

Full Length Research Paper

The validity and accuracy in foot-to-foot bioelectrical impedance analysis measuring models referenced by dual-energy X-ray absorptiometry in body composition in standing position

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Accepted 15 March, 2011

The criterion validity of foot-to-foot (Z_{F-F}) by bioelectrical impedance analysis (BIA) in a standing position measuring models was referenced by dual-energy X-ray absorptiometry (DEXA) and hand-to-foot (Z_{H-F}). In order to cross match analysis, both of the Z_{H-F} and Z_{F-F} measuring by BIA were performed in the same event to the identical subject, simultaneously. 105 males (7 to 70 years old) and 108 females (7 to 67 years old) were measured by BIA and DEXA. The Z_{F-F} value was 481.85 ± 63.37 ohm in male and 554.35 ± 74.97 ohm in female. The Z_{H-F} value was 586.82 ± 81.56 ohm in male and 703.28 ± 97.70 ohm in female. Regression equations for Z_{F-F} and Z_{H-F} were $Z_{F-F} = 0.926 Z_{H-F} - 63.093$, ($R = 0.85$) in male and $Z_{F-F} = 0.909 Z_{H-F} - 86.673$ ($R = 0.86$) in female. The fat free mass (FFM), measured by DEXA was 49.42 ± 10.03 kg in male and 34.52 ± 4.45 kg in female. The correlation (R value) for Z_{F-F} to DEXA was 0.93 and for Z_{H-F} was 0.96 in male, and 0.85 and 0.87 in female, respectively. The high correlation between Z_{H-F} and Z_{F-F} vs. whole body DEXA in both male and female renders it applicable to develop the clinical instrument by foot-to-foot measuring models by BIA in standing position.

Key words: Hand-to-foot bioimpedance analysis, foot-to-foot bioimpedance analysis, relative body fat (BF), fat free mass (FFM), dual-energy X-ray absorptiometry (DEXA).

INTRODUCTION

Bioelectrical impedance was first used at about score of the 1930s to assay body composition till present (Horton and Van, 1935; Burger and Van, 1943; Thomasset, 1962). The safe, non-invasive, simple, quick and non-expensive characteristics rendered the widely usage by, BIA method to predict the body composition such as

body fat (BF), fat free mass (FFM), skeletal muscle mass (Janssen et al., 2000), visceral fat (Tomio et al., 1995), and subcutaneous adipose tissue (Smith et al., 2001). On the developed history of BIA, the supine lying position BIA with the tetra-polar gel electrodes hand-to-foot clinical model was developed earlier than the standing position commercial model. On the view of validate and accuracy, most of the published papers measuring impedance value (Z) were done by the clinical analytic supine lying position BIA and few studies were done by the standing position BIA. The hand-to-foot BIA model, performed by tetra-polar gel electrodes in a supine lying position, had been shown great accuracy in measurement

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of fat free mass (Lukaski et al., 1986; Segal et al., 1988). The accuracy of standing position BIA remained a mystery for commercial consideration so as to misunderstand the accuracy of standing position BIA to be less accurate than that of the supine lying position BIA. A derived prediction equation to determine fat free mass, fat mass and percentage body fat referenced with DEXA, the foot-to-foot BIA was an accurate technique in the measurement of body composition which was better than anthropometric indices in children (Tyrrell et al., 2001). The foot-to-foot BIA body composition analyzer with the manufacturer's prediction equations was not recommended for application to individual overweight or obese children (Radley et al., 2009).

It was shown that, the leg-to-leg BIA system accurately assessed fat free mass in both obese and non-obese women (Utter et al., 1999). Foot-to-foot in standing position BIA model, when compared to the DEXA value of children, has been validated as an alternative method to measure body fat (Sung et al., 2001). However, the foot-to-foot BIA body composition analyzer with the manufacturer's prediction equations was not recommended for application to individual children who are overweight and obese (Radley et al., 2009). Many parameters affect the accuracy of prediction equation in BIA, such as height, weight, gender and age (Rising et al., 1991; Kyle et al., 2004). Many factors, such as changes in body water distribution caused by different posture (Shinichi et al., 2001), configuration and the location of electrodes (Graves et al., 1989; Ohkawara et al., 2003), could affect the accuracy and precision of measurement. That is to say that the prediction equation will be improved by imposed above interior variables. Limitations of the hand-to-foot clinical BIA model in the laboratory were inconvenient operation for operators and embarrassing treatment for subjects. The development of foot-to-foot in standing position measuring models by BIA could supply the simpler, quicker and more convenient way to measurement of fat free mass.

The almost present measurements by BIA in studies are performed in supine position on a nonconductive surface with the standard placement of surface electrodes on wrists and ankles. The inconvenient usage limited it in some specific laboratories and medical centers. However, the most applicable and prevalent measurements in BIA by commercial products were performed with the standing position on the platform embedded with stainless tetra-polar electrodes or the holding handle grips embedded with stainless bi-polar electrodes. The convenient and applicable utilities made them more prevalence in clinic usage. The precision and accuracy in the body composition measurements by BIA with stainless electrodes in standing position should become more and more important issues, especially, the predictive equations established in machines were not published for the commercial secrets' sakes (Lukaski and Siders, 2003; Kushner et al., 1996). Despite the fact that

validity and accuracy in determination of body composition have been published, the comparison of various measuring models in the validity and accuracy in determination of body composition was necessary to provide more practicable data for application.

DEXA is currently used as reference method to measure body composition (Salamone et al., 2000; Prior et al., 1997), whereas, some studies had shown the lower precision and accuracy in clinical BIA method in comparison with Panotopoulos et al. (2001) and Houtkoop et al. (2001). In contrast, excellent agreement that exists between clinical BIA and DXEA had also been reported in some studies (Bolanowski and Nilsson, 2001; Smith et al., 2001).

Foot-to-foot BIA measurements validated for specific ethnic groups, populations and conditions can accurately measure body fat in those populations (Bosy-Westphal et al., 2008; Boneva-Asiova and Boyanov, 2008). In addition, most of the published papers on foot-to-foot BIA measurements differentiate the indirect performed data from unpublished built-in predicted equations rather than directly impedance value by foot-to-foot BIA with referenced methods. The aims of the present study include: To directly validate the measuring impedance value by bioelectrical impedance analysis in a standing position, this study intend to clarify the correlation of the hand-to-foot and foot-to-foot measuring models by BIA with the same body posture, by the same electrodes connected to the same instrument in the same time, for the identical subject. DEXA will be used as reference method to validate. The second aim is to find a predictive equation to estimate the body composition with more accuracy, convenience and applicable by foot-to-foot measuring model by BIA in standing position.

MATERIALS AND METHODS

Subjects

A total of 108 females and 105 males, from the health cohort without any clinic diseases as hepatitis relative diseases, chronic pulmonary diseases, hypertension, diabetes mellitus, cancer, renal functional failure diseases, pregnant status and any artificially electrical implantation, were recruited with formal consents permitted by the Institutional Review Board of IRB Advisory Committee at Jen-Ai Hospital in Taiwan. All of the subjects were well informed on the experimental purpose, methods, procedures, steps and any safety relative comments before any treatment.

Bioelectrical impedance measurement

Subjects, which were in uniform cotton dress without any metal attachments before dinner four hours ago, were measured by DEXA (Lunar Prodigy, GE Corp, USA.) with the software "enCore 2003 Version 7.0". The water consumption was restricted for 4 h before measurements. The whole body scanning protocol were performed at 20 μ Gy by the professional operator in Department of Radiology, Dah Li County Jen-Ai Hospital in Taiwan to estimate the total body fat and FFM. After the measurement, subjects stood up

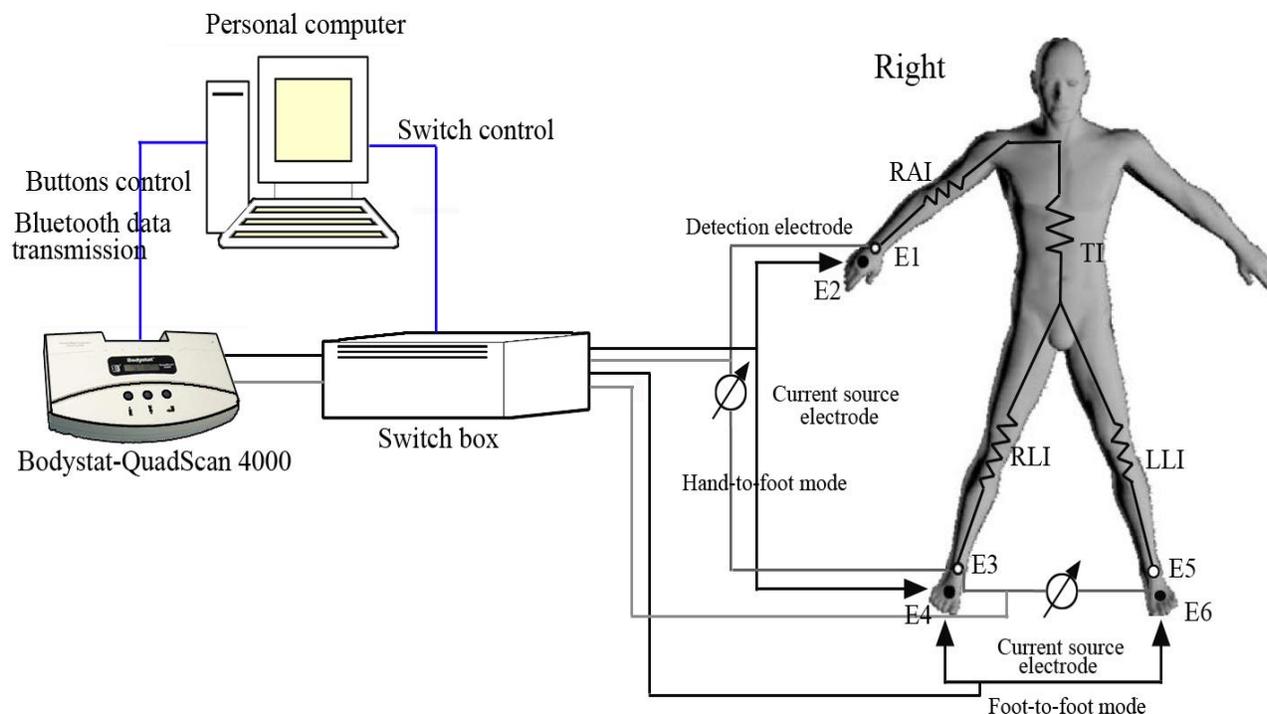


Figure 1. Measuring platform and bioelectric impedance measurement of improved system.

at platform embedded with tetra-polar electrodes and griped a handle embedded with bi-polar electrodes to carry out the measurement of BIA. The modified BIA instrument, designed by this study, was created independently and it detects electrodes and current source electrodes in each hand and foot.

The computer that connected to QuadScan4000 (Bodystat Corp., U.K.) can automatically shift the measuring current to hand-to-foot models or hand to hand models. The current at $400 \mu\text{A}$ with frequency at 50 KHz were used during measurement. The electronic impedance from electrode to electrode was much greater than bioelectronics' impedance. To ascertain the same accuracy and precision as original instrument, all modifications were carefully verified. As shown in Figure 1, the E1, E3 and E5 were current electrodes and E2, E4 and E6 were measuring electrodes. The E1, E2, E5 and E6 are located on the handle and E3 and E4 on the right side on platform. The bio-electronic impedances yield in each human segment was termed as followed: RAI as right arm impedance, TI as trunk impedance, LAI as left arm impedance and RLI as right leg impedance.

By connecting the circuit between E1 and E3, the measurement of E2 and E4 yielded body right hand side impedance to be $\text{RAI} + \text{TI} + \text{RLI}$, in term of impedance of hand-to-foot. Likewise, the circuit between E1 and E5 can measure the E2 and E6 yielded right foot to left foot impedance as $\text{RLI} + \text{LLI}$, in term of impedance of foot-to-foot. All the measurements were completed at 25°C in conditioned room at 75% relative humidity (RH).

Statistics analysis

All the experimental data were analyzed by SPSS.14.0 software (SPSS Inc., Chicago, IL, USA). Results were presented as mean \pm SD. The confidence level at 5% ($p < 0.05$) was considered significant in this study. R values from linear regression analysis and Pearson were expressed to describe the correlation between

any variability. By using the linear regression equation, the program suggested by Bland and Altman (1998) was followed to survey the variability and distributions between FFM values estimated by the earlier correlation equations vs. FFM values measured by DEXA.

RESULTS

The range of age was about 7.1 to 70.4 in male and 7.1 to 67.3 in female. The body mass index (BMI) 14.2 to 34.7 in male and 14.3 to 35.4 in female (Table 1). The range of body composition determined by DEXA in males and females were about 51 to 95 and 49 to 84, respectively (Table 2). After linear regression analysis, the R values of height, weight, age, $Z_{\text{H-F}}$, $Z_{\text{F-F}}$ and FFM in male and female are listed as Tables 3 and 4, respectively. Relations between $Z_{\text{H-F}}$ and $Z_{\text{F-F}}$ were described by using simple linear regression analysis as 1.a in male and 1.b in female and plotted in Figure 2:

$$\text{Male: } Z_{\text{F-F}} = 0.926 Z_{\text{H-F}} - 63.093, (R = 0.85) \quad (1.a)$$

$$\text{Female: } Z_{\text{F-F}} = 0.909 Z_{\text{H-F}} - 86.673, (R = 0.86) \quad (1.b)$$

Where, $Z_{\text{F-F}}$ is the bioelectrical impedance value in foot-to-foot (ohm) and $Z_{\text{H-F}}$ is the bioelectrical impedance value in hand-to-foot (ohm).

Variables, including height, weight, $Z_{\text{H-F}}$ and $Z_{\text{F-F}}$, as well as dependant variables, as FFM, were used to perform linear regression analysis and described as Equations (2.a), (2.b), (2.c) in male and (3.a), (3.b), (3.c) in female

Table 1. Characteristics of the subjects in the present study.

Parameter	Male (n = 105)			Female (n = 108)		
	Mean	SD	Range	Mean	SD	Range
Age (years)	34.80	17.31	7.10–70.40	34.64	15.27	7.10–67.30
Height (m)	1.68	0.12	1.24–1.86	1.57	0.08	1.24–1.73
Weight (kg)	64.13	12.95	21.96–89.93	52.41	10.58	24.37–88.87
BMI (kg/m ²)	22.56	3.38	14.20–34.70	21.33	4.17	14.30–35.36

Table 2. Body composition determined by foot-to-foot, hand-to-foot BIA and DEXA.

Parameter	Male (n = 105)			Female (n = 108)		
	Mean	SD	Range	Mean	SD	Range
Z _{F-F} (ohm)	481.85	63.37	326.00–683.70	554.35	74.97	385.40–742.00
Z _{H-F} (ohm)	586.82	81.56	439.80–860.00	703.28	97.70	479.20–954.20
DEXA-FFM (kg)	49.42	10.03	18.93–66.30	34.52	4.45	21.95–47.59
DEXA-FFM (%)	77.61	9.86	50.88–94.61	66.97	8.29	49.24–84.47
DEXA-fat (kg)	14.71	7.78	3.03–33.46	17.89	7.15	2.41–41.28
DEXA-fat (%)	22.39	9.86	5.39–49.12	33.03	8.29	15.53–50.76

The Z_{F-F}: bioelectrical impedance value in foot-to-foot (ohm), Z_{H-F}: bioelectrical impedance value in hand-to-foot (ohm). DEXA-FFM (kg): fat free mass measured by DEXA and expressed as kg, DEXA-FFM (%): fat free mass measured by DEXA and expressed as percentage. DEXA-fat (kg): fat mass measured by DEXA and expressed as kg, DEXA-fat (%): fat mass measured by DEXA and expressed as percentage

Table 3. The correlation (R values) in every two factors in male.

Parameter	Age	Height	Weight	Z _{H-F}	Z _{F-F}	FFM
Age		0.106	0.387	-0.313	-0.084	0.105
Height			0.746	-0.620	-0.450	0.885
Weight				-0.774	-0.637	0.799
Z _{H-F}					0.854	-0.783
Z _{F-F}						-0.716
FFM						

The R values were come from the linear regression between every two factors. The Z_{F-F}: bioelectrical impedance value in foot-to-foot (ohm), Z_{H-F}: bioelectrical impedance value in hand-to-foot (ohm). FFM: fat free mass.

Table 4. The correlation (R values) in every two factors in female.

Parameter	Age	Height	Weight	Z _{H-F}	Z _{F-F}	FFM
Age		0.139	0.546	-0.523	-0.390	0.339
Height			0.356	0.016	-0.055	0.654
Weight				-0.745	-0.721	0.744
Z _{H-F}					0.866	-0.559
Z _{F-F}						-0.596
FFM						

The R values are from the linear regression between every two factors. The Z_{F-F}, bioelectrical impedance value in foot-to-foot (ohm); Z_{H-F}, bioelectrical impedance value in hand-to-foot (ohm); FFM, fat free mass.

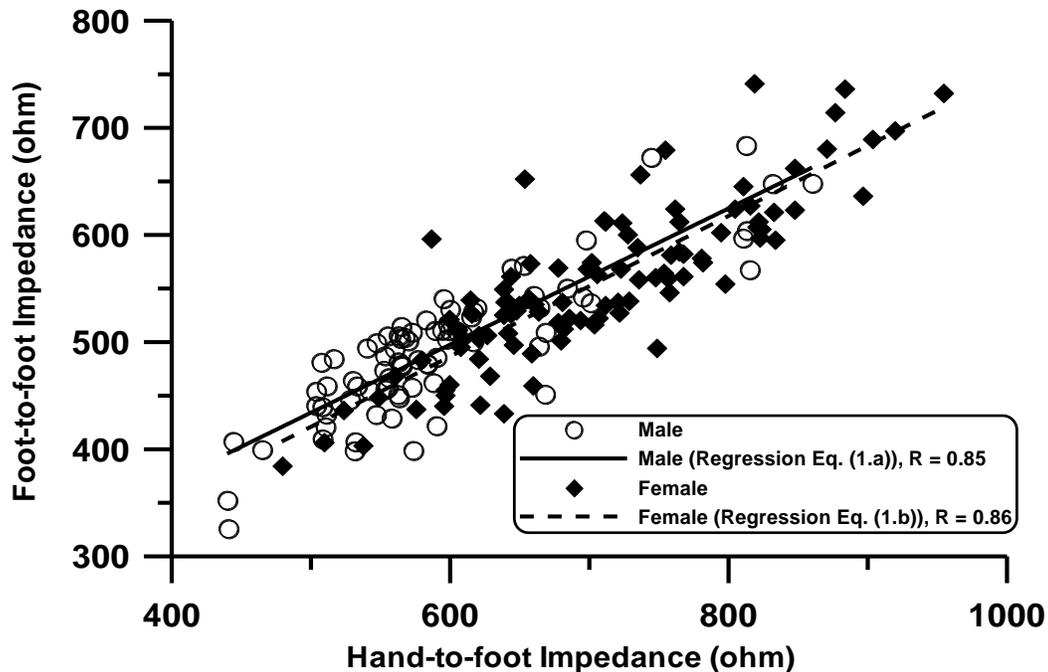


Figure 2. The relationship between Z_{H-F} and Z_{F-F} in male and female. Eq (1.a) is the relations between Z_{H-F} and Z_{F-F} in male and is described by using simple linear regression analysis. Eq (1.b) is the relations between Z_{H-F} and Z_{F-F} in female described by using simple linear regression analysis. The cycle is male while the solid diamond is female. The solid line is the regression equation for male while the dotted line is the regression equation for female.

Equations of linear regression analysis for male:

$$\text{FFM} = 3.333 + 3803.711 h^2 / Z_{F-F} + 0.338 w, (R = 0.93, \text{SD} = 3.50 \text{ kg}) \quad (2.a)$$

$$\text{FFM} = 3.740 + 5980.665 h^2 / Z_{H-F} + 0.223 w, (R = 0.96, \text{SD} = 2.84 \text{ kg}) \quad (2.b)$$

$$\text{FFM} = 3.156 + 6225.017 h^2 / Z_{H-F} + 471.110 h^2 / Z_{F-F} + 0.173 w, (R = 0.97, \text{SD} = 2.64 \text{ kg}) \quad (2.c)$$

The equation of linear regression analysis for female:

$$\text{FFM} = 7.968 + 4955.184 h^2 / Z_{F-F} + 0.078 w, (R = 0.85, \text{SD} = 2.73 \text{ kg}) \quad (3.a)$$

$$\text{FFM} = 7.414 + 6978.150 h^2 / Z_{H-F} + 0.042 w, (R = 0.87, \text{SD} = 2.54 \text{ kg}) \quad (3.b)$$

$$\text{FFM} = 6.564 + 2983.011 h^2 / Z_{H-F} + 3589.843 h^2 / Z_{F-F} + 0.020 w, (R = 0.88, \text{SD} = 2.47 \text{ kg}) \quad (3.c)$$

Where, h is the body height (m); w is the body weight (kg) and FFM is the fat free mass (kg).

As a result of the aforementioned equation, the correlation between the FFM, measured by DEXA and Z_{H-F} or Z_{F-F} values, and also by BIA, could be well described. After being adopted by Bland and Altman (1998), this study can evaluate the variability and distributions

between FFM estimated by earlier correlation equations vs. FFM values measured by DEXA. The result for hand-to-foot in male was expressed in Figure 3 and foot-to-foot in Figure 4. The result for hand-to-foot in female was expressed in Figure 5 and foot-to-foot in Figure 6. Relations between FFM estimated by hand-to-foot BIA correlation equations and foot-to-foot was described by using simple linear regression analysis plotted in Figure 7 for male and in Figure 8 for female. The high R value 0.95 was obtained in male and 0.93 in female.

DISCUSSION

All the subjects in the present study are distributed in wild range from about 7 to 70 years in age and from about 14 to 35 in BMI. By the measurements performed in standing position simultaneously by specifically changeable electrodes connected to the same instrument simultaneously, it was logical to find the correlation between hand-to-foot and foot-to-foot measuring models by BIA. Both data from them have shown great correlation with data from whole body DEXA in this study. Such a controlled condition as almost same situation in both measuring models by BIA has never been discussed in other papers since different postures changed body water distribution and body composition measured by BIA (Shinichi et al., 2001).

The great correlation between hand-to-foot and foot-to-

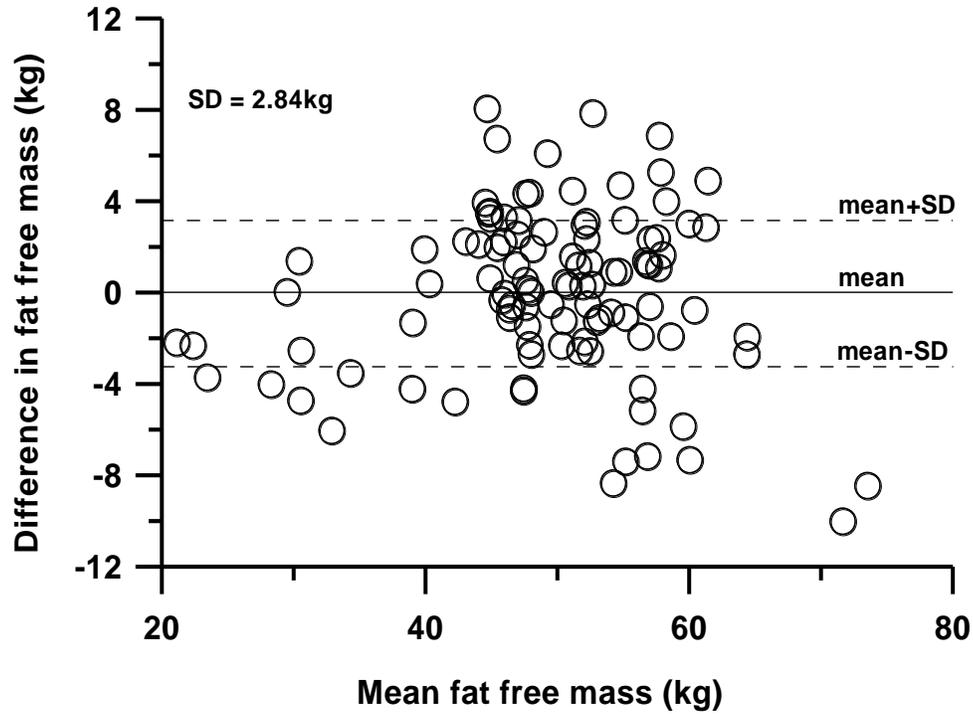


Figure 3. The distribution of difference in predictive FFM by hand-to-foot BIA in male along with the FFM measured by DEXA. The difference in predictive FFM by hand-to-foot BIA in male were obtained by the fat free mass (FFM) measured by DEXA minus FFM measured by hand-to-foot BIA. SD, standard deviation.

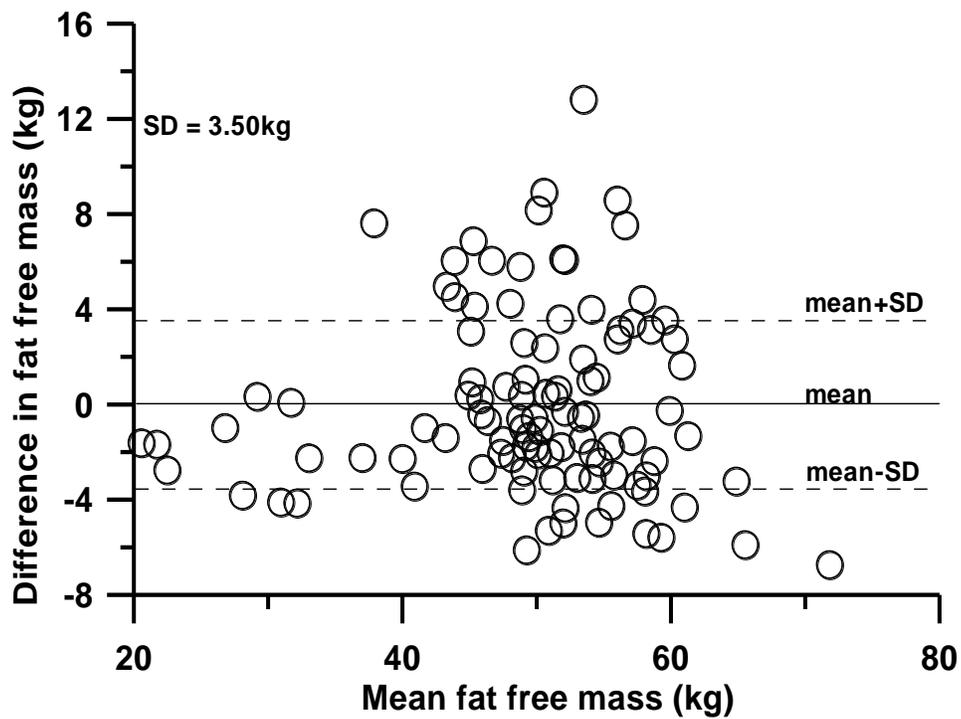


Figure 4. The distribution of difference in predictive FFM by foot-to-foot BIA in male along with the FFM measured by DEXA. The difference in predictive FFM by foot-to-foot BIA in male were obtained by the fat free mass (FFM) measured by DEXA minus FFM measured by foot-to-foot BIA. SD, standard deviation.

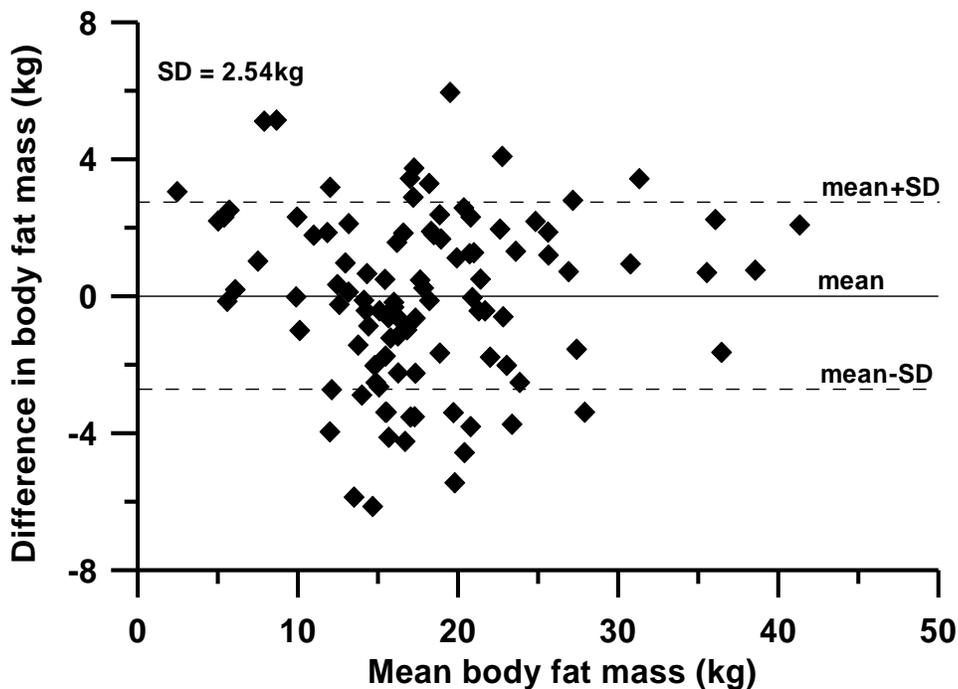


Figure 5. The distribution of difference in predictive FFM by hand-to-foot BIA in female along with the FFM measured by DEXA. The difference in predictive FFM by hand-to-foot BIA in female were obtained by the fat free mass (FFM) measured by DEXA minus FFM measured by hand-to-foot BIA. SD, standard deviation.

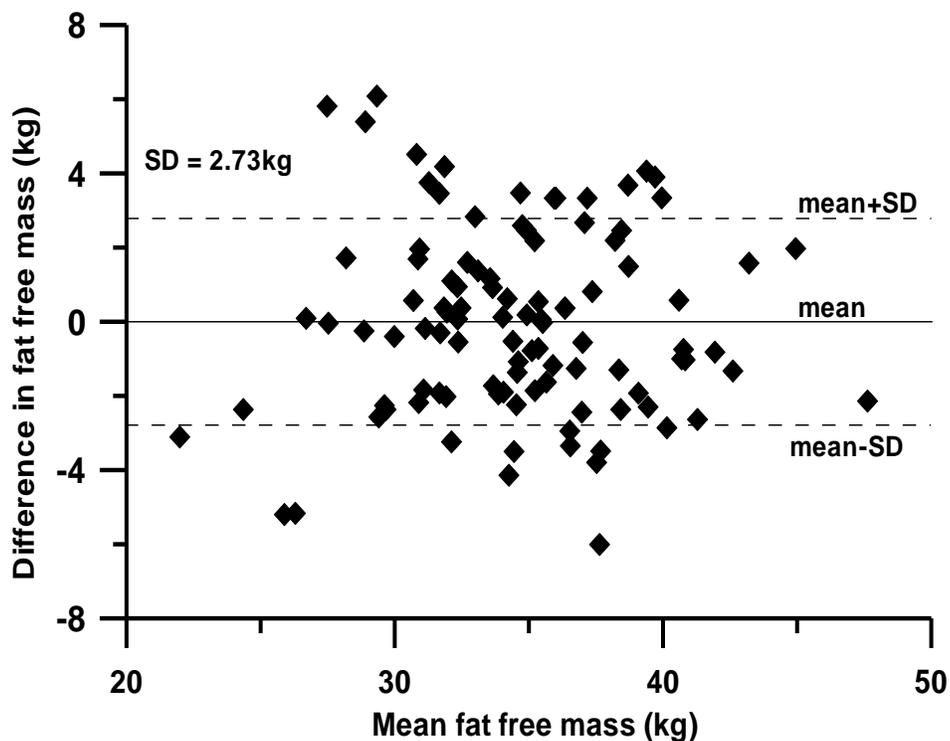


Figure 6. The distribution of difference in predictive FFM by foot-to-foot BIA in female along with the FFM measured by DEXA. The difference in predictive FFM by foot-to-foot BIA in female were obtained by the fat free mass (FFM) measured by DEXA minus FFM measured by foot-to-foot BIA. SD, standard deviation.

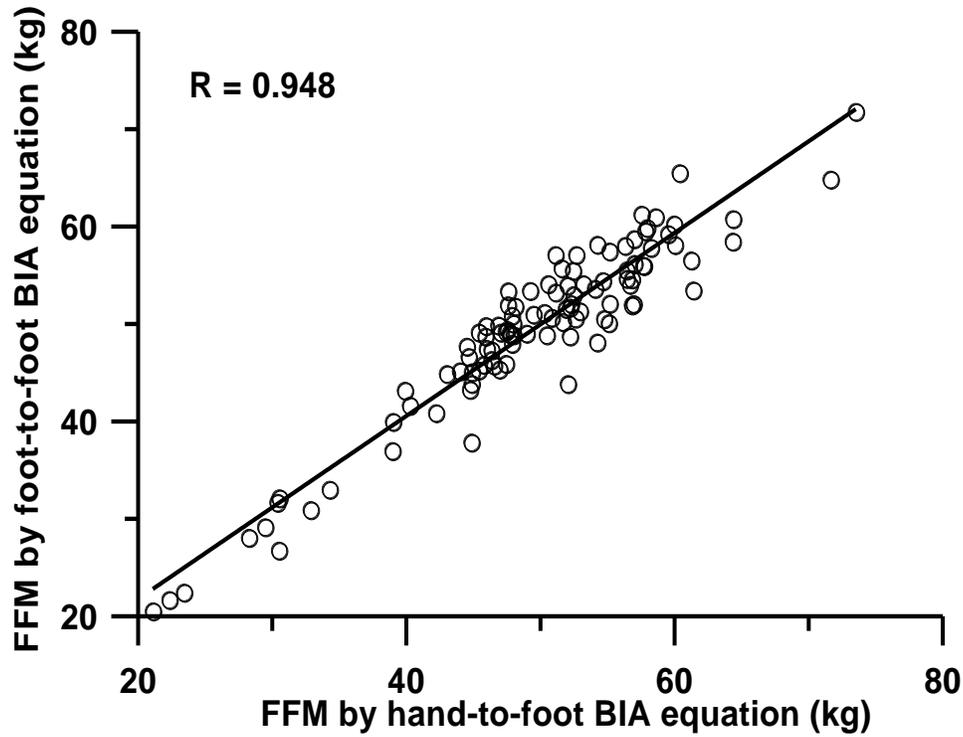


Figure 7. The relationship between the FFM estimated by prediction equation about Z_{H-F} and Z_{F-F} in male. The solid line is the regression equation. $R = 0.95$. The X-axis variable is from (2.a), Y-axis variable is from (2.b).

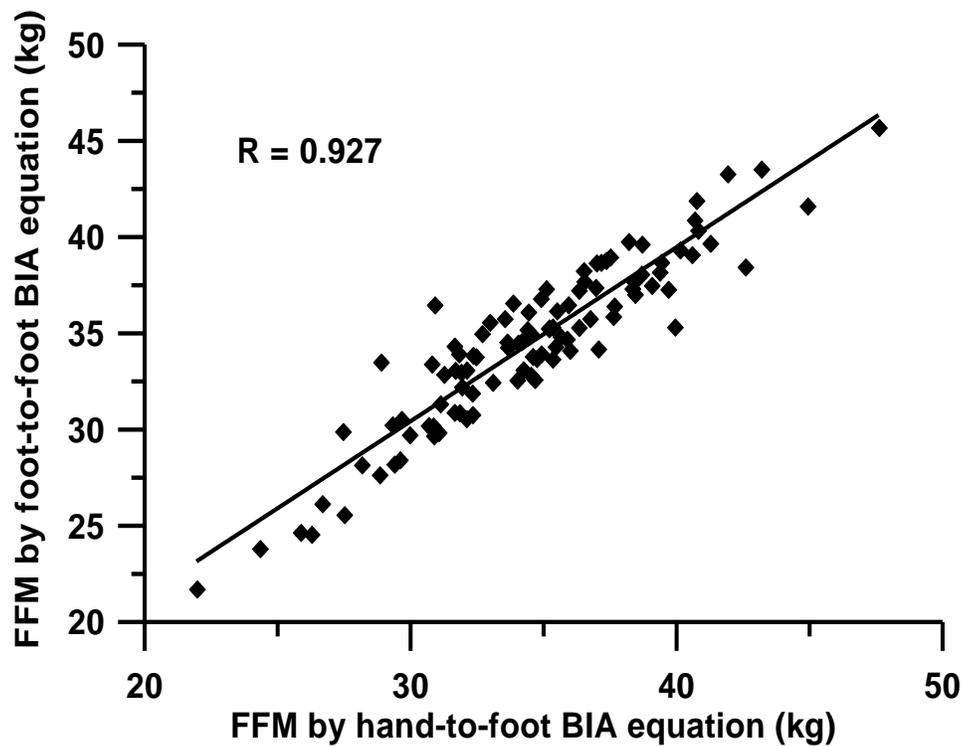


Figure 8. The relationship between the FFM estimated by prediction equation about Z_{H-F} and Z_{F-F} in female. The solid line is the regression equation. $R = 0.93$. The X-axis variable is from (3.a), Y-axis variable is from (3.b).

foot measuring models was exhibited in both male and female groups independently. The bioelectrical impedance values in foot-to-foot (Z_{F-F}) and hand-to-foot (Z_{H-F}) measuring models for male were 481.85 ± 63.37 and 586.82 ± 81.56 ohm, and that for female were 554.35 ± 74.97 and 703.28 ± 97.70 ohm, respectively. There existed high correlation between Z_{H-F} and Z_{F-F} in both the male and female as 0.871 and 0.848, respectively. Similar results can also be shown (Nuñez et al., 1997). Therefore, it is applicable to develop the foot-to-foot measuring models by BIA for body composition measurement. After imposing other critical naïve factors such as body weight, body length and gender as well as the Z_{H-F} or Z_{F-F} , new equations were created by calculation to predict the fat free mass. And then, they were compared to the data of fat free mass from DEXA. To validate critical naïve factors, which can affect the accuracy of equation, this study cross match the factors such as age, body weight, body length, gender, Z_{H-F} , Z_{F-F} and FFM. The age was the least critical factor for prediction of FFM in the equation; it was excluded in the equation. The other naïve factors, which exhibit greater correlation to fat free mass FFM, can critically contribute to create the high correlation in the new equation. Notably, the correlation (R value) of equation by naïve factors and Z_{H-F} to DEXA was 0.96 and that of Z_{F-F} was 0.93 in male, and, was 0.87 and 0.85 in female, respectively. This new equations could efficiently predict the fat free mass. It seems that the gender factor plays an important role in prediction of fat free mass by BIA. In comparison with the FFM values measured by DEXA, the standard deviation yielded from the equations by Z_{F-F} or Z_{H-F} for male and lower SD, the equations by Z_{F-F} for male seemed to have greater accuracy than by Z_{H-F} to predict the FFM. By contrast, it cannot be observed in female. Similar evidences can also be indicated by Stewart et al., (1993). The differences may attribute to the greater BF, visceral fat and menstrual status in female (Xie et al., 1999; Le Donne et al., 2008). The published papers about the validation of FFM by foot-to-foot BIA were almost focused on the predictive data from built-in prediction equations in instruments rather than that of the crude data of impedance values, nevertheless, the only one from that of the crude data of impedance values was performed in children (Tyrrell et al., 2001). The R values of correlation between DEXA and foot-to-foot BIA in the estimation of FFM, fat mass and percentage BF were .0.98, 0.98 and 0.94, respectively (Tyrrell et al., 2001). However, it could be hard to compare the validity between Tyrrell's and that of this study, since the parameter, subject population and subject age were not the same.

In order to acquire greater accuracy, this study intended to combine Z_{H-F} and Z_{F-F} together to create a new predictive equation. Nevertheless, it could not effectively raise the R value. In other words, the predictive Equations (2.c) and (3.c) exhibit no significant differences

between (2.a), (2.b), (3.a) and (3.b). It was possible that the R values are too high in equations only by Z_{H-F} or Z_{F-F} to have more increment.

Conclusion

Collectively, high correlation between Z_{H-F} and Z_{F-F} occurred in both male and female. However, correlations between DEXA to Z_{H-F} or to Z_{F-F} in male were greater than in female. Similar criterion in this study's foot-to-foot measuring model and hand-to-foot measuring model in a standing position was observed. The novel predictive equation which imposed other parameters such as weight, height, gender and Z_{H-F} or Z_{F-F} , exhibited great correlation to the data measured by DEXA, and rendered clinical application by foot-to-foot measuring model in a standing position. Further study will be launched to clarify other factors that improve the correlation in female in the future.

Abbreviations

Z_{F-F} , Bioelectrical impedance value in foot-to-foot; Z_{H-F} , bioelectrical impedance value in hand-to-foot; Z , impedance value; **BIA**, bioelectrical impedance analysis; **DEXA**, dual-energy X-ray absorptiometry; **FFM**, fat free mass; **BF**, body fat; **RAI**, right arm impedance; **LAI**, left arm impedance; **RLI**, right leg impedance; **h**, body height; **w**, body weight; **SD**, standard deviation.

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