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Muscularity and the density of the fat-free mass in athletes

BARRY M. PRIOR, CHRISTOPHER M. MODLESKY, ELLEN M. EVANS, MARK A. SLONIGER, MICHAEL J. SAUNDERS, RICHARD D. LEWIS, AND KIRK J. CURETON

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Prior, Barry M., Christopher M. Modlesky, Ellen M. Evans, Mark A. Sloniger, Michael J. Saunders, Richard D. Lewis, and Kirk J. Cureton. Muscularity and the density of the fat-free mass in athletes. *J Appl Physiol* 90: 1523–1531, 2001.—The purpose of this study was to use estimates of body composition from a four-component model to determine whether the density of the fat-free mass (D_{FFM}) is affected by muscularity or musculoskeletal development in a heterogeneous group of athletes and nonathletes. Measures of body density by hydrostatic weighing, body water by deuterium dilution, bone mineral by whole body dual-energy X-ray absorptiometry (DXA), total body skeletal muscle estimated from DXA, and musculoskeletal development as measured by the mesomorphy rating from the Heath-Carter anthropometric somatotype were obtained in 111 collegiate athletes (67 men and 44 women) and 61 nonathletes (24 men and 37 women). In the entire group, D_{FFM} varied from 1.075 to 1.127 g/cm³ and was strongly related to the water and protein fractions of the fat-free mass (FFM; $r = -0.96$ and 0.89) and moderately related to the mineral fraction of the FFM ($r = 0.65$). Skeletal muscle (%FFM) varied from 40 to 68%, and mesomorphy varied from 1.6 to 9.6, but neither was significantly related to D_{FFM} ($r = 0.11$ and -0.14) or to the difference between percent fat estimated from the four-component model and from densitometry ($r = 0.09$ and -0.16). We conclude that, in a heterogeneous group of young adult athletes and nonathletes, D_{FFM} and the accuracy of estimates of body composition from body density using the Siri equation are not related to muscularity or musculoskeletal development. Athletes in selected sports may have systematic deviations in D_{FFM} from the value of 1.1 g/cm³ assumed in the Siri equation, resulting in group mean errors in estimation of percent fat from densitometry of 2–5% body mass, but the cause of these deviations is complex and not simply a reflection of differences in muscularity or musculoskeletal development.

body composition; body water; bone mineral; densitometry; dual-energy X-ray absorptiometry; multicomponent models

ESTIMATES OF BODY COMPOSITION are used to assess nutritional status, disease risk, and physical fitness and to separate the body mass (BM) into metabolically active and inactive components (11). In athletes, body compo-

sition measures are widely used to prescribe desirable body weights, to optimize competitive performance, and to assess the effects of training (34). Traditional indirect methods for evaluating body composition in humans, such as densitometry, hydrometry, and ⁴⁰K spectrometry, are based on a two-component model in which it is assumed that the body consists of fat and fat-free components (35). Densitometry, long considered the most accurate indirect method (13), assumes that the body consists of a fat component with a density of 0.9007 g/cm³ and a fat-free component with a density (D_{FFM}) of 1.1 g/cm³. The fat-free mass (FFM) is assumed to be composed of 73.8% water with a density of 0.9937 g/cm³, 6.8% mineral with a density of 3.038 g/cm³, and 19.4% protein with a density of 1.34 g/cm³ (5). Variability in D_{FFM} is the primary factor limiting the accuracy of body composition estimates from body density (35), but the extent of variability in atypical groups, such as athletes, is not established.

It has been suggested that the density and composition of the FFM of athletes with atypical muscularity and bone mass may differ from assumed values; therefore, estimates of body composition from densitometry using a two-component model may be inaccurate (20, 44). However, the effect of musculoskeletal development on body composition estimated from body density is difficult to predict. Increased muscularity should decrease D_{FFM} , because the density of fat-free muscle is ~ 1.066 g/cm³ (1), whereas increased skeletal development should increase D_{FFM} , because the density of bone mineral is ~ 3.317 g/cm³ (5). If muscle and bone vary in proportion, the effect on D_{FFM} may be dominated by bone because of its greater density (23, 47). However, bone and muscle may not vary in proportion. Modlesky et al. (26) found that the D_{FFM} in weight lifters with high musculoskeletal development was 1.089 ± 0.005 g/cm³. The lower than assumed D_{FFM} was due to high water and low mineral content of the FFM, apparently because muscle, with high water content, was increased disproportionately relative to bone. Withers et al. (46) reported similar results for bodybuilders. Whether the effect of musculoskeletal devel-

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opment on D_{FFM} observed in those studies can be generalized to other groups of athletes is uncertain.

Until recently, estimates of D_{FFM} in vivo were limited by the ability to accurately measure the FFM. Technological advances have led to the development of methods for estimating body composition using a four-component (fat, water, mineral, protein) model based on measurements of body density, water, and bone mineral (21, 22). Estimates of fat and FFM based on a four-component model are more accurate than those from body density, because fewer assumptions are made concerning the composition of FFM by accounting for variations in body water and mineral, which are among the most variable components of FFM (3, 22). Studies on some small groups of athletes have found systematic differences between estimates of percent fat based on a four-component model and estimates from body density (26, 46), indicating D_{FFM} different from 1.1 g/cm³, whereas studies of other groups have not (2, 31, 45).

The primary purpose of this study was to use estimates of body composition from a four-component model to determine whether muscularity or musculoskeletal development affects D_{FFM} and, thus, the accuracy of estimates of body composition from body density using the Siri equation in a heterogeneous group of athletes and nonathletes. On the basis of the study of Modlesky et al. (26), we hypothesized that muscularity and musculoskeletal development would be inversely related to D_{FFM} . In individuals with high and low muscularity or musculoskeletal development, we hypothesized that estimates of percent fat from body density would overestimate and underestimate, respectively, percent fat based on a four-component model.

METHODS

Subjects. One hundred seventy-two young men and women, 111 collegiate athletes and 61 nonathletes, participated in the study. Varsity athletes were recruited from the University of Georgia football (41 men), basketball (7 men

and 1 woman), volleyball (5 women), gymnastics (11 women), swimming (10 men and 14 women), and track and field (9 men and 13 women) teams. Twenty-nine of the male and 10 of the female athletes were black; the others were white. Male and female nonathletes who were active in recreational activities but who did not participate in >20 min of exercise three times per week were recruited as reference groups from the university student population. Ten of the male and 13 of the female nonathletes were black; the others were white. The study was approved by the University's Institutional Review Board, and written consent was obtained before testing. Physical characteristics of the subjects are summarized in Table 1.

Protocol. Physical characteristics, anthropometric measurements, body density, total body water, and total body bone mineral were measured during a single test session lasting ~3.5 h. Subjects were instructed not to perform vigorous activity 24 h before the test session. They reported to the laboratory after 8–12 h without food or beverages except water and were asked to arrive at the laboratory well hydrated. Hydration was normal as indicated by urine specific gravity (1.020 ± 0.009 g/ml). All individuals were within 2 SDs of the mean. Subjects did not consume food or beverage during the session.

Densitometry. Body density was measured using underwater weighing and Archimedes' principle to determine body volume. BM in air was measured using an electronic scale to the nearest 0.05 kg. BM under water was measured using an autopsy scale (Chatillon, Greensboro, NC) to the nearest 0.025 kg. Residual lung volume was measured at the time of underwater weighing using an oxygen-rebreathing, nitrogen-dilution technique modified from Goldman and Buskirk (14). Volume of gas in the gastrointestinal tract was assumed to be 0.1 liter. The within-subjects SD of replicate measurements of body density on 2 days ~1 wk apart was 0.0016 g/cm³ (26).

Body water. Total body water was determined by deuterium (D_2O) dilution. After a baseline blood sample, subjects ingested a known quantity of D_2O [0.31 ± 0.01 (SD) g/kg BM] in 100 ml of distilled water and rinsed with an additional 100 ml of distilled water to ensure complete ingestion of the tracer. After a 3-h equilibration period during which all urine was collected, another blood sample was taken. Blood samples were centrifuged at 3,000 rpm for 20 min, and the plasma was stored at -80°C. Plasma samples were purified by diffusion (10); equal volumes (3 ml) of plasma and distilled

Table 1. Subject characteristics, body composition, and musculoskeletal development by gender and athletic status

	Female Nonathletes (n = 37)	Male Nonathletes (n = 24)	Female Athletes (n = 44)	Male Athletes (n = 67)
Age, yr	22.3 ± 2.4	22.3 ± 2.8	20.6 ± 2.8	20.8 ± 1.7
Height, cm	164.6 ± 5.2	176.7 ± 4.4	166.0 ± 8.0	185.1 ± 7.7
Mass, kg	62.5 ± 14.0	72.2 ± 8.3	60.7 ± 7.7	97.8 ± 19.7
%Fat _D	27.8 ± 6.4	13.9 ± 4.0	18.4 ± 5.8	14.6 ± 5.8†
%Fat _{D,W,M}	27.3 ± 6.9	14.1 ± 4.7	18.2 ± 5.4	11.9 ± 6.2
D_{FFM} , g/cm ³	1.098 ± 0.013	1.101 ± 0.006	1.099 ± 0.011	1.093 ± 0.007*
W/FFM, %	73.1 ± 3.9	72.1 ± 1.8*	72.9 ± 2.9	74.2 ± 1.7
M/FFM, %	6.2 ± 0.5*	6.1 ± 0.5*	6.3 ± 0.6*	5.8 ± 0.5*
P/FFM, %	20.6 ± 3.7	21.8 ± 1.8*	20.8 ± 2.6*	20.0 ± 1.6*
Mesomorphy	4.2 ± 1.5	4.9 ± 1.1	4.1 ± 1.1	6.6 ± 1.6
SM/FFM _{D,W,M} , %	50.5 ± 5.4	58.1 ± 3.6	54.4 ± 4.1	60.0 ± 3.7
SM/FFM _{DXA} , %	51.4 ± 4.9	57.2 ± 3.6	53.8 ± 3.6	61.0 ± 3.9

Values are means ± SD; n, number of subjects. D_{FFM} , density of fat-free mass; W, total body water; M, total body mineral; P, total body protein; SM, total body skeletal muscle mass from dual-energy X-ray absorptiometry (DXA); FFM, fat-free mass estimated using 4-component model. *Significantly different from values based on cadaver analysis (5): $D_{\text{FFM}} = 1.100$ g/cm³, W/FFM = 73.8%, M/FFM = 6.8%, P/FFM = 19.4% ($P < 0.05$). †Significantly different from %Fat_{D,W,M} ($P < 0.05$).

water were incubated at 37°C in a sealed Conway diffusion dish (Bel-Air Products, Pequannock, NJ) for 48 h. In our laboratory, recovery of known quantities of D_2O from plasma solutions using this method averaged 98% (range 95–102%) (26). In 12 of the subjects, blood samples could not be obtained and urine was purified instead. The purified sample was analyzed using an infrared spectrophotometer (Miran 1FF, Foxboro, Foxboro, MA) with a 0.2-mm sealed CaFl flow cell and a fixed wavelength of 4.0 μm interfaced to a personal computer. Readings from the analyzer were taken at 10 Hz for 1 min using Labtech Notebook data acquisition software (version 8.0, Cambridge, MA) after the sample had equilibrated for 5 min. The concentration of D_2O in plasma was determined from a standard curve. Total body water was corrected for D_2O lost in urine and decreased 4% to account for hydrogen exchange with protein and carbohydrate during the 3-h equilibration period (33). The within-subjects SD of replicate measurements of total body water on 2 days ~1 wk apart in five subjects was 0.75 liter (26).

Body mineral. Total body bone mineral was measured using dual-energy X-ray absorptiometry (DXA; Hologic QDR-1000W, Waltham, MA, Enhanced Whole Body analysis software version 5.71). Quality control of the instrument was checked before each test session by scanning simulated lumbar vertebrae made of calcium hydroxyapatite embedded in a Lucite cube. The coefficient of variation of 164 scans was 0.27%. The within-subjects SD of replicate measurements of bone mineral content (BMC) on 2 days ~1 wk apart in five subjects was 7.2 g (26).

Hologic DXA is calibrated to assess the mass of bone mineral with X-ray attenuation properties of hydroxyapatite. Bone mineral differs slightly from hydroxyapatite and contains extra water of crystallization and bicarbonate (5). Ho et al. (16) found that mineral in lumbar vertebrae assessed with the Hologic QDR-1000W was more closely related to ashed weight than bone dry weight. We assumed that the mineral measured by DXA approximates bone ash, which is the total bone mineral minus the volatile components lost in ashing, such as water of crystallization and carbon dioxide from carbonate (5). Ash was multiplied by 1.2741 to estimate total body mineral content. The constant 1.2741 assumes that 4% of the bone mineral is lost during the ashing process (25) and that nonosseous mineral mass is 23% of bone mineral ash (5).

Thirty-one subjects were taller than the scanning region of the bone densitometer. Bone mineral for these subjects was estimated from the summed bone mineral from two separate scans (upper and lower body divided at the neck) using a regression equation from a validation study in which BMC from a single scan of 20 subjects <183 cm was predicted from BMC based on the sum of two scans ($y = 1.003x - 46$, $r^2 = 0.99$, SE of estimate = 30 g) (29). The regression equation was used because there was a small systematic difference (~46 g) between BMC measured with a single scan and that determined from two scans.

Muscularity. Total body skeletal muscle mass was estimated using a regression equation of Wang et al. (43) predicting total body skeletal muscle assessed with serial computed tomography (CT) scans from appendicular soft lean tissue assessed by DXA. The percentage of the FFM comprised of skeletal muscle (SM/FFM) was considered an index of muscularity. FFM was estimated using the four-component model ($\text{FFM}_{\text{D,W,M}}$, where D is density, W is water, and M is bone mineral) and from DXA (FFM_{DXA}), so that the index was completely independent of body composition estimated using the four-component model.

Musculoskeletal development. Musculoskeletal development was characterized using the mesomorphy rating from

the Heath-Carter anthropometric somatotype (8). This rating reflects relative skeletal muscle and bone development per unit height and is determined from measures of upper arm (AC) and calf circumferences (CC), corrected for skinfold thickness, humerus biepichondylar (HW) and femur bichondylar (FW) widths, and height (HT) with the following equation: mesomorphy rating = $0.858 \text{ HW} + 0.601 \text{ FW} + 0.188 \text{ AC} + 0.161 \text{ CC} - 0.131 \text{ HT} + 4.5$ (8). Scores vary from ~0.5 to 9.

Body composition calculations. The percentage of BM that was fat was estimated from body density ($\% \text{Fat}_D$) on the basis of a two-component model using the Siri equation (35)

$$\% \text{Fat}_D = [(4.95/D_b) - 4.50]100$$

where D_b is body density.

The percentage of BM that was fat was also estimated from body density, body water, and body mineral ($\% \text{Fat}_{\text{D,W,M}}$) on the basis of a four-component model using the following equation of Lohman (21)

$$\% \text{Fat}_{\text{D,W,M}} = [(2.747/D_b) - (0.714W) + (1.146M) - 2.0503]100$$

where W is total body water relative to BM and M is total body mineral relative to BM.

D_{FFM} was estimated from the water (W), mineral (M), and protein (P) contents of the FFM (estimated from the 4-component model) and their respective densities using the following equation

$$D_{\text{FFM}} = 1/[(W/D_w) + (M/D_m) + (P/D_p)]$$

Statistical analysis. Statistical analyses were done with SPSS for Windows (version 6.1.3, SPSS, Chicago, IL). Means and SDs for dependent variables of interest were calculated for male and female athletes and nonathletes and for athletes in selected sports. The significance of mean differences between $\% \text{Fat}_D$ and $\% \text{Fat}_{\text{D,W,M}}$ within groups from zero and the differences of D_{FFM} , W/FFM, M/FFM, and P/FFM from assumed values based on cadaver analyses (5) were determined using a one-sample *t*-test. Because Visser et al. (40) showed that gender and race have minimal effect on D_{FFM} , the strength of the relationships between the measures of musculoskeletal development and components of the FFM with D_{FFM} was assessed using Pearson correlations in the total group. An experiment-wise α -level of 0.05 was used for all significance tests. Significance values were corrected for multiple comparisons using the Bonferroni method.

RESULTS

Individual differences between $\% \text{Fat}_{\text{D,W,M}}$ and $\% \text{Fat}_D$ ranged from -8.5 to 8.1% BM. In the entire sample, $\% \text{Fat}_D$ was significantly greater than $\% \text{Fat}_{\text{D,W,M}}$ by $1.2 \pm 3.4\%$ of BM. $\% \text{Fat}_D$ was significantly greater than $\% \text{Fat}_{\text{D,W,M}}$ in male athletes by $2.7 \pm 2.5\%$, but $\% \text{Fat}_D$ and $\% \text{Fat}_{\text{D,W,M}}$ were not significantly different in male nonathletes or in female athletes and nonathletes (Table 1). In athletes for whom there were sufficient numbers for meaningful analysis by sport, substantial, significant differences between $\% \text{Fat}_D$ and $\% \text{Fat}_{\text{D,W,M}}$ were found. $\% \text{Fat}_D$ was significantly greater than $\% \text{Fat}_{\text{D,W,M}}$ by $2.7 \pm 3.4\%$ of BM in football players and by 5.0 ± 2.0 and $3.4 \pm 1.8\%$ of BM in male and female swimmers. In gymnasts, $\% \text{Fat}_{\text{D,W,M}}$

Table 2. *Body composition and musculoskeletal development of selected athletes*

	Football Players (<i>n</i> = 41)	Male Swimmers (<i>n</i> = 10)	Female Swimmers (<i>n</i> = 14)	Gymnasts (<i>n</i> = 11)
%Fat _D	15.6 ± 6.5†	15.1 ± 3.8†	23.5 ± 5.8†	16.4 ± 3.4†
%Fat _{D,W,M}	12.9 ± 6.9	10.1 ± 4.3	20.1 ± 6.2	20.8 ± 3.3
D_{FFM} , g/cm ³	1.092 ± 0.007*	1.087 ± 0.005*	1.090 ± 0.005*	1.114 ± 0.007*
W/FFM, %	74.4 ± 1.8	75.2 ± 1.4	75.0 ± 1.6	69.0 ± 1.4*
M/FFM, %	5.8 ± 0.5*	5.2 ± 0.4*	5.7 ± 0.3*	6.6 ± 0.6
P/FFM, %	19.8 ± 1.8	19.6 ± 1.3	19.3 ± 1.6	24.4 ± 1.0*
Mesomorphy	7.6 ± 1.0	5.2 ± 1.1	3.8 ± 1.0	4.9 ± 1.0
SM/FFM _{D,W,M} , %	61.5 ± 3.1	55.6 ± 3.2	50.8 ± 3.0	55.6 ± 2.8
SM/FFM _{DXA} , %	63.0 ± 2.4	55.6 ± 3.4	51.1 ± 2.6	53.4 ± 2.8

Values are means ± SD; *n*, number of subjects. *Significantly different from values based on cadaver analysis (5): $D_{\text{FFM}} = 1.100 \text{ g/cm}^3$, W/FFM = 73.8%, M/FFM = 6.8%, P/FFM = 19.4% ($P < 0.05$). †Significantly different from %Fat_{D,W,M}.

was significantly greater than %Fat_D by $4.4 \pm 2.0\%$ of BM (Table 2).

The %Fat_{D,W,M}-%Fat_D difference was almost completely explained by variability in D_{FFM} . The correlation between D_{FFM} and the %Fat_{D,W,M}-%Fat_D difference in the entire sample was 0.99 (Fig. 1). In the entire sample, D_{FFM} varied from 1.075 to 1.127 g/cm³. The mean D_{FFM} was significantly less than the assumed value of 1.1 g/cm³ in the entire sample ($1.097 \pm 0.010 \text{ g/cm}^3$) and in male athletes ($1.093 \pm 0.007 \text{ g/cm}^3$) but was not significantly different from 1.1 g/cm³ in male nonathletes or in female athletes and nonathletes (Table 1). In football players and male and female swimmers, D_{FFM} was significantly lower than 1.1 g/cm³, but in female gymnasts, D_{FFM} was significantly greater than 1.1 g/cm³ (Table 2).

Variability in D_{FFM} was strongly related to variability in W/FFM ($r = -0.96$) and P/FFM ($r = 0.89$) and moderately related to the variability in M/FFM ($r = 0.65$; Fig. 2). W/FFM varied from 65.1 to 79.4% ($73.4 \pm 2.7\%$), P/FFM varied from 13.9 to 29.0% ($20.6 \pm 2.5\%$), and M/FFM varied from 4.5 to 7.6% ($6.0 \pm 0.6\%$). In the entire sample, W/FFM was not significantly different from the 73.8% assumed; M/FFM was significantly lower than the 6.8% assumed, and P/FFM was signif-

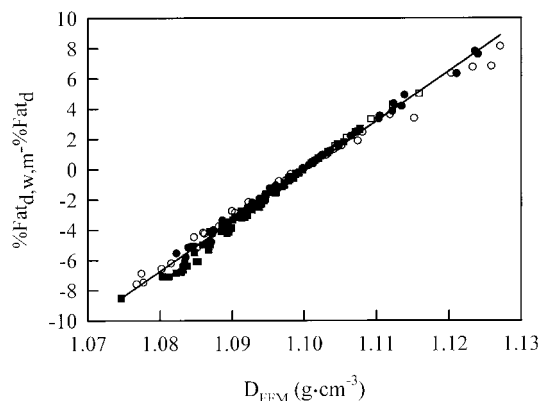


Fig. 1. Relation of percent body fat estimated from body density, body water, and body mineral content (%Fat_{D,W,M})-percent fat estimated from body density (%Fat_D) difference to density of fat-free mass (D_{FFM}). ○, Female nonathletes; □, male nonathletes; ●, female athletes; ■, male athletes. Regression equation: $y = 331.4x - 364.7$, $r = 0.99$, SE of estimate = 0.4% body mass.

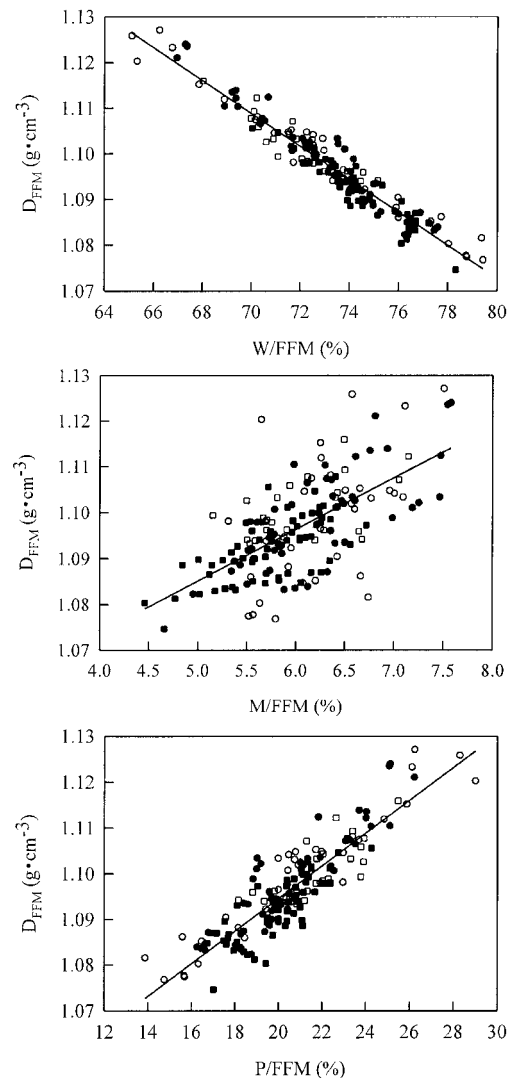


Fig. 2. *Top*: relation of D_{FFM} to water content of fat-free mass (W/FFM) expressed as a percentage of fat-free mass (FFM). Regression equation: $y = -0.004x + 1.4$, $r = -0.96$, SE of estimate = 0.003 g/cm³. *Middle*: total body mineral expressed as a percentage of FFM (M/FFM). Regression equation: $y = 0.011x + 1.0$, $r = 0.65$, SE of estimate = 0.008 g/cm³. *Bottom*: total body protein expressed as a percentage of FFM (P/FFM). Regression equation: $y = 0.004x + 1.0$, $r = 0.89$, SE of estimate = 0.005 g/cm³. See Fig. 1 legend for explanation of symbols.

icantly higher than the 19.4% assumed. Systematic deviations from assumed values for some components of the FFM also were observed within subgroups of male and female athletes and nonathletes (Table 1) and within athletes of selected sports (Table 2).

Total skeletal muscle, expressed as a percentage of $\text{FFM}_{\text{D,W,M}}$, varied from 40 to 64% in women and from 49 to 68% in men. In the entire sample, $\text{SM}/\text{FFM}_{\text{D,W,M}}$ was unrelated to D_{FFM} ($r = 0.11$; Fig. 3) or to the $\% \text{Fat}_{\text{D,W,M}} - \% \text{Fat}_{\text{D}}$ difference ($r = 0.09$). The corresponding correlations for $\text{SM}/\text{FFM}_{\text{DXA}}$ were $r = -0.08$ with D_{FFM} and $r = -0.10$ with the $\% \text{Fat}_{\text{D,W,M}} - \% \text{Fat}_{\text{D}}$ difference.

Mesomorphy values ranged from 1.6 to 8.9 in women and from 2.7 to 9.6 in men. In the entire sample, mesomorphy was positively correlated with $\text{SM}/\text{FFM}_{\text{D,W,M}}$ ($r = 0.59$) and $\text{SM}/\text{FFM}_{\text{DXA}}$ ($r = 0.70$) but was not significantly related to D_{FFM} ($r = -0.14$; Fig. 3) or to the $\% \text{Fat}_{\text{D,W,M}} - \% \text{Fat}_{\text{D}}$ difference ($r = -0.16$).

DISCUSSION

The primary objectives of this study were 1) to determine the relation of muscularity and mesomorphy rating to the density and composition of the FFM and 2) to assess the validity of body composition estimates from body density, using estimates from a four-component model as the criterion, in a large, diverse group of athletes and nonathletes that included men and

women and blacks and whites who varied in muscularity and musculoskeletal development. Important features of the study include the use of a four-component body composition model to accurately assess the FFM and its density and composition and the use of DXA to obtain a more direct measure of total body skeletal muscle than has been available in the past. Previous hypotheses or studies concerning the effect of muscularity on the density and composition of the FFM have been based on theory (23), assumed differences between groups of athletes and nonathletes (47), or the mesomorphy rating from the Heath-Carter anthropometric somatotype, which reflects bone as well as muscular development (26).

On the basis of the data of Modlesky et al. (26), we hypothesized that muscularity and mesomorphy rating would be inversely related to D_{FFM} . The primary finding of this study was that, in this large, heterogeneous sample, muscularity and mesomorphy were unrelated to D_{FFM} . These data conflict with previous studies that have found an association between muscularity or musculoskeletal development and D_{FFM} . Womersley et al. (47), using FFM derived from ^{40}K spectrometry, estimated that the D_{FFM} was lower in "muscular" than in sedentary men and women. In contrast, Vickery et al. (38), using FFM derived from body density estimated from skinfolds, found that black men, who had a higher mesomorphy rating, also had a higher estimated D_{FFM} than white men. Both studies calculated D_{FFM} from potentially inaccurate estimates of FFM (i.e., 2-component model), which may have compromised the validity of the D_{FFM} estimates. Modlesky et al., however, calculated D_{FFM} on the basis of body composition estimates from a four-component model and found a significant moderate negative relationship ($r = -0.64$) between mesomorphy and D_{FFM} in a sample of white male weight lifters and nonathletes with markedly different musculoskeletal development. Higher mesomorphy in the weight lifters was associated with higher W/FFM and lower M/FFM and P/FFM than controls. Their correlation, however, may have resulted from combining two very dissimilar groups. Withers et al. (46) also reported a low D_{FFM} ($1.094 \pm 0.003 \text{ g/cm}^3$) in bodybuilders with very high mesomorphy (8.6 ± 0.7). In the present study, we had a larger range and continuous distribution of mesomorphy values. In addition, the findings using mesomorphy were corroborated with a more direct and contemporary measure of skeletal muscle mass, which reflects variation in muscularity only and not a combination of muscle and bone development. The lack of relation of muscularity or mesomorphy rating to D_{FFM} is probably due to the larger, more heterogeneous sample and may reflect different relative contributions of muscle and bone to D_{FFM} in the subgroups.

It has long been hypothesized that certain athletes may be atypical in FFM composition. The atypical, extreme physiques required for success in many sports and the intense training that often accompanies participation in sports may alter FFM composition. Consequently, methods for estimating body composition

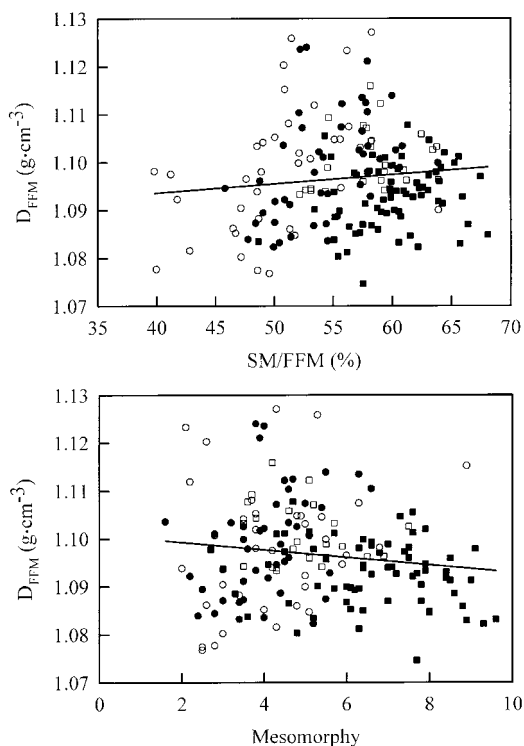


Fig. 3. *Top*: relation of D_{FFM} to skeletal muscle expressed as a percentage of FFM ($\text{SM}/\text{FFM}_{\text{D,W,M}}$). Regression equation: $y = 0.0002x + 1.086$, $r = 0.11$, SE of estimate = 0.01 g/cm^3 . *Bottom*: mesomorphy rating from the Heath-Carter anthropometric somatotype. Regression equation: $y = -0.0008x + 1.1$, $r = -0.14$, SE of estimate = 0.01 g/cm^3 . See Fig. 1 legend for explanation of symbols.

that assume constant FFM proportions may be inaccurate and inappropriate when applied to certain athletes (20, 34). The FFM density and composition of athletes relative to the assumed values have been largely unknown. It has been suggested that athletes who participate in high-intensity, explosive training may have greater M/FFM and D_{FFM} than nonathletes (6, 23), whereas some studies suggest that athletes may have higher W/FFM and lower D_{FFM} than nonathletes (20, 26, 47). Our data support both of these suggestions to some extent and suggest that athletes may have atypical density and composition of the FFM that is sport dependent. In the present study, male athletes as a group had lower D_{FFM} , caused by lower M/FFM and higher W/FFM, than assumed on the basis of cadaver data (5). In addition, their D_{FFM} was significantly lower than that of male nonathletes. Female athletes as a group and male and female nonathletes did not have a D_{FFM} that was significantly different from the assumed value of 1.1 g/cm^3 , although the composition of the FFM in each of these groups differed somewhat from that assumed. However, female gymnasts had a D_{FFM} significantly greater than the assumed value of 1.1 g/cm^3 , whereas female swimmers had a D_{FFM} significantly less than 1.1 g/cm^3 . Overall, these findings indicate that the D_{FFM} of athletes may be higher or lower than assumed values and that generalization across athletes in different sports is not possible.

Atypical density and composition of the FFM in athletes could reflect genetic predisposition or the effects of training. Several studies have suggested that intense, rhythmic loading of the musculoskeletal system, by weight lifting and other strenuous exercise, causes increased bone mineralization (15, 36). In contrast, prolonged unloading of the musculoskeletal system, especially the limbs, may cause bone demineralization (17). Such loading and unloading are thought to affect M/FFM and, consequently, D_{FFM} . In the present study, female gymnasts, whose training involves intense, whole body skeletal loading, had higher D_{FFM} and M/FFM and lower W/FFM than male and female swimmers, whose training involves a relative unloading of the skeletal system and may provide a greater stimulus for increasing total body water (9). The present data support the data of Robinson et al. (32), who found female collegiate gymnasts to have higher bone mineral density than female collegiate swimmers. These findings indirectly support the idea that type of athletic training may have an effect on the density and composition of the FFM.

The high D_{FFM} of the female gymnasts, caused by lower W/FFM and higher P/FFM than assumed and higher M/FFM than in the other groups of athletes and nonathletes, was particularly interesting, because it differed from the pattern observed in the other groups of athletes. Their low W/FFM was not related to low SM/FFM, which, although lower than in male athletes and nonathletes, was similar to that in other female athletes and higher than that in female nonathletes. Their low W/FFM could have reflected hypohydration;

however, this seems unlikely, because their urine specific gravity ($1.023 \pm 0.006 \text{ g/ml}$) did not differ markedly from that of the other subjects ($1.020 \pm 0.009 \text{ g/ml}$), and there was no indication that they did not adhere to the instructions designed to ensure normal hydration. The relatively high M/FFM reflected relatively high BMC, probably resulting from their training as discussed above. The reason for the high P/FFM is unclear, although it undoubtedly reflects in part the relatively low W/FFM and high M/FFM, since the fractional components sum to 1.0.

On the basis of their heavy resistance training, we expected the football players to have FFM composition similar to that of the weight lifters in the study of Modlesky et al. (26), i.e., relatively low M/FFM and slightly high W/FFM, and this was found. The FFM composition of the football players may reflect a greater stimulus of their resistance training to increase body water (7), which may be associated with muscle hypertrophy (26) or increased water content of the muscle due to increased muscle glycogen (30), which would tend to increase W/FFM and suppress M/FFM and P/FFM. Football players had the highest SM/FFM and mesomorphy rating of any of the groups of athletes. The high skeletal muscle and low D_{FFM} in football players suggest that these two variables might be inversely related in this group. It may be that skeletal muscle must be markedly increased before it has a systematic effect on W/FFM and D_{FFM} . However, skeletal muscle hypertrophy, if it has an effect, is not the only cause of high W/FFM and low D_{FFM} in athletes. Male and female swimmers had higher mean values for W/FFM and lower D_{FFM} than football players but lower means for SM/FFM and mesomorphy. Although gymnasts had SM/FFM and mesomorphy values that were intermediate compared with other groups of athletes and nonathletes, their W/FFM was markedly lower and D_{FFM} markedly higher than those of other groups. Thus our results are consistent with the hypothesis that different types of athletic training may have different effects on the density and composition of the FFM but indicate that these effects are complex and are not simply a reflection of differences in muscularity or musculoskeletal development.

Variability in D_{FFM} in the entire sample ($\text{SD} = 0.010 \text{ g/cm}^3$) was equal to that estimated for the general population by Siri (35). Siri's estimated variation in D_{FFM} was based on estimated variation in W/FFM and in the mineral-to-protein ratio. In the present study, variation in W/FFM in all subjects ($\text{SD} = 2.7\% \text{ FFM}$) was greater than Siri had estimated ($\pm 2\%$) for the general population, whereas the variance in the mineral-to-protein ratio (± 0.04) was less than Siri's estimate (± 0.10). We were surprised that the SD of D_{FFM} in our sample was not larger than that estimated by Siri, given the atypical athletes included. However, although there were systematic deviations in mean D_{FFM} from 1.1 g/cm^3 in the groups of athletes, individual D_{FFM} values in athletes fell within the range observed for nonathletes. The SD of D_{FFM} in the male and female athletes ($\text{SD} = 0.007$ and 0.011 g/cm^3) was not

greater than in the male and female nonathletes ($SD = 0.006$ and 0.013 g/cm^3 ; Table 2).

Lohman (19) suggested that in a homogenous group the variability in D_{FFM} should be less ($SD \sim 0.006 \text{ g/cm}^3$) than Siri's estimate for the general population. Moreover, if there are systematic differences in D_{FFM} among subgroups of the general population, more accurate estimates of body composition can be obtained via densitometry and a modified Siri equation, if the mean D_{FFM} is known. Our findings on athletes in different sports support this suggestion. In the athletes in sports for which there were sufficient numbers for meaningful analysis (Table 2), the SD for D_{FFM} for athletes in a given sport ranged from 0.005 to 0.007 g/cm^3 , and there was significant deviation in the mean D_{FFM} from assumed values and from the reference groups. Differences between $\% \text{Fat}_D$ and $\% \text{Fat}_{D,W,M}$ of 2.5 – 5.0% in these athletes indicate that deviations of D_{FFM} from the 1.1 g/cm^3 assumed in the Siri equation resulted in substantial errors in estimating percent fat by densitometry. In theory, use of a modified Siri equation based on D_{FFM} values specific to athletes in these sports would eliminate this error. However, more research is needed on athletes in specific sports to confirm our data and to establish whether the use of sport-specific D_{FFM} values in deriving modifications of the Siri equation is justified.

Variability in D_{FFM} was more strongly related to variance in W/FFM than M/FFM . Considered independently, water explained 93% and mineral explained 42% of the variance in D_{FFM} . This finding is similar to that of others (4, 26, 40) and supports the hypothesis that, of the various chemical components of the FFM, variability in water has the greatest effect on D_{FFM} (3, 19). Others have argued that mineral, because of its greater density (3.038 g/cm^3 at 36°C) than water (0.9937 g/cm^3), has a greater impact on D_{FFM} than water (23, 24, 41). On the basis of regression analysis of data in the present study, a 1% change in M/FFM (from 5 to 6% FFM) was associated with a threefold greater change in D_{FFM} than a 1% change in W/FFM (from 72 to 73% FFM). However, the variability in W/FFM for the total sample was 4.5 times the variability in M/FFM ($SD = 2.7$ vs. 0.6%). In addition, water occupies ~ 11 times greater proportion of the FFM than mineral. Thus any small change in water will have a greater effect on D_{FFM} simply because of the proportion of FFM that is water. The strong relationship between D_{FFM} and W/FFM means that, for demographic or physical characteristic variables such as musculoskeletal development to have a substantial effect on D_{FFM} , they must have a direct or indirect effect on W/FFM .

Absolute values for estimates of the density and composition of the FFM are affected by the method used to obtain bone mineral data. Tothill et al. (37) showed that bone densitometers from different manufacturers and different software versions from the same manufacturer result in different estimates of bone mineral. The Lunar DPX-L (software version 1.3Z) densitometer has been shown to measure bone mineral an average of 11% higher than the densitometer and

software version used in the present study (Hologic QDR-1000W, Enhanced Whole Body Analysis software version 5.71) (28). If the estimates of bone mineral were 11% higher in this study, M/FFM and W/FFM would increase, P/FFM would decrease, and D_{FFM} would increase from 1.097 to 1.099 g/cm^3 (27). Although the potential error in the measurement of bone mineral would affect the absolute values of the density and composition of the FFM, it would not affect the relative differences between groups or the relations to muscularity and mesomorphy. Additional research on the validity of bone mineral and body composition estimates from different bone densitometers is needed to resolve this issue.

Day-to-day biological variation and technical errors in each of the measures used to estimate D_{FFM} , $\% \text{Fat}_D$, and $\% \text{Fat}_{D,W,M}$ also contribute to day-to-day differences in the body composition estimates. Of particular concern in validation studies in which the four-component model has been used as the criterion has been the possibility that propagation of errors associated with the three measures used in the calculation of D_{FFM} and $\% \text{Fat}_{D,W,M}$ may negate the advantage of measuring more of the sources of variability in D_{FFM} . We (26) and others (12), however, have reported that errors associated with these measures are quite small, with the within-subjects SD for replicate determinations of D_{FFM} and $\% \text{Fat}_{D,W,M}$ being $\sim 0.002 \text{ g/cm}^3$ and 1% BM, respectively.

We assessed total body skeletal muscle from appendicular lean soft tissue determined by DXA (43). This approach assumes that all DXA lean soft tissue is skeletal muscle and that appendicular skeletal muscle is a constant proportion (79%) of total body skeletal muscle. Validation studies have shown that DXA lean soft tissue is highly correlated with, but overestimates, appendicular skeletal muscle measured by CT scanning in men and women, primarily because the DXA measurement includes skin, connective tissue, and nonfat components of adipose tissue that are not included in the skeletal muscle volume and mass determined by CT scanning (18, 39, 42, 43). Although more sophisticated approaches have been developed to account for these nonmuscle components (42), we chose to use the regression equation of Wang et al. (43), which predicts total body skeletal muscle determined by serial CT scanning from DXA appendicular lean soft tissue. This prediction corrects for the overestimation and provided an accurate estimate of skeletal muscle in a limited sample of nonathletic white men ($r = 0.95$, SE of estimate = 2.1 kg). The primary limitation is that its validity with athletes, women, and other ethnic groups has not been established. It is possible the nonmuscular components of the DXA lean soft tissue and the relation of appendicular to total body skeletal muscle may be somewhat different from that in the sample of Wang et al.

We conclude that, in a heterogenous sample of young male and female athletes and nonathletes, D_{FFM} and the accuracy of estimates of body composition from body density using the Siri equation are not related to

muscularity or musculoskeletal development. Athletes in selected sports may have systematic deviations in D_{FFM} from the value of 1.1 g/cm^3 assumed in the Siri equation, resulting in group mean errors in estimation of %Fat_D of 2–5% body mass, but the cause of these deviations is complex and not simply a reflection of differences in muscularity or musculoskeletal development.

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