA / BIS using a foot to hand technology at multifrequency	50 / 800	Equations owned by manufacturer for the TBW, ECW, and ICW estimations	Deuterium and bromide dilution	 BIS showed no difference for the TBW estimation in well-hydrated (difference mean value: -0.2 L, LoA: -3.1 to 2.7), euhydrated (difference mean value: -0.3 L, LoA: -2.8 to 2.2), and dehydrated (difference mean value: 0.0 L, LoA: -1.9 to 2.0) athletes BIS showed no difference for the ECW estimation in well-hydrated (difference mean value: -0.1 L, LoA: -3.3 to 3.0), euhydrated (difference mean value: -0.1 L, LoA: -3.4 to 3.6), and dehydrated (difference mean value: -1.2 L, LoA: -6.2 to 2.7) athletes
							BIS showed no difference for the ICW estimation in well- hydrated (difference mean value: -0.1 L, LoA: -4.3 to 4.1), euhydrated (difference mean value: -0.1 L, LoA: -4.1 to 3.9), and dehydrated (difference mean value: 1.2 L, LoA: 3.7 to 6.3) athletes
(Coratella et al. 2021)	Cross- sectional	185 athletes (men: n = 132, age $21.7 \pm$ 5.1 y; women: n = 53, age 20.3 ± 4.5 y) involved in different sports	101 Anniversary, AKERN Systems; Florence, Italy / BIA using a foot to hand technology at single frequency	50 / 400	(Matias et al. 2016b): TBW = $0.286 + 0.195 * S^2/R +$ 0.385 * Wt + 5.086 * Sex, where Sex is 0 if female and 1 if male; ECW = $1.579 +$ $0.055 * S^2/R + 0.127 * Wt +$ $0.006 * S^2/Xc + 0.932 * Sex$,	Deuterium and bromide dilution	Matias et al. (Matias et al. 2016b) equation showed no difference for the TBW estimation in women (difference mean value: -0.3 L, LoA: -2.9 to 2.3) and men (difference mean value: 0.1 L, LoA: -2.3 to 2.4). Matias et al. (Matias et al. 2016b) equation showed no difference for the ECW estimation in women (difference mean value: -0.3 L, LoA: -1.4 to 1.7) and men (difference mean value: -0.6 L, LoA: -2.7 to 1.5).

where Sex is 0 if female and 1 if male; ICW = TBW - ECW

(Sun et al. 2003): TBW = $1.20 + 0.45 * S^2/R + 0.18 * Wt$ for men and TBW = $3.75 + 0.45 * S^2/R + 0.11 * Wt$ for women

(Schoeller and Luke 2000): TBW = $0.499*S^2/R + 0.080*Wt + 2.9$

(Kushner et al. 1992): TBW = 0.59* S/R + 0.065*Wt + 0.04

(Kotler et al. 1996): TBW = Male: 0.58^* (S^{1.62}/impedance^{0.7})* (1/1.35) + $0.32^*Wt - 3.66$ and Female: $0.76^*(^{S1.99}/impedance^{0.58})^*$ (1/18.91) + $0.14^*Wt - 0.86$

(Lukaski and Bolonchuk 1988): TBW = $0.377* S^2/R + 0.14*Wt - 0.08*age + 2.9*Sex+ 4.65$, where Sex is 0 if female and 1 if male; ECW = $0.189*(S^2/R) + 0.052*Wt - 0.0002*(S^2/Xc) + 1.03$ Sun et al. (Sun et al. 2003) equation underestimated TBW in women (difference mean value: -1.5 L, LoA: -5.1 to 2.1) and men (difference mean value: -1.8 L, LoA: -6.9 to 3.3).

Schoeller and Luke (Schoeller and Luke 2000) equation underestimated TBW in women (difference mean value: -1.7 L, LoA: -5.3 to 2.0) and men (difference mean value: -4.1 L, LoA: -9.5 to 1.3).

Kushner et al. (Kushner et al. 1992) equation underestimated TBW in women (difference mean value: -0.7 L, LoA: -4.3 to 2.3) and men (difference mean value: -1.4 L, LoA: -6.7 to 3.9).

Kotler et al. (Kotler et al. 1996) showed no difference for the TBW estimation in women (difference mean value: 0.5 L, LoA: -3.4 to 4.1) and men (difference mean value: -1.6 L, LoA: -7.1 to 3.4).

Lukaski and Bolonchuk (Lukaski and Bolonchuk 1988) equation underestimated TBW in women (difference mean value: -4.1 L, LoA: -8.1 to 0.2) and men (difference mean value: -5.4 L, LoA: -11.3 to 0.4). Lukaski and Bolonchuk (Lukaski and Bolonchuk 1988) equation underestimated ECW in women (difference mean value: -1.9 L, LoA: -3.6 to 0.1), while showed no difference in men (difference mean value: -0.1 L, LoA: -3.5 to 3.4).

Sergi et al. (Sergi et al. 1994) underestimated ECW in women (difference mean value: -2.3 L, LoA: -4.1 to 0.6) and men (difference mean value: -1.8 L, LoA: -5.4 to 1.2). (Sergi et al. 1994)ECW = -5.22 + 0.2*S²/R + 0.005/Xc + 0.08*Wt + 1.9 + 1.86*Sex, where Sex is 0 if female and 1 if male

Note: Data are shown as mean ± standard deviation. BIA: bioimpedance analysis; BIS: bioimpedance spectroscopy; N/A: not available; LoA: limits of agreements; R: resistance; Xc: reactance; TBW: total body water; ECW: extracellular water; ICW: intracellular water; Wt: weight in kilograms; S: stature in meters.

Authors	Study	Participants	Bioimpedance device /	Sampling	Analytical procedure	Reference	Main results
	design		method	frequency		method	
				(kHz) /			
				Current (µA)			
(Campa et	Longitudi	58 athletes (men: $n = 39$,	101 Anniversary,	50 / 400	R and Xc adjusted according	Deuterium and	Reductions in vector length were associated with increases
al. 2020)	nal	age 18.7 ± 4.0 y;	AKERN Systems;		to the Classic BIVA approach	bromide	in TBW (r = -0.718 , p < 0.01) considering the athletes as
		women: n = 19, age 19.2	Florence, Italy / BIA		(adjusted for S)	dilution	an entire group
		\pm 6.0 y) involved in	using a foot to hand				
		different sports	technology at single				Phase angle was positively correlated with the change in
			frequency				ICW/ECW ratio ($r = 0.436$, $p < 0.01$) considering the
							athletes as an entire group
(Marini et	Cross-	202 athletes (men: n =	101 Anniversary,	50 / 400	R and Xc adjusted according	DXA	Specific vector length was positively correlated with %FM
al. 2020)	sectional	ctional 139 age 21.5 ± 5.0 y; women: n = 63 age 20.7 ± 5.1 y) involved in	AKERN Systems;		to the Classic BIVA (adjusted	Deuterium and	(men: $r = 0.569$, $p < 0.001$; women: $r = 0.773$, $p < 0.001$).
			Florence, Italy / BIA		for S) and the Specific BIVA	Bromide	
			using a foot to hand		(adjusted for body	dilution and 4C	Classic vector length was negatively correlated with TBW
		different sports	technology at single		geometries) approaches	according to the	(men: $r = -0.880$, $p < 0.001$; women: $r = -0.829$, $p < 0.001$)
			frequency			Wang et al.	
						(2002) equation	Phase angle was positively correlated with the ICW/ECW
							ratio (men: r = 0.493, p < 0.001; women: r 1=0.408, p <
							0.001)
(Silva et	Longitudi	27 male judo athletes	Hydra 4200, Xitron	50 / N/A	R and Xc adjusted according	Deuterium and	Decreases in TBW were accompanied by vector
al. 2020)	nal	(age 23.2 ± 2.8 y)	Technologies, San		to the Classic BIVA approach	Bromide	elongations (T ² =2.6, F=1.2, P=0.3, Mahalanobis distance=
			Diego, CA, US / BIS			dilution	0.39), and vice versa (T ² =4.1, F=1.8, P=0.2, Mahalanobis
			using a foot to hand				distance= 0.64)
			technology at				
			multifrequency				Phase angle was positively correlated with the ICW/ECW
							ratio ($\beta = 0.050$, p=0.004)

Table 3. Articles comparing bioimpedance vector outcomes with total body water and percentage of fat mass using a reference method.

(Campa et	Longitudi	80 athletes of	Xitron 4000b, Xitron	50 / N/A	R and Xc adjusted according	DXA	Specific vector length was associated with change in %FM
al. 2021a)	nal	different sports (age	technologies, San		to the Specific BIVA		$(r^2 = 0.246; p < 0.001)$ considering the athletes as an entire
		$43.9\pm9.2~\text{y})$	Diego, CA / BIS using a		approach		group
		including 27 women	foot to hand technology				
		and 53 men	at multifrequency				
(Stagi et	Cross-	50 athletes (25	101 Anniversary,	50 / 400	R and Xc adjusted according	DXA	Good agreement between DXA and BIVA (F=14.89, p $<$
al. 2021)	sectional	men: age 24.37 ± 4.79 y;	AKERN Systems;		to Specific BIVA		0.001) in both sexes and all body segments.
		25 women: age 24.32 \pm	Florence, Italy / BIA				
	4. di	4.43 y) involved in	using a foot to hand				Specific vector length was positively correlated with
		different sports	technology at single				$\%FM_{\rm DXA}$ in the whole body and all body segments, and the
			frequency				phase angle was correlated with FFMI _{DXA} .

Note: Data are shown as mean ± standard deviation. BIA: bioimpedance analysis; BIS: bioimpedance spectroscopy; BIVA: bioelectrical impedance vector analysis; N/A: not available; R: resistance; Xc: reactance; TBW: total body water; ECW: extracellular water; ICW: intracellular water; FM: fat mass; Wt: weight in kilograms; S: stature in meters.

Click here to access/download Supplementary Material Supplementary Table 1.docx

Table

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Not applicable

Ethics approval: Not applicable