Validity of methods of body composition assessment in young and older men and women

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Abstract:

We examined the validity of percent body fat (%Fat) estimation by two-compartment (2-Comp) hydrostatic weighing (Siri 2-Comp), 3-Comp dual-energy X-ray absorptiometry (DEXA 3-Comp), 3-Comp hydrostatic weighing corrected for the total body water (Siri 3-Comp), and anthropometric methods in young and older individuals ($n = 78$). A 4-Comp model of body composition served as the criterion measure of %Fat (Heymsfield 4-Comp; S. B. Heymsfield, S. Lichtman, R. N. Baumgartner, J. Wang, Y. Kamen, A. Aliprantis, and R. N. Pierson Jr., *Am. J. Clin. Nutr.* 52: 52–58, 1990.). Comparison of the Siri 3-Comp with the Heymsfield 4-Comp model revealed mean differences of ≤0.4 %Fat, r values ≥ $r = 0.997$, total error values ≤ 0.85 %Fat, and 95% confidence intervals (Bland-Altman analysis) of ≤1.7 %Fat. Comparison of Siri 2-Comp, DEXA, and anthropometric models with the Heymsfield 4-Comp revealed that total error scores ranged from ±4.0 to ±10.7 %Fat, and 95% confidence intervals associated with the Bland-Altman analysis ranged from ±5.1 to ±15.0 %Fat. We conclude that the Siri 3-Comp model provides valid and accurate body composition data when compared with a 4-Comp criterion model. However, the individual variability associated with the Siri 2-Comp, DEXA 3-Comp, and anthropometric models may limit their use in research settings. The use of anthropometric estimation methods resulted in large mean differences and a considerable amount of interindividual variability. These data suggest that the use of these techniques should be viewed with caution.

Keywords: body density | body water | dual-energy X-ray absorptiometry | body fat

Article:

Until recently, hydrodensitometry has been suggested as a "gold standard" for body composition assessment (5, 15, 35). This two-compartment model [2-Comp; fat mass (FM) and fat-free mass (FFM)] of body composition assessment assumes that the constituents of the FM and FFM

compartments have constant densities (0.0900 kg/l for FM and 1.100 kg/l for FFM) and that the relative amounts of the three major components of the FFM (aqueous, mineral, and protein) are known, additive, and constant in all individuals (5, 15,21, 35, 40). However, methods based on the 2-Comp model may have limitations when used on individuals who have changes in bone mineralization or hydration of the FFM due to aging and disease. For example, in children and in an older population, both bone mineral content (BMC) and total body water (TBW) have been shown to change with maturation and age (1, 14, 22, 23, 29, 33). Furthermore, gender and ethnic differences in the composition of the FFM have been reported (1,14, 15, 40). Exercise training may also result in changes in BMC and TBW such that the assumptions of the 2-Comp model are violated (27). In all of these clinical settings, total body percent body fat (%Fat) may not be estimated accurately by the 2-Comp model (1, 20, 27).

Development of various methodologies for estimation of the different components of the body has led to the emergence of three- (3-Comp) and four-compartment (4-Comp) models of body composition assessment (1, 15,21, 36). These models employ measurements of body density (D_b) and the aqueous and/or mineral compartments, instead of making assumptions based on the so-called "reference man." Some of the 4-Comp models have been validated against neutron-activation analysis, which offers the most complete body composition analysis available at present (15). In recent years, the use of multicompartment models in research and studies has become more widespread (1, 8-11, 14, 15, 23, 27-29, 31,40-42).

The emergence of the 4-Comp model as a new "gold standard" for body composition measurement provides an opportunity to reevaluate existing body composition prediction techniques. For example, in the past decade the development of whole body dual-energy X-ray absorptiometry (DEXA) has provided accurate and precise information regarding BMC (g) and areal bone density (g/cm^2; Ref. 24). DEXA has also been suggested as a criterion method for measuring %Fat (19, 25). Although DEXA is now widely used to estimate %Fat and also has potential to estimate regional body fat distribution, concerns have arisen about the validity of DEXA %Fat measures. These concerns stem from the assumptions made regarding the hydration of the mineral-free lean mass and the ability of DEXA to assess soft tissue (19, 32). Snead et al. (37) recently demonstrated that estimates of %Fat by DEXA showed considerable disparity from %Fat estimates by hydrodensitometry in older individuals. In that study the aqueous component of the FFM was not measured. Therefore, the level of disparity between estimates of %Fat by DEXA and measures of 4-Comp %Fat may be even greater than reported by Snead et al. Support for this notion comes from earlier work (1), which has demonstrated that 4-Comp models were better measures of body composition than were 2-Comp models in older individuals, with variation in TBW having a greater influence on body composition than did changes in total body bone mineral. However, D_b determination by hydrostatic weighing at residual volume may be more difficult in older subjects and, therefore, subject to greater error in older individuals. Thus the use of DEXA to measure body composition offers practical advantages, particularly in the context of a multicenter study.

In addition to DEXA, the use of anthropometric models for estimating body composition is extremely popular in clinical and field settings. The available generalized skinfold equations (16, 17) and girth equations (38, 39) were derived by using 2-Comp models (hydrostatic weighing) as the criterion method. Therefore, the validity of these techniques may be different

when a 4-Comp model body composition is used as the criterion method. We are aware of only one skinfold model that used a 4-Comp model as the criterion method (41); however, in that study no cross-validation data were provided. Therefore, the purpose of the present study was to compare body composition results derived from a 2-Comp model (hydrodensitometry), 3-Comp models (including DEXA and the combined use of D_b and TBW), and anthropometric techniques with those derived from 4-Comp models in young and older healthy adults.

METHODS

Subjects

Seventy-eight healthy subjects participated in this study. They included 17 young women (15 Caucasian, 1 Asian, and 1 Hispanic), 14 young men (9 Caucasian, 4 African American, and 1 Hispanic), 19 older women (18 Caucasian, 1 African American), and 28 older men (28 Caucasian). Subjects were recruited by local media advertisement for participation in a variety of ongoing clinical investigations at the General Clinical Research Center (University of Virginia Health Sciences Center, Charlottesville, Virginia). Physical characteristics of the subjects are summarized in Table 1. All subjects completed a detailed medical history and underwent a physical examination before participation. Each subject provided written informed consent in accordance with the guidelines established by the University of Virginia Human Investigation Committee. None of the subjects was taking medications known to affect body composition measures, including exogenous use of estrogen (i.e., oral contraceptives or estrogen replacement therapy). The young women included in this investigation were eumenorrheic and were studied during the early follicular phase of the menstrual cycle (*days 1–5* of the menstrual cycle).

Table 1. Physical characteristic of the subjects

	Young Women (n=17)	Young Men (n=14)	Older Women (n=19)	Older Men (n=28)
Age, yr	24.2 ± 0.5[a]	23.4 ± 1.0[a]	65.8 ± 1.4[b]	66.5 ± 1.0[b]
Weight, kg	65.4 ± 2.4[a]	78.0 ± 2.2[b]	69.2 ± 3.0[a]	84.0 ± 2.3[b]
Height, cm	167.1 ± 1.6[a]	177.9 ± 1.5[b]	161.7 ± 1.4[c]	176.6 ± 1.4[b]
BMI, kg/m²	23.4 ± 2.9[a]	24.7 ± 3.1[a,b]	26.4 ± 4.4[b]	26.9 ± 3.1[b]
TBM, kg	3.1561 ± 0.4831[a]	4.0388 ± 0.4600[b]	2.5461 ± 0.3704[c]	3.8520 ± 0.5829[b]
TBW, liters	37.6 ± 6.[a]	45.5 ± 6.4[b]	31.2 ± 4.1[c]	44.9 ± 6.6[b]
Chest skinfold*, mm	10.5 ± 1.8[a,c]	5.2 ± 1.0[a]	17.6 ± 2.2[b]	13.6 ± 1.5[b,c]
Abdomen skinfold*, mm	20.2 ± 2.4[a]	19.9 ± 2.7[a]	31.0 ± 2.4[b]	28.2 ± 1.8[b]
Thigh skinfold*, mm	20.3 ± 1.6[a]	12.3 ± 1.6[b]	32.4 ± 2.2[c]	14.8 ± 1.6[b]
Triceps skinfold*, mm	16.3 ± 1.4[a]	9.4 ± 1.6[b]	21.8 ± 1.9[c]	11.9 ± 1.0[b]
Subscapular skinfold*, mm	15.6 ± 2.1[a,c]	13.0 ± 1.7[a]	18.8 ± 2.1[b,c]	19.2 ± 1.0[b,c]
Suprailiac skinfold*, mm	12.8 ± 1.6[a]	11.6 ± 2.3[a]	21.2 ± 2.1[b]	15.5 ± 1.6[a]
Midaxillary skinfold*, mm	12.4 ± 1.6[a]	10.6 ± 1.7[a]	19.2 ± 2.2[b]	20.1 ± 1.7[b]
Calf skinfold*, mm	9.6 ± 2.1[a]	5.2 ± 0.7[b,d]	16.1 ± 2.3[c]	7.6 ± 0.7[a,d]
Mean abdomen circumference*, cm	78.3 ± 2.0[a]	84.5 ± 2.2[a,b]	90.4 ± 3.3[b]	98.0 ± 1.7[c]
Hip circumference*, cm	97.4 ± 1.6[a]	98.4 ± 1.5[a]	104.6 ± 2.1[b]	103.4 ± 1.3[b]
Iliac circumference*, cm	81.6 ± 2.3[a]	86.0 ± 2.3[a]	96.3 ± 3.6[b]	99.3 ± 1.8[b]

Values are means ± SE for n = 78 subjects. BMI, body mass index; TBM, total body bone mineral mass, TBW, total body water. * Young women subject no. reduced (n=16); older women subject no. reduced (n=18). Different superscripted letters indicate that group means are significantly different (P<0.05). TBM by dual-energy X-ray absorptiometry (DEXA) bone mineral ash multiplied by 1.279 (Hologic QDR 2000; pencil beam mode). TBW by tritium dilution; corrections were made for nonaqueous hydrogen exchange (5%), and the density of water at body temperature was assumed to be 0.99371 kg/l. All anthropometric measurements made according to the guidelines established at the Airlie Conference (5, 12). The mean abdominal circumference was the mean of the waist and abdominal circumference (36, 37).

Testing Procedures

TBW. Subjects were admitted to the General Clinical Research Center on the evening before the TBW procedures. TBW was measured in the morning, after an overnight fast, by a tritiated water

dilution technique modified for use with plasma samples (13). The isotope was administered orally (between 0600 and 0800), and blood samples were collected after 1, 2, 3, and 4 h of equilibration. Tritium concentration in prepared blood samples was analyzed by scintillation counting. Corrections were made for nonaqueous hydrogen exchange (5%), and the density of water at body temperature was assumed to be 0.99371 kg/l. TBW (kg) was calculated as ^3H_2O dilution space (liters) × 0.95 × 0.99371 (Ref. 40). In young women TBW was determined during the early follicular phase (*days 1–5*) of the menstrual cycle.

D_b. D_b was measured by hydrostatic weighing corrected for residual lung volume, as previously described (34). Briefly, subjects were weighed in air on an Accu-weigh beam scale (accurate to 0.1 kg; Metro Equipment, Sunnyvale, CA) and were weighed under water with a 9-kg Chatillon autopsy scale (accurate to 10 g; Chatillon, New York, NY). Water temperature was maintained between 35 and 37°C. Underwater weight was measured at residual lung volume for 5–10 trials. The average of the last three trials was used for D_b determination (18). Residual volume was measured by using an oxygen dilution technique (43). Because of potential concerns associated with D_b determination by hydrostatic weighing in the elderly, we examined data on 13 older subjects (7 women, 6 men) who had D_b determined on at least two occasions. Despite the fact that 12–40 mo separated D_b determination (subjects participated in multiple studies), excellent agreement for D_b determination was observed. The mean difference between the D_b measures was 0.009 g/ml, the correlation coefficient was $r = 0.97$, and the total error (TE) was ±0.0052 g/ml. These data are similar to test-retest data determined within 48 h that were recently reported for D_b determined by hydrostatic weighing (2). If the present "test-retest" data were determined over a shorter time frame (i.e., several days), the agreement between tests would likely be even stronger. Therefore, we are confident that the older subjects who participated in the present study were able to perform the methodology associated with hydrostatic weighing and residual volume without difficulty.

DEXA. Total body bone mineral mass (TBM) was estimated from bone mineral ash measured by DEXA (Hologic QDR-2000, enhanced whole body analysis software version 5.64, Waltham, MA). Bone mineral ash was multiplied by 1.279 to estimate TBM (the sum of osseous mineral and cell mineral; Ref. 15). In addition, total body bone ash was multiplied by 0.4180 to compute total mineral volume (15). DEXA was also used to estimate %Fat. DEXA scans were performed in the pencil beam mode (scan time ~12 min, radiation exposure ~10 mrem). The subjects were instructed to remove all objects such as jewelry and eyeglasses and wore only a standard hospital gown during the scan procedures. A single trained investigator analyzed all DEXA scans (J. L. Clasey). DEXA total body scans were performed twice for an independent sample of subjects ($n = 12$) to determine measurement precision. There were no mean differences found in the BMC ($P = 0.72$) or %Fat ($P = 0.42$) measurements. For BMC and %Fat, the percent mean differences were 0.2 and 0.4%, and the TE were ±0.035 kg and ±0.61 %Fat, respectively. The intrascan analysis reliability for this investigator ($r \geq 0.99$) has been previously reported (7).

Skinfold and girth measures. Skinfold and girth measurements were taken in triplicate, and the mean was used according to the guidelines established at the Airlie Conference (6, 12). All skinfold measurements were taken on the right side of the body by using a Harpenden skinfold caliper, and girth measurements were made with a nonelastic tape. The anthropometric measurements used in subsequent analyses to estimate %Fat included chest, abdomen, thigh,

triceps, subscapular, midaxillary, and calf skinfolds; and waist, abdomen, hip, and iliac circumferences. A single trained investigator performed all anthropometric measurements (J. L. Clasey). Anthropometric measurements were performed for an independent sample of subjects ($n = 10$) on 2 consecutive days to determine measurement precision. There were no mean differences found for any of the anthropometric measurements ($P = 0.10$–0.89), and the percent mean differences ranged from 0.4 (suprailiac skinfold) to 3.3% (chest skinfold). The TE around the line of identity ranged from ± 0.16 (calf skinfold) to ± 1.98 cm (hip circumference).

Body Composition (%Fat) Assessment

4-Comp models. The 4-Comp models of Heymsfield et al. (Ref. 15; Heymsfield 4-Comp) and Baumgartner et al. (Ref. 1; Baumgartner 4-Comp) were used to calculate %Fat. These models require the measurement of D_b, TBW, and TBM. For the purpose of the present study, Heymsfield 4-Comp served as the criterion model of body composition assessment (Table 2).

Table 2. Body composition equations used to estimate percent body fat

Model	Ref. No.	Equation
Heymsfield 4-Comp	15	$\%\text{Fat} = [[2.748/D(P+F) - 2.051]$ $[BW - (A+M)]/BW] \times 100$
Baumgartner 4-Comp	1	$\%\text{Fat} = [[2.75(BV) - 0.714(A) +$ $1.148(M) - 2.05(BW)]/BW\} \times 100$
Siri 3-Comp	36	$\%\text{Fat} = (2.11/D_b) - (0.78W - 1.354)$ $\times 100$
DEXA 3-Comp		$\%\text{Fat} = $ proprietary equation supplied by the manufacturer
Siri 2-Comp	35	$\%\text{Fat} = (4.95/D_b - 4.50) \times 100$
Williams	41	
Men		$\%\text{Fat} = 0.486(\text{Sum } 4_A) - 0.0015$ $(\text{Sum } 4_A^2) + 0.067(\text{Age}) - 3.83$
Women		$\%\text{Fat} = 0.428(\text{Sum} 4_B) - 0.0011$ $(\text{Sum} 4_B^2) + 0.127(\text{Age}) - 3.01$
Jackson-Pollock		
Men	16	$D_b = 1.11200000 - 0.00043499(X_1)$ $+ 0.00000055(X_1)^2 - 0.00028826$ (Age)
Women	17	$D_b = 1.0970 - 0.00046971(X_1)$ $+ 0.00000056(X_1)^2 - 0.00012828$ (Age)
Tran-Weltman		
Men	38	$\%\text{Fat} = -47.371817 + 0.57914807$ $(\text{Mean AB}) + 0.25189114(\text{Hip})$ $+ 0.21366088(\text{Iliac}) - 0.35595404$ (BW)
Women	39	$D_b = 1.1168897 - 0.002824$ $(\text{Mean AB}) + 0.0000122098$ $(\text{Mean AB})^2 - 0.000733128$ $(\text{Hip}) + 0.000510477(\text{Ht})$ $- 0.0002\,16161(\text{Age})$

%Fat, percent body fat; Comp, compartment; D(P+F), density of protein-plus-fat compartment mixtures; BW, body weight (kg); A, aqueous mass (kg); M, mineral mass (kg); BV, body volume; D_b, body density; W, total body water as a fraction of body weight; Sum 4_A, sum of chest, subscapular, midaxillary, and thigh skinfold thickness (cm); Age, in yr; Sum 4_B, sum of triceps, subscapular, abdomen, and calf skinfold thickness (cm); X_1, sum of 7 skinfolds (chest, midaxillary, triceps, subscapular, abdomen, suprailiac, and thigh skinfold thickness) (cm); AB, abdominal circumference (cm); Hip, hip circumference (cm); Iliac, iliac circumference (cm); Ht, standing height (cm).

2-Comp model. The equation developed by Siri (Ref. 35; Siri 2-Comp) was used to convert D_b determined by hydrostatic weighing to %Fat (Table 2).

3-Comp models. The 3-Comp model developed by Siri (Ref. 36; Siri 3-Comp), which requires the measurement of D_b and TBW, was used to estimate %Fat (Table 2).

DEXA. The DEXA estimation of %Fat is based on a 3-Comp model (DEXA 3-Comp), which includes a mineral-free lean and a mineral component. The proprietary equation supplied by the manufacturer was used to determine %Fat.

Skinfold models. The generalized equations of Jackson and Pollock and Jackson et al. (Refs. 16, 17; Jackson-Pollock equations; developed using the 2-Comp hydrostatic weighing model as the criterion) and the equations of Williams et al. (Ref. 41; Williams equation; developed using the 4-Comp model as the criterion) were applied to provide estimates of %Fat (Table 2).

Girth models. The generalized equations of Tran and Weltman (Refs. 38, 39; Tran-Weltman equations; developed using the 2-Comp hydrostatic weighing model as the criterion) were applied to provide estimates of %Fat (Table 2).

Statistical Analyses

Comparisons between %Fat measured with the Heymsfield 4-Comp model (criterion method) and %Fat estimated from the other techniques were made with ANOVA with repeated measures. Where mean differences were observed, mean comparisons were examined. Degrees of freedom were corrected for correlated data by using Huynh-Feldt epsilons (SuperANOVA, Abacus Concepts, Berkeley, CA). All values are expressed as means ± SE. Regression analyses and the Bland and Altman procedure (Ref. 3; Bland-Altman) were also employed to examine the strength of the relationships between Heymsfield 4-Comp %Fat and the other estimates of %Fat.

RESULTS

TBW and Aqueous Fraction of the Fat-Free Body

TBW values for young women, young men, older women, and older men were 37.6 ± 1.5, 45.5 ± 1.7, 31.2 ± 1.0, and 44.9 ± 1.2 liters, respectively (Table 1). This corresponded to an aqueous fraction of the fat-free body of 0.763 ± 0.009, 0.723 ± 0.014, 0.756 ± 0.016, and 0.744 ± 0.009 for the young women, young men, older women, and older men, respectively.

Comparison of Body Composition Models With the Criterion 4-Comp Model

The relationships between the criterion Heymsfield 4-Comp %Fat and the Baumgartner 4-Comp, the Siri 3-Comp, the DEXA 3-Comp, and the Siri 2-Comp %Fat body composition models are presented in Table 3. For all subjects combined ($n = 78$), a significant main effect for body composition model was observed ($P = 0.002, F = 4.994$, df = 231). Mean comparisons revealed

significant differences between the Siri 2-Comp and the Heymsfield 4-Comp %Fat models ($P =$ 0.01). Correlation coefficients ranged from $r = 0.874$ (Siri 2-Comp vs. Heymsfield 4-Comp) to $r = 1.000$ (Baumgartner 4-Comp vs. Heymsfield 4-Comp). TE around the line of identity ranged from ±0.30 %Fat (Baumgartner 4-Comp vs. Heymsfield 4-Comp) to ±5.71 %Fat (Siri 2-Comp vs. Heymsfield 4-Comp). Similar analyses were performed within each age group and gender.

Table 3. Comparison of estimates of percent body fat using 2-, 3-, and 4-Comp models

Model	Mean	SE	Mean Difference	R	TE, %
All subjects (n = 78)					
Heymsfield 4-Comp	28.1	1.2			
Baumgartner 4-Comp	28.4	1.2	−0.3	1.000	0.30
Siri 3-Comp	27.9	1.2	0.2	0.998	0.72
DEXA 3-Comp	28.8	1.2	−0.7	0.884	5.28
Siri 2-Comp	29.8	1.2	−1.7*	0.874	5.71
Young women (n = 17)					
Heymsfield 4-Comp	24.4	2.1			
Baumgartner 4-Comp	24.7	2.1	−0.3	1.000	0.31
Siri 3-Comp	24.0	2.1	0.4	0.998	0.73
DEXA 3-Comp	28.9	1.8	−4.5†	0.896	5.86
Siri 2-Comp	27.8	1.7	−3.4†	0.891	5.17
Young men (n = 14)					
Heymsfield 4-Comp	18.7	2.5			
Baumgartner 4-Comp	19.1	2.5	−0.4	1.000	0.29
Siri 3-Comp	19.0	2.5	−0.3	0.997	0.78
DEXA 3-Comp	17.8	2.4	0.9	0.870	4.69
Siri 2-Comp	17.8	3.0	0.9	0.845	5.80
Older women (n = 19)					
Heymsfield 4-Comp	39.0	2.1			
Baumgartner 4-Comp	39.3	2.1	−0.3	1.000	0.31
Siri 3-Comp	38.7	2.1	0.3	0.997	0.85
DEXA 3-Comp	41.2	1.8	−2.2	0.854	5.07
Siri 2-Comp	41.6	1.8	−2.6	0.753	6.39
Older men (n = 28)					
Heymsfield 4-Comp	27.6	1.5			
Baumgartner 4-Comp	27.9	1.5	−0.3	1.000	0.29
Siri 3-Comp	27.4	1.5	0.2	0.998	0.58
DEXA 3-Comp	25.9	1.3	1.7	0.763	5.32
Siri 2-Comp	29.1	1.1	−1.5	0.728	5.46

Mean differences, correlation coefficients, and total error scores compared with Heymsfield 4-Comp model are shown. TE, total error. Significantly different: * $P < 0.01$; † $P < 0.003$.

For young women ($n = 17$), a significant main effect for body composition model was observed ($P = 0.001, F = 16.705$, df $= 48$). Mean comparisons revealed that results obtained with the Heymsfield 4-Comp %Fat model were significantly different from those obtained with the DEXA 3-Comp ($P = 0.0003$) and the Siri 2-Comp %Fat model ($P = 0.003$). Correlation coefficients ranged from $r = 0.891$ (Siri 2-Comp vs. Heymsfield 4-Comp) to $r = 1.000$ (Baumgartner 4-Comp vs. Heymsfield 4-Comp). TEs ranged from ±0.31 %Fat (Baumgartner 4-Comp vs. Heymsfield 4-Comp) to ±5.86 %Fat (DEXA 3-Comp vs. Heymsfield 4-Comp).

For young men (n = 14), no significant main effect for body composition model was observed (P = 0.72). Correlation coefficients ranged from r = 0.870 (DEXA 3-Comp vs. Heymsfield 4-Comp) to r = 1.000 (Baumgartner 4-Comp vs. Heymsfield 4-Comp). TEs ranged from ±0.29 %Fat (Baumgartner 4-Comp vs. Heymsfield 4-Comp) to ±5.80 %Fat (Siri 2-Comp vs. Heymsfield 4-Comp).

For older women (n = 19), a significant main effect for body composition model was observed (P = 0.03, F = 3.180, df = 54). Although mean comparisons did not reveal significant differences, comparisons between the Heymsfield 4-Comp %Fat results and the results obtained with the DEXA 3-Comp and the Siri 2-Comp %Fat models approached statistical significance (P = 0.09 and 0.06, respectively). Correlation coefficients ranged from r = 0.753 (Siri 2-Comp vs. Heymsfield 4-Comp) to r = 1.000 (Baumgartner 4-Comp vs. Heymsfield 4-Comp). TEs ranged from ±0.30 %Fat (Baumgartner 4-Comp vs. Heymsfield 4-Comp) to ±6.39 %Fat (Siri 2-Comp vs. Heymsfield 4-Comp).

For older men (n = 28), a significant main effect for body composition model was observed (P = 0.006, F = 4.527, df = 81). Although mean comparisons did not reveal significant differences, comparisons between the Heymsfield 4-Comp and results obtained with the DEXA 3-Comp and Siri 2-Comp models approached significance (P = 0.08 and 0.10, respectively). Correlation coefficients ranged from r = 0.728 (Siri 2-Comp vs. Heymsfield 4-Comp) to r = 1.000 (Baumgartner 4-Comp vs. Heymsfield 4-Comp). TEs ranged from ±0.29 %Fat (Baumgartner 4-Comp vs. Heymsfield 4-Comp) to ±5.46 %Fat (Siri 2-Comp vs. Heymsfield 4-Comp).

Figure 1 shows the Bland-Altman plots for the Baumgartner 4-Comp vs. the Heymsfield 4-Comp models. The mean ±2 SD ranges for the entire group are shown in the figure. Separate analyses were also performed for each age by gender group. Virtually identical results were observed for the Baumgartner vs. Heymsfield 4-Comp models, with the largest mean difference for the different age and gender groups (Heymsfield 4-Comp vs. Baumgartner 4-Comp) being −0.31 %Fat and the 95% confidence intervals (±2 SD) ranging from ±0.07 to ±0.19 %Fat. For the Siri 3-Comp model (Fig. 2), mean differences for the different age and gender groups ranged from −0.20 to +0.48 %Fat, and the 95% confidence intervals ranged from ±1.1 to ±1.7 %Fat. For the DEXA 3-Comp model (Fig. 3), mean differences for the different age and gender groups ranged from −4.5 to +1.7 %Fat, and the 95% confidence intervals ranged from ±7.8 to ±10.5 %Fat. For the Siri 2-Comp model (Fig. 4), mean differences for the different age and gender groups ranged from −3.4 to 1.0 %Fat, and the 95% confidence intervals ranged from ±8.1 to ±12.0 %Fat.
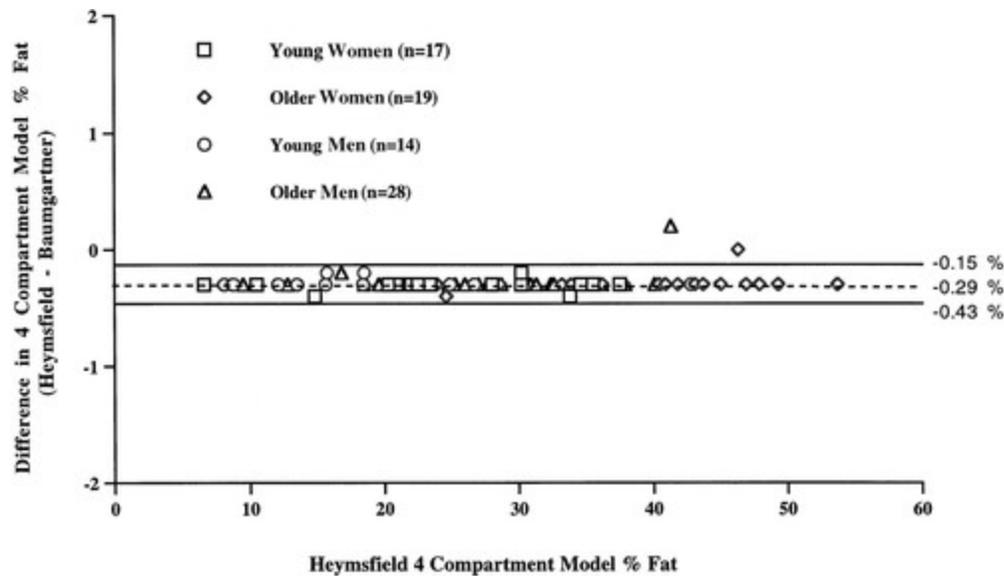
Fig. 1. Comparison of difference between 4-compartment (4-Comp) models of Heymsfield et al. (15; Heymsfield 4-Comp) and Baumgartner et al. (1; Baumgartner 4-Comp) for assessment of percent body fat (%Fat) [$n = 78$; Bland and Altman (3; Bland-Altman) technique]. Dashed line, mean measurement difference (Heymsfield 4-Comp vs. Baumgartner 4-Comp); solid lines, ±2 SD of the mean measurement difference; n, no. of subjects. When subjects were placed into groups by age and gender, the following results were observed for mean measurement difference and ±2 SD, respectively: young women, −0.31 and 0.09 %Fat; older women, −0.29 and 0.15 %Fat; young men, −0.29 and 0.07 %Fat; older men, −0.28 and 0.19 %Fat.
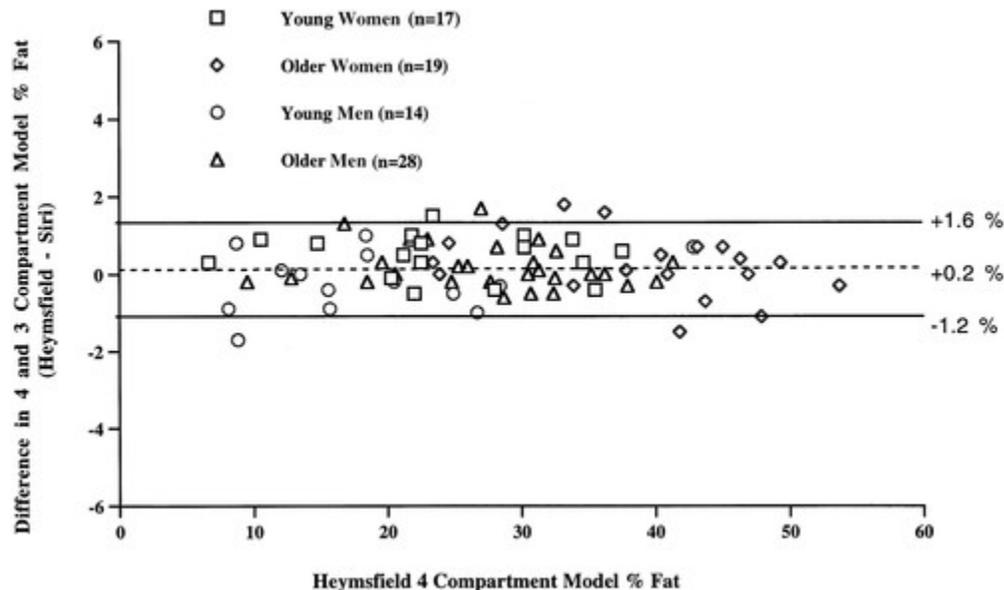

Fig. 2. Comparison of difference between Heymsfield 4-Comp model and 3-Comp model of Siri (36; Siri 3-Comp) for assessment of %Fat ($n = 78$; Bland-Altman technique). Mean measurement difference, Heymsfield 4-Comp vs. Siri 3-Comp. See Fig. 1 legend for definition of lines, symbols, and n. When subjects were placed into groups by age and gender, the following results were observed for mean measurement difference and ±2 SD, respectively: young women, 0.48 and 1.13 %Fat; older women, 0.24 and 1.68 %Fat; young men, −0.20 and 1.56 %Fat; older men, 0.19 and 1.14 %Fat.
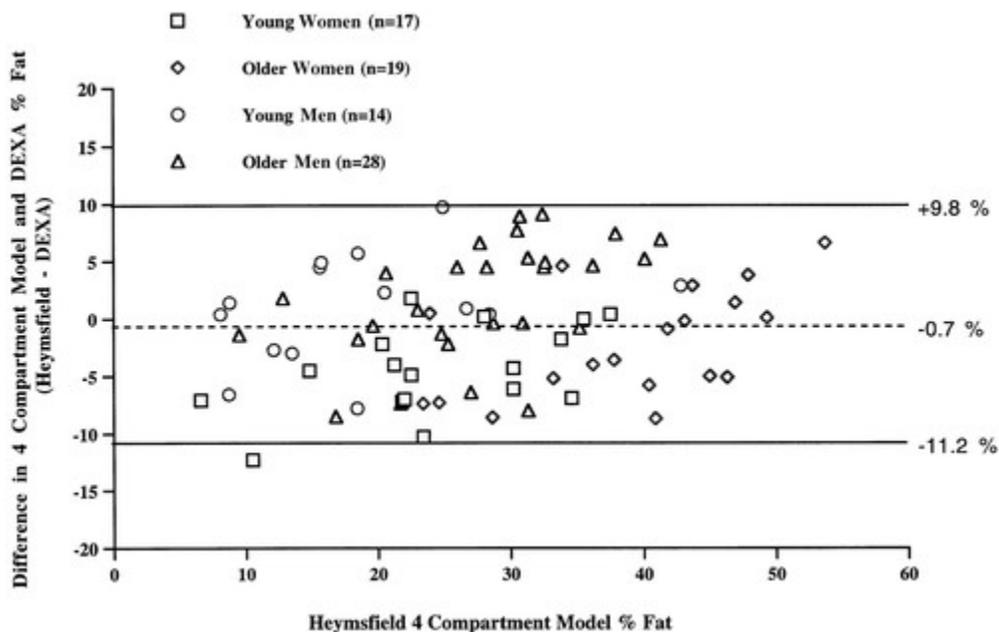
Fig. 3. Comparison of difference between Heymsfield 4-Comp and dual-energy X-ray absorptiometry (DEXA) models for assessment of %Fat ($n = 78$; Bland-Altman technique). Mean measurement difference, Heymsfield 4-Comp vs. DEXA. See Fig. 1 legend for definition of lines, symbols, and n. When subjects were placed into groups by age and gender, the following results were observed for mean measurement difference and ±2 SD, respectively: young women, −4.48 and 7.78 %Fat; older women, −2.21 and 9.39 %Fat; young men, 0.93 and 9.55 %Fat; older men, 1.70 and 10.27 %Fat.
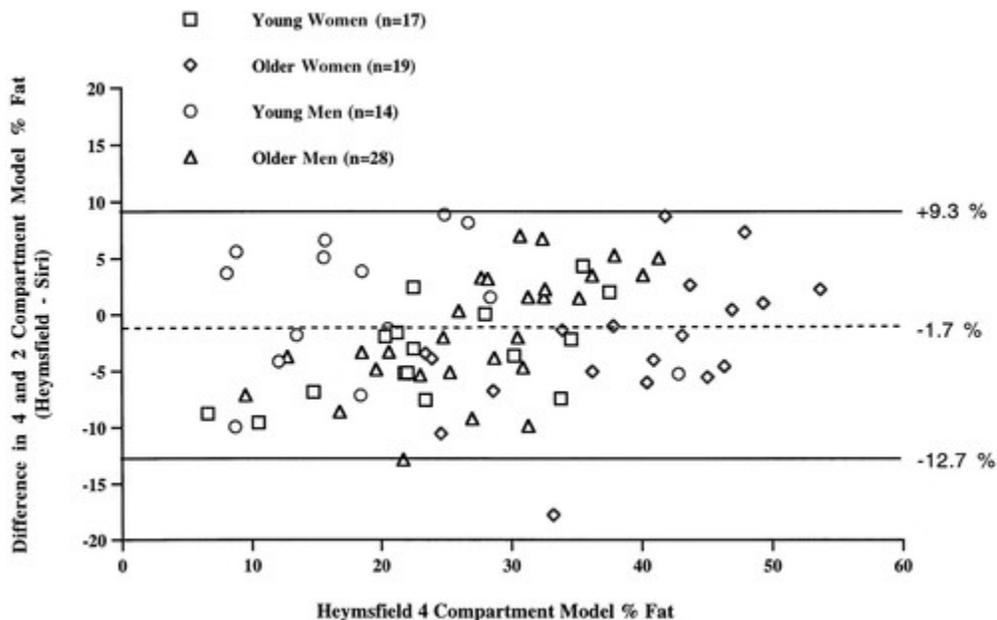

Fig. 4. Comparison of difference between Heymsfield 4-Comp model and 2-Comp model of Siri (35; Siri 2-Comp) for assessment of %Fat ($n = 78$; Bland-Altman technique). Mean measurement difference, Heymsfield 4-Comp vs. Siri 2-Comp. See Fig. 1 legend for definition of lines, symbols, and n. When subjects were placed into groups by age and gender, the following results were observed for mean measurement difference and ±2 SD, respectively: young women, −3.38 and 8.06 %Fat; older women, −2.59 and 12.01 %Fat; young men, 1.00 and 11.92 %Fat; older men, −1.46 and 10.72 %Fat.

Table 4 shows the relationship between the anthropometric predictions of %Fat and the 4-Comp criterion measure of %Fat. One young female subject and one older female subject did not have anthropometric measurements, thus reducing the number of subjects analyzed to 76. For all subjects combined, a significant main effect for body composition estimation was observed ($P = 0.001, F = 45.58$, df $= 225$). Mean comparisons revealed significant differences between the Heymsfield 4-Comp model and results obtained with the Jackson-Pollock ($P = 0.0001$) and Williams equations ($P = 0.0001$). Correlation coefficients ranged from $r = 0.770$ (Williams vs. Heymsfield 4-Comp) to $r = 0.823$ (Tran-Weltman vs. Heymsfield 4-Comp). TE around the line of identity ranged from ±6.24 %Fat (Tran-Weltman vs. Heymsfield 4-Comp) to ±9.07 %Fat (Jackson-Pollock vs. Heymsfield 4-Comp). Similar analyses were performed within each age group and gender.

Table 4. Comparison of anthropometric estimates of percent body fat with a criterion 4-Comp model

Model	Mean	SE	Mean Difference	r	TE, %
All subjects (n = 76)					
Heymsfield 4-Comp	27.9	1.3			
Jackson-Pollock	22.0	1.0	5.9*	0.775	9.07
Tran-Weltman	28.5	1.1	−0.6	0.823	6.24
Williams	24.6	1.1	3.3*	0.770	7.71
Young women (n = 16)					
Heymsfield 4-Comp	23.6	2.1			
Jackson-Pollock	21.2	1.7	2.4§	0.817	5.23
Tran-Weltman	28.8	1.2	−5.2§	0.773	7.44
Williams	21.7	1.8	1.9	0.786	5.38
Young men (n = 14)					
Heymsfield 4-Comp	18.7	2.5			
Jackson-Pollock	10.9	1.6	7.6‡	0.761	9.99
Tran-Weltman	16.9	1.5	1.6	0.805	6.04
Williams	14.5	1.7	4.2‡	0.811	6.98
Older women (n = 18)					
Heymsfield 4-Comp	39.1	2.2			
Jackson-Pollock	31.2	1.8	7.9†	0.653	10.74
Tran-Weltman	40.0	1.5	−0.9	0.873	4.76
Williams	33.3	1.7	5.8†	0.574	9.71
Older men (n = 28)					
Heymsfield 4-Comp	27.6	1.5			
Jackson-Pollock	22.1	1.1	5.5†	0.393	9.30
Tran-Weltman	26.8	1.0	0.8	0.572	6.40
Williams	25.7	1.3	1.9	0.426	7.88

Mean differences, correlation coefficients, and TE scores compared with Heymsfield 4-Comp model are shown. Significantly different: * $P < 0.0001$; † $P < 0.002$; ‡ $P < 0.01$; § $P < 0.03$.

For young women ($n = 16$), a significant main effect for body composition estimation was observed ($P = 0.001, F = 21.00$, df $= 45$). Mean comparisons revealed significant differences between the Heymsfield 4-Comp model and results obtained with the Jackson-Pollock ($P = 0.04$) and Tran-Weltman equations ($P = 0.0001$). Differences between the Williams equation and the Heymsfield 4-Comp model approached significance ($P = 0.09$). Correlation coefficients ranged from $r = 0.773$ (Tran-Weltman vs. Heymsfield 4-Comp) to $r = 0.817$ (Jackson-Pollock vs.

Heymsfield 4-Comp). TEs ranged from ±5.23 %Fat (Jackson-Pollock vs. Heymsfield 4-Comp) to ±7.44 %Fat (Tran-Weltman vs. Heymsfield 4-Comp).

For young men ($n = 14$), a significant main effect for body composition estimation was observed ($P = 0.001, F = 16.83$, df = 39). Mean comparisons revealed significant differences between the Heymsfield 4-Comp model and results obtained with the Jackson-Pollock ($P = 0.0001$) and Williams equations ($P = 0.01$). Correlation coefficients ranged from $r = 0.761$ (Jackson-Pollock vs. Heymsfield 4-Comp) to $r = 0.811$ (Williams vs. Heymsfield 4-Comp). TEs ranged from ±6.04 %Fat (Tran-Weltman vs. Heymsfield 4-Comp) to ±9.99 %Fat (Jackson-Pollock vs. Heymsfield 4-Comp).

For older women ($n = 18$), a significant main effect for body composition estimation was observed ($P = 0.001, F = 21.43$, df = 51). Mean comparisons revealed significant differences between the Heymsfield 4-Comp model and results obtained with the Jackson-Pollock ($P = 0.0001$) and Williams equations ($P = 0.002$). Correlation coefficients ranged from $r = 0.574$ (Williams vs. Heymsfield 4-Comp) to $r = 0.873$ (Tran-Weltman vs. Heymsfield 4-Comp). TEs ranged from ±4.76 %Fat (Tran-Weltman vs. Heymsfield 4-Comp) to ±10.74 %Fat (Jackson-Pollock vs. Heymsfield 4-Comp).

For older men ($n = 28$), a significant main effect for body composition estimation was observed ($P = 0.0001, F = 9.727$, df = 81). Mean comparisons revealed significant differences between the Heymsfield 4-Comp model and the Jackson-Pollock equation ($P = 0.002$). Correlation coefficients ranged from $r = 0.393$ (Jackson-Pollock vs. Heymsfield 4-Comp) to $r = 0.572$ (Tran-Weltman vs. Heymsfield 4-Comp). TEs ranged from ±6.40 %Fat (Tran-Weltman vs. Heymsfield 4-Comp) to ±9.30 %Fat (Jackson-Pollock vs. Heymsfield 4-Comp).

Figures 5-7 show the Bland-Altman plots for the Jackson-Pollock, Tran-Weltman, and Williams equations vs. the Heymsfield 4-Comp model. For the Jackson-Pollock equation (Fig. 5), mean differences for the different age and gender groups ranged from 2.4 to 7.9 %Fat, and the 95% confidence intervals ranged from ±9.6 to ±15.3 %Fat. For the Tran-Weltman equations (Fig.6), mean differences for the different age and gender groups ranged from −5.2 to 1.8 %Fat, and the 95% confidence intervals ranged from ±9.7 to ±12.9 %Fat. For the Williams equation (Fig. 7), mean differences for the different age and gender groups ranged from 1.8 to 5.8 %Fat, and the 95% confidence intervals ranged from ±10.3 to ±15.6 %Fat.
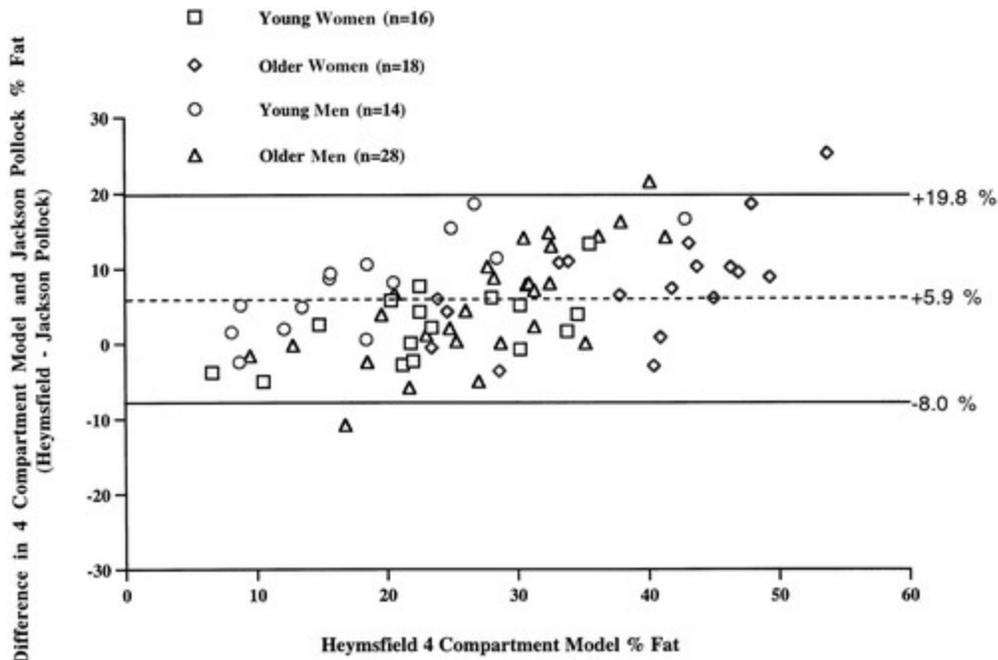
Fig. 5. Comparison of difference between Heymsfield 4-Comp and Jackson and Pollock and Jackson et al. (16, 17; Jackson-Pollock) models for assessment of %Fat ($n = 76$; Bland-Altman technique). Mean measurement difference, Heymsfield 4-Comp vs. Jackson-Pollock. See Fig. 1 legend for definition of lines, symbols, and n. When subjects were placed into groups by age and gender, the following results were observed for mean measurement difference and ±2 SD, respectively: young women, 2.41 and 9.59 %Fat; older women, 7.90 and 14.31 %Fat; young men, 7.91 and 12.64 %Fat; older men, 5.49 and 15.27 %Fat.
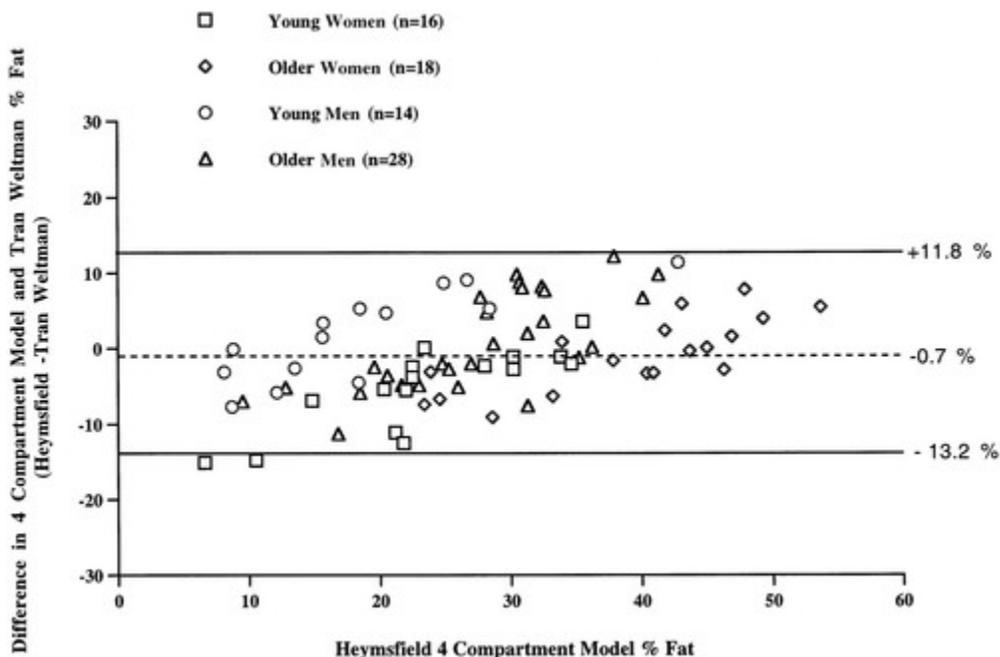

Fig. 6. Comparison of difference between Heymsfield 4-Comp and Tran and Weltman (38, 39; Tran-Weltman) models for assessment of %Fat ($n = 76$; Bland-Altman technique). Mean measurement difference, Heymsfield 4-Comp vs. Tran-Weltman. See Fig. 1 legend for definition of lines, symbols, and n. When subjects were placed into groups by age and gender, the following results were observed for mean measurement difference and ±2 SD, respectively: young women, −5.18 and 11.02 %Fat; older women, −0.87 and 9.71 %Fat; young men, 1.83 and 11.94 %Fat; older men, 0.84 and 12.93 %Fat.
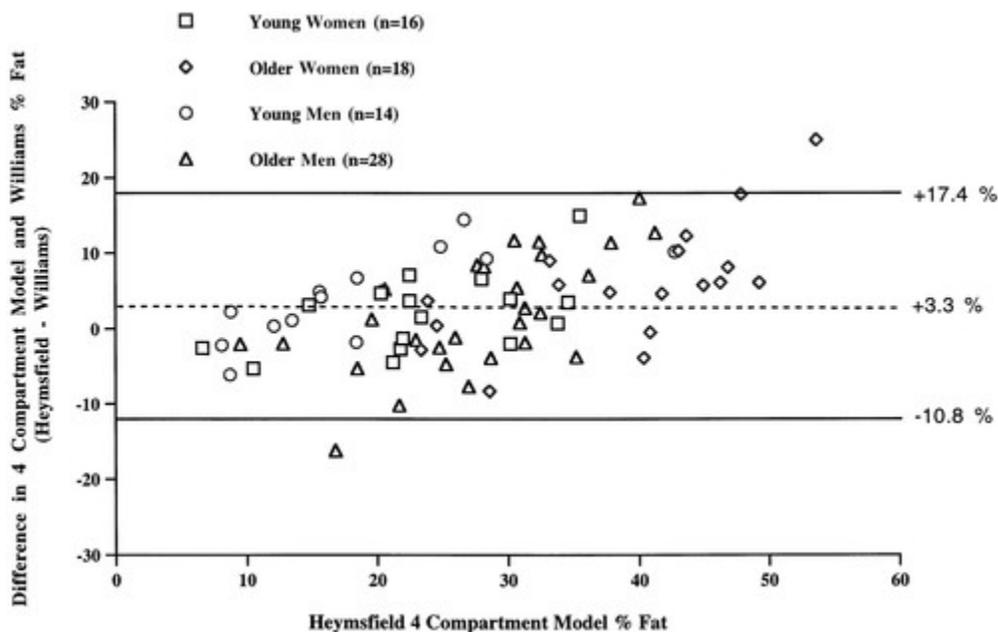
Fig. 7. Comparison of difference between Heymsfield 4-Comp and Williams et al. (41; Williams) models for assessment of %Fat ($n = 76$; Bland-Altman technique). Mean measurement difference, Heymsfield 4-Comp vs. Williams. See Fig. 1 legend for definition of lines, symbols, and n. When subjects were placed into groups by age and gender, the following results were observed for mean measurement difference and ± 2 SD, respectively: young women, 1.96 and 10.34 %Fat; older women, 5.79 and 15.59 %Fat; young men, 4.23 and 11.53 %Fat; older men, 1.87 and 15.60 %Fat.

DISCUSSION

Until recently, the criterion measure of body composition has utilized a 2-Comp model in which body weight is partitioned into FM and FFM (35). The limitation of this model is that the assumptions made about the composition of FFM may not apply to all subjects (15, 40). In certain samples of subjects, changes in TBW or BMC may lead to inaccurate results when 2-Comp models are used. There are several potential problems associated with applying a 2-Comp hydrostatic weighing model in physically trained or in young and older adults (1,21, 27). Changes in TBW or BMC that may occur with training or age may violate the basic assumptions of these models (15, 40). Cross-sectional studies indicate that changes in TBW with aging are attributed to decreases in intracellular fluid and the corresponding loss of body cell mass, whereas extracellular fluid either is preserved or may be increased (4, 23, 30, 33). Baumgartner et al. (1) noted that the differences between estimates of %Fat with 2- and 4-Comp models in older persons have been associated with significant variation in the aqueous fraction or hydration of FFM. The inclusion of the aqueous and mineral fractions in a 4-Comp model provided increased accuracy over the 2-Comp model. Furthermore, the addition of the mineral fraction provided only a marginal increase in the accuracy in their sample, leading to the conclusion that the addition of the aqueous fraction into the 4-Comp model accounted for most of the biological variability in FFM (1). Williams et al. (41) have also suggested that both the aqueous and the mineral fractions of the 4-Comp FFM are significantly and independently related to the change in %Fat in white men and women aged 49–82 yr. More specifically, the aqueous fraction of the 4-Comp FFM accounted for the largest share of the variance in %Fat in men; whereas, in

women, the mineral fraction of the 4-Comp FFM accounted for the largest portion of the variance in %Fat. Recent data of Modlesky et al. (27) suggest that intense training may also have an impact. They reported that weight trainers had lower density of the FFM because of higher water and lower mineral and protein fractions of the FFM. In contrast, recent data of Visser et al. (40) suggest that, on a group level, the underlying assumptions about TBW and BMC for use in a 2-Comp model using hydrostatic weighing are valid in black, older, and mildly-to-moderately obese subjects. That is, in healthy adults ranging in age from 20 to 94 yr, FFM density was not associated with race, age, or level of body fatness, and the mean FFM density was not significantly different from 1.100 kg/l in any subgroup. However, the individual variation in FFM density was considerable and mainly caused by individual differences in the water fraction of the FFM. The authors suggest that, when results were examined on an individual level, the use of a 4-Comp model would be more accurate and would be advisable in those studies in which individual values are important or small groups of subjects are being compared (40).

Results of the present study show that estimations of %Fat by using 2-Comp Siri model, DEXA, and anthropometry differ significantly from a 4-Comp model in young and older men and women (Table 3, Figs.1-4). The present data indicate that the Heymsfield (Ref. 15; developed on a wide age range) and the Baumgartner (Ref. 1; developed on older individuals) 4-Comp models provide virtually identical results independent of age and gender (Table 3, Fig. 1). Results of the present study also support previous findings which suggest that variation in the aqueous fraction of the FFM plays an important role in the error in the estimation of %Fat with a 2-Comp model (1, 40). That is, comparison of the Siri 3-Comp model with the Heymsfield 4-Comp model revealed mean differences of ≤0.4 %Fat, r values ≥ 0.997, TE values ≤ 0.85 %Fat, and 95% confidence intervals (Bland-Altman) of ≤1.7 %Fat (Table 3, Fig. 2). These data indicate that, when the use of a 4-Comp model is not available, the Siri 3-Comp model is a valid and highly accurate alternative.

When 2- and 4-Comp models were compared, mean differences ranged between 1 and 3 %Fat. These data compare favorably with the recent findings of Visser et al. (40), who reported average group errors of <2 %Fat when hydrostatic weighing was compared with a 4-Comp model. Although the group differences in the present study were relatively small (Table 3), the individual variability associated with the 2-Comp model was considerable. For hydrostatic weighing, TE scores ranged from ±5.17 to ±6.39 %Fat (Table 3), and 95% confidence intervals associated with the Bland-Altman analysis ranged from ±5.1 to ±12.0 %Fat (Fig. 4).

The advent of DEXA has resulted in an improvement in the accuracy and precision of BMC and real bone mineral density (g/cm^2) measurements (19, 25,32). It has been suggested that DEXA can also be used as an independent estimate of body composition (19, 25). Because many DEXA instruments allow for the partitioning of the soft tissue into fat and fat-free components, it is possible to develop an independent 3-Comp model of body composition consisting of total body bone mineral, mineral-free lean tissue mass, and FM (19, 25). It has been suggested that, because DEXA is less dependent on assumptions regarding biological consistency, it has the potential to provide a more accurate assessment of body composition than the 2-Comp hydrostatic weighing model does (19). However, the accuracy of assessment of soft tissue by DEXA in different populations of subjects remains to be established (19). In the present study, mean differences between %Fat estimates by DEXA and 4-Comp model ranged from 0.9 to 4.5%, with the largest

mean differences in the young women. However, when all subjects were considered, the mean difference of −0.7 %Fat did not reach statistical significance. The DEXA TE scores ranged from ±4.69 to ±5.86 %Fat (Table 3), and 95% confidence intervals associated with the Bland-Altman analysis ranged from ±7.8 to ±10.5 %Fat (Fig. 3).

Thus the errors associated with estimation of %Fat by DEXA are similar to those associated with hydrostatic weighing. The fact that both hydrostatic weighing and DEXA assume a constant hydration state for the FFM of all individuals (73.2%) may have contributed significantly to the large individual errors in the estimation of %Fat by both DEXA and the 2-Comp model. Snead et al. (37) reported that, although good agreement in %Fat estimates by 2-Comp hydrodensitometry and DEXA (Hologic QDR-1000, Waltham, MA) was reported in young people, in older individuals discrepancies between the methods were observed. These investigators identified potential problems with DEXA for assessing %Fat in older adults by manipulating the FM by placing lard over the center and peripheral regions of the body. Exogenous FM was correctly assessed when it was positioned over the lower body (96% of the exogenous fat was identified correctly) but was markedly underestimated when the exogenous fat was overlying the trunk region (only 55% of the exogenous fat was identified correctly) (37). It was speculated that the inaccurate assessment of soft tissue may be related to the fact that soft tissue evaluation is possible only in those pixels that do not contain bone mineral. The authors suggest that, in those individuals with increased upper body adipose tissue (i.e., obese, older individuals), DEXA may underestimate %Fat. Similar findings were reported in young adults by using a Lunar DPX-L (Lunar, Madison, WI) (26). These investigators reported that exogenous FM was underestimated both at the thigh and at the abdomen, with a greater underestimation observed at the abdomen. In contrast, Mazess (24) has suggested that the techniques used by Snead et al. (37) and Milliken et al. (26) are inappropriate as they do not simulate physiological changes of composition. He states that the addition of packets of lard, water, or ground beef on human subjects resulted in regional changes of %Fat of only ~1%. He argues that these changes are within the measurement error reported for %Fat when DEXA is used.

In addition, it should be realized that other concerns regarding DEXA assessment of %Fat exist. Variability exists in the methods of calibration, data acquisition, and data analysis among manufacturers (19). These concerns can be partially addressed by the use of a central quality assurance center for analysis of DEXA data in multicenter trials. It has been suggested that errors associated with varying tissue thickness, hydration status, and the estimation of soft tissue composition in regions surrounding bone must be investigated (19). Finally, our results suggest that specific manufacturer-derived regression equations developed for DEXA %Fat estimation need to be validated by using accepted criterion measures (i.e., 4-Comp models or neutron activation analysis).

Although the 2-Comp and more recently the 4-Comp and neutron activation analysis models for body composition assessment have been considered as criterion techniques for body composition assessment (1, 5, 15, 35), the applicability of these methods in clinical and field settings is often not feasible. This has led to the development of numerous alternative techniques for body composition estimation. The application of skinfold and girth techniques for the estimation of body composition has become a convenient and popular technique for body composition estimation. Population-specific and generalized equations based on the 2-Comp model as well as

more recent equations based on the 4-Comp model of body composition measurement have been presented in the literature (16, 17, 38, 39, 41). To our knowledge, these equations have not been cross validated against a criterion 4-Comp model. The present data suggest that commonly used anthropometric estimates of %Fat are associated with unacceptably high error compared with the Heymsfield 4-Comp model (Table 4, Figs. 5-7). Although %Fat values estimated with these techniques were reasonably correlated with %Fat measured by the Heymsfield 4-Comp model (Table 4) in young subjects, this was not always the case in the older subjects. Mean differences ranged from ~1 to 8 %Fat (Table 4), TE values of ±4.8 to ±10.7 %Fat were observed, and the 95% confidence intervals associated with the Bland-Altman analysis were ±8.0 to ±15.0 %Fat (Figs. 5-7). Our data suggest that estimation of %Fat with equations utilizing girth measurements may be more accurate than estimation with those equations utilizing skinfold measurements. Overall, the mean difference of −0.6 %Fat between the Tran-Weltman equations and the 4-Comp model did not reach statistical significance. In contrast, the %Fat estimates by the Jackson-Pollock and Williams equations were significantly different from %Fat measured with the 4-Comp model. Nevertheless, the present data indicate that caution should be used when employing these predictive techniques in a clinical or a field setting.

It should be realized that, although the 4-Comp models employed in the present study have advantages over 2-Comp and DEXA estimates of %Fat, the 4-Comp model relies on certain assumptions (40) and is also subject to error from the combined technical errors that occur when each component is estimated separately. The law of propagation of error indicates that when FFM is estimated from the sum of TBW, BMC, and protein, the technical errors in each of these estimate components affect the TE in estimating FFM. As long as the technical errors are relatively small in each of these components, the cumulative error is also relatively small. Despite these limitations, the 4-Comp model is, presently, the best in vivo body composition model available (40).

In summary, data of the present study suggest that the Siri 3-Comp model provides valid and accurate body composition data when compared with the Heymsfield 4-Comp model. Although the use of Siri 2-Comp and DEXA 3-Comp models may be acceptable for the estimation of group mean %Fat (resulting in mean differences of ~2 to 3 %Fat compared with the Heymsfield 4-Comp model), the individual variability associated with these models may limit their use in research settings in which individual changes are important and/or small groups of subjects are studied. In addition, the use of anthropometric estimation methods resulted in large mean differences and a considerable amount of interindividual variability. These data suggest that the use of these techniques, even in a nonresearch setting, should be viewed with caution.

References

1. Baumgartner, R. N., S. B. Heymsfield, S. Lichtman, J. Wang, and R. N. Pierson, Jr. Body composition in elderly people: effect of criterion estimates on predictive equations. Am. J. Clin. Nutr. 53: 1345–1353, 1991.

2. Bemben, M. G., B. H. Massey, D. A. Bembem, R. A. Boileau, and J. E. Misner. Age-related variability in body composition methods for assessment of percent fat and fat-free mass in men aged 20–74 years. Age Ageing 27: 147–153, 1998.

3. Bland, J. M., and D. G. Altman. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1: 307–310, 1986.

4. Borkan, G. A., and A. H. Norris. Fat redistribution and the changing body dimensions of the adult male. Hum. Biol. 49: 495–514, 1977.

5. Brozek, J., F. Grande, J. T. Anderson, and A. Keys. Densitometric analysis of body composition: revision of some quantitative assumptions. Ann. NY Acad. Sci. 110: 113–140, 1963.

6. Callaway, C. W., W. C. Chumlea, C. Bouchard, J. H. Hines, T. G. Lohman, A. D. Martin, C. D. Mitchell, W. H. Mueller, A. F. Roche, and V. O. Seefeldt. Circumferences. In: Anthropometric Standardization Reference Manual, edited by T. G. Lohman, A. F. Roche, and R. Martoell. Champaign, IL: Human Kinetics, 1988, p. 39–54.

7. Clasey, J. L., M. L. Hartman, J. Kanaley, L. Wideman, C. D. Teates, C. Bouchard, and A. Weltman. Body composition by DXA in older adults: accuracy and influence of scan mode. Med. Sci. Sports Exerc. 29: 560–567, 1997.

8. Fogelholm, G. M., H. T. Sievanen, W. D. van Marken Lichtenbelt, and K. R. Westerterp. Assessment of fat-mass loss during weight reduction in obese women. Metabolism 46: 968–975, 1997.

9. Forslund, A. H., A. G. Johansson, A. Sjodin, G. Bryding, S. Ljunghall, and L. Hambraeus. Evaluation of modified multicompartment models to calculate body composition in healthy men. Am. J. Clin. Nutr. 63: 856–862, 1996.

10. Friedel, K. E., J. P. DeLuca, L. J. Marchietelli, and J. A. Vogel. Reliability of body-fat estimations from a four-compartment model by using density, body water, and bone mineral measurements. Am. J. Clin. Nutr. 55: 764–770, 1992.

11. Goran, M. I., E. T. Poehlman, E. Danforth, Jr., and K. S. Nair. Comparison of body fat estimates derived from underwater weight and total body water. Int. J. Obes. 18: 622–626, 1994.

12. Harrison, G. G., E. R. Buskirk, J. E. L. Carter, F. E. Johnson, T. G. Lohman, M. L. Pollock, A. F. Roche, and J. Wilmore. Skinfold thicknesses and measurement technique. In: Anthropometric Standardization Reference Manual, edited by T. G. Lohman, A. F. Roche, and R. Martoell. Champaign, IL: Human Kinetics, 1988, p. 55–70.

13. Heiling, V. J., J. M. Miles, and M. D. Jensen. How valid are isotopic measurements of fatty acid oxidation? Am. J. Physiol. 261 (Endocrinol. Metab. 24): E572–E577, 1991.

14. Hewitt, M. J., S. B. Going, D. P. Williams, and T. G. Lohman. Hydration of the fat-free body mass in children and adults: implications for body composition assessment. Am. J. Physiol. 265 (Endocrinol. Metab. 28): E88–E95, 1993.

15. Heymsfield, S. B., S. Lichtman, R. N. Baumgartner, J. Wang, Y. Kamen, A. Aliprantis, and R. N. Pierson, Jr. Body composition of humans: comparison of two improved four-compartment models that differ in expense, technical complexity, and radiation exposure. Am. J. Clin. Nutr. 52: 52–58, 1990.

16. Jackson, A. S., and M. L. Pollock. Generalized equations for predicting body density of men. Br. J. Nutr. 40: 497–504, 1978.

17. Jackson, A. S., M. L. Pollock, and A. Ward. Generalized equations for predicting body density of women. Med. Sci. Sports Exerc. 12: 175–182, 1980.

18. Katch, F. I., E. D. Michael, and S. M. Horvath. Estimation of body volume by underwater weighing: description of a simple method. J. Appl. Physiol. 23: 811–813, 1967.

19. Kohrt, W. M. Body composition by DXA: tried and true? Med. Sci. Sports Exerc. 27: 1349–1353, 1995.

20. Lohman, T. G. Applicability of body composition techniques and constants for children and youths. Exerc. Sport Sci. Rev. 14: 325–357, 1986.

21. Lohman, T. G. Assessment of body composition in children. Pediatr. Exerc. Sci. 1: 19–30, 1989.

22. Lohman, T. G., M. H. Slaughter, R. A. Boileau, J. Bunt, and L. Lussier. Bone mineral measurements and their relation to body density in children, youth, and adults. Hum. Biol. 56: 667–679, 1984.

23. Mazariegos, M., Z. Wang, D. Gallagher, R. N. Baumgartner, D. B. Allison, J. Wang, R. N. Pierson, Jr., and S. B. Heymsfield. Difference between young and old females in the five levels of body composition and their relevance to the two-compartment chemical model. J. Gerontol. 49: M201–M208, 1994.

24. Mazess, R. B. Inappropriate testing of DEXA in vitro. Int. J. Obes. 21: 162, 1997.

25. Mazess, R. B., H. S. Barden, J. P. Bisek, and J. Hanson. Dual-energy X-ray absorptiometry for total body and regional bone-mineral and soft-tissue composition. Am. J. Clin. Nutr. 51: 1106–1112, 1990.

26. Milliken, L. A., S. B. Going, and T. G. Lohman. Effects of variations in regional composition on soft tissue measurements by dual-energy X-ray absorptiometry. Int. J. Obes. 20: 677–682, 1996.

27. Modlesky, C. M., K. J. Cureton, R. D. Lewis, B. M. Prior, M. A. Sloniger, and D. A. Rowe. Density of fat-free mass and estimates of body composition in male weight trainers. J. Appl. Physiol. 80: 2085–2096, 1996.

28. Nelson, M. E., M. A. Fiatarone, J. E. Layne, I. Trice, C. D. Economos, R. A. Fielding, R. Ma, R. N. Pierson, and W. J. Evans. Analysis of body-composition techniques and models for detecting change in soft tissue with strength training. Am. J. Clin. Nutr. 63: 678–686, 1996.

29. Nielsen, D. H., S. L. Cassady, K. F. Janz, J. S. Cook, J. R. Hansen, and Y. T. Wu. Criterion methods of body composition analysis for children and adolescents. Am. J. Hum. Biol. 5: 211–223, 1993.

30. Pierson, R. N., Jr., J. Wang, J. C. Thornton, T. B. Van Itallie, and E. W. D. Colt. Body potassium by 4-pi counting: an anthropometric correction. Am. J. Physiol. 245 (Renal Fluid Electrolyte Physiol. 14): F234–F239, 1983.

31. Roemmich, J. N., P. A. Clark, A. Weltman, and A. D. Rogol. Alterations in growth and body composition during puberty. I. Comparing multicompartment body composition models. J. Appl. Physiol. 83: 927–935, 1997.

32. Roubenoff, R., J. J. Kehayias, B. Dawson-Hughes, and S. B. Heymsfield. Use of dual-energy X-ray absorptiometry in body-composition studies: not yet a ''gold-standard.'' Am. J. Clin. Nutr. 58: 589–591, 1993.

33. Schoellar, D. A. Changes in total body water with age. Am. J. Clin. Nutr. 50: 1176–1181, 1989.

34. Seip, R. L., D. Snead, and A. Weltman. Validity of anthropometric techniques for estimating percentage body fat in obese females before and after sizable weight loss. Am. J. Hum. Biol. 5: 549–557, 1993.

35. Siri, W. E. The gross composition of the body. In: Advances in Biological and Medical Physics IV, edited by C. A. Tobias and J. H. Lawrence. New York: Academic, 1956.

36. Siri, W. E. Body composition from fluid spaces and density. Analysis of methods. In: Techniques for Measuring Body Composition, edited by J. Brozek and A. Henschel. Washington, DC: National Academy of Sciences, National Research Council, 1961, p. 223–244.

37. Snead, D. B., S. J. Birge, and W. M. Kohrt. Age-related differences in body composition by hydrodensitometry and dual-energy X-ray absorptiometry. J. Appl. Physiol. 74: 770–775, 1993.

38. Tran, Z. V., and A. Weltman. Predicting body composition of men from girth measurements. Hum. Biol. 60: 167–175, 1988.

39. Tran, Z. V., and A. Weltman. Generalized equation for predicting body density of women from girth measurements. Med. Sci. Sports Exerc. 21: 101–104, 1989.

40. Visser, M., D. Gallagher, P. Duerenberg, J. Wang, R. N. Pierson, and S. B. Heymsfield. Density and fat-free body mass: relationship with race, age, and level of fatness. Am. J. Physiol. 272 (Endocrinol. Metab. 35): E781–E787, 1997.

41. Williams, D. P., S. B. Going, T. G. Lohman, M. J. Hewitt, and A. E. Haber. Estimation of body fat from skinfold thicknesses in middle-aged and older men and women: a multiple component approach. Am. J. Hum. Biol. 4: 595–605, 1992.

42. Williams, D. P., S. B. Going, L. A. Milliken, M. C. Hall, and T. G. Lohman. Practical techniques for assessing body composition in middle-aged and older adults. Med. Sci. Sports Exerc. 27: 776–783, 1995.

43. Wilmore, J. H. A simplified method for the determination of residual lung volume. J. Appl. Physiol. 27: 96–100, 1969