

# Comparison of Bioelectrical Impedance and Skinfolds with Hydrodensitometry in the Assessment of Body Composition in Healthy Young Adults

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## Abstract

Bioelectrical impedance analysis (BIA) is a widely used method for estimating body composition, yet issues concerning its validity persist in the literature. The purpose of this study was to validate percentage of body fat (BF) values estimated from BIA and skinfold (SF) with those obtained from hydrodensitometry (HD). Percent BF values measured via hand-to-hand BIA (BIA-H), foot-to-foot BIA (BIA-F), sum of three skinfolds (SF-3), and sum of seven skinfolds (SF-7) were compared to HD in 64 young caucasian adults (33 males, 31 females, mean age  $\pm$  SD = 21.2  $\pm$  3.4 years) in the same morning. Correlations with HD ranged from  $r = .71 - .73$  except for (BIA-F), which was  $r = .63$ . BIA-F significantly overpredicted body fatness (%BF) ( $t = 3.8, p < .001$ ) in comparison with HD. BIA-H, SF-3, and SF-7 were not significantly different (SE = 0.78 - .83) from HD. Caution should be exercised when using BIA-F based on existing manufacturer's equations with young adults. These data suggest that BIA-H can produce acceptable body fat measures for young adults but is not superior to SF-3 estimates.

**Key words:** Body fatness, validity

## Introduction

Accurate, noninvasive and easy to use field methods for assessing body composition are needed in clinical, community, and research settings to properly identify a client's health risk of excessively high or low body fatness. One of these methods, bioelectrical impedance analysis (BIA), is a growing technique that ranks similar to skinfold measurement in its accuracy, precision and objectivity (Houtkooper, Lohman, Going, & Howell, 1996).

BIA is based on the principle of resistance to the flow of electrical current due to differences in water content of fat and lean tissue (Wagner & Heyward, 1999). Lean tissue contains large amounts of water and electrolytes and is a good conductor of electrical current. Fat tissue, on the other hand, is anhydrous and a poor conductor; therefore, the larger the fat tissue, the higher the resistance to electrical current and the higher the adiposity.

BIA has proven to be a popular method of body composition assessment because it is quick, inexpensive, and does not intrude upon the client's privacy. In many clinical and community settings, it has replaced skinfold measurement as the field method of choice. This may be in part due to the fact that accurate measurement of skinfolds is dependent on the technique, skill, and experience of the tester (Roche, 1996), whereas BIA may be administered by examiners with little or no experience. In addition, Wagner and Heyward (1999) note that "because it is difficult to obtain accurate SKF measurements on older adults and obese individuals due to loose connective tissue and large fatfolds, BIA is the preferred field

method of estimating percent body fat (BF) in these populations," (p. 144).

Validation studies have been undertaken on a number of cohorts and have focused primarily on a comparison of BIA with criterion methods. The research is extensive and has produced equivocal findings. For example, a review of 18 BIA studies on athletes and body builders found significant differences between BIA and HD in 13 of them (Clark, et al., 1993; Clark, Kuta, & Sullivan, 1994; Clark, Bartok, Sullivan, & Schoeller, 2005; Colville, Heyward, & Sandoval, 1989; Cordain, Richau, & Johnson, 1995; Diboll & Moffit, 2003; Dixon, Deitrick, Pierce, Cutrufello, & Drapeau, 2005; Dixon, Deitrick, Cutrufello, Drapeau, & Lovallo, 2006; Hortobagyi, et al., 1992; Kilduff, Lewis, Kingsley, Owen, & Dietzig, 2007; Kirkendall, Grogan, & Bowers, 1991; Moon, Tobkin, Smith, et al., 2008a; Moon, Tobkin, Costa, et al., 2008b; Oppliger, Nielsen, & Vance, 1991; Oppliger, Nielsen, Shetler, Crowley, & Albright, 1992; Utter, et al., 2005; Utter & Lambeth, 2010; Volpe, Melanson & Kline, 2010). Similarly, in 15 body composition studies on women, only 4 showed a high level of agreement between BIA and criterion methods (Andreoli, Melchiorri, & De Lorenzo, 2002; Brandon & Bond, 1999; Civar, Aktop, Tercan, Ozdol, & Ozer, 2006; Demura, Sato, & Kitabayashi, 2004; Eaton, Israel, O'Brien, Hortobagyi, & McCammon, 1993; Erselcan, Candan, Saruhan, & Ayca, 2000; Evans, Arngrimsson, & Cureton, 2001; Heyward, et al., 1992; Iswara, Lukito, & Schultink, 2007; Jakicic, Wing, & Lang, 1998; Lupoli, et al., 2004; Miyatake, Takenami, Kawasaki, & Fujii, 2005; Segal, Gutin, Presta, Wang, & Van Itallie, 1985; Stolarczyk, Heyward, Hicks, & Baumgartner, 1994; Stolarczyk, Heyward, Goodman, Grant, Kessler, et al., 1995). On the other hand, among active, young nonathletes, who were the focus of the present study, prior research found significant differences between BIA and reference methods in only one of four studies (Civar, Ozer, Aktop, Tercan, & Ayceman, 2003; Civar et al., 2006; Kaminsky & Whaley, 1993; Swartz, Swartz, Evans, King, & Thompson, 2002). In almost all of these studies the authors suggested further validation of BIA.

More recently, two second-generation BIA devices have replaced the traditional tetrapolar BIA in the marketplace - a foot-to-foot machine (BIA-F) resembling a bathroom scale, and a hand-to-hand machine (BIA-H). The Tanita TBF-315 Body Fat Monitor is a common BIA-F instrument in the marketplace. With the BIA-F, the individual stands barefoot on the footpads while a low-level electrical current is introduced into the body at a fixed frequency. The Omron Body Logic Fat Loss Monitor is a popular BIA-H instrument in which the individual stands erect with the arms extended shoulder-height and in front of the body. Each hand grasps one side of the handle on the device while the electrical current is introduced.

Previously, BIA-F and BIA-H have been compared to traditional tetrapolar BIA (Ritchie, Miller, & Smiciklas-Wright, 2005) and to reference methods but rarely to each other. Recently, Williams, Barnes, & Pujol (2010) compared two different BIA-

F models, the Tanita BF-350, Tanita BF-522, with three BIA-H instruments, the Omron HBF-500, Omron HBF-300 and Omron HBF-306 and found only the Omron HBF-500 to have a high level of agreement with DEXA. Considering the inherent possibilities of measurement inaccuracy using BIA, it is important for fitness specialists and other strength and conditioning professionals who utilize BIA instruments to understand the relative validities of these devices. Therefore, the purpose of this study was to compare BF measurements provided by foot-to-foot and hand-to-hand BIA to a criterion method (HD) and Jackson-Pollock skinfold measures.

## Method

### Participants and Procedures

Students from a midsize comprehensive university in the Southeastern United States were recruited from majors' classes, a campus recreation center, and by word of mouth. Individuals with physical limitations, those taking diuretics, or athletes involved in daily practices were excluded from study participation due to known BIA measurement standards (NIH, 1994). After providing consent, participants included 64 young, healthy Caucasian adults (33 males, 31 females ( $21 \pm 3$  years of age)). The Institutional Review Board of the university granted approval for the study. The order of measurement was randomly assigned to participants as they entered the laboratory.

Body fatness via foot-to-foot BIA (BIA-F) was measured using the Tanita Body Fat Monitor, Model TBF-315 (Tanita Corporation of America, Inc., Arlington Heights, IL) to the nearest 0.1%. Subjects stood erect with bare feet on the device's footpads. Body fatness via hand-to-hand BIA (BIA-H) was measured using the Omron Body Logic Fat Loss Monitor (Omron Healthcare, Inc., Bannockburn, IL). Subjects stood erect with arms forward at shoulder height. The investigator asked the subject about the amount of physical activity performed weekly and selected either the adult or athlete mode depending on the response. Since BIA estimates have previously established reliability within the same activity mode setting (Cordain, Whicker & Johnson, 1988; Erceg, et al., 2010; Houtkooper et al., 1996; NIH, 1994), only singles measures for BIA-H and BIA-F were needed and therefore obtained.

Because BIA estimates are affected by changes in water content, hydration levels and blood circulation are known to have an effect. In accordance with manufacturer's specifications, participants were tested in early morning before water, food, caffeine, or alcohol intake, exercise or showering. Subjects verbally verified adherence to these instructions before testing. Temperature ( $21-22^{\circ}\text{C}$ ) and relative humidity ( $\sim 740$  mmHg) of the laboratory were maintained at a comfortable level throughout testing.

Skinfold measurements were taken with Harpenden skinfold calipers at carefully marked sites on the anterior thigh, anterior iliac crest, subscapular, chest, midaxilla, abdomen, and triceps by two experienced skinfold testers. Intertester reliability ( $r = .97$ ) was established using a separate random sample of 10 college students from a class in exercise science. Harpenden skinfold calipers are widely accepted as the "Gold Standard" instrument for skinfold measurement (Whitehead, 1990). The calipers were calibrated for tension and with a substance of known width prior to testing. Sites were carefully marked and a minimum of two trials at rotating sites were taken. If the two measures at a site differed by more

than 3 mm, a third measure was taken. The mean of the two closest measures was recorded and used in the calculation of BF.

Using anterior thigh, anterior iliac crest, and triceps measures (women) and anterior thigh, chest, and abdomen measures (men), body densities were determined (Jackson & Pollock, 1978; Jackson, Pollock & Ward, 1980) and the Siri (1956) formula generated BF estimates from the sum of three skinfolds (SF-3). All seven measures were summed to compute the sum of seven skinfolds (SF-7), which then produced BF estimates.

Whole-body density was determined by underwater weighing in a fasted state. After determining body mass in air to the nearest 0.1 kg on a Detecto scale, residual volume was measured using spirometry. Following this, participants entered the underwater weighing tank and were seated in a chair suspended from a 9-kg Chatillion autopsy scale. A minimum of seven measurements were taken to obtain three weights within 100 g (Bonge & Donnelly, 1989). The mean of the three highest trials was used as the underwater weight. Body density values were converted to BF using the Siri equation (1956). The reader is referred to the classic work of Behnke and Wilmore (1974) and the later article by Wagner and Heyward (1999) for more thorough reviews of these techniques.

### Analysis of Data

Pearson product-moment correlations were calculated between HD and each of the field methods. Paired t-tests were used to compare the mean BF of the methods. Significance was set at  $p < .01$  to reflect the increased chance of error associated with multiple t-test comparisons. All analyses were performed using SPSS version 17.0.

## Results

Mean ( $\pm$ SD) BF for all methods of body composition analysis are presented in Table 1. Only BIA-F was found to be significantly different from HD ( $p < .01$ ) in its estimate of BF.

**Table 1. Descriptive Statistics for Body Composition Methods (%BF)**

Method		Females (n=31)	Males (n=33)	Both (n=64)
BIA-F	M	25.8	19.1	22.4*
	SD	6.9	7.6	8.0
BIA-H	M	20.6	16.1	18.3
	SD	5.5	6.5	6.4
SF-3	M	21.6	15.5	18.5
	SD	5.6	6.3	6.7
SF-7	M	21.9	15.3	18.5
	SD	5.4	6.2	6.7
HD	M	21.0	17.8	19.3
	SD	5.3	6.8	6.3

BIA-F = Tanita TBF-515 Body Fat Monitor/Scale (Foot-to-Foot)

BIA-H = Omron Body Logic Fat Loss Monitor (Hand-to-Hand)

SF-3 = Sum of Three Skinfolds

SF-7 = Sum of Seven Skinfolds

HD = Hydrodensitometry

\* Significantly different from HD,  $p < .01$

Significant intermethod agreement (Table 2) was demonstrated between each of the methods and HW ( $p < .01$ ). Correlations between the two bioelectrical impedance measures, BIA-F and BIA-H, with HD were  $r = 0.63$  and  $r = 0.73$  respectively.

**Table 2. Correlations between Bioelectrical Impedance, Skinfolds and Hydrodensitometry.**

	BIA-F	BIA-H	HD	SF-3	SF-7
BIA-F	1.0	.61*	.63*	.66*	.65*
BIA-H	.61*	1.0	.73*	.69*	.73*
HD	.63*	.73*	1.0	.71*	.72*
SF-3	.66*	.69*	.71*	1.0	.92*
SF-7	.65*	.73*	.72*	.92*	1.0

\*Significant at  $p < .01$

The correlation between BIA-F and its sister method, BIA-H, was  $r = 0.61$ . BIA-F significantly overpredicted BF ( $t = 3.8$ ,  $p < .001$ ) in comparison with HD (Table 3). The skinfold measures consistently underpredicted BF in comparison with HD. The small differences (1.0 – 1.2%) in BF with BIA-H, SF-3, and SF-7 were not significantly different from HD.

**Table 3. Summary of Mean Differences From Hydrodensitometry (%BF).**

Method	MD	SD	95% CI	t
BIA-F	3.042	6.348	1.46 - 4.63	3.83*
BIA-H	-1.014	4.640	-2.17 - .14	-1.75
SF-3	-0.886	4.950	-0.35 - 2.12	1.43
SF-7	-0.792	4.896	-0.43 - 2.02	1.30

\* Significant at  $p < 0.01$   
 MD = mean difference  
 SD = standard deviation  
 95% CI = 95% confidence interval

**Discussion**

The results of this study on the validity of the BIA-F and BIA-H methods demonstrated generally high intermethod agreement among BIA, skinfolds and HD. The only significantly different estimate of BF from HD was found with the BIA-F method (mean difference – 3.1%).

A review of more than 70 previous BIA studies with different cohorts found considerable variability in intermethod agreement. Among non-obese, adult non-athletes, some evidence supports the validity of BIA with this population (Biaggi et al., 1999; Eaton et al., 1993; Erceg et al., 2010; Erselcan et al., 2000; Evans et al., 2001; Heyward et al., 1992; Kaminsky & Whaley, 1993; Kremer et al., 1998; Kyle et al., 2004; Levenhagan et al., 1999; Maughan, 1993; Moon et al., 2008a; Ross et al., 1989; Swartz et al., 2002; Unick, Utter, Schumm, & McInnis, 2006).

In some studies, BF differences between BIA and reference methods were significant. BIA overestimated BF by more than 3% and 4% in men and women when BF was higher than 15% and 25% respectively (Sun et al., 2005). In a study on young, healthy women, Andreoli et al., found a significant difference in BF between a Tanita bipedal BIA and DEXA (2002). Paijmans, Wilmore and Wilmore compared BIA and SF with HD in

individuals who underwent rapid weight loss and found significant differences between methods (1992).

In another study, Williams et al., found differences between DEXA and five different BIA instruments, including both BIA-H and BIA-F models, in a study on young adult nonathletes (2010). No explanation was offered by the authors to explain this discrepancy. However, earlier work suggests that the different equations used for athletes and non-athletes may have created some bias (Fogelhom & van Marken Lichtenbelt, 1997). Alternately, variations in fluid distribution may have manifested these differences. This study is interesting because fitness practitioners who measure their clients' BF may be likely to pick up the most readily available BIA instrument, believing it to be accurate, and this may not be the case.

Kyle, et al., (2004) have suggested that BIA works well in healthy subjects with stable water and electrolytes balance with a BIA equation appropriate to age, sex and race. On the other hand, Dehghan and Merchant (2008) have cautioned against the use of BIA for large epidemiological populations where race, ethnic group, and conditions vary. Based on this and earlier research, BIA-H would appear to be a reasonably valid method of body composition analysis for use with adult non-obese Caucasians, whereas BIA-F is a less acceptable alternative method with this population.

Future research should assess the validity of bioelectrical impedance analysis among more culturally diverse samples, with older adults and obese individuals.

**References**

Andreoli, A., Melchiorri, G., & De Lorenzo, A. (2002). Bioelectrical impedance measures in different position and vs dual-energy X-ray absorptiometry (DXA). *Journal of Sports Medicine and Physical Fitness*, 42(2), 186-189.

Behnke, A., & Wilmore, J. (1974). *Evaluation and Regulation of Body Build and Composition*. Englewood Cliffs, NJ: Prentice-Hall.

Biaggi, R.R., Vollman, M.W., Nies, M.A., Brener, C.E., Flakoll, P.J., Levenhagen, D.K., Sun, M., Karabulut, Z., & Chen, K.Y. (1999). Comparison of air-displacement plethysmography with hydrostatic weighing and bioelectrical impedance analysis for the assessment of body composition in healthy adults. *American Journal of Clinical Nutrition*, 69(5), 898-903.

Bonge, D., & Donnelly, J.E. (1989). Trials to criteria for hydrostatic weighing at residual volume. *Research Quarterly for Exercise and Sport*, 60, 176-179.

Brandon, L.J., & Bond, V. (1999). Are practical methods of evaluating body fat in African-American women accurate? *American Journal of Health Promotion*, 13(4), 200-202.

Civar, S., Ozer, K., Aktop, A., Tercan, E., & Ayceman, N. (2003). Validity of leg-to-leg bioelectrical impedance measurement in highly active males. *Biology of Sport*, 20(3), 209-219.

Civar, S., Aktop, A., Tercan, E., Ozdol, Y., & Ozer, K. (2006). Validity of leg-to-leg bioelectrical impedance measurement in highly active women. *Journal of Strength and Conditioning Research*, 20(2), 359-365.

Clark, R.R., Kuta, J.M., Sullivan, J.C., Bedford, W.M., Penner, J.D., & Studesville, E.A. (1993). A comparison of methods to predict minimal weight in high school wrestlers. *Medicine and Science in Sports and Exercise*, 25(1), 151-158.

Clark, R.R., Kuta, J.M., Sullivan, J.C. (1994). Cross-validation of methods to predict body fat in African-American and Caucasian collegiate football players. *Research Quarterly for Exercise and Sport*, 65(1), 21-30.

Clark, R.R., Bartok, C., Sullivan, J.C., & Schoeller, D.A. (2005). Is leg-to-

- leg BIA valid for predicting minimum weight in wrestlers? *Medicine and Science in Sports and Exercise*, 37(6), 1061-1068.
- Colville, B.C., Heyward, V.H., & Sandoval, W.M. (1989). Comparison of two methods for estimating body composition of bodybuilders. *Journal of Applied Sport Science Research*, 3(3), 57-61.
- Cordain, L., Whicker, R.E., & Johnson, J.E. (1988). Body composition determination in children using bioelectrical impedance. *Growth, Development, and Aging*, 52(1), 37-40.
- Cordain, L., Richau, L.L., & Johnson, J.E. (1995). Variability of body composition assessments in men exhibiting extreme muscular hypertrophy. *Journal of Strength and Conditioning Research*, 9(2), 85-89.
- Dehghan, M., & Merchant, A.T. (2008). Is bioelectrical impedance accurate for use in large epidemiological studies? *Nutrition Journal*, 7, 7.
- Demura, S., Sato, S., & Kitabayashi, T. (2004). Percentage of total body fat as estimated by three automatic bioelectrical impedance analyzers. *Journal of Physiological Anthropology and Applied Human Science*, 23(3), 93-99.
- Diboll, D.C., & Moffit, J.K. (2003). A comparison of bioelectrical impedance and near-infrared interactance to skinfold measures in determining minimum wrestling weight in collegiate wrestlers. *Journal of Exercise Physiology- online*, 6(2), 26-36.
- Dixon, C.B., Deitrick, R.W., Pierce, J.R., Cutrufello, P.T., & Drapeau, L.L. (2005). Evaluation of the BOD POD and leg-to-leg bioelectrical impedance analysis for estimating percent body fat in National Collegiate Association Division III collegiate wrestlers. *Journal of Strength and Conditioning Research*, 19(1), 85-91.
- Dixon, C.B., Deitrick, R.W., Cutrufello, P.T., Drapeau, L.L., & Lovallo, S.J. (2006). Effect of mode selection when using leg-to-leg BIA to estimate body fat in collegiate wrestlers. *The Journal of Sports Medicine and Physical Fitness*, 46(2), 265-270.
- Eaton, A.W., Israel, R.G., O'Brien, K.F., Hortobagyi, T., & McCammon, M.R. (1993). Comparison of four methods to assess body composition in women. *European Journal of Clinical Nutrition*, 47(5), 353-360.
- Erceg, D.N., Dieli-Conwright, C.M., Rossuello, A.E., Jency, N.E., Sun, S., & Schroeder, E.T. (2010). The Stayhealthy bioelectrical impedance analyzer predicts body fat in children and adults. *Nutrition Research*, 30(5), 297-304.
- Erselcan, T., Candan, F., Saruhan, S., & Ayca, T. (2000). Comparison of body composition analysis methods in clinical routine. *Annals of Nutrition and Metabolism*, 44(5-6), 243-248.
- Evans, E.M., Arngrimsson, S.A., & Cureton, K.J. (2001). Body composition estimates from multicomponent models using BIA to determine body water. *Medicine and Science in Sports and Exercise*, 33(5), 839-845.
- Fogelholm, M., & van Marken Lichtenbelt, W. (1997). Comparison of body composition methods: a literature analysis. *European Journal of Clinical Nutrition*, 51, 495-503.
- Heyward, V.H., Cook, K.L., Hicks, V.L., Jenkins, K.A., Quatrochi, J.A., & Wilson, W.L. (1992). Predictive accuracy of three field methods for estimating relative body fatness of nonobese and obese women. *International Journal of Sport Nutrition*, 2(1), 75-86.
- Hortobagyi, T., Israel, R.G., Houmar, J.A., O'Brien, K.F., Johns, R.A., & Wells, J.M. (1992). Comparison of four methods to assess body composition in black and white athletes. *International Journal of Sport Nutrition*, 2(1), 60-74.
- Houtkooper, L.B., Lohman, T.G., Going, S.B., & Howell, W.H. (1996). Why bioelectrical impedance analysis should be used for estimating adiposity. *American Journal of Clinical Nutrition*, 64(Suppl.), 436S-448S.
- Iswara, R., Lukito, W., & Schultink, J.W. (2007). Comparison of body composition indices assessed by underwater weighing, bioelectrical impedance and anthropometry in Indonesian adolescent girls. *Asia Pacific Journal of Clinical Nutrition*, 16(4), 641-648.
- Jackson, A.S., & Pollock, M.L. (1978). Generalized equations for predicting body density of men. *British Journal of Nutrition*, 40, 497-504.
- Jackson, A.S., Pollock, M.L., & Ward, A. (1980). Generalized equations for predicting body density of women. *Medicine and Science in Sports and Exercise*, 12, 175-182.
- Jakicic, J.M., Wing, R.R., & Lang, W. (1998). Bioelectrical impedance analysis to assess body composition in obese adult women. *International Journal of Obesity and Related Metabolic Disorders*, 22(3), 243-250.
- Kaminsky, L.A., & Whaley, M.H. (1993). Differences in estimates of percent body fat using bioelectrical impedance. *Journal of Sports Medicine and Physical Fitness*, 33(2), 172-177.
- Kilduff, L.P., Lewis, S., Kingsley, M.C., Owen, N., & Dietzig, R.E. (2007). Reliability and detecting change following short-term creatine supplementation: comparison of two-component body composition methods. *Journal of Strength and Conditioning Research*, 21(2), 378-384.
- Kirkendall, D.T., Grogan, J.W., & Bowers, R.G. (1991). Field comparison of body composition techniques: hydrostatic weighing, skinfold thickness, and bioelectrical impedance. *Journal of Orthopedic Sports Physical Therapy*, 13(5), 235-239.
- Kremer, M.M., Latin, R.W., Berg, K.E., & Stanek, K. (1998). Validity of bioelectrical impedance analysis to measure body fat in Air Force members. *Military Medicine*, 163(11), 781-785.
- Kyle, U.G., Bosaeus, I., De Lorenzo, A.D., Deurenberg, P., Elia, M., Manuel Gomez, J., Lilienthal Heitmann, B., Kent-Smith, L., Melchior, J.C., Pirlich, M., Scharfetter, H.M.W.J., Schols, A., & Pichard, C. (2004). Bioelectrical impedance analysis-part II: utilization in clinical practice. *Clinical Nutrition*, 23(6), 1430-1453.
- Levenhagen, D.K., Borel, M.J., Welch, D.C., Piasecki, J.H., Piasecki, D.P., Chen, K.Y., & Flakoll, P.J. (1999). A comparison of air displacement plethysmography with three other techniques to determine body fat in healthy adults. *Journal of Parenteral and Enteral Nutrition*, 23(5), 293-299.
- Lupoli, L., Sergi, G., Coin, A., Perissinotto, E., Volpato, S., Busetto, L., Inelmen, E.M., & Enzi, G. (2004). Body composition in underweight elderly subjects: reliability of bioelectrical impedance analysis. *Clinical Nutrition*, 23(6), 1371-1380.
- Maughan, R.J. (1993). An evaluation of a bioelectrical impedance analyser for the estimation of body fat content. *British Journal of Sports Medicine*, 27(1), 63-66.
- Miyatake, N., Takenami, S., Kawasaki, Y., & Fujii, M. (2005). Comparison of air displacement plethysmograph and bioelectrical impedance for assessing body composition changes during weight loss in Japanese women. *Diabetes, Obesity and Metabolism*, 7(3), 268-272.
- Moon, J.R., Tobkin, S.E., Smith, A.E., Roberts, M.D., Ryan, E.D., Dalbo, V.J., Lockwood, C.M., Walter, A.A., Cramer, J.T., Beck, T.W., & Stout, J.R. (2008). Percent body fat estimations in college men using field and laboratory methods: A three-compartment model approach. *Dynamic Medicine*, 7, 7.
- Moon, J.R., Tobkin, S.E., Costa, P.B., Smalls, M., Mieding, W.K., O'Kroy, J.A., Zoeller, R.F., & Stout, J.R. (2008). Validity of the BOD POD for assessing body composition in athletic high school boys. *Journal of Strength and Conditioning Research*, 22(1), 263-269.
- Oppliger, R.A., Nielsen, D.H., & Vance, C.G. (1991). Wrestlers' minimal weight: anthropometry, bioimpedance, and hydrostatic weighing compared. *Medicine and Science in Sports and Exercise*, 23(2), 247-253.
- Oppliger, R.A., Nielsen, D.H., Shetler, A.C., Crowley, E.T., & Albright, J.P. (1992). Body composition of collegiate football players: bioelectrical impedance and skinfolds compared to hydrostatic weighing. *Journal of Orthopedic Sports Physical Therapy*, 15, 187-192.
- Paijmans, I.J., Wilmore, K.M., & Wilmore, J.H. (1992). Use of skinfolds and bioelectrical impedance for body composition assessment after weight reduction. *Journal of the American College of Nutrition*, 11(2), 145-151.
- Ritchie, J.D., Miller, C.K., & Smiciklas-Wright, H. (2005). Tanita foot-to-foot bioelectrical impedance analysis system validated in older adults. *Journal of the American Dietetic Association*, 105, 1617-1619.
- Roche, A.F. (1996). Anthropometry and ultrasound. In A.F. Roche, S.B. Heymsfield, T.G. Lohman (Eds). *Human Body Composition*.

- Champaign, IL: Human Kinetics.
- Ross, R., Leger, L., Martin, P., & Roy, R. (1989). Sensitivity of bioelectrical impedance to detect changes in human body composition. *Journal of Applied Physiology*, 67(4), 1643-1648.
- Segal, K.R., Gutin, B., Presta, E., Wang, J., & Van Itallie, T.B. (1985). Estimation of human body composition by electrical impedance methods: a comparative study. *Journal of Applied Physiology*, 58(5), 1565-1571.
- Siri, W.S. Gross composition of the body. (1956). In J.H. Lawrence & C.A. Tobias (Eds). *Advances in Biological and Medical Physics*. New York: Academic Press.
- Stolarczyk, L.M., Heyward, V.H., Hicks, V.L., & Baumgartner, R.N. (1994). Predictive accuracy of bioelectrical impedance in estimating body composition of Native American women. *The American Journal of Clinical Nutrition*, 59(5), 964-970.
- Stolarczyk, L.M., Heyward, V.H., Goodman, J.A., Grant, D.J., Kessler, K.L., Kocina, P.S., & Wilmerding, V. (1995). Predictive accuracy of bioimpedance equations in estimating fat-free mass of Hispanic women. *Medicine and Science in Sports and Exercise*, 27(10), 1450-1456.
- Sun, G., French, C.R., Martin, G.R., Youngusband, B., Green, R.C., Xie, Y.G., Mathews, M., Barron, J.R., Fitzpatrick, D.G., Gulliver, W., & Zhang, H. (2005). Comparison of multifrequency bioelectrical impedance analysis with dual-energy X-ray absorptiometry for assessment of percentage body fat in a large, healthy population. *American Journal of Clinical Nutrition*, 81(1), 74-78.
- Swartz, A.M., Swartz, A.M., Evans, J.M., King, G.A., & Thompson, D.L. (2002). Evaluation of a foot-to-foot bioelectrical impedance analyzer in highly active, moderately active and less active young men. *British Journal of Nutrition*, 88(2), 205-210.
- Unick, J.L., Utter, A.C., Schumm, S., & McInnis, T. (2006). Evaluation of leg-to-leg BIA in assessing body composition in high-school-aged males and females. *Research in Sports Medicine*, 14(4), 301-313.
- U.S. National Institutes of Health. Office of Medical Applications of Research. (1994). Bioelectrical impedance analysis in body composition measurement. *National Institutes of Health Technology Assessment Conference statement*.
- Utter, A.C., Nieman, D.C., Mulford, G.J., Tobin, R., Schumm, S., McInnis, T., & Monk, J.R. (2005). Evaluation of leg-to-leg BIA in assessing body composition of high-school wrestlers. *Medicine and Science in Sports and Exercise*, 37(8), 1395-1400.
- Utter, A.C., & Lambeth, P.G. (2010). Evaluation of multifrequency bioelectrical impedance analysis in assessing body composition of wrestlers. *Medicine and Science in Sports and Exercise*, 42(2), 361-367.
- Volpe, S.L., Melanson, E.L., & Kline, G. (2010). Validation of bioelectrical impedance analysis to hydrostatic weighing in male body builders. *Acta Diabetologica*, 47(1), 55-58.
- Wagner, D.R., & Heyward, V.H. (1999). Techniques of body composition assessment: a review of laboratory and field methods. *Research Quarterly for Exercise and Sport*, 70(2), 135-149.
- Whitehead, J.R. (1990). A study of the measurement variation among different skinfold calipers. *British Journal of Physical Education (Research Supplement)*, 7, 10-14.
- Williams, R.D., Barnes, J.T., & Pujol, T.J. (2010). Comparison of body composition assessment techniques in a non-athletic, non-obese young adult population. *Journal of Strength and Conditioning Research*, 24(1), 1. ■