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REVIEW

Body composition in athletes and sports nutrition: an examination of the bioimpedance analysis technique

JR Moon[1,2]

BACKGROUND/OBJECTIVES: The purpose of the current review was to evaluate how body composition can be utilised in athletes, paying particular attention to the bioelectrical impedance analysis (BIA) technique.
SUBJECTS/METHODS: Various body composition methods are discussed, as well as the unique characteristics of athletes that can lead to large errors when predicting fat mass (FM) and fat-free mass (FFM). Basic principles of BIA are discussed, and past uses of the BIA technique in athletes are explored. Single-prediction validation studies and studies tracking changes in FM and FFM are discussed with applications for athletes.
RESULTS: Although extensive research in the area of BIA and athletes has been conducted, there remains a large gap in the literature pertaining to a single generalised athlete equation developed using a multiple-compartment model that includes total body water (TBW).
CONCLUSIONS: Until a generalised athlete-specific BIA equation developed from a multiple-compartment is published, it is recommended that generalised equations such as those published by Lukaski and Bolonchuk and Lohman be used in athletes. However, BIA equations developed for specific athletes may also produce acceptable values and are still acceptable for use until more research is conducted. The use of a valid BIA equation/device should produce values similar to those of hydrostatic weighing and dual-energy X-ray absorptiometry. However, researchers and practitioners need to understand the individual variability associated with BIA estimations for both single assessments and repeated measurements. Although the BIA method shows promise for estimating body composition in athletes, future research should focus on the development of general athlete-specific equations using a TBW-based three- or four-compartment model.

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INTRODUCTION

Body composition evaluations are necessary in order to monitor obesity class, nutritional status, training outcomes and general health.[1] Fat mass (FM) and fat-free mass (FFM) are often used to identify nutritional requirements and energy expenditure.[2,3] Sports nutrition experts can use body composition values to help develop specific dietary interventions, and strength coaches, as well as athletic trainers, can use body composition values to help create, optimise and evaluate training programs. Laboratory methods used to estimate body composition such as hydrostatic weighing (HW), dual-energy X-ray absorptiometry (DXA), air-displacement plethysmography, total body potassium counting and multiple-compartment models, such as the three- and four-compartment models, are impractical to use in large populations or sports settings. Furthermore, laboratory body composition methods are expensive and inconvenient. Body composition field methods are often the choice of sports and sports nutrition professionals who are interested in the fat and fat-free composition of athletes because of the techniques' low cost, convenience and ease of use. However, field methods, such as anthropometric measurements (skinfolds and circumferences), near-infrared interactance and bioelectrical impedance analysis (BIA) are inherently prone to estimation errors. Specifically, field methods require prediction equations that have been derived from laboratory methods. If the equations for the field method were not developed in the same population being tested, the values can be impractical. However, prediction errors in laboratory methods also exist.

All laboratory methods are not all created equal. Errors between laboratory methods can exceed 3 kg of fat compared with the most advanced multiple-compartment model, the six-compartment model.[4] Because 'true' body composition values (FM and FFM) are 'unmeasurable in living humans', criterion laboratory methods used to develop equations for field methods should be as accurate as possible.[4] Laboratory methods are inherently prone to error, albeit often much less than field methods. Quantifying tissue masses (FM and FFM) in living humans requires laboratory methods as well in order to include assumptions or constants, which can vary from person to person. Constants used for unknown variables in laboratory methods depend on the method. For example, two-compartment models such as HW and air-displacement plethysmography assume a constant hydration of FFM to be 0.73, among other assumptions. DXA also requires the assumption of a constant 0.73 for the hydration of FFM. Therefore, the aforementioned methods assume that FFM (all non-FM) consists of 73% water in all individuals. However, known deviations in the hydration of FFM have been reported from 68 to 81%,[5,6] and thus the constant of 0.73 is not applicable in all individuals and has a range as large as 18%. As water is the largest component of FFM (68–81%) and the largest molecular-level component, methods that assume a 0.73 FFM hydration

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onstant have been shown to be less accurate compared with methods not required to assume a 0.73 FFM hydration constant.[4] Accordingly, multiple-compartment models of three compartments or more including a total body water (TBW) measurement 'form a core with the six-compartment criterion model' because of their low technical/total errors under 0.8 kg and mean differences <1.1 kg for FM.[4]

Body composition among athletes has been shown to be a function of the physical task and is varied across different types of athletes.[7,8] However, an increase in body fat (BF) has been shown to decrease performance.[9] Not surprisingly, football players were found to have body compositions based on position ranging from 4 to 29% BF (% BF), suggesting that within the same sports, body composition is highly variable. In light of the variations in body composition among athletes, it is necessary to use appropriate methods to predict accurate estimations of FM and FM for use in program development or calculating nutritional requirements for athletes. Large variations in FFM hydration have been observed in athletes owing to the large variations in body composition between athletes participating in different sports, as well as within the same sport.[10,11] Therefore, because of the aforementioned known deviations in FFM hydration, it has been suggested that multiple-compartment models including a TBW measurement be used in body composition predictions for athletes.[10–13] However, no field techniques use a criterion method for estimating TBW, such as isotope dilution, and few include prediction equations developed using a multiple-compartment model including TBW. The bioimpedance field method has shown promise in its ability to predict TBW and accurately estimate fat and FFM, yet there is limited research in athletes and the validity of bioimpedance to estimate fat and FFM in addition to TBW is unclear. In addition, the ability of bioimpedance to accurately track body composition changes is uncertain. The purpose of this review is to identify past uses of bioimpedance in athletes and to identify the validity of this technique in various athletic populations. The accuracy of bioimpedance to track changes in athletes will also be discussed, as well as future directions for bioimpedance in athletes.

BASIC PRINCIPLES OF BIOIMPEDANCE

Bioimpedance methods are classified by the number of frequencies used for analysis. Single-frequency devices are typically referred to as 'BIA' devices, whereas multiple frequency devices are referred to as 'bioimpedance spectroscopy' (BIS) devices. The term spectroscopy is used because BIS methods utilise a 'spectra' of frequencies. However, the number of frequencies needed before a BIA device can be considered a BIS device is not clear. Typically, BIS devices use Cole modeling[14] and mixture theories[15] rather than regression equations to predict body composition variables.[16] Therefore, BIA devices that use multiple frequencies are typically called 'multiple-frequency bioelectrical impedance analysers' (MFBIA). However, it has been reported that BIS using the Cole model[14] is the 'best model' for predicting body composition via bioimpedance,[16] yet the main principles behind how these devices can be used to predict body composition are the same.

By sending electrical currents through the body, bioimpedance devices can calculate impedance (Z), otherwise known as the resistivity (R) and reactance (Xc) of the current.[17] This is possible because cell membranes in the human body behave as capacitors, and impedance to electrical flow is dependent on the frequency of the electrical current.[14,18] At low frequencies (<50 kHz), the electrical current cannot penetrate cell membranes and, therefore, can be used to predict extracellular water. Higher frequencies (>50 kHz) can penetrate cell membranes and be used to estimate intracellular volumes. This basic principle is the foundation for BIA, MFBIA and BIS devices to estimate body composition. However, there is a fundamental assumption made by all bioimpedance devices that the human body is composed of uniform cylinders. Although this is not the case, total body bioimpedance can still accurately predict body composition compartments. This is possible because the body's fluid is evenly distributed and body segmental lengths are proportional to segmental circumferences.[19] BIA devices use a single 50-kHz current to calculate the body's impedance (R and Xc). These values are then used in regression equations to predict various body composition compartments. Surprisingly, the use of 50 kHz was not intended for predicting body composition but for tracking changes in dialysis patients.[20] It has been reported that the BIA technique using 50 kHz is 'scientifically unsound';[16] still, 50 kHz remains the standard for BIA devices. Typically, body composition equations predict FFM because there is a relative constant relationship between TBW and FFM (0.73 constant as discussed above).[6] As the electrolytes in the body's water are the best conductors of electrical current, bioimpedance most accurately predicts fluid volumes. However, TBW contains both intracellular water and extracellular water, and a 50-kHz frequency may not account for all of the intracellular water because it may not penetrate cell membranes. It has been reported that a frequency of 100 kHz cannot completely penetrate through a cell.[21] Because muscles contain a large portion of intracellular water, bioimpedance methods that use higher frequencies are preferred for predicting FFM.[16,22]

Advanced MFBIA devices use several frequencies to predict body composition compartments. MFBIA devices typically use frequencies ranging from 5 to 500 kHz, allowing for a more accurate estimate of intracellular and extracellular volume compared with single-frequency devices. However, MFBIA equations are limited by the same assumptions as single-frequency devices and are also considered inferior to BIS because they do not use modeling techniques.[16] Arguments exist in favour of both BIA and BIS techniques,[16,23–25] yet BIS is the most comprehensive bioimpedance method, and data support its accuracy for predicting fluid volumes and other body composition variables.[26–30] BIS is considered superior to BIA and MFBIA because the calculation of fluid volumes is not based on equations but on Cole modeling[14] and mixture theories.[15] However, BIS is subject to the same assumptions as BIA and MFBIA. Nevertheless, BIS can calculate resistivity at both an infinite frequency and at a frequency of zero. Using these resistance values, intracellular (R_i) and extracellular resistance (R_e) can be calculated, and subsequent volumes can also be calculated. BIS, however, still uses a constant FFM hydration (0.73) to predict FFM. Recently, owing to the complexity of the method, BIS has been used to develop prediction equations for total body muscle mass.[31] Overall, the appropriateness of BIA, MFBIA and BIS for the prediction of total body muscle mass, FM, FFM and TBW for use in an athletic population remains unclear.

BIA devices can range in price from less than one hundred dollars to several thousands of dollars, and the electrical signal sent through the body can vary from leg to leg, arm to arm and leg to arm depending on the device. MFBIA devices typically include four measurement points including two arms and two legs and are more expensive than BIA devices. BIS devices typically use a leg-to-arm setup. However, only two methods of generating and measuring electrical current are used for all bioimpedance devices: either electrode or metal contacts. Bioimpedance procedures for electrode-based systems have evolved over the past several years, with the standard now coming from the ESPEN (The European Society for Clinical Nutrition and Metabolism) guidelines for the clinical application of bioimpedance analysis.[32]

After subjects are made to rest in the supine position for 5–10 min, measurements are taken while they lie supine on a table with their arms $\geqslant 30$ degrees away from their torso with legs separated. After hair removal and cleaning with alcohol, proximal electrodes should be placed on the right side of the body at the wrist (dorsal surface at the ulnar styloid process) and ankle (dorsal surface between the malleoli). After placing the proximal electrodes, distal electrodes can be placed at a distance of at least 5 cm between electrode centres or placed on the hand (dorsal surface of the metacarpal phalangeal joint, 1 cm proximal to the knuckle of the middle finger) and foot (dorsal surface of the metatarsal phalangeal joint, 1 cm proximal to the joint of the second toe). Images of electrode placements have been recently published by Moon *et al.*[33] In addition, Moon *et al.*[33] compared both electrode placements and identified the differences between placements for a single measurement, as well as multiple measurements, over several weeks. Ultimately, the 5-cm placement slightly improved reliability, and there were small differences between the two placements for a single measurement. These findings suggest that electrode placements for BIA measurements should be consistent with the electrode placements used when the equations were developed. However, both placements should provide similar results with only slight mean differences due to the addition of more tissue being measured in the latter electrode placement protocol. More information about electrode placement and tracking changes is included later in the *tracking changes* section.

Non-electrode-based bioimpedance systems use metal contacts typically on the ball of the foot and heel, as well as on the palm of the hand and the thumb. However, depending on the device, contacts may be located at various anatomical locations, making direct comparisons between devices difficult at best. Because of the vast number of BIA devices and differences between devices and between body composition equations (either known or unknown in the device), it is suggested that athletes use an electrode-based system that provides raw data (*R* and Xc) in order to use the appropriate equation for their body type, sex, age, sport and so on.

BIA IN ATHLETES

To date, no generalised BIA equations have been specifically developed for athletes using a criterion method that includes TBW estimations. However, several studies have been conducted looking at the validity of proprietary equations or equations developed using two-compartment models or DXA, which assume a constant FFM hydration. There is a large gap in the literature regarding BIA equations in multiple types of athletes, in addition to a lack of prediction equations developed using a TBW-based criterion method. BIA equations developed using a criterion model that does not include a criterion TBW estimation will have errors no better than the laboratory method itself. More importantly, comparing HW with a four-compartment model including TBW has produced mean differences as large as 5% fat, total errors $>2.3\%$ fat and individual errors exceeding $\pm 4.2\%$ fat.[10,11,34] DXA has also produced mean differences in female athletes exceeding 3.7% fat compared with a multiple-compartment model and a total error of 4.9% fat and individual errors exceeding $\pm 6.3\%$ fat.[11,13,34] Thus, the errors associated with HW and DXA will be embedded in the BIA prediction equations. In addition, there will be added prediction errors on top of the criterion errors, consequently increasing prediction equations' errors even more when compared with a multiple-compartment model that includes TBW. Prediction equations developed or validated in athletes using a criterion method that does not use a multiple-compartment model with a TBW estimation may not be appropriate for use in any athletic population.

Over the past few decades, the BIA method has been used in athletes for various purposes. However, owing to the lack of evidence supporting the validity of BIA in athletic populations for single assessments of FM or FFM and the lack of literature validating BIA for tracking body composition changes in athletes, results of these studies should be interpreted with caution. As early as in 1993, BIA has been used to compare different types of athletes.[35] A study by Giada *et al.*[36] in 1996 compared professional soccer players with body builders and found increased FFM in body builders. Later, in 1998, Bouix *et al.*[37] found a positive relationship between red blood cell aggregability and FM in rugby athletes. In professional soccer players, Manetti *et al.*[38] discovered an increase in the size of the left ventricle of the heart over 13 months of training with no changes in FM or FFM. In 2001, Grund *et al.*[39] found that strength- and endurance-trained men had less FM and a greater TBW% compared with untrained men and that strength-trained men had greater FFM compared with endurance-trained and untrained men. Years later, Gurd and Klentrou[40] looked at physical growth and sexual maturation in young male gymnasts and found no differences in FFM on comparing the athletes with controls, as well as a significant negative relationship between % BF and energy expenditure. Astorino *et al.*[41] tracked changes in field hockey players from in-season to pre-season and found a decrease in % BF. An investigation by Mihajlovic and Mijatov[42] found that ballet dancers had significantly lower FM compared with controls. In 2008, Knechtle *et al.*[43] discovered that male ultra-endurance triathletes lost % BF throughout the 10-day event. Quiterio *et al.*[44] observed an increase in TBW and extracellular fluids using BIS in adolescent athletes who trained more than 9 h per week compared with athletes training less than 9 h per week. On comparing pre- and post-TBW in ultrarunners, Knechtle *et al.*[45] found an increase in TBW even though the athletes became more dehydrated as reported by urine-specific gravity, haematocrit and plasma sodium. Most research using bioimpedance for body composition in athletes has either tracked changes or compared groups/types of athletes of athletes. However, the majority of BIA literature in athletes has attempted to validate the BIA method (and equations) in different populations compared with a criterion method, to compare BIA with other non-criterion methods and to identify potential methodological and physiological concerns when using BIA to predict body composition.

Following the proper pre-testing guidelines and adhering to the correct testing protocols are crucial in order to obtain accurate and reliable body composition estimations using BIA in athletes. Early in the history of BIA, Deurenber *et al.*[46] discovered that eating and strenuous exercise 2–4 h before testing decreased impedance, and that testing 1 week before or after the onset of menstruation in women significantly changes impedance. A year later, Gleichauf and Roe[47] discovered that the weight changes during menses from an altered hydration status contributed to the different impedance measurements. In the same year, Bunt *et al.*[48] discovered that weight changes during menses also resulted in significantly different body density values from underwater weighing using a 2C model. Later, Saunders *et al.*[49] concluded that BIA was not valid in athletes with abnormal hydration status (hypohydrated, rehydrated and superhydrated). Therefore, in addition to individual hydration status variability due to differing body compositions as discussed earlier, acute changes in hydration from training and menses can also reduce the validity of BIA in athletes. However, if the BIA guidelines are followed and athletes are tested under the ideal conditions, BIA can provide valid body composition estimations similar to 2C models, such as underwater weighing and air-displacement plethysmography.

VALIDATION STUDIES AND EQUATIONS

There have been numerous investigations comparing BIA methods with criterion methods. However, most comparisons have been with 2C models or DXA. Results comparing BIA equations and devices with 2C models in a wide variety of athletes have produced similar valid results with *r* values exceeding 0.667, standard error of estimate values $<4.3\%$ BF and total errors $<4.6\%$ BF and 2.4 kg of FFM.[50–60] Several equations and methods still resulted in significant mean differences. Studies comparing BIA with DXA have identified results similar to those found when BIA was compared with 2C models.[61–68] For male and female athletes participating in various sports and activities across multiple age ranges, BIA produced FFM standard error of estimate values ranging from 1.1 to 2.6 kg, but significant mean differences were observed in several studies showing a significant overestimation, as well as underestimations.[61–68] Many studies have compared BIA with anthropometric equations with varying results.[35,69–72] However, all studies have shown good agreement between methods. As stated earlier, there are limited studies comparing BIA in athletes with multiple-compartment models containing a criterion TBW estimation. Andreoli *et al.*[73] discovered that BIA overestimated % BF by 12.1% and produced a low *r* value of 0.49 in male water-polo players compared with a four-compartment (4C) model. In contrast, Clark *et al.*[74] revealed a total error of only 3.08 kg for minimal weight predictions in NCAA wrestlers and concluded that BIA was an acceptable alternative to a 4C model. Discrepancies in literature could be due to several issues such as different methods and equations for the 4C models and different athletic populations. However, the largest variabilities in BIA research are the BIA devices themselves, as well as the equations used, making a direct comparison between athletes, models and equations difficult.

Recommended equations[63,75,76] have been suggested by experts in the body composition field,[77] and additional equations for athletes have been published in the past.[53,68,78] However, there are no equations for athletes developed using a multiple-compartment model that includes a TBW estimation, and the validity of published equations in various athletic populations is still unknown. Notwithstanding, the BIA method could be a valid tool for athletes if a generalised equation was developed using a TBW-based multiple-compartment model in a large group of varying athletes.

TRACKING CHANGES IN BODY COMPOSITION

Although BIA has been used to track changes in the body compositions of athletes, limited research supports its validity. Specifically, there has not been an investigation in athletes comparing BIA methods/equations with a TBW-based multiple-compartment model over time. However, Pearman *et al.*[79] compared HW with BIA before and after dehydration and found that BIA produced a larger amount of fat loss (2.1% BF) compared with HW (0.9% BF). In addition, BIA resulted in an increase of TBW by 2.6% after dehydration, suggesting the BIA is not valid for tracking acute changes in hydration. Kilduff *et al.*[80] examined acute body composition changes after 1 week of creatine supplementation in male athletes. Compared with HW, results indicated the same change in FFM (0.9 kg). Similarly, results in other populations have shown conflicting results. Several studies have looked at the ability of BIA to track body composition changes in obese and overweight women compared with various criterion methods.[81–86] Results have indicated good agreement between BIA and DXA, deuterium oxide, 4C models and nitrogen balance. However, small constant errors were observed ranging from 0.5 to 5 kg of FFM in some studies,[81–83] whereas no significant differences were observed in others.[84–86] All results indicated that small changes in body composition detected by BIA may not be accurate and that using raw impedance values could be valuable.[81–86] In healthy men, Ross *et al.*[87] found good agreement using multiple BIA equations compared with HW (*r* 0.85–0.90), whereas van der Kooy *et al.*[88] found no correlations between HW and BIA on comparing body composition changes in healthy men and women, and determined that BIA was not valid for tracking changes. In addition, BIA produced significantly different FFM values compared with deuterium oxide and HW. In children, Elberg *et al.*[89] indicated that BIA significantly overestimated BF changes compared with DXA by 1.37% BF. On the basis of the current literature, the ability of BIA to track changes in athletes, regardless of sport, age, race or body composition, is still unclear. More research is needed to determine the appropriate equations to track changes in FFM and FM in athletes. A longitudinal study comparing several BIA equations and methods needs to be conducted in a wide range of athletes before BIA can be recommended for use in athletes to track changes. In addition, raw impedance values can potentially be used to track body composition changes without the errors associated with prediction equations, yet more research is needed in this area as well.

CONCLUSIONS

Although extensive research in the area of BIA and athletes has been conducted, there remains a large gap in the literature pertaining to a single generalised athlete equation developed using a multiple-compartment model that includes TBW similar to those that exist for anthropometrics equations.[90] Nevertheless, generalised anthropometric equations not developed specifically for athletes, such as the Jackson and Pollock skinfold equations,[91,92] have proven to be valid in athletes compared with a 4C model.[12,90] Therefore, until a generalised athlete-specific BIA equation developed from a multiple-compartment is published, it is recommended that generalised equations such as those published by Lukaski and Bolonchuk[93] and Lohman[94] be used in athletes.

Lukaski and Bolonchuk:

FFM (kg) $= 0.734\ (Ht^2/R) + 0.116\ Wt + 0.096\ Xc + 0.878\ sex - 4.03$

($Ht =$ height in cm, $Wt =$ body weight in kg, male $= 1$ and female $= 0$)

Lohman:

male and female children 8–15 years: FFM (kg) $= 0.620\ (Ht^2/R) + 0.210\ Wt + 0.100\ Xc + 4.2$

Females 18–30 years: FFM (kg) $= 0.476\ (Ht^2/R) + 0.295\ Wt + 5.49$

Females (active) 18–35 years: FFM (kg) $= 0.666\ (Ht^2/R) + 0.164\ Wt + 0.217\ Xc - 8.78$

Females 30–50 years: FFM (kg) $= 0.536\ (Ht^2/R) + 0.155\ Wt + 0.075\ Xc + 2.87$

Females 50–70 years: FFM (kg) $= 0.470\ (Ht^2/R) + 0.170\ Wt + 0.030\ Xc + 5.7$

Males 18–30 years: FFM (kg) $= 0.485\ (Ht^2/R) + 0.338\ Wt + 5.32$

Males 30–50 years: FFM (kg) $= 0.549\ (Ht^2/R) + 0.163\ Wt + 0.092\ Xc + 4.51$

Males 50–70 years: FFM (kg) $= 0.600\ (Ht^2/R) + 0.186\ Wt + 0.226\ Xc - 10.9$

($Ht =$ height in cm and $Wt =$ body weight in kg)

However, the above equations may overestimate and/or underestimate both FM and FFM depending on the athlete. Bioimpedance equations developed for specific athletes may also produce acceptable values and are still suggested for use until more research is conducted. Currently, owing to variations in FFM density and FFM hydration in athletes, multiple-compartment models containing a valid TBW estimation are needed for the accurate estimation of FM or FFM in individual athletes. In addition, the same multiple-compartment models are needed to track small changes in body composition in athletes. However, if large changes exceeding 4–5 kg in either FM or FFM occur, the BIA estimation may have improved accuracy. Future research should focus on the development of general athlete-specific equations using a TBW-based three-compartment or 4C model. Furthermore, researchers and practitioners need to understand the individual variability associated with BIA estimations for both single assessments and repeated measurements. Following proper testing procedures and using reliable BIA methods/devices will allow for more precise impedance measurements.

CONFLICT OF INTEREST

JRM is Research Institute Director at MusclePharm Corporation, but the corporation was not involved in the submission.

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