Associations between energy demands, physical activity, and body composition in adult humans between 18 and 96 y of age[1–3]

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ABSTRACT

Background: Associations between body composition and the energy expended on basal metabolism and activity are complex and age dependent.

Objective: The objective was to examine associations between body composition and daily (DEE), basal (BEE), and activity energy expenditure (AEE) throughout the adult life span.

Design: A cross-sectional study was conducted in 529 adults aged 18–96 y. DEE was measured by using doubly labeled water, BEE by using respirometry, and body composition by isotope dilution. AEE was calculated as DEE − BEE, and physical activity level (PAL) was calculated as DEE/BEE.

Results: Up to age 52 y, fat-free mass (FFM) and fat mass (FM) were positively associated with age in men, but no significant effect was observed in women. No effects of age on DEE and AEE were observed. The average DEE in men (14.1 MJ/d) was 27% greater than that in women (10.7 MJ/d). PAL averaged 1.84 in men and 1.75 in women. Above and including the age of 52 y, FFM, FM, DEE, BEE, and AEE were all negatively associated with greater age. The effect of age on AEE was greater than on BEE; consequently, PAL by the age of 95 y was only 1.36. PAL and AEE were both unrelated to FFM (both age adjusted).

Conclusions: PAL and AEE were not associated with age in subjects aged <52 y. AEE, BEE, and PAL were all negatively associated with age in subjects aged ≥52 y. An absence of a relation between age-adjusted PAL and FFM suggested that greater physical activity was not associated with higher FFM in the elderly. *Am J Clin Nutr* 2010;92:826–34.

INTRODUCTION

The interrelations between energy expenditure and body composition during adulthood are complex and appear to vary with life stage and with sex. During the first half of adulthood, individuals gradually accumulate body fat (1–4), but the extent of accumulation differs widely. Low energy expenditure, due either to low basal energy demands (5–7) or to low physical activity energy expenditure (AEE) (8, 9), have both been suggested to contribute to the energy imbalance that influences the extent of this increasing fat deposition. However, other studies have disputed these associations with basal (10) and AEE (5, 11, 12). Basal energy expenditure (BEE), however, clearly depends on the amount of metabolizing tissue (13), with independent effects of fat-free mass (FFM) and fat mass (FM) observed in many studies (14–23). Age has also been suggested to have a direct effect on tissue basal metabolic rate (15, 24–28), and consequently, the actual change in BEE with age is a balance between this direct negative effect and an increase due to the expanding quantity of respiring tissue.

In contrast, in older individuals, total body mass tends to decline (29). In particular, the skeletal muscle component of FFM may be progressively lost (sarcopenia), notably in males (30). In later adulthood this decline in skeletal muscle mass is one of the key factors leading to immobility (31). Combined with the age-related decline in basal tissue metabolism, the loss of FFM leads to a large decline in BEE as individuals age. Physical activity level (PALs) also decline as individuals get older (32). However, whether this decline in activity is driven by the progression of sarcopenia or whether physical activity can reduce the rate of skeletal tissue loss is unknown. The causes of sarcopenia are complex and multifactorial (33). Strong evidence indicates that resistance training can stem the extent of skeletal muscle loss (34–37), but the role of general physical activity as a protective measure is controversial (38–42). Our aim in the present study, therefore, was to explore associations between PALs (by using the gold standard doubly labeled water method to assess energy expended on physical activity) and body composition. More generally, we aimed to define energy requirements across the life span. Energy is a key nutrient, and understanding patterns of energy requirements with age is of fundamental importance for nutritional professionals,

We used a large cross-sectional sample of >500 adults aged 18–96 y to explore the relations between energy demands and body composition across adulthood. Daily energy expenditure (DEE) was measured by using the doubly labeled water method, BEE by indirect calorimetry, and body composition by isotope dilution. Activity energy demands were captured directly from the difference between total and basal expenditures.

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SUBJECTS AND METHODS

Between 1983 and 2005, 529 subjects (289 men and 240 women) underwent measurements in Maastricht, Netherlands (first publication 1988), with both the DLW method and direct estimates of their BEE. This sample excluded individuals aged <18 y, undergoing interventions involving energy intake, undergoing physical activity including athletic performance, and those who were pregnant, lactating, or diseased (**Table 1**). For studies involving dietary or exercise interventions, only the preintervention data or those for control groups were used. Because data were collected over a prolonged time period during which there has been a profound change in obesity levels there is the potential for the date of the study to act as a confounding factor. However, during the time period in question, obesity levels increased modestly in the Netherlands (from 5% to 9%), and the age of the subjects was not biased in relation to the dates of the studies. Moreover, we previously showed no effect of the year of study on DEE (11). The population of the Netherlands has a slightly higher level of physical activity (measured as the PAL, *see* below) than other Western societies, such as the United States (11), but otherwise is a representative population.

Estimates of DEE, BEE, AEE, PAL, and body composition were derived from doubly labeled water studies. Doubly labeled water is an isotope-based technique in which subjects are dosed with labels of heavy oxygen and heavy hydrogen, and their differential elimination is a measure of their DEE (43). The method has a long history of application to the study of human energy demands (44). BEE was measured with indirect calorimetry. DEE was measured over 2-wk periods according to the Maastricht protocol (45). In brief, isotopes were administered orally as a mixture of ^2H_2O (99.9 atom%) and $H_2{}^{18}O$ (10 atom %), which resulted in an initial excess body water enrichment of ≈150 ppm for deuterium and 300 ppm for oxygen-18. This dose leaves a sufficient excess enrichment at the end of the 14-d observation period. The dose volume was typically 80–160 mL, depending on body mass. The isotopes were administered as the last consumption before bedtime. Subjects provided a background body water sample (blood or urine) immediately before isotope consumption (46; method D). Equilibration took place overnight, and the first postdosing sample was collected in the early morning, in case of urine from the second voiding. Additional duplicate samples (second daily void) were collected on days 8 and 14 after dosing.

PAL was derived by expressing DEE as a multiple of BEE (PAL = DEE/BEE). Alternatively, AEE was calculated as (0.9 × DEE) – BEE, assuming that diet-induced energy expenditure is one-tenth of DEE in subjects in whom intake matches expenditure (47). FFM was derived from isotope dilution, assuming a 73% hydration of FFM (48), where dilution spaces were corrected for exchange of the label with nonaqueous substances in the body by dividing the dilution space of ^{18}O and ^2H by 1.01 and 1.04, respectively (49).

All analyses were performed separately for women (n = 228) and men (n = 275). Differences in FFM between subjects were adjusted for differences in FM by calculating the residual of the regression of FM on FFM, where fat mass was calculated as body mass minus FFM. To answer the question of whether age-related differences in FFM were related to PAL, the residual of the regression of PAL on age was analyzed as a function of the residual of FFM on fat mass and age. Data were tested for consistency to normality before analysis (Shapiro-Wilk test). When data were not normally distributed, they were transformed by log conversion to normalize the data distributions. Data analysis refers to transformed data, but the original data values are shown in the figures for clarity. When data were transformed, the nature of the transformation is mentioned at the appropriate location in the results. Data were considered significant at $P < 0.05$.

Visual inspection of the data showed that, in all cases, there was a transition point at the age of ≈50y. Before 50 y, traits tended to be constant or higher with increasing age, whereas

TABLE 1
Subject characteristics by age decade[1]

Age	No. of subjects	BMI	FFM	FM	FM	BEE	AEE	DEE	PAL
Men		*kg/m²*	*kg*	*kg*	*%*	*MJ/d*	*MJ/d*	*MJ/d*	
18–29 y	62	22.4 ± 3.4	60.0 ± 7.7	13.6 ± 7.2	17.9 ± 6.0	7.5 ± 1.0	5.1 ± 1.8	14.0 ± 2.5	1.88 ± 0.24
30–39 y	71	27.1 ± 7.0	63.7 ± 9.6	24.4 ± 17.6	25.6 ± 8.9	7.8 ± 1.4	4.7 ± 1.9	14.0 ± 2.8	1.79 ± 0.25
40–49 y	58	28.1 ± 5.7	63.2 ± 7.0	24.8 ± 12.9	26.7 ± 8.0	7.6 ± 1.2	5.2 ± 1.8	14.2 ± 2.6	1.88 ± 0.25
50–59 y	23	29.6 ± 4.5	65.7 ± 7.8	28.8 ± 11.1	29.6 ± 6.0	7.8 ± 0.8	5.3 ± 2.3	14.5 ± 2.7	1.88 ± 0.34
60–69 y	23	26.1 ± 4.7	56.3 ± 7.7	22.6 ± 9.4	27.7 ± 6.3	7.0 ± 0.9	3.6 ± 1.7	11.7 ± 2.2	1.69 ± 0.30
70–79 y	39	25.9 ± 2.6	53.3 ± 5.6	24.4 ± 6.0	31.1 ± 5.4	6.9 ± 1.1	2.8 ± 1.3	10.7 ± 1.7	1.57 ± 0.23
80–89 y	39	26.2 ± 2.8	49.9 ± 4.2	24.5 ± 6.0	32.6 ± 4.8	6.5 ± 0.6	1.6 ± 1.0	9.0 ± 1.7	1.37 ± 0.14
90–99 y	7	23.6 ± 3.4	46.3 ± 2.6	21.2 ± 8.8	30.5 ± 8.8	6.0 ± 0.8	1.3 ± 0.8	8.0 ± 0.6	1.36 ± 0.17
Women									
18–29 y	83	23.5 ± 5.6	46.1 ± 5.7	20.7 ± 12.5	29.1 ± 9.3	6.1 ± 0.8	3.5 ± 1.1	10.7 ± 1.7	1.75 ± 0.20
30–39 y	51	27.3 ± 6.9	46.6 ± 6.8	27.9 ± 13.7	35.2 ± 10.2	6.2 ± 1.1	3.1 ± 1.0	10.4 ± 1.8	1.68 ± 0.19
40–49 y	32	29.2 ± 8.2	50.9 ± 8.8	30.5 ± 17.4	35.0 ± 10.8	6.4 ± 1.2	3.6 ± 1.2	11.2 ± 2.3	1.71 ± 0.16
50–59 y	19	28.5 ± 7.4	45.2 ± 5.3	32.8 ± 14.3	40.7 ± 6.8	5.9 ± 0.7	2.9 ± 0.7	9.8 ± 1.3	1.65 ± 0.11
60–69 y	24	25.7 ± 2.5	42.4 ± 4.7	24.7 ± 5.6	36.5 ± 5.0	5.6 ± 0.7	2.7 ± 0.9	9.2 ± 0.9	1.67 ± 0.24
70–79 y	6	23.6 ± 3.4	39.0 ± 3.3	22.5 ± 6.5	36.2 ± 7.9	5.2 ± 0.3	2.4 ± 1.0	8.4 ± 1.2	1.63 ± 0.21
80–89 y	9	22.1 ± 3.2	36.8 ± 4.7	18.5 ± 3.8	33.3 ± 5.1	5.0 ± 0.5	0.6 ± 0.4	6.2 ± 0.8	1.23 ± 0.08
90–99 y	10	23.3 ± 4.4	37.0 ± 5.1	21.0 ± 9.7	34.6 ± 9.9	4.9 ± 0.6	1.1 ± 0.7	6.7 ± 1.2	1.36 ± 0.13

[1] All values are means ± SDs. FFM, fat-free mass; FM, fat mass; BEE, basal energy expenditure; AEE, activity energy expenditure; DEE, daily energy expenditure; PAL, physical activity level (ie, DEE/BEE).

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they tended to be lower above the approximate age of 50 y with increasing age. The exact location of the transition appeared to vary with the trait under consideration and between the sexes. We explored the position of this transition using segmented regression (50) and the publically available computer program SEGREG (www.waterlog.info/segreg.htm). This program identified the location and significance of the breakpoint in the data relative to the fit of a simple linear regression model. We subsequently split the data at the appropriate breakpoints and performed the analyses for each trait separately on younger and older cohorts. All procedures described in this manuscript were reviewed by the University of Maastricht Ethical review board prior to their use.

RESULTS

Body-composition and energy expenditure characteristics of the study population stratified by age and sex are presented in Table 1. There was a strong difference in the effect of age on these variables at different times of life. Visual examination indicated that there appeared to be transitions in the data for all traits around the age of 40–60 y. We identified the exact position of these transitional breakpoints in the data by using segmented regression analysis (**Table 2**) on the data separated by sex. In all cases, the incorporation of a breakpoint in the analysis significantly improved the fit of the data above a simple linear regression with age as the predictor (Table 2). However, the position of the breakpoints varied significantly between traits and also between the sexes. With respect to body composition, the breakpoint for FFM in men (57.8 y: SE = 0.7) was significantly later than for women (46.8 y: SE = 0.45), whereas the breakpoint for FM did not differ significantly between the sexes (women: 47.8 y, SE = 3.55; men: 54.2 y, SE = 5.3). With respect to the BEE and DEE, the breakpoints were also at significantly greater ages in men than in women (Table 2). For AEE and PAL, no significant sex effect was observed on the position of the breakpoint. We performed regression analyses of the effect of subject age on the various variables, splitting each trait into younger and older cohorts for both men and women (**Table 3**) using the optimal breakpoints from the segmented regression analysis to identify where to split the data. This analysis showed that all the traits were either constant or greater with subject age up to the breakpoints, except PAL in women, which was significantly lower with increasing subject age; however, for subjects above the breakpoint, age was negatively associated with all the traits except FM in men.

The breakpoints had an average age of 54.6 y for men and 48.9 y for women (paired $t_5 = 1.44$, $P = 0.21$). To facilitate comparisons between the sexes we took the average of these breakpoints (52 y), and the analyses were performed separately for a younger cohort of subjects aged 18–52 y (n = 166 women and 185 men) and for an older cohort of subjects aged ≥52.1 y (n = 74 women and 104 men).

Effects in subjects aged <52 y

Up to the age of 52 y, a large sex-related difference in body composition and energy expenditure was observed. On average, women younger than 52 y had a mean (± SD) FFM of 47.2 ± 7.0 kg; in men, FFM was 30% greater and averaged 62.5 ± 8.4 kg ($P < 0.001$). Both FFM and FM were significantly positively associated with subject age between 18 and 52 y in women (least-squares regression: $\log_e$ converted data to normalize: $F_{1,\ 164} = 10.42$, $P = 0.002$ and $F_{1,\ 164} = 17.59$, $P < 0.001$, respectively) and in men (least-squares regression: $\log_e$ converted data to normalize: $F_{1,\ 183} = 11.3$, $P < 0.001$ and $F_{1,\ 183} = 47.8$, $P < 0.001$, respectively, **Figure 1**). Because both FFM and FM were higher with increasing age, body mass index (in kg/m^2) was also positively related to subject age (Table 1). At age 45 y, almost half the subjects were obese (body mass index > 30). It is well established that greater FM is associated with elevated FFM. When FM was adjusted for the levels of FFM, there was no longer any trend with subject age between 18 and 52 y in women ($F_{1,\ 164} = 1.79$, $P = 0.18$), but there was

TABLE 2
Characteristics of segmented regression analysis on all traits[1]

Trait	BP	BPse	F	P	r^2(lin)	r^2(seg)
Men						
FFM	57.8	0.68	71.9	<0.001	0.133	0.306
FM	54.2	5.3	28.4	<0.001	0.038	0.125
BEE	57.8	0.98	27.1	<0.001	0.069	0.139
DEE	53.1	0.99	209.7	<0.001	0.229	0.319
AEE	52.3	1.1	24.4	<0.001	0.214	0.275
PAL	52.3	1.27	15.5	<0.001	0.173	0.214
Women						
FFM	46.8	0.45	31.6	<0.001	0.082	0.189
FM	47.8	3.55	32.3	<0.001	0.023	0.123
BEE	39.8	2.14	19.6	<0.001	0.099	0.168
DEE	43.7	1.57	18.2	<0.001	0.272	0.324
AEE	54.6	1.44	8.91	<0.01	0.269	0.296
PAL	60.9	3.7	5.67	<0.02	0.214	0.231

[1] BP, optimal breakpoint age (in y); BPse, SE of optimal breakpoint; F, test statistic for significance, including breakpoint into regression analysis (df = 1, 287 for men and 1, 238 for women); r^2(lin), coefficient of determination for the simple linear regression; r^2(seg), coefficient of determination for the segmented regression; FFM, fat-free mass; FM, fat mass; BEE, basal energy expenditure; AEE, activity energy expenditure; DEE, daily energy expenditure; PAL, physical activity level.

TABLE 3
Parameters of regression fits for various traits in relation to age (y) below and above the optimal breakpoint (< or >BP) identified by segmented regression analysis[1]

	Regression equation	df	F	P
Men				
FFM (kg)				
<BP	FFM = 54.99 + 0.222Age	1, 198	16.0	<0.001
>BP	FFM = 78.83 − 0.349Age	1, 87	28.1	<0.001
FM (kg)				
<BP	FM = 1.58 + 0.587Age	1, 186	27.8	<0.001
>BP	FM = 28.62 − 0.07Age	1, 79	0.94	0.335
BEE (MJ/d)				
<BP	BEE = 7.108 + 0.016Age	1, 198	4.04	0.046
>BP	BEE = 9.463 − 0.036Age	1, 87	11.9	<0.001
DEE MJ/d				
<BP	DEE = 13.33 + 0.022Age	1, 185	1.08	0.299
>BP	DEE = 22.89 − 0.165Age	1, 100	87.5	<0.001
AEE (MJ/d)				
<BP	AEE = 4.85 + 0.005Age	1, 183	0.12	0.727
>BP	AEE = 10.37 − 0.102Age	1, 102	55.9	<0.001
PAL				
<BP	PAL = 1.86 − 0.0004Age	1, 183	0.04	0.84
>BP	PAL = 2.53 − 0.013Age	1, 102	29.3	<0.001
Women				
FFM (kg)				
<BP	FFM = 40.07 + 0.236Age	1, 160	13.1	<0.001
>BP	FFM = 51.52 − 0.139Age	1, 76	8.1	0.006
FM (kg)				
<BP	FM = 6.68 + 0.589Age	1, 161	19.8	<0.001
>BP	FM = 42.44 − 0.251Age	1, 75	10.8	0.002
BEE (MJ/d)				
<BP	BEE = 5.505 + 0.022Age	1, 132	3.16	0.078
>BP	BEE = 7.607 − 0.029Age	1, 104	38.1	<0.001
DEE (MJ/d)				
<BP	DEE = 10.45 + 0.009Age	1, 150	0.20	0.655
>BP	DEE = 14.56 − 0.086Age	1, 86	95.75	<0.001
AEE (MJ/d)				
<BP	AEE = 3.94 − 0.015Age	1, 168	2.13	0.146
>BP	AEE = 6.13 − 0.056Age	1, 68	62.82	<0.001
PAL				
<BP	PAL = 1.86 − 0.004Age	1, 187	9.05	0.003
>BP	PAL = 2.43 − 0.012Age	1, 49	28.1	<0.001

[1] The actual BPs are shown in Table 2. FFM, fat-free mass; FM, fat mass; BEE, basal energy expenditure; AEE, activity energy expenditure; DEE, daily energy expenditure; PAL, physical activity level.

a significant positive relation in men ($F_{1,\ 183}$ = 8.04, P = 0.005) (**Figure 2**). Percentage body fat in the youngest age group (18–29) averaged 17.9% in men and 29.1% in women and in the oldest cohort under 52 y (40–52) averaged 26.8% and 34.7% in men and women, respectively.

The mean (±SD) total DEE in men younger than 52 y was 14.1 ± 2.6 MJ/d, whereas DEE was significantly lower in women by 27% (10.7 ± 1.9 MJ/d). This difference of 3.4 MJ/d in DEE was contributed to by significantly greater basal and AEE in the men. Hence, BEE was 6.2 ± 1.0 MJ/d in the women and 7.6 ± 1.2 MJ/d in the men (analysis on log-converted data: t = 13.2, P < 0.001)—an average difference of 1.4 MJ/d (40% of the overall difference in DEE). The difference in AEE between men and women was even greater. Hence, women expended an average of 3.4 ± 1.1 MJ/d in AEE compared with 5.0 ± 1.8 MJ/d in men (comparison on log-converted data: t_{321} = 9.46, P < 0.001) (**Figure 3**). This difference contributed to 60% of the overall difference in DEE between the sexes.

At the individual level, BEE was significantly positively related to FFM (general linear model with $\log_e$ FFM, $\log_e$ FM and age entered as covariates to predict $\log_e$ converted BEE: $F_{1,\ 348}$ = 1015, P < 0.001), independently to $\log_e$ FM ($F_{1,\ 348}$ = 87.4, P < 0.001), and negatively related to subject age ($F_{1,\ 348}$ = 20.7, P < 0.01). The least-squares fit multiple regression explained 80.1% of the total variation in $\log_e$ BEE. Once these effects had been accounted for, there was still a small residual effect of sex ($F_{1,\ 350}$ = 8.7, P = 0.003); women had a slightly lower BEE than anticipated from body composition. Because the oldest individuals in the cohort aged <52 y (ages 40–52 y) were fatter and heavier than the younger members of this cohort, the net effect of subject age on BEE was a marginally significant positive effect in women ($F_{1,\ 164}$ = 4.12, P = 0.044) but no significant effect in men ($F_{1,\ 183}$ = 2.99, P = 0.085; **Figure 4**). In contrast, AEE was independent of age (least-squares fit linear regression of $\log_e$ AEE against age: $F_{1,\ 350}$ = 0.50, P = 0.54; Figure 3). Consequently, there was no significant trend in PAL

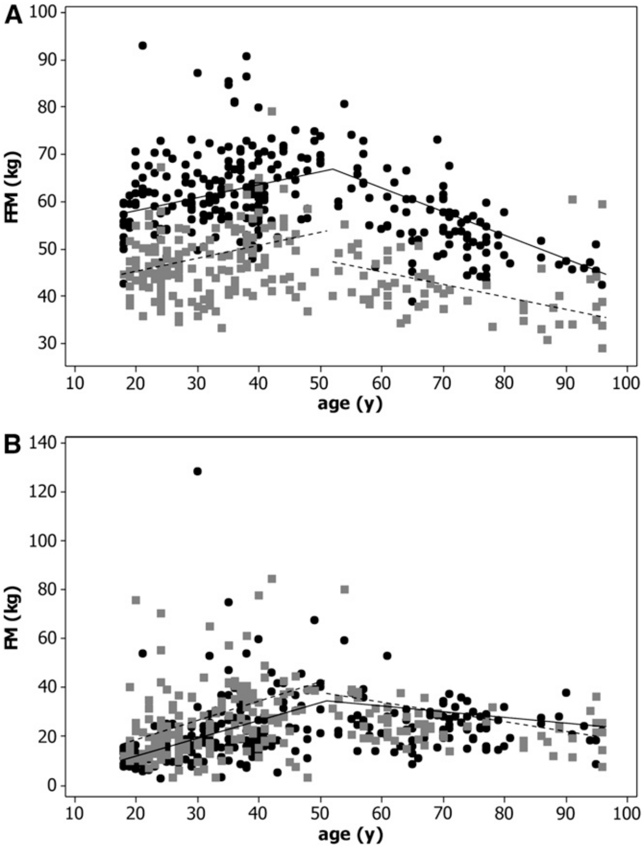

FIGURE 1. Fat-free mass (FFM; A) and fat mass (FM; B) as a function of age in women (n = 240: gray squares) and men (n = 289: black circles). Lines are fitted regressions for each sex above and below an average break point of 52 y.

with age in men ($F_{1,\ 183}$ = 0.04, P = 0.84). The distribution of PAL was consistent with normality by the Shapiro-Wilk test ($P > 0.15$) and was not transformed, but there was a slight but significantly lower PAL with age in women ($F_{1,\ 164}$ = 5.58, P = 0.19; **Figure 5**). There was no significant relation between FFM (logged data adjusted for $\log_e$ FM and age) and PAL (adjusted

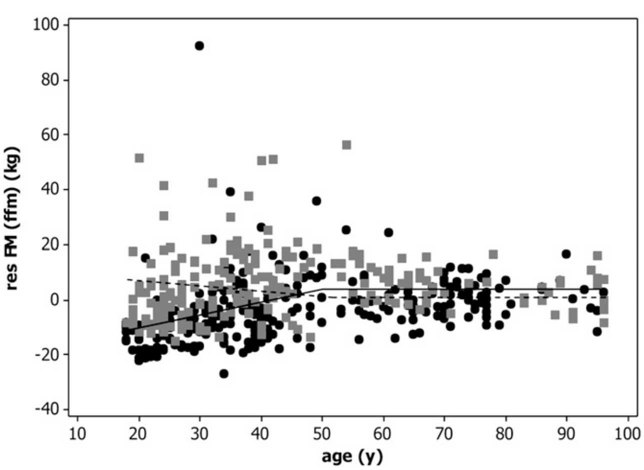

FIGURE 2. The residual (res) of the regression of fat-free mass (ffm) on fat mass (FM) as a function of age for women (n = 240; gray squares) and men (n = 289; black circles). Lines are fitted regressions for each sex above and below an average break point of 52 y.

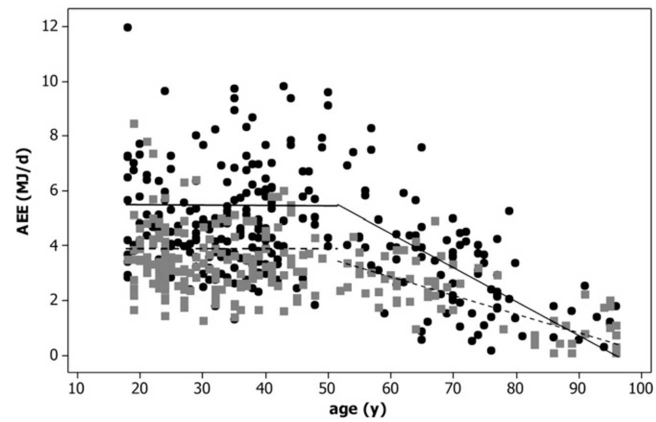

FIGURE 3. Activity energy expenditure (AEE) as a function of age in women (n = 240; gray squares) and men (n = 289; black circles). Lines are fitted regressions for each sex above and below an average break point of 52 y.

for age) in men aged 18–52 y ($F_{1,\ 183}$ = 3.47, P = 0.064), but in women aged 18–52 y there was a statistically significant but very weak positive relation ($F_{1,\ 164}$ = 3.9, P = 0.05, r^2 = 0.023) (**Figure 6**A). Individuals aged 18–52 y with greater FFM (independent of FM) were generally not more physically active.

Effects in subjects aged ≥52 y

Above and including the age of 52 y in both men and women, greater subject age was associated with lower FFM and FM (ie, decadal averages from 50 to 59 y onward show progressively lower values; Table 1, Figure 1). Moreover, the lower FFM in older subjects remained when it was adjusted for differences in $\log_e$ FM (FFM distribution was consistent with normality, but FM was not and had to be log transformed: $F_{1,\ 175}$ = 25.1, $P <$ 0.001). The effect of age on adjusted FFM was different between sexes, being lower in women than in men. On average, FFM in the women aged ≥52 y was lower by 0.13 kg/y (95% CI: 0.05, −0.20 kg/y), whereas in men it was lower by an average of 0.42 kg/y (95% CI: −0.32, −0.53 kg/y). In the very oldest individuals aged 90–100 y, the average sex difference in FFM was

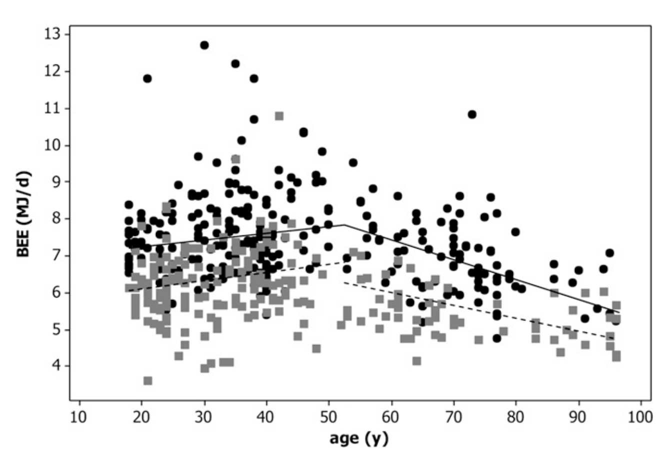

FIGURE 4. Basal energy expenditure (BEE) as a function of age in women (n = 240; gray squares) and men (n = 289; black circles). Lines are fitted regressions for each sex above and below an average break point of 52 y.

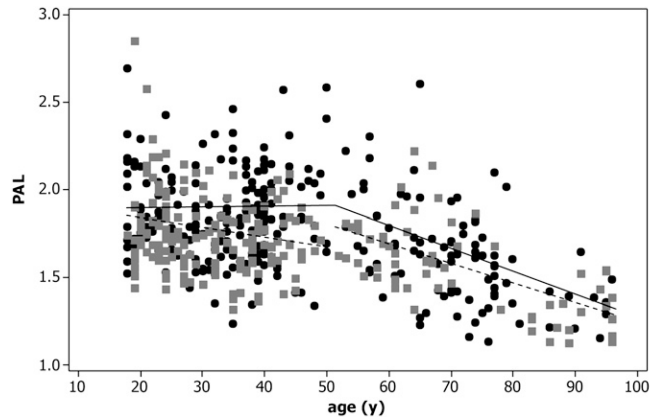

FIGURE 5. Physical activity level (PAL) as a function of age in women (n = 240; gray squares) and men (n = 289; black circles). Lines are fitted regressions for each sex above and below an average break point of 52 y.

<10 kg, compared with a 15-kg difference in subjects aged 18–52 y (Table 1).

Above and including the age of 52 y, all distributions of the measures of energy expenditure (BEE, AEE, DEE, and PAL) were consistent with normality, except for AEE and PAL in men, which were log transformed to normalize them. All of these traits were age dependent and were lower in the older subjects (Figures 3–6). The lower BEE with increasing subject age in subjects aged ≥52 y (Figure 4) was similar for women (-22 kJ $\cdot$ d^{-1} $\cdot$ y^{-1}; 95% CI: -15, -38 kJ $\cdot$ d^{-1} $\cdot$ y^{-1}) and men (-45 kJ $\cdot$ d^{-1} $\cdot$ y^{-1}; 95% CI: -26, -60 kJ $\cdot$ d^{-1} $\cdot$ y^{-1}). As established for individuals aged <52 y, BEE was significantly related to FFM and $\log_e$ FM, both of which were negatively related to subject age in subjects aged ≥52 y (Table 1 and Figure 1B). When we included FFM and $\log_e$ FM as predictors of BEE in the multiple regression model, the effect of subject age disappeared (FFM: $F_{1,\ 173} = 368$, $P < 0.001$; $\log_e$ FM: $F_{1,\ 173} = 7.28$, $P = 0.008$; age: $F_{1,\ 173} = 0.12$, $P = 0.735$). The lower BEE in older subjects in this age group, therefore, appeared solely due to older subjects having a lower FM and FFM.

AEE was also significantly lower in older subjects (Figure 3). AEE was not normally distributed and was therefore was log converted to normalize it before analysis. There was a strong effect of a subject's age on $\log_e$ AEE ($F_{1,\ 173} = 124$, $P < 0.001$) but no effect of sex ($F_{1,\ 173} = 0.12$, $P = 0.75$) and no sex-by-age interaction ($F_{1,\ 173} = 0.21$, $P = 0.64$) (Figure 4); hence, the effect of age was not significantly different between men and women. Because the lower AEE in older subjects was much greater than the effect of subject age on BEE, PAL was strongly dependent on age for those subjects aged ≥52 y (Figure 5). On average the PAL between ages 18 and 52 y averaged 1.84 in men and 1.75 in women. In the subjects aged 90–100 y, PAL averaged only 1.36 in both sexes (Table 1). The sex difference in the effect of subject age on PAL after age 52 y for women (-0.010; 95% CI: -0.007, -0.014) and men (-0.013; 95% CI: -0.008, -0.017) was not significant.

Above and including the age of 52 y, both FFM (adjusted for $\log_e$ FM) and PAL were generally lower in older individuals, although an age effect was less noticeable early in this period, particularly in men. It was necessary, therefore, to statistically remove this age effect before seeking a relation between adjusted FFM and PAL. In effect, this analysis asked whether there

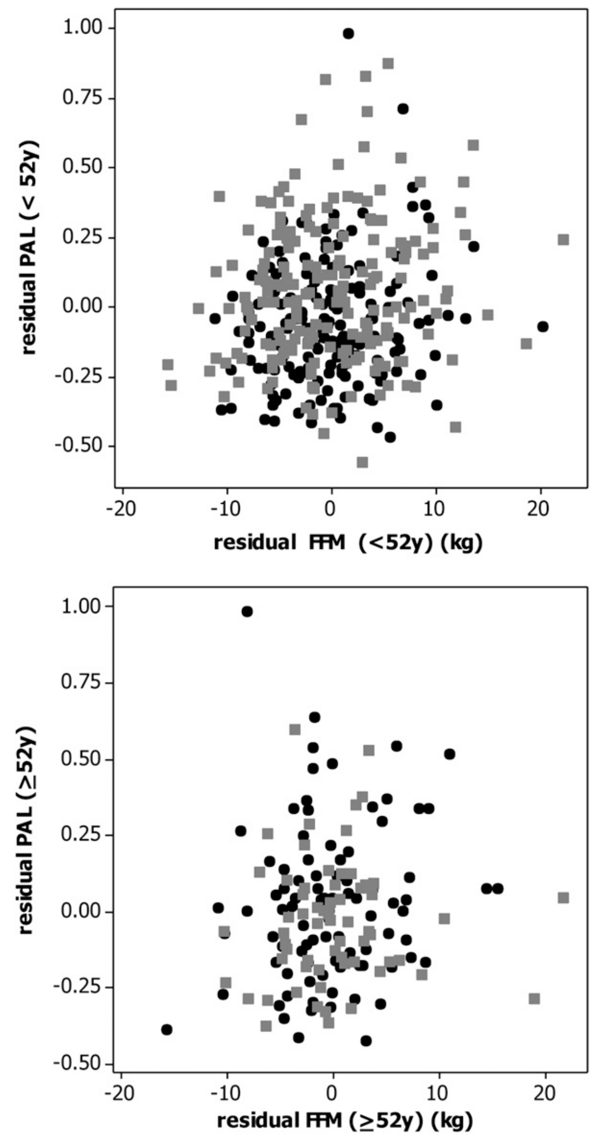

FIGURE 6. Residual of the regression of physical activity level (PAL) on age as a function of the residual of the regression of fat-free mass (FFM) on age and fat mass in women (gray squares) and men (black circles). The upper plot is for adults aged <52 y, and the lower plot is for adults aged ≥52 y.

is a relation between adjusted FFM and PAL, independent of the overall effect of age on these variables. There was no significant relation between age-adjusted FFM (also adjusted for FM) and age-adjusted PAL (Figure 6B) in men ($F_{1,\ 102} = 1.06$, $P = 0.306$) or in women ($F_{1,\ 72} = 0.01$, $P = 0.901$). Consequently, individuals in this older age cohort with greater FFM for their age and body fatness were not more physically active. Alternatively greater physical activity at any particular age was not associated with higher FFM.

DISCUSSION

Transition points

All the traits measured showed transition points around the middle of the age range. Before the transitions, the traits tended to be independent of subject age or increased in older subjects; after the transition, all the traits tended to be reduced in individuals that were older. These trends were consistent with many previous studies (references for individual traits follow). The age of the breakpoints did not differ significantly between men and women and occurred at a mean (±SE) age of 52 ± 1.8 y (n = 12). In cross-sectional data, such as in the current study, little significance can be drawn from the different breakpoints for the different traits.

Effects of age on body-composition differences

Up to the age of 52 y in this cohort, greater subject age was associated with elevated FM and FFM in men but not in women. The elevation of FM was not just associated with elevated FFM, because there was a significant independent effect of age on the adjusted FM. Our data are consistent with many previous studies that have found age-related increases in FM in younger men (1–3, 51, 52), although other studies have reported no change (53). Most previous studies have also established similar age-related effects in women, and the absence of an effect in our cohort was therefore unexpected. Subjects who were older than 60 y tended to have lower FFM and FM. This pattern was also observed previously (1–3), but, again was not universal—some studies reporting progressive accumulation of FM beyond the age of 50 y (54). In this cohort, the effect of subject age was much greater in men than in women. A greater prevalence of sarcopenia in older men was also previously indicated (30, 55).

Effect of age on BEE

Up to the age of 52 y, there was a significant positive effect of FFM and an independent contribution of FM, which, combined with a small negative effect of age, explained 81% of the total variation in BEE. This pattern is consistent with many other studies that have explored the effect of body composition and age on BEE (12, 13, 15–19, 21–23), although some studies have failed to find an independent effect of FM beyond that of FFM (56–60). Several previous studies have suggested that the large sex effect on BEE is only due to the large difference in size and body composition between women and men (12, 22, 61, 62), whereas our data were consistent with other data that have suggested a persistent sex effect after body composition is accounted for (63, 64). The reasons for the differences between these studies are not immediately apparent. The lower BEE of older subjects in the age range 50–100 y has been reported many times (15, 25, 26, 65–67) although contradictory studies showing no age effect have also been published (68). There has been much dispute over the contribution of changes in body composition to this effect (69), with some studies consistent with the current study, suggesting that body-composition changes can explain the reduced BEE or lack of change, but others suggesting it cannot (66). The present data set suggested no additional age effect beyond that caused by subject differences in FFM and FM. Differences between studies may reflect variation in the causes of differences in FFM between studies. It is well established that FFM is heterogeneous in composition and comprises tissues with widely differing metabolic rates (70, 71) and that this variability may contribute to wider scaling effects of metabolic rate (72–74). Recent studies attempting to account for this heterogeneity have suggested that there may be an additional physiologic component to the age-related differences in BEE (19, 75–77).

Effects of subject age on AEE and PAL

There were no effects of subject age on either AEE or PAL, up to the age of 52 y. Previous studies have not reported significant age effects on these variables in this age group, which suggests that it is generally the case that physical activity is sustained until subjects are in their 50s. Thereafter, there was a profound negative effect of subject age on both AEE and PAL. This pattern is consistent with that previously observed (24, 24, 78, 79). Blanc et al (62) noted that women in their 80s had a much lower AEE than did men but that PAL was not different, consistent with our observations in the older subjects.

The data presented here are cross-sectional. Some longitudinal studies have been performed in older adults, and their results generally contrast with those found in the current study. For example, Rothenberg et al (67) found no changes in AEE and PAL in a longitudinal comparison between ages 73 and 78 y. Moreover, Reilly et al (80) also found no differences in PAL over time in a cohort studied between the ages of 65 and 72 y. However, in both of these cases the sample sizes were small and the duration of follow-up short. Studies of larger cohorts with longer follow-up, however, are much harder to perform, hence their absence in the literature. It seems likely that the cross-sectional nature of our sample would actually tend to minimize the effect of age on PAL, because in all age classes we selected participants who were free-living and able-bodied. As subjects age they become increasingly likely to suffer from a lack of mobility, and such subjects would have a low PAL and a low probability of being included in these studies.

The lower levels of physical activity in older subjects who also had a lower FFM has led to the suggestion that these phenomena are causally linked (39, 81–85), either because elevated physical activity protects against age-related FFM loss or because preserved FFM loss allows greater physical activity. The data presented here do not support this interpretation because, once the confounding influence of age had been removed, we found no association between FFM and PAL (Figure 6B). This analysis is consistent with previous studies based on a smaller sample size (66) and studies measuring physical activity by accelerometry (42) or by questionnaire rather than directly as expended energy on exercise (38, 40, 41) Consistent with our correlational findings, other studies have shown that physical activity interventions may alter muscle function and increase fat loss, but do not halt the progress of muscle mass loss in the elderly (86, 87). Interestingly, Hunter et al (36) found that resistance training could reverse the decline in FFM in the elderly, and that the increase in FFM was associated with an increase in DEE. This was due in part to an increase in BEE because of the greater FFM. However, there was also a suggestion of an increase in AEE, but this was not significant (P = 0.06). Whether this was a type II error because of the low sample size (8 men and 7 women) remains uncertain. Generally, however, it is now regarded that lower physical activity is due more to changes in muscle composition and physiology than to quantity (88, 89) and that sarcopenia is caused by a complex interaction of nutritional factors, such a protein intake, oxidative stress, inflammatory changes, and hormonal effects (84, 90–95).

In summary, our data show that up to the age of 52 y, fat and FFM were positively associated with subject age, whereas BEE, DEE, AEE, and hence PALs, were broadly independent of subject age. After the age of 52 y, older subjects tended to have lower values for all these variables. This effect of subject age was most noticeable in FFM and also in AEE and PAL. Older subjects aged > 52 y had a lower FFM and lower levels of energy expenditure on physical activity. For a person at any given age ($\geq$52 y), however, there was no association between the amount of energy expended on physical activity and FFM, which suggests that routine physical activity does not protect against loss of FFM, and that loss of FFM is not associated with lower routine PALs.

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