Accuracy of Plantar Electrodes Compared with Hand and Foot Electrodes in Fat-free-mass Measurement

Michel Y Jaffrin* and Sana Bousbiat
Department of Biological Engineering, UMR CNRS 7338, Technological University of Compiegne, Compiegne Cedex, France

Submitted November 2013. Accepted for publication February 2014.

ABSTRACT
This paper investigates the measurement of fat-free mass (FFM) by bioimpedance using foot-to-foot impedancemeters (FFI) with plantar electrodes measuring the foot-to-foot resistance R_{34} and hand-to-foot medical impedancemeters. FFM measurements were compared with corresponding data using Dual X-ray absorptiometry (DXA). Equations giving FFM were established using linear multiple regression on DXA data in a first group of 170 subjects. For validation, these equations were used on a second group of 86 subjects, and FFM were compared with DXA data; no significant difference was observed. The same protocol was repeated, but using electrodes on the right hand and foot in standing position to measure the hand to-foot resistance R_{13}. Mean differences with DXA were higher for R_{13} than for R_{34}. Effect of electrode size and feet position on resistance was also investigated. R_{34} decreased when electrode area increased or if feet were moved forward. It decreased if feet were moved backward. A proper configuration of contact electrodes can improve measurement accuracy and reproducibility of FFI.

Keywords: body composition, bioimpedance, foot-to-foot impedancemeter, electrode design

1. INTRODUCTION
Overweight and obesity are recurrent problems in developed countries, especially with children, which may lead to various diseases such as diabetes, cancers, and cardiovascular disease [1]. It is thus important for this population to be able to monitor the development of their fat mass (FM) in order to adapt their food intake and exercise. Dual X-Ray absorptiometry (DXA) provides a detailed and accurate distribution of FM, lean body mass (LBM) which includes cells and muscles, together with bone mineral content (BMC) in the body, but it is expensive and cannot be repeated frequently because of exposure to radiation.

*Corresponding author. Emeritus Professor, Department of Biological Engineering, UMR CNRS 7338, Technological University of Compiegne, BP 20529, 60205 Compiegne Cedex, France. Tel: +33 3 44 23 43 98, Fax +33 3 44 20 48 13. Email: michel.jaffrin@utc.fr. Other author: s.bousbiat@hotmail.fr.

Bioimpedance is a simple technique for measuring body composition, including fat-free-mass (FFM) which combines LBM and BMC. The measurement of FFM is based on the fact that these tissues are electrically conductive due to ions contained in body fluids, unlike FM which is not electrically conductive. FFM is calculated using an empirical equation determined by comparison with DXA data and containing weight (W), height (H), subject age, and the body resistance (R), or the impedance (Z). FM is then easily calculated as the difference between W and FFM.

The first goal of this paper is to compare two different techniques of whole body impedancemetry: the classical method with two electrodes on right hand and two on right foot to measure hand-to-foot electrical resistance of a supine subject, and a more recent one with four contact electrodes placed on a body scale measuring the foot-to-foot resistance in standing position, called leg-to leg or foot-to-foot impedancemeters (FFI). The accuracy of FFM measurements by both techniques will be evaluated by comparison with DXA measurements. A second goal is to study the effect of electrode area and their configuration on the accuracy and reproducibility of foot-to-foot resistance measurement by FFI in order to increase FFM accuracy. The third goal is to examine whether FFI could reliably measure body fluid volumes with appropriate software in addition to FFM, FM and weight. Since deuterium and bromide dilution measurements were not available, FFI measurements of extracellular water (ECW) and total body water (TBW) were compared with those obtained using a Xitron 4200 BIS impedancemeter.

1.1. Medical impedancemeters

Medical hand-to-foot impedancemeters measure the body resistance in supine position, using four disposable adhesive gel electrodes, two current electrodes, one on the right hand and the other on right foot and two voltage ones on the right wrist and the right ankle at about 6 cm from current electrodes. The body resistance measured is the sum of right arm and right leg resistances, plus the trunk longitudinal resistance. The right side is selected to avoid perturbation from the heart and its blood volume. Bioimpedance analysis (BIA) devices use a 50 kHz frequency, while impedancemeters measuring resistance of body fluids use several frequencies from 5 kHZ to 1 MHz to measure independently ECW(at low frequency) and TBW (at high frequency) [2]. The advantages of these impedancemeters are that their electrodes have a standardized shape and area and are placed at well defined positions. BIA devices can use equations from the literature obtained at 50 kHz [3]. Their drawbacks are that they are expensive and their measurements take about 10-15 min for placing electrodes and waiting for fluid equilibrium in supine position.

1.2. Body Fat Analyzers (Foot-to-Foot Impedance meters)

A foot-to-foot impedancemeter is typically included in a body scale equipped with four metal contact electrodes, two current ones transmitting a small current of about 0.8 mA in the toes and two voltage ones measuring the resistance between the heels. The scale measures and stores the resistance value and the user enters body height, age and gender to calculate FM with the scale software, which is displayed on a small screen together

with the weight. Advantages of FFI are the rapidity of their measurements as they are taken in standing position without fluid displacement and that their electrodes are indefinitely reusable. They are also relatively inexpensive because of their mass producibility.

The body resistance measured by FFI is different from that measured in supine position by a medical impedancemeter, even with the same electronics. It will be smaller as arm resistances are larger than leg ones because of their smaller cross section. Secondly, in standing position, body fluids accumulate in the calves and forearms due to gravity, which slightly decrease limb resistance. The drawback of FFI is that body resistance is sensitive to electrode size and feet position relative to electrodes, which both affect its accuracy [4]. Thus, the scale design of an FFI is important, as it must help the user to place feet correctly on the electrodes. Unlike medical BIA impedancemeters, FFI must, in principle, use specific equations adapted to their characteristics.

1.3. Review of FFM and FM measurements by FFI and medical impedancemeters

Tanita Corporation (Tokyo, Japan) produced the first commercially available FFI around 1992. Nunez et al. [5] compared the foot-to-foot resistance from a Tanita TFB 105 with those measured with a Valhalla medical impedancemeter, both operating at 50 kHz, using gel electrodes pasted under the feet for the Valhalla. The Tanita yielded resistances which were systematically 15 Ω higher than the Valhalla. They attributed this difference to a better conductivity of the gel electrodes. They also observed a better agreement with DXA data for the FFM measured by the Valhalla in supine position. However, Utter et al. [6] compared FFM measurements in 98 obese and 27 non-obese women using a Tanita TBF 105 and underwater weighing, and found no significant differences between the two methods. They concluded that the Tanita software was suitable for a large range of morphologies and ages and could accurately monitor small changes in body composition due to exercise or dietary regimen. Jebb et al. [7] also investigated the accuracy of a Tanita 305 body fat analyser in 58 overweight women during weight loss and regain periods, against a three-compartment model (3c) combining measurements of BMC by DXA, of body density with an air displacement plethysmograph, and TBW measurements by deuterium dilution. They compared Tanita FM data with those measured by a BIA medical impedancemeter (Bodystat 1500). During 40 weeks of weight gain period, the Tanita device gave the best results with a mean bias of –0.25±1.15 kg relative to the 3c model vs. 0.29±3.80 kg for the Bodystat. The authors attributed the lower performance of the Bodystat to the large contribution of the arm to the body resistance.

A comparison of two FFI, a Tanita BF 625, a Tefal Bodymaster Vision and an RJL 101 50 kHz medical impedancemeter (Detroit, USA) against a Hologic DXA was carried out by Lazzer et al. [8] in 53 overweight and obese adolescents. They found that, in comparison with DXA, both Tanita and Tefal devices underestimated FM less than the RJL one with respective mean biases and standard deviation (SD) of –0.7±5.8 kg, –1.7±3.1 kg versus –2.3±2.3 kg for the RJL. They concluded that foot-to-foot impedance could be acceptable to assess body composition in groups of overweight adolescents, but should not be recommended for measuring individual

body composition, because of significant differences with DXA. Linares et al. [9] compared measurements of FM in 5740 obese subjects with a mean BMI of 37.7± 8.2 kg-m^{-2} using a Tanita BC-420 FFI, with those using a Hologic DXA. They found that the FFI overestimated FM relatively to DXA by 1.1±6.1 kg. This is an unusual result as BIA generally underestimate FM in overweigh subjects. Radley et al. [10] investigated the validity of a Tanita BF-310 FFI in FM measurements in overweight and obese children by comparing with a 4-compartment model. The FFI underestimated FM by −0.8±9.3 kg in males and by −0.5±5.5 kg in females. They also did not recommend the FFI for individual application to obese children.

Pichler et al. [11] compared FM measurements using an SFB7 multifrequency Impedimed impedancemeter with DXA values in a cohort of 32 healthy subjects and 83 patients with various diseases (hypertension, atherosclerosis, kidney disease, etc.) They found that the SFB7 software overestimated FM by 6.55±3.86 kg as compared to DXA. As this software did not seem to be appropriate to their population, they developed their own bioimpedance spectroscopy (BIS) equation using resistances at zero frequency R_0 and at infinite frequency R_∞:

$$\text{FMb (kg)} = -18.43 + 0.6W - 0.57H^2/R_\infty + 0.62H^2/R_0 \quad (1)$$

where H is body height in cm and W is body weight in kg. The mean bias for FMb as compared with DXA was a small underestimation of −0.70±3.75 kg, a better result than with the SFB7. Verdich et al. [12] also compared measurements of FM and FFM in a multicenter European study using a BIA Bodystat Quadscan 4000 and a Hologic DXA in 84 obese women trying to lose weight. At the start of treatment, the Bodystat significantly underestimated FM by −0.98±4.24 kg compared to DXA, confirming the FM underestimation by BIA in obese population. The authors proposed a new BIA equation for FFM for subjects scanned by a Lunar DXA

$$\text{FFM}= 0.314\ H^2/Z_{50} + 0.74W + 0.143\ \text{Age} + 12.1 \quad (2)$$

where H is in cm, W is in kg, and Z_{50} is the impedance at 50 kHz. The mean difference with DXA using Eq. 2 was 1.84±3.05 kg or less compared with the Bodystat software. For patients scanned with the Hologic DXA, the equation was

$$\text{FFM} = 0.813\ H^2/Z_{50} + 8.91 \quad (3)$$

Van Venrooij et al. [13] compared the preoperative and postoperative FFM in 26 patients undergoing cardiac surgery using a BodyScout BIS impedancemeter (Fresenius Kabi, Germany) and a Hologic QDR 4500 DXA. Their weight and FFM declined between pre- and post-operation as measured with both BodyScout and DXA, but none of these devices showed a change in FM. Preoperatively, the BodyScout overestimated FFM by 2.3±2.9 kg compared to DXA, with a p-value of 0.261 (NS). Post-operatively, the overestimation was 2.1±3.1kg. Although it is known that impedance overestimates FFM

(and underestimates FM) in obese subjects, the authors estimated that these differences were also due to DXA, which can be affected by severe obesity and overhydration.

Ling et al. [14] used an 8-electrode InBody720 and a Hologic QDR4500 DXA on 480 Caucasian middle age subjects with a mean BMI of 26.3 kg-m^{-2} to measure their FM. They found that the mean FM was overestimated by the InBody compared to DXA by 2.4±2.51 kg in male subjects and by 1.2±2.55 kg in females. They found that the mean FM overestimation by the InBody increased with BMI. Nigam et al. [15] compared the FM of healthy Indian subjects measured by DXA with those measured with a Tanita MC-180Ma FFI. The Caucasian equation of the FFI underestimated the mean FM of male subjects compared to DXA by 4.7 kg, while the Asian equation underestimated it by 6.39 kg. The mean FMs of female subjects were underestimated by 2.9 and 5.35 kg, respectively. The authors concluded that the FFI Asian software was not adequate for an Indian population.

Vine et al. [16] measured the FFM of 16 hemodialysed patients, 12 renal undialyzed patients, and 23 controls with an SFB7 medical impedancemeter and a Lunar Prodigy DXA. The SFB7 underestimated the mean FFM of dialysed patients by –0.94± 5.32 kg compared to DXA, while it overestimated that of undialyzed patients by 1.89±6.42 kg and that of controls by 1.10±4.12 kg, as if they were overweight. They concluded that more studies were needed before recommending monitoring FFM in dialyzed patients by impedance.

2. METHODS

2.1. Determination of FFM using 50 kHz Medical Impedancemeters

As the four limbs and the trunk can be approximated as five cylinders, if the resistivity ρ of each one of them is assumed to be homogeneous, the resistance can be expressed by

$$R = \rho L/A = \rho L^2/V \tag{4}$$

where L is the cylinder length, A its cross section, and V its volume. The body volume V_b may be approximated by the equation

$$V_b = 2L_aA_a + 2L_1A_1 + L_tA_t \tag{5}$$

where subscripts a, 1, t denote arm, leg, and trunk, respectively. The wrist-to-ankle resistance R_{wa} is given by

$$R_{wa} = \rho(L_a{}^2/V_a + L_1{}^2/V_1 + L_t{}^2/V_t) \tag{6}$$

De Lorenzo et al. [2] have shown that it is possible to express V_b using Eqns. 5 - 7 as

$$V_b = K_b\, \rho\, H^2/R_{13} \tag{7}$$

where H is body height and K_b is a shape coefficient which depends upon subject anatomy. They suggested a value of 4.3 for K_b based on statistical analysis of experimental data.

It can be assumed that FFM is proportional to body volume, with a coefficient depending on the subject. This is why empirical equations for FFM are generally expressed as linear functions of W and H^2/R. For instance, Sun et al. [17] have proposed the following:

$$FFM = 0.65\ H^2/\ R_{13} + 0.26W + 0.02\ R_{13} - 10.68 \qquad \text{for men} \tag{8}$$

and

$$FFM = 0.69\ H^2/\ R_{13} + 0.18W + 0.02\ R_{13} - 9.53 \qquad \text{for women} \tag{9}$$

where FFM is in kg, H is in cm, R_{13} is in Ω, and W is in kg. Eqns. 8 and 9 have been validated by comparison with values of FFM measured by DXA in a normal population using a multiple linear regression software.

Equations common to men and women have been also proposed in the literature. For instance, Kyle et al. [18] suggested:

$$FFM = 0.518\ H^2/R_{13} + 0.231\ W + 0.13\ X - 4.104 + 4.23\ sex \tag{10}$$

where X denotes the reactance which represents about 12% of R_{13}, and sex = 1 in men and 0 in women. The fat mass can be determined by

$$FM = W - FFM \tag{11}$$

An extensive review of BIA equations utilized in clinical practice for body composition (fluid volumes, FFM, body cell mass, etc.) has been published by Kyle et al. [3].

Most body fat analyzers also operate at 50 kHz, or in the case of Tefal FFI (Rumilly, France), with a square signal at a frequency slightly above 50 kHz. They use similar equations as those reported above, but specifically designed for their characteristics.

2.2. Subjects and Measurement Protocol

In this study, measurements of FFM were performed at the Medical Imaging Center of Compiegne (CIMA) under a protocol approved by the Ethical Committee of Picardy on a cohort of 127 male and 129 female subjects composed of students and university staff of age ranging from 20 to 74 years, who gave informed consent. After emptying bladder, the subject undressed and wore a light gown and the body height was measured with a wall-mounted stadiometer. Body weight and FFM were measured by a commercial Tefal FFI, (BodyVision). A Hologic Delphi W8/N71224 DXA system, equipped with a Hologic 11.2 software scanned the subject immediately after the BodyVision measurement. In order to compare foot-to-foot and hand-to-foot FFM measurements, we used a modified BodyVision in which four additional electrodes, two for currents and two for voltages, were mounted on two handles to measure both the hand-to-foot resistance (R_{13}) and the foot-to-foot one (R_{34}), in standing position.

The physical characteristics of these subjects, divided into four cohorts, are given in Table 1. The first two, containing 85 males (M85) and 85 females (F85), were used to determine FFM equations by comparing with DXA data. The last two, with 42 males (VF42) and 44 females (VF44) permitted to make an independent validation of these equations by comparing with DXA data.

For tests of section 3.3 concerning the accuracy of resistance measurement, we used smaller groups mainly composed of young adults. Since the accuracy of measured resistances determines the accuracy of FFM measurements, we investigated the effect of electrode contact area with feet on the resistance. We used a podoscope, shown in Figure 1, consisting of a thick horizontal glass plate

Table 1. Mean physical characteristics of the four cohorts of subjects

	Height, m	Age, yr	Weight, kg	BMI, kg-m^{-2}	FFMd, kg	R_{13}, ohm	R_{34}, ohm
Males, M85 N= 85	1.77 ±0.07	45.7 ±17.4	81.47 ±12.80	26.09 ±3.79	61.02±7.55	545±65	467±61
Females, F85 N=85	1.63 ± 0.06	46.8 ±16.4	65.15 ±12.94	24.41 ±4.60	42.57±5.46	666±86	528±77
Males VM 42 validation cohort, N=42	1.75 ±0.06	46.39 ± 16.0	81.14 ±14.13	26.34 ±4.05	60.55±7.77	555±71	462±74
Females, VF44 validation cohort N=44	1.62 ±0.06	45.7 ±16.3	66.57 ±12.12	25.45 ±4.52	42.37±5.07	648±88	533±71

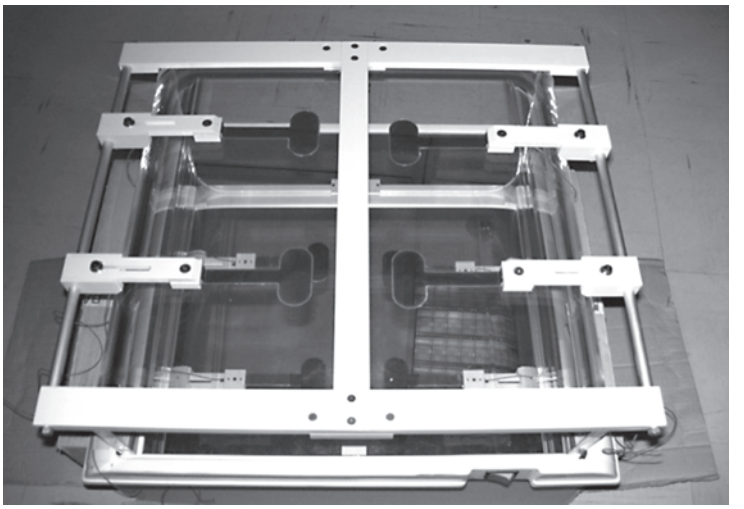

Figure 1. Podoscope with adjustable metal electrodes (in black)

Figure 2. Black and white podoscope pictures after removal of bright zones outside the feet. White areas correspond to feet contact zones without electrodes (left) and with electrodes (right).

supported by a metal frame to which metal electrodes can be attached, allowing to visualize and measure this contact area. Flat aluminum electrodes of different areas (16, 27, 38 and 56 cm^2) were fixed successively on the podoscope and connected to the electronics of a BodySignal Tefal FFI which was modified to display the resistance. A lamp and a mirror underneath the glass plate allow to photograph feet soles by placing the lens of a camera on the glass. A photograph of the soles was first taken without electrodes and another one with electrodes and feet in the same position (Figure 2). The two pictures are then superposed and a Mathlab software calculates in pixels the contact area of feet with electrodes. This area is converted into cm2 as a calibration showed that 860 pixels correspond to 1 cm^2.

2.3. Statistics

Mean values and SD were calculated and data were plotted with linear regression lines and correlations coefficients R^2. Comparisons between different methods were analyzed using Student's t-tests and Blandt–Altman graphs. Data were considered to be significantly different if the p-value was < 0.05.

3. RESULTS

3.1. Measurement of FFM with a Foot-to-Foot Impedancemeter

These impedancemeters measure the sum of leg resistances and the transverse resistance of the trunk at waist, denoted as R_{34}. This resistance is generally lower than the wrist-ankle resistance measured by medical hand-to-foot impedancemeters. In a study conducted in our laboratory with healthy volunteers using a Tefal BodyVision FFI, we found mean values of R_{34} of 467 ohms in males and 549 ohms in females, versus mean values of 500 ohms for R_{13} in men and 632 in women. Therefore, FFI equations for FFM have different coefficients from those for medical devices. Females' resistances are higher because of smaller leg cross section. By comparison with DXA measurements, we developed the following L2 equations for FFM (denoted FFMi, FFM

by impedance) using linear regression in the first group of 85 females subjects (F85) and 85 males ones (M85) [19]. For females subjects,

$$\text{L2:} \quad FFMi = 0.354(H^2/R_{34}) + 0.229W - 0.0430\ Age + 0.0177\ R_{34} + 1.91 \quad (12)$$

and for males,

$$\text{L2:} \quad FFMi = 0.528(H^2/R_{34}) + 0.306W - 0.0698Age + 0.0353\ R_{34} - 12.6 \quad (13)$$

Correlations of FFMi with FFM measured by DXA (FFMd) are shown in Figure 3 for the F85 cohort using Eqn. 12 and in Figure 4 for the M85 cohort using Eqn. 13. Correlations coefficients R^2 are high, 0.73 in female subjects and 0.859 in male ones, respectively.

In order to validate the accuracy of these equations, we applied them to the second group of 44 women (VF44) and 42 men (VM42), and their FFMi values were compared with corresponding FFMd values, using the paired Student t-test. Results are given in Table 2 which also gives FFMt measured by the Tefal proprietary software, established from a six-site international cross-validation study [20]. This

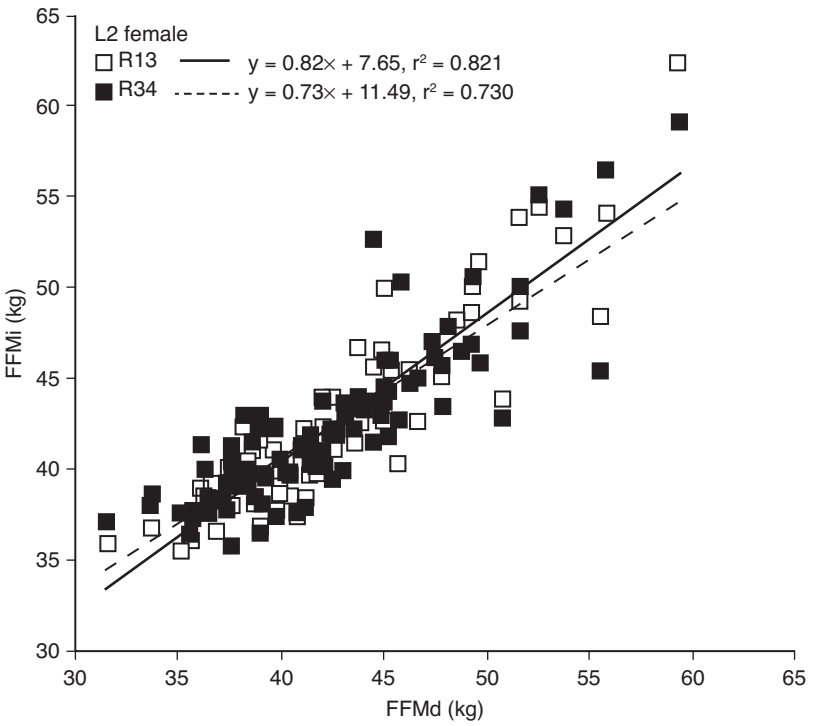

Figure 3. Correlation of FFMi with FFMd for BF 85 cohort using Eqn. 12 with R_{34} and Eqn. 14 with R_{13}.

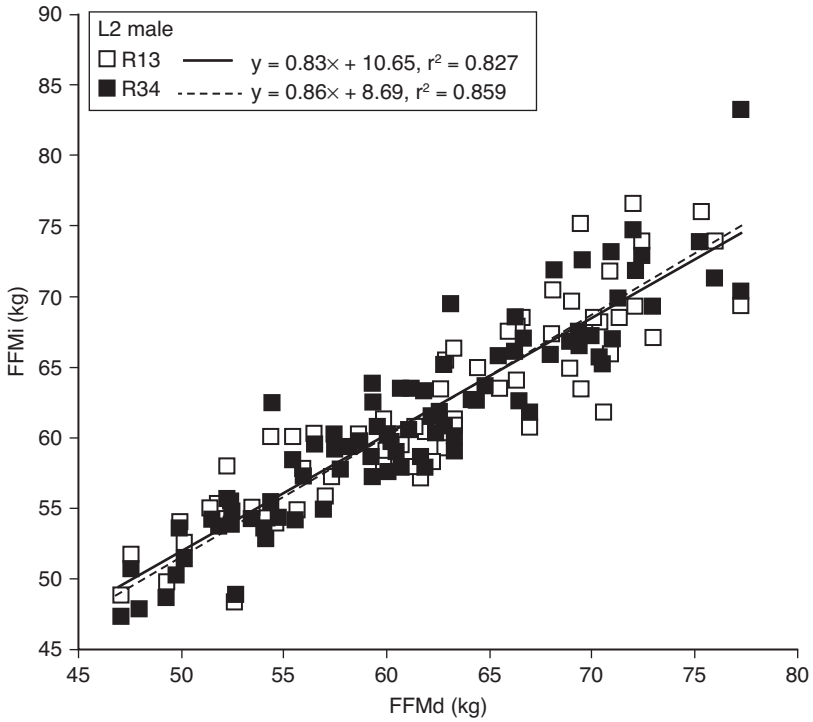

Figure 4. Correlation of FFMi with FFMd for BM 85 cohort using Eq. 13 with R_{34} and Eq. 15 with R_{13}

Table 2. Comparison of FFM calculated in validation cohorts VF $_{44}$ and VM42 using equations L1 and L2 and R_{13} or R_{34} with DEXA values. Results are not significantly different if p > 0.05

		Female subjects N=44			Male subjects N=42		
	Equation	L1	L2	Tefal	L1	L2	Tefal
R_{34}	FFMi ±SD	42.58±4.15	42.42±4.1	42.1±4.74	60.95±7.07	60.61±7.27	60.2±7.72
	FFMi-FFMd	0.22±1.99	0.05±1.94	-0.27±1.83	0.19±3.92	0.06±2.77	-0.35±2.41
	P-value	0.475	0.859	0.329	0.380	0.884	0.341
R_{13}	FFMi ±SD	43.07±4.87	42.86±4.89		60.84±7.93	60.73±7.88	
	FFMi-FFMd	0.71±2.42	0.49±2.28		0.29±2.71	0.18±2.5	
	p-value	0.059	0.158		0.486	0.641	

table shows that Equation L2 gives FFMi values closer to DXA data than L1 equations without terms proportional to resistance, which is confirmed by higher p-values. Our equations L2 also give FFMi values closer to FFMd than the Tefal software of the BodySignal.

3.2. Comparison of Hand-to-Foot Resistance R_{13} with the Foot-to-Foot Resistance R_{34} for Measuring FFM

Since FFI do not take into account the arm and upper trunk resistance, it is legitimate to assume that the hand-to-foot resistance better reflects the whole body composition than the foot-to-foot one. However, several authors [21, 23] have pointed out that the trunk longitudinal resistance accounts for only 4 to 6 % of hand-to-foot resistance, while the trunk represents about half of body FFM. Thus a relatively large variation in trunk resistance due to a different morphology will only slightly modify R_{13}. In addition, the arm resistance is 5 to 10% higher than the leg one, but its FFM is, on average, about 2.7 smaller [24].

The modified BodyVision FFI with hand electrodes described earlier was used to compare the accuracy of both methods. Corresponding equations using R_{13} determined for the first group are shown below for women:

$$\text{L2} \qquad FFMi = 0.653(H^2/R_{13}) + 0.186W - 0.0242\ Age + 0.0177\ R_{13} - 5.21 \qquad (14)$$

and for men:

$$\text{L2} \qquad FFMi = 0.517(H^2/R_{13}) + 0.369W - 0.0607Age + 0.0473\ R_{13} - 15.5 \qquad (15)$$

Correlations of FFMi with FFMd using R_{13} are also shown in Figure 3 for the F85 cohort using Eq. 14 and in Figure 4 for the 85M cohort using Eq. 15. The correlation coefficient is slightly higher in women for R_{13} at 0.859 than for R_{34} while it is the opposite for men with $R^2 = 0.821$ when using R_{13}. The comparison of FFMi calculated using Eqns. 12 and 14 for the 44 women of the second group and Eqns. 13 and 15 for the 42 men, with corresponding DXA data, are displayed in Table 2. L1 equations, listed in Table 2, are given below:
For female subjects,

$$\text{L1} \qquad FFMi = 0.221(H^2/R_{34}) + 0.235W - 0.0436\ Age + 18.45 \qquad (16a)$$

$$\text{L1} \qquad FFMi = 0.468(H^2/R_{13}) + 0.190W - 0.0384\ Age + 12.87 \qquad (16b)$$

For male subjects,

$$\text{L1} \qquad FFMi = 0.339(H^2/R_{34}) + 0.314W - 0.102Age + 17.52 \qquad (17a)$$

$$\text{L1} \qquad FFMi = 0.281(H^2/R_{34}) + 0.385W - 0.0927Age + 18.0 \qquad (17b)$$

It is seen that the mean differences FFMi-FFMd and their SD are smaller when obtained from R_{34} than when using R_{13} for both female and male subjects. This is confirmed by p-values which are larger for R_{34} at 0.859 (F) and 0.884 (M) when using L2 equations. However, p-values with R_{13} were 0.158 and 0.641, respectively, indicating that differences

relative to DXA data were not significant. It is interesting to note that L1 equations without the linear resistance term have lower p- values and larger mean bias than L2 equations.

Bland-Altman graphs of comparison of FFMi calculated with Eqns. 14 and 15 for the validation cohorts using R_{13}, and R_{34} resistances and FFMd measured by DXA are shown in Figures 5 and 6 for female and male, respectively, together with those using different equations K3, given in [19]. For both female and male subjects, there is only one point (2.3% of data) lying outside the limits of agreement (mean±2SD). This confirms a normal distribution as the percentage of points outside these limits is less than 5%.

A possible explanation for a better accuracy of FFI is that they avoid the higher variability of arm resistances measurements. Jaffrin and Morel [24] reported that standard deviations of arm resistances in a normal adult population, measured with an eight-electrode BodyVision FFI, were 16.2% in left arm and 18.6% in right arm, against 9.4% in left leg and 7% in right leg.

3.3. Effect of Feet and Heels Position on Resistance Measurement

Although the use of R_{34} seems preferable to R_{13} for calculating FFM, the use of reusable plantar electrodes rather than adhesive gel ones may induce some measurements errors.

3.3.1. Variation of Resistance R34 with Contact Area of Feet with Current Electrode

These tests were conducted on nine subjects using current electrodes of area ranging from 16 to 56 cm^2 with voltage electrodes of 27 cm^2 mounted on the podoscope connected to the electronics of a BodySignal V2 Tefal FFI. In order to accommodate different feet sizes, current electrodes must be about 10 cm long so that they can be

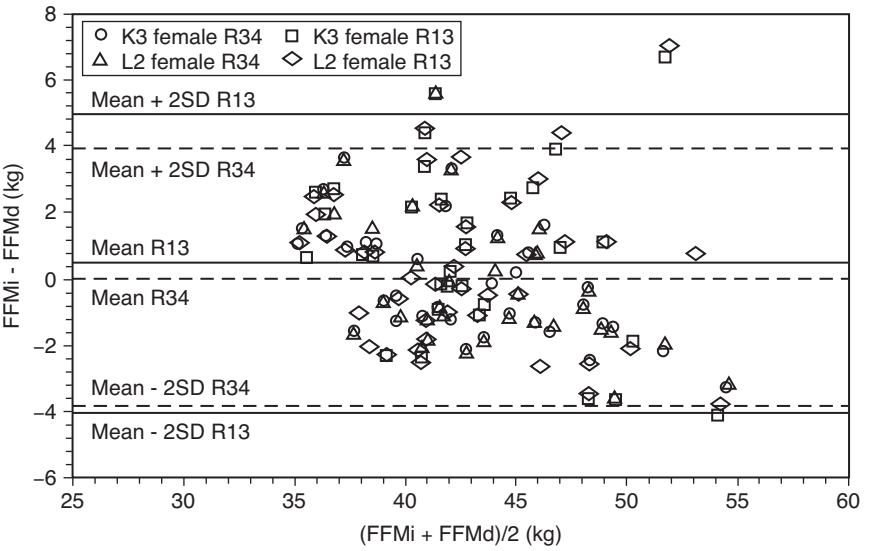

Figure 5. Bland-Altman graphs of differences between FFM by K3 and L2 method and DXA in VF44 cohort using R_{13} and R_{34}.

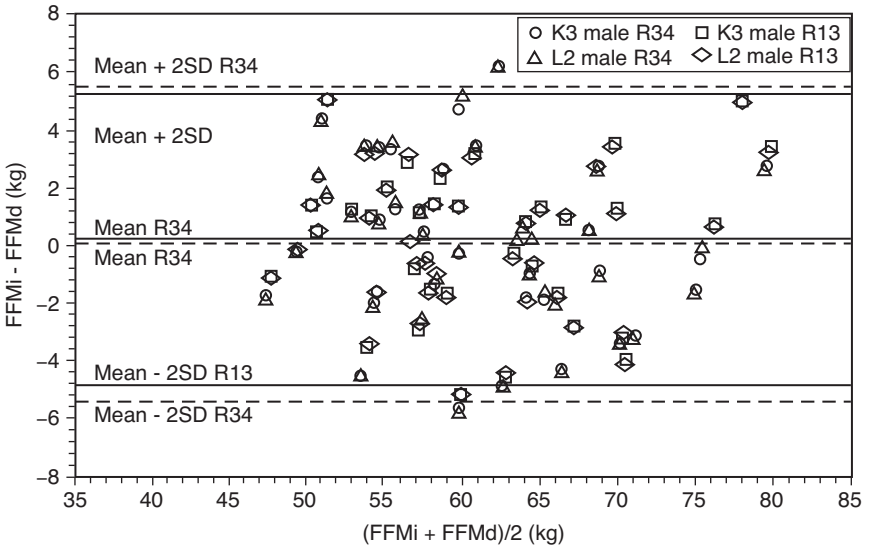

Figure 6. Bland-Altman graphs of differences between FFMi by K_3 and L_2 methods and DXA in VM42 cohort using R_{13} and R_{34}.

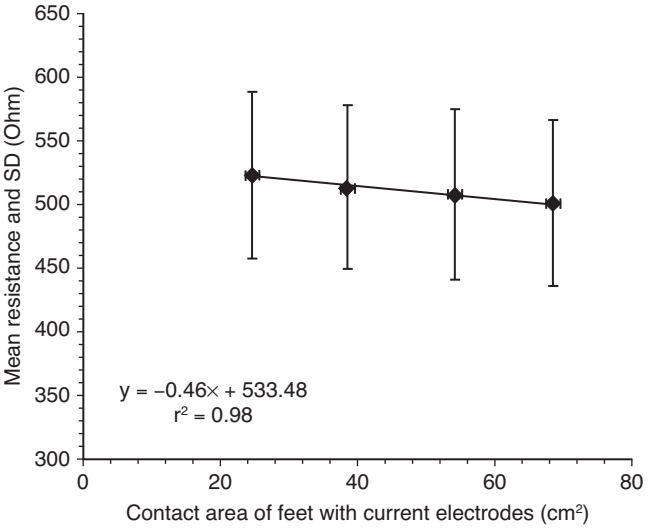

Figure 7. Variation of mean resistance and SD with contact area of feet with current electrodes using the BodySignal V2 for 9 subjects.

reached by toes of children. Figure 7 shows the variation of mean resistances and their SD versus the contact area of feet with current electrodes (Scc) for the 9 subjects. Details of mean resistance variation are given in Table 3. It decayed linearly with increasing contact area from 519.3 Ω for 16 cm^2 electrode with a

Table 3. Variation of mean resistances with contact area of current electrode (left) and with voltage electrodes (right) using the BodySignal V2

Electrode size, cm^2		BodySignal V2 N=9			Electrode size, cm^2		BodySignal V2 N=10		
Voltage, V	Current, A	Mean R_{34},Ω	SD, Ω	Scc, cm^2	Voltage, V	Current, A	Mean R_{34}, Ω	SD, Ω	Svc, cm^2
27	16	519.3	59.5	22.5	16	38	521.0	68.8	27.1
27	27	509.8	58.2	36.0	27cm^2	38	522.2	52.3	43.1
27	38	502.6	58.9	53,.8	56 cm^2	38	511.1	88.5	52.5
27	56	497.8	59.9	67.3	38 cm^2	38	514.1	72.9	63.1
		Mean	507.6	59.1	44.9		517.1	70.6	46.4

contact area for both feet of 22.5 cm^2 to 497.8 Ω for 56 cm^2 electrodes with a contact area of 44.9 cm^2. This may be due to a decrease in skin resistance as current intensity decayed.

3.3.2. Variation of resistance R_{34} with contact area of feet with voltage electrode

The same tests were conducted on the same subjects plus a tenth one, but keeping the same current electrode area of 38 cm^2 and increasing the voltage electrode unit area from 16 to 56 cm^2. The mean variation of mean resistances and their SD versus contact area of feet with voltage electrodes (Scv) is displayed in Figure 8. It shows the same decay trend as in Figure 7, but with a smaller slope. Details of this variation range are also given in the right part of Table 3. The decay was less compared with current electrodes, ranging from 521 Ω with 16 cm^2 electrodes to 511 Ω with 38 cm^2 ones.

The mean resistance SD was at 71 Ω higher compared with current electrodes (59 Ω) as the resistance depends upon the relative position of heels with voltage electrodes.

3.3.3. Effect of heels position on resistance and measurement reproducibility

Resistances were measured on the same ten subjects as in section 3.3.2 with four 27 cm^2 electrodes on the podoscope, first in normal position with heels centred on voltage electrodes, then after moving the feet forward and backward by 5 cm. Mean values and SD of resistances and their variations after the moves are shown in Table 4. Backward moves increased the mean resistance by 37 Ω as the path length under the sole between the front parts of voltage electrodes increased, while it decreased by 16.6 Ω in forward moves. It is thus important for the user to center heels precisely on voltage electrodes, for instance by using narrow transverse electrodes which can be easily seen by the user.

3.3.4. Effect of resistance variation on Fat Mass (FMi) measurements

In order to evaluate the error in FM caused by an error in resistance measurements, we have selected a group of four men and four women with various body mass indexes (BMI) who had their FM measured by DXA (FMd). Their FM value was calculated from their foot-to-foot resistance R_{34} using Eqs 16a or 17a, denoted as FMi. We then

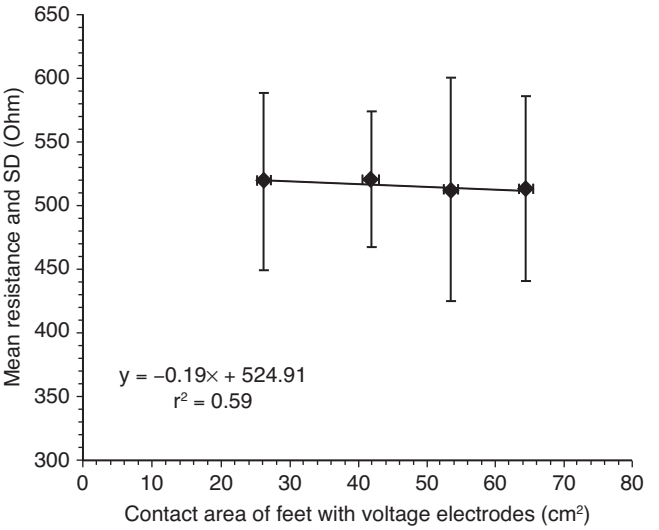

Figure 8. Variation of mean resistance and SD with contact area of feet with voltage electrodes using the BodySignalV2 for 10 subjects.

Table 4. Variations of mean resistance R_{34} when feet are moved backward and forward from normal position by 5 cm

	Normal position	Feet moved back 5 cm	Feet moved forward 5 cm
N = 10	R_{34}, Ω	Δ R_{34}, Ω	Δ R_{34}, Ω
Mean	511.2	36.9	-16.6
SD, Ω	61.7	16.3	9.7
SD, % of R_{34}		44.2	-58.6

recalculated the FMi of these eight subjects by adding and subtracting 6 Ω from the normal resistance. The FMi variation (ΔFMi) caused by a 12-Ω resistance variation is plotted in Figure 9 for these subjects as a function of their normal resistance, while detailed results are given in Table 5.

The FMi variation decreases with resistance, which corresponds to a decrease in BMI. In men, the smallest FMi variation (0.46 kg) corresponds to subject 3H with largest resistance and smallest BMI, and the largest variation (1.4 kg) to the subject 4H with largest BMI and smallest resistance. This was expected since the percentage of resistance variation was smallest in subject 3H and largest for subject 4H. Results are similar in women as the largest variations occurred to the subject with smallest resistance and vice-versa. FMi % variations are larger in men than in women, and the

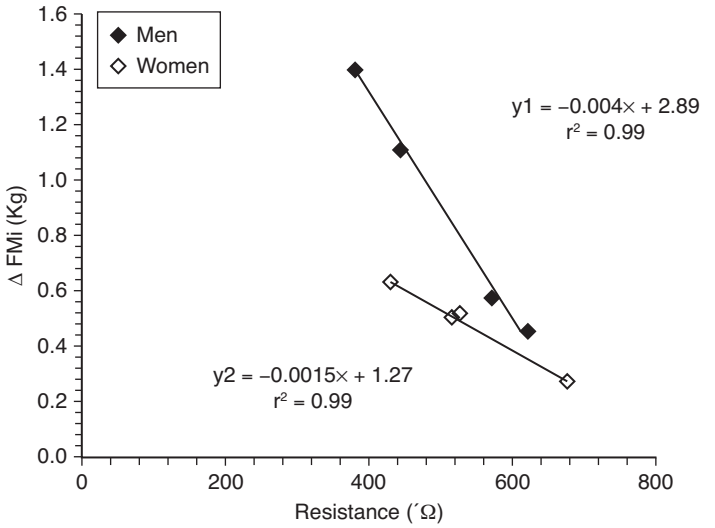

Figure 9. Variation of FMi calculated by impedance in 8 subjects produced by a 12-Ω resistance variation as a function of their foot-to-foot resistance

Table 5. Effect of a resistance variation of ±6 Ω on values of FM calculated by impedance (FMi) on eight subjects and comparison with DXA (FMd). $\Delta FMi = FM_{-6} - FM_{+6}$ where FM_{-6} = FMi at R_{34}-6 Ω and FM_{+6} = FMi at R_{34}+6 Ω

Subject	R_{34}, Ω	FMd kg	H, cm	W, kg	BMI, kg/m²	FMi, kg	FMi-FMd, kg	ΔFMi, kg	%ΔFMi, %
1H	571	14.3	175	64.2	21.0	10.4	-3.9	0.58	5.5
2H	444	10.0	188	78.9	22.3	11.8	1.8	1.11	9.4
3H	621	10.0	169	59.7	20.9	9.2	-0.8	0.46	5.0
4H	381	49.3	181	126.6	38.6	44.1	5.2	1.40	3.7
1F	525	13.4	170	61.2	21.2	18.2	4.8	0.52	2.8
2F	675	15.9	159	4705	18.8	11.6	-4.3	0.27	2.3
3F	516	17.7	165	5309	19.8	13.4	-4.3	0.50	3.7
4F	429	62.1	154	116.7	49.2	63.7	1.6	0.63	1.0
Mean	520	24.1	170	76.0	26.4	22.8	0.012	0.68	4.2

smallest values in men and women were found for subject 4H (3.7%) and 4F (1%), respectively, both with largest BMI.

3.4. Measurements of body fluid volume with FFI

Although FFI is mainly used for FM, FFM and weight measurements, it can also measure TBW, ECW and ICW like medical impedancemeters.

3.4.1. Extracellular Water (ECW)Volume

Since TEFAL FFI uses a square electric signal, it can measure a low frequency resistance R_t at the top of the signal. Jaffrin et al. [25] have investigated the feasibility of measuring ECW with a Tefal Bodymaster Vision by comparing with a multifrequency Xitron Hydra 4200 medical impedancemeter in 60 subjects. The Xitron measures the ECW resistance Re by extrapolation to zero frequency, which increases the resistance and their values were 11% higher in men and 20% higher in women than those measured by the Bodymaster at the top of its signal. This was expected as the Bodymaster resistance R_t could not be extrapolated to zero frequency. Differences between the mean FFI ECW (Ve_t) and the Xitron one (Ve) were 0.05±0.81 L in men and 0.02±0.49 L in women and not significantly different since p-values were 0.75 and 0.83, respectively. A similar method was also applied by Jaffrin and Morel [26] to adapt the BIS method of Xitron to BIA.

3.4.2. Total body water

Some FFIs calculate TBW based on FFM by assuming a universal hydration coefficient of 73.2%:

$$TBW = FFM/0.732 \tag{18}$$

However, hydration coefficient can vary among individuals, as hypo-hydration may affect elderly persons or athletes after heavy training, and oedema can induce hyper-hydration. Jaffrin and Moreno [27] proposed to treat TBW as a single fluid, macroscopically homogeneous with a mean resistivity ρ_μ since current penetrates cell membranes at very high frequencies, a method successfully validated using a Xitron Hydra [28]. TBW measured by the Xitron V_{tx} is

$$V_{tx} = K_x\,(H^2W^{0.5}/R_\propto)^{2/3} \tag{19}$$

with

$$K_x = 10^{-2}(4.3\,\rho_\propto)^{2/3}D_b^{-1/3} \tag{20}$$

where D_b = 1.05 kgL^{-1} is the body density. Values of K_x were determined by comparison with FFMd assuming V_{tx} =0.732FFMd based on a group of 58 volunteers. Values of K_x were found from eqn. 20 to be 0.576 for men, and 0.561 for women. Jaffrin and Moreno [27] calculated the coefficient K_i for each subject of the same group using the Bodymaster Vision resistance R_{34} from the following equation:

$$V_{tx} = K_i\,(H^2W^{0.5}/R_{34})^{2/3} \tag{21}$$

The new constant K_t for the Bodymaster was taken as the average of K_i and is given in Table 6 together with mean values V_{tx} and V_{tt}, hydration rates and p-values. They are larger than for the Xitron as R_{34} are larger than R_μ due to its lower frequency. In order to obtain an independent validation of this method by comparison with deuterium

Table 6. Mean values and standard deviations of FFMTBW volumes measured by Xitron (V_{tn}) and by Tefal (V_{tt}), individual coefficients Ki, differences V_{tt} - V_{tn}, P-values and hydration coefficient Th_t = FFM/TBW.

	FFM, kg	V_{tn}, L	K_i	V_{tt}, L	V_{tt} - V_{tn}, L	P value	Th_t, kgL^{-1}
Male subjects N = 27	59.8±7.4	44.6 ±5.9	0.645 ±0.032	44.5 ±7.1	0.1 ±2.27	0.694	0.716 ±0.055
Female subjects N = 29	42.4±4.2	31.6 ± 3.6	0.591 ±0.032	31.7 ±3.5	0.04±1.9	0.902	0.736 ±0.036

dilution, Eqn. 19 was applied to a database obtained from a Caucasian group of 91 subjects who had their resistance measured by the same FFI Bodymaster Vision and their TBW measured by deuterium dilution (Vtd) [20]. The mean difference $V_{tt} - V_{td}$ was −0.38±2.27 L with a p-value of 0.237 for men and 0.72±2.37 L with p = 0.60 for women, confirming that these differences were not significant, especially in men.

4. DISCUSSION

Measuring the whole body FFM by bioimpedance rapidly and with only two electrodes on hand and two on foot is a challenge. According to Organ et al. [22], the resistance of the trunk, which has a large volume, accounts for only 7.7% of the R_{13} resistance, while the arm resistance represents 42.3% and the leg 50%. Mean FFM of trunks and limbs were measured in [24] for the M85 cohort and represented 12.2% of the whole FFM for the arms, 33.3% for the legs, leaving 54.5% for the trunk and head. Since FFI ignores arm resistances, it is not subject to their variability. Among several authors quoted in section 1.3, who compared FFI measurements with those of a medical impedancemeter against DXA data [5, 7, 8], only Nunez et al. [5] reported a slight advantage for the medical device. Lazzer et al. [8] obtained less FM mean underestimation with two FFI than with RJL impedancemeter, but differences SD were larger with the FFI. This could be expected as a part of differences SD can be attributed to incorrect feet position during measurement using an FFI. However, Jebb et al. [7] observed a slightly higher mean bias with DXA for a Tanita than with a Bodystat, but smaller SD of differences. They also noted that bioimpedance measurement overestimated FM in very lean subjects, while it underestimated it in obese subjects; they attributed this situation to the effect of FFM hydration. Bousbiat et al. [19] reported a smaller FFM difference with DXA data when the foot-to-foot resistance (eqns. 12 and 13) was used, than with the hand–to-foot resistance (eqns. 14 and 15).

It is clear that FFIs have several advantages over conventional wrist-ankle impedancemeters in terms of cost, rapidity, and possibly in terms of accuracy due to the elimination of arm resistance. Medical impedancemeters have their own advantages in terms of electrode standardization and precise positioning. Their measurement

reproducibility is generally better than that of FFI, but we have shown that that FFI reproducibility and accuracy can be improved by proper design of the body scale which facilitates positioning the heels. Current electrodes must be long for accommodating feet of different sizes, but voltage electrodes should be narrow and placed transversally to the feet, so that the user can ensure that heels are positioned precisely on the electrode to minimize the sole skin resistance. The FFI software could also include the measurement of ECW for detecting leg edemas and that of TBW for measuring hydration rate [25, 27].

Another important potential asset of FFI is that they can be modified by adding four additional electrodes for the hands on handles mounted on a vertical column. With proper software, these eight-electrode impedancemeters can provide automatically the resistance of each limb and the trunk by measuring the resistances of five paths between hands and feet [22, 24]. It is then possible, by comparing with DXA measurements, to determine equations giving the FFM and FM of each limb and the trunk. Tanita corporation (Tokyo, Japan) was the first to propose such a system - the BC 418 at 50 kHz. They have commercialized the MC780 MA with 3 frequencies, that performs a full segmental body composition analysis. Biospace Co. Ltd., Korea, produces three 8-electrodes multifrequency systems, the InBody 720 which measures TBW, ECW and ICW in addition to segmental FFM and FM, and the InBody 520 and 230. Lim et al. [29] used an eight-electrode InBody 720 (Biospace, Korea) and a GE Lunar DXA to measure FFM and FM in 166 healthy children aged 6-18 yrs. Mean differences of FFM with DXA were –0.69± 1.13 kg, and those of FM were 0.85±1.41 kg, good results for such a diverse population.These systems could also permit to measure appendicular skeletal muscle and regional fat distribution.

The limitations of our study are that tests concerning the effect of electrode geometry were performed on a limited number of subjects and did not include extreme morphologies such as athletes and obese persons. However, we believe that our investigation on the effect of electrode geometry on resistance measurement was original and should help improving the accuracy and reproducibility of FFI.

5. CONCLUSION

This paper has shown that the use of the foot-to-foot resistance R_{34} instead of the hand-to-foot resistance R_{13} gives a small advantage to FFI because it avoids the variability of arm resistance. However, to exploit this advantage, the design of the body scale plantar electrodes should facilitate positioning heels exactly on the voltage electrodes, as it is important for FFI accuracy and reproducibility. Thus, with a software validated by DXA and proper electrode design, FFI can make fast and fairly accurate measurements of FFM and FM, at least in a normal population. FFI can also measure TBW and ECW with proper software. Eight-electrodes FFI can further measure segmental FFM and FM in the limbs and trunk in addition to whole body measurements. Since body composition varies with the degree of physical training and with ethnic origin, FFM equations for both FFI and hand-to-foot impedancemeters should take into account these parameters to increase their accuracy. The introduction of BMI as a parameter in the software may help in correcting the underestimation of FM in obese subjects and its overestimation in athletes and lean subjects.

ACKNOWLEDGMENTS
The authors thank Tefal Company for its financial and technical support and the Centre d'Imagerie Medicale Avancée (CIMA) of Compiegne for access to their DXA.

CONFLICT OF INTEREST
None declared.

Nomenclature

H	body height, m
R_{13}	hand-to-foot resistance, Ω
R_{34}	foot-to-foot resistance, Ω
Scc	contact area of current electrode with foot, cm^2
Scv	contact area of voltage electrode with foot, cm^2Ve extracellular volume
Ve_t	extracellular volume by Tefal
V_{tx}	extracellular volume by Xitron
W	body weight, kg
Z	impedance
Z_{50}	impedance at 50 kHz

Abbreviations

BIS	bioimpedance spectroscopy
BMC	bone mineral content, kg
BMI	body mass index, kg-m^{-2}
DXA	Dual X-ray absorptiometer
ECW	extracellular water volume, L
FFI	foot-to-foot impedancemeter
FM	fat tissue mass, kg
FMd	fat tissue mass by DXA, kg
FMi	fat tissue mass by impedance, kg
FFM	fat-free mass, kg
FFMd	FFM measured by DXA, kg
FFMi	FFM measured by impedance, kg
FFMt	FFM measured by Tefal, kg
LBM	lean body mass, kg
SD	Standard deviation
TBW	total body water, L

Greek

ρ	resistivity, ohm-cm
Ω	ohm

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