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Nutritional requirements and status

Sex Differences in Measures of Energy Expenditure and Body Composition in Young, Middle-Aged, and Older Adults

Hannah E Cabre [1], Kara L Marlatt [2], Rodrigo Fernández-Verdejo [1,3], Robbie Beyl [1], Leanne M Redman [1], Philip N Ainslie [4], Heliodoro Alemán-Mateo [5], Lene F Andersen [6], Liam J Anderson [4,7], Lenore Arab [8], Kweku Bedu-Addo [9], Alberto G Bonomi [10], Carlijn VC Bouten [11], Pascal Bovet [12], Soren Brage [13], Maciej S Buchowski [14], Nancy F Butte [15], Stefan G Camps [16], Regina Casper [17], Graeme L Close [4], Lisa H Colbert [18], Jamie A Cooper [19], Richard Cooper [20], Sai Krupa Das [21], Sanjoy Deb [22,23], Terrence Forrester [24], Melanie Gillingham [25], Annelies H Goris [26], Michael Gurven [27], Catherine Hambly [28], Sumei Hu [29], Annemiek M Joosen [26], Peter Katzmarzyk [1], Kitty P Kempen [26], Misaka Kimura [30], William E Kraus [31], Wantanee Kriengsinyos [32], Robert F Kushner [33], Nader Lessan [34], Marie Löf [35], Corby K Martin [1], Eric Matsiko [36], Anine C Medin [6,37], James C Morehen [4,38], James P Morton [4], Marian L Neuhouser [39], Ross L Prentice [39], Susan B Racette [40], David A Raichlen [41], Rebecca M Reynolds [42], Susan B Roberts [43], Luís B Sardinha [44], Albertine J Schuit [45], Analiza M Silva [44], Samuel S Urlacher [46], Mauro Eduardo Valencia [5], Ludo M Van Etten [26], Jeanine A Verbunt [26], George Wilson [4], Brian M Wood [47,48], Tsukasa Yoshida [49], Xueying Zhang [28,29,50,51], Alexia J Murphy-Alford [52], Cornelia U Loechl [52], Amy H Luke [53], Herman Pontzer [54], Jennifer Rood [1], Hiroyuki Sagayama [55], Dale A Schoeller [56], Klaas R Westerterp [57], William W Wong [15], Yosuke Yamada [30,49], John R Speakman [28,29,50,51,**], Eric Ravussin [1,*], for the IAEA DLW Database Consortium

*[1] Pennington Biomedical Research Center, Louisiana State University, Baton Rouge, LA, United States; [2] Advisory Board, Washington, DC, United States; [3] Department of Nutrition and Dietetics, School of Health Sciences, Faculty of Medicine, Pontifical Catholic University of Chile, Santiago, Chile; [4] Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Liverpool, United Kingdom; [5] Body Composition and Functionality Laboratory, Center for Food and Development Research, A.C., Hermosillo, Sonora, México; [6] Department of Nutrition, Institute of Basic Medical Sciences, University of Oslo, Norway; [7] School of Sport, Exercise and Rehabilitation Sciences, University of Birmingham, Birmingham, United Kingdom; [8] David Geffen School of Medicine, University of California, Los Angeles, United States; [9] Department of Physiology, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana; [10] Phillips Research, Eindhoven, The Netherlands; [11] Department of Biomedical Engineering and Institute for Complex Molecular Systems, Eindhoven University of Technology, Eindhoven, The Netherlands; [12] University Center for Primary Care and Public Health (Unisanté), Lausanne, Switzerland; [13] MRC Epidemiology Unit, University of Cambridge, Cambridge, United Kingdom; [14] Division of Gastroenterology, Hepatology and Nutrition, Department of Medicine, Vanderbilt University, Nashville, TN, United States; [15] Department of Pediatrics, Baylor College of Medicine, USDA/ARS Children's Nutrition Research Center, Houston, TX, United States; [16] Clinical Nutrition Research Center, Singapore Institute for Clinical Sciences, Agency for Science, Technology, and Research (A*STAR) and National University Health System, Singapore; [17] Psychiatry and Behavioral Sciences, Stanford University, Stanford, CA, United States; [18] Kinesiology, University of Wisconsin, Madison, WI, United States; [19] Department of Nutritional Sciences, University of Wisconsin, Madison, WI, United States; [20] Department of Public Health Sciences, Parkinson School of Health Sciences and Public Health, Loyola University, Maywood, IL,*

Abbreviations: DLW, doubly labeled water; FM, fat mass; FFM, fat-free mass; IAEA, International Atomic Energy Agency; PAL, physical activity level; REE, resting energy expenditure; TDEE, total daily energy expenditure.

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* Corresponding author.
** Corresponding author. *E-mail addresses:* j.speakman@abdn.ac.uk (J.R. Speakman), eric.ravussin@pbrc.edu (E. Ravussin).

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United States; [21] Jean Mayer USDA Human Nutrition Research Center on Aging, Tufts University, Boston, MA, United States; [22] Centre for Nutraceuticals, School of Life Sciences, University of Westminster, London, United Kingdom; [23] Department of Circulation and Medical Imaging, Faculty of Medicine and Health Sciences, Norwegian University of Science and Technology, Trondheim, Norway; [24] Solutions for Developing Countries, University of the West Indies, Kingston, Jamaica; [25] Department of Molecular and Medical Genetics, Oregon Health & Science University, Portland, OR, United States; [26] Maastricht University, Maastricht, The Netherlands; [27] Department of Anthropology, University of California Santa Barbara, Santa Barbara, CA, United States; [28] Institute of Biological and Environmental Sciences, University of Aberdeen, Aberdeen, United Kingdom; [29] State Key Laboratory of Molecular Developmental Biology, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, Beijing, China; [30] Institute for Active Health, Kyoto University of Advanced Science, Kyoto, Japan; [31] Department of Medicine, Duke University, Durham, NC, United States; [32] Institute of Nutrition, Mahidol University, Bangkok, Thailand; [33] Feinberg School of Medicine, Northwestern University, Chicago, IL, United States; [34] Imperial College London Diabetes Centre, Imperial College London, London, United Kingdom; [35] Department of Biosciences and Nutrition, Karolinska Institute, Stockholm, Sweden; [36] Department of Human Nutrition and Dietetics, University of Rwanda, Kigali, Rwanda; [37] Department of Nutrition and Public Health, Faculty of Health and Sport Sciences, University of Agder, Kristiansand, Norway; [38] The FA Group, Burton-Upon-Trent, United Kingdom; [39] Division of Public Health Sciences, Fred Hutchinson Cancer Research Center and School of Public Health, University of Washington, Seattle, WA, United States; [40] Arizona State University Phoenix, Phoenix, AZ, United States; [41] Biological Sciences and Anthropology, University of Southern California, CA, United States; [42] Centre for Cardiovascular Sciences, The Queen's Medical Research Institute, University of Edinburgh, Edinburgh, United Kingdom; [43] Geisel School of Medicine, Dartmouth College, Hanover, NH, United States; [44] Exercise and Health Laboratory, CIPER, Faculty of Human Kinetics, University of Lisbon, Lisbon, Portugal; [45] Wageningen University & Research Centre Health and Society, University of Wageningen, Wageningen, The Netherlands; [46] Department of Anthropology, Baylor University, Waco, TX, United States; [47] Department of Anthropology, University of California Los Angeles, Los Angeles, CA, United States; [48] Department of Human Behavior, Ecology, and Culture, Max Planck Institute for Evolutionary Anthropology, Leipzig, Germany; [49] National Institute of Health and Nutrition, National Institutes of Biomedical Innovation, Health and Nutrition, Tokyo, Japan; [50] Center for Energy Metabolism and Reproduction, Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen, China; [51] Chinese Academy of Sciences (CAS) Center of Excellence in Animal Evolution and Genetics, Kunming, China; [52] Nutritional and Health Related Environmental Studies Section, Division of Human Health, International Atomic Energy Agency, Vienna, Austria; [53] Division of Epidemiology, Department of Public Health Sciences, Loyola University School of Medicine, Maywood, IL, United States; [54] Evolutionary Anthropology, Duke University, Durham, NC, United States; [55] Faculty of Health and Sport Sciences, University of Tsukuba, Ibaraki, Japan; [56] Biotech Center and Nutritional Sciences University of Wisconsin, Madison, WI, United States; [57] Nutrition and Translational Research in Metabolism, Maastricht University Medical Centre, Maastricht, The Netherlands

A B S T R A C T

Background: Total daily energy expenditure (TDEE) is vital for energy balance and cardiometabolic health, yet its trajectory across the lifespan, particularly in females, remains poorly understood.

Objectives: We sought to examine the effects of aging and sex on body composition and TDEE.

Methods: In a cross-sectional analysis of data from research centers across 9 European Countries and the United States from the International Atomic Energy Agency database, TDEE and body composition measures of 2326 participants (1560W/766M; 50.7 ± 12 .6 y) were stratified across age groups: young (30–39 y; YOUNG), middle-aged (40–54 y; MID), and old (55–70 y; OLD). Doubly labeled water was used to estimate TDEE and fat-free mass (FFM). Fat mass (FM) was calculated as the difference between body mass and FFM, and %fat was ratio between FM and body mass as a percentage. Linear models were used for analysis.

Results: Females demonstrated greater FM and lower FFM with each age group, compared with males ($P < 0.001$). In females, OLD had lower absolute TDEE than YOUNG (−217 kcal/d, $P < 0.001$) and MID (−208 kcal/d, $P < 0.001$). Male absolute TDEE was lowered across all age groups (OLD compared with YOUNG: −334 kcal/d; OLD compared with MID: −210 kcal/d; MID compared with YOUNG: −124 kcal/d; $P < 0.001$). Adjusted TDEE was similar within age groups between females and males.

Conclusions: These results suggest that age influences changes in body composition and energy expenditure similarly between males and females. The most significant change in TDEE occurs as individuals transition from middle age to older adulthood. Females generally have a higher percentage of %fat and FM, along with lower FFM, compared with males across all age groups. These findings are important for understanding how aging affects metabolism and body composition, which could inform sex-specific health strategies and interventions.

Keywords: menopause, sex differences, total daily energy expenditure, body composition, aging, obesity, energy balance

Introduction

Obesity is a major public health concern that disproportionately affects females compared with males [1]. In the United States, the prevalence of obesity among females is 39.7% for those aged 20–39 y and 43.3% for both the 40–59 and 60+ age groups [1]. This rise in obesity rates aligns with the menopause transition (typically between ages 40 and 52), with lasting effects into the postmenopausal years (>52 y) [2–5]. The dramatic decreases in circulating estrogens during menopause reduce resting energy expenditure (REE) at midlife [3,6–8], whereas the stable decline in testosterone in males may attenuate variation in REE during aging [9]. However, REE comprises only 50%–70% of total daily energy expenditure (TDEE). Accurately assessing how TDEE increases or decreases across the lifespan is imperative for identifying alterations in nutritional requirements that may influence energy balance and body weight. Yet, despite its importance, little is known about how TDEE differentially changes between young, middle-age, and older males and females.

In general, males have more fat-free mass, whereas females have more fat mass and a higher body fat percentage, and these sex-dependent differences in body composition emerge at puberty primarily due to estrogen's and testosterone's role in regulating body composition [10]. During aging, changes to anatomy such as decreases in fat-free mass are often responsible for decreases in TDEE [11–13]. Menopause is associated with a gain in weight, relative body fat, and fat mass [6,14–16], and with an acceleration in the loss of fat-free mass [6,17,18]. Similar alterations in body composition have also been observed in age-matched males [10]. Nevertheless, the loss of fat-free mass and increase in fat mass occur much more rapidly in females than in males, suggesting a sex-dependent age-accelerating role in fat mass accretion [10]. Shifts in body composition and energy expenditure around the menopausal age range may reflect additional influence of menopause on TDEE. Doubly labeled water (DLW) provides an assessment of TDEE and body composition, allowing for measurements of free-living energy expenditure and body composition across the lifespan [19].

Given that energy expenditure is strongly influenced by activity level, especially in males [9], it is essential to characterize physical activity. Utilizing the ratio of TDEE to REE is the most accurate assessment of physical activity level (PAL) [20]. The International Atomic Energy Agency (IAEA) database v.3.7 [19, 21] has the largest data collection of TDEE and REE. Recent analyses of the IAEA database have shown clear age-related trajectories in TDEE [22], highlighted the role of body composition in variation [23], and addressed methodological considerations and variability in energy expenditure estimates [9]. Interestingly, 1 study found that even after accounting for age, height, and body composition, males showed greater variation in total, activity, and basal energy expenditure compared to females. However, with aging, variation in TDEE declined with a more rapid decrease in males [9]. Given the inherent sex-based variability in energy expenditure, examining whether age influences TDEE and body composition differently in females and males is important. Assessing specific age groups that reflect the menopause transition adds further clarity, as the menopausal period involves hormonal and metabolic changes that may uniquely affect females' energy expenditure and body composition. Using males as a comparator can help elucidate the factors influencing these potential changes. This distinction is important for identifying when and how metabolic decline occurs across the lifespan to inform sex-specific strategies for maintaining energy balance and metabolic health.

Using the IAEA dataset, we aimed to determine the effects of aging and sex on body composition and TDEE, both measured by DLW. We expected to see a greater reduction in TDEE adjusted for body composition earlier in females compared with males, primarily through lower fat-free mass and greater fat mass. Our objective was to provide essential insights into TDEE and body composition changes at different life stages to provide more precise caloric and nutrition recommendations in an age- and sex-appropriate manner. Such recommendations may help the implementation of interventions to prevent weight gain and subsequent cardiometabolic risk factors.

Methods

Participants

Measures of TDEE and body composition were taken in 2326 healthy, adult males and females who were 30–70 y old. We classified males and females as young (30–39 y), middle-aged (40–54 y), and older (55–70 y). These age groups also reflect the stages of menopause (premenopause, perimenopause, and postmenopause, respectively) [19,21], because reproductive status was not confirmed for females in the IAEA dataset. We excluded participants who were pregnant or lactating, were not weight stable (± 5 kg in the last 3 mo), or had a diagnosis of diseases. If an individual had >1 TDEE measurement in the IAEA dataset ($N = 5$), the first available measurement was included. The dataset for this analysis comprised TDEE and body composition measurements from 1560 females and 766 males (Figure 1). Detailed information on the subjects is listed in Supplementary Tables 1 and 2.

Study design

TDEE in the IAEA database was calculated using a common method for respiratory exchange ratio to convert CO_2 production from DLW, and all participants had ≥5 d of DLW data [19, 21]. Fat-free mass was derived from total body water (^{18}O isotope dilution in liters/0.73) [24], and fat mass was calculated as the difference between body mass and fat-free mass. Percent body fat was calculated as the ratio between fat mass and body weight expressed as a percentage. Participants were enrolled across multiple studies and provided written informed consent prior to participation. Although the total IAEA database contains data from 30 countries, the majority of the data (~65%) are from participants in the United States and European countries [9]; therefore, we restricted the dataset to participants in the United States and Europe due to their relative similarities in environment, socioeconomic status, and diet, which help provide a more controlled comparison across age and sex (Supplementary Table 2). In our exploratory analysis of the full dataset, we observed substantial variability in TDEE, often exceeding ±3 SDs from the mean, among participants from regions outside the United States and Europe, further supporting our decision to focus on these cohorts to improve data consistency and interpretability. PAL values were calculated in a subsample of 604 participants from the IAEA dataset who underwent REE testing (e.g., indirect calorimetry) by dividing the absolute TDEE by REE (Supplementary Table 3 and 4). PAL was used to classify the groups as sedentary (PAL = 1.0–1.39), low active (PAL = 1.4–1.59), active (PAL = 1.6–1.89), and very active (PAL = 1.9–2.5) [25]. Participants with PAL >2.5 were removed from the analysis ($n = 16$).

Statistical analysis

Individuals with TDEE values ≥3.5 SDs above or below the mean of the sample for each sex were considered outliers and removed from analyses ($N = 14$) [26]. For our first aim, to evaluate differences in body composition (percent body fat, fat mass, fat-free mass) variables, and TDEE between young, middle-aged, and older participants within each sex, we used a linear model with age group as the factor split by sex. In the case of a significant linear relationship, Tukey SD posthoc pairwise comparisons were conducted. Linear regression analyses were used to determine differences in TDEE between age groups within each sex after adjusting for fat-free mass and fat mass. Data were expressed as the residuals of the regression plus the mean TDEE value for each sex and with age as a continuous variable (Supplementary Figure 1). For our second aim, to evaluate differences in body composition and TDEE between sexes within each age group, univariate generalized linear models with sex as the factor were used. Secondarily, univariate generalized linear models with sex as the factor and age as a continuous variable were used. To evaluate PAL between young, middle-aged, and older participants within each sex, we used a

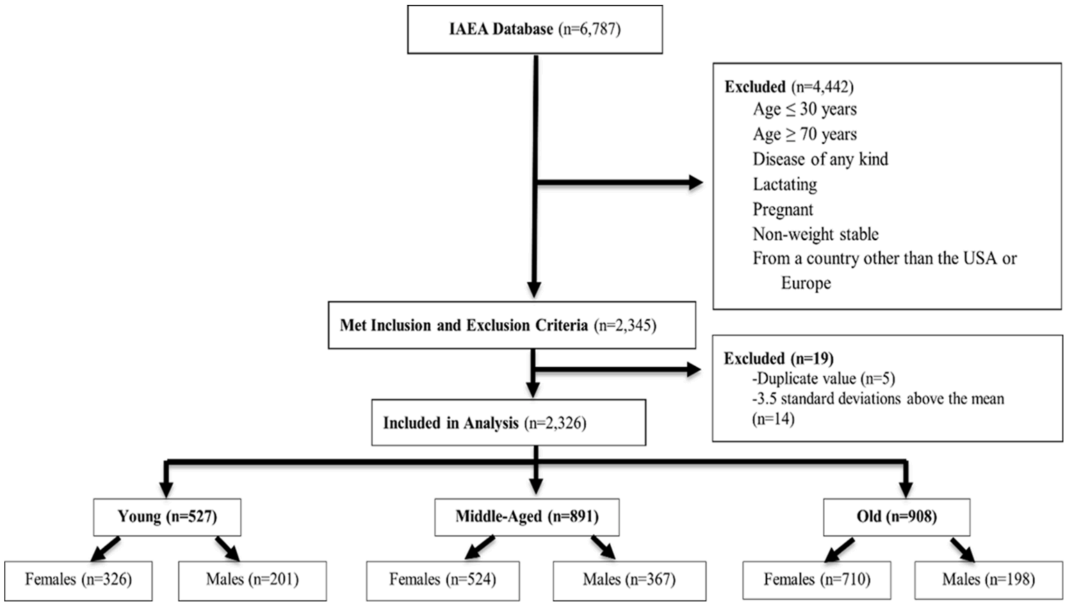

FIGURE 1. CONSORT diagram of data collation. IAEA, International Atomic Energy Agency.

linear model with age group as the factor split by sex. Sensitivity analyses were conducted to assess the relationship between adjusted TDEE, REE, and PAL with age as a continuous variable. We confirmed that the linear models presented were the best fit based on visual inspection of residual plots and through examination of residuals. Adjusted R^2 values are provided for the relationships between age and fat mass, and fat-free mass and TDEE. Results are presented as mean ± SD and mean difference

TABLE 1
Participant demographics, body composition, and total daily energy expenditure sex and age groups

	Females			Males			Females vs. males comparison[1]			
	Young (*n* = 326)	Middle-aged (*n* = 524)	Old (*n* = 710)	Young (*n* = 201)	Middle-aged (*n* = 367)	Old (*n* = 198)	Young	Middle-aged	Old	Overall[2]
Age (y)	34.4 ± 2.9[3,4]	46.1 ± 4.3[3,5]	65.0 ± 3.8[4,5]	34.4 ± 2.9[6,7]	46.5 ± 4.4[6,8]	62.8 ± 4.4[7,8]	0.864	0.188	<0.001	—
Height (cm)	165.0 ± 6.1[4]	164.2 ± 6.2[5]	162.2 ± 6.6[4,5]	179.3 ± 6.7[6,7]	177.6 ± 7.0[6,8]	176.0 ± 6.9[7,8]	<0.001	<0.001	<0.001	<0.001
Weight (kg)	77.2 ± 20.1	79.2 ± 22.9	76.7 ± 17.1	88.0 ± 20.3	87.7 ± 18.1	87.8 ± 15.8	<0.001	<0.001	<0.001	<0.001
BMI (kg/m^2)	28.3 ± 7.0	29.3 ± 8.2	29.1 ± 6.3	27.3 ± 5.9	27.9 ± 5.4	28.3 ± 4.3	0.075	<0.001	0.075	<0.001
FM (kg)	30.0 ± 14.0[3,4]	33.0 ± 16.1[3]	33.7 ± 12.1[4]	23.7 ± 14.2[7]	26.2 ± 12.1	28.4 ± 9.9[7]	<0.001	0.002	<0.001	<0.001
FFM (kg)	47.1 ± 7.7[4]	46.2 ± 8.3[5]	43.0 ± 6.3[4,5]	64.3 ± 9.9[6,7]	61.5 ± 8.5[6,8]	59.4 ± 8.3[7,8]	<0.001	<0.001	<0.001	<0.001
%Fat	37.2 ± 8.9[3,4]	39.7 ± 8.6[3,5]	42.8 ± 6.8[4]	25.6 ± 8.7[6,7]	28.8 ± 7.3[6,8]	31.7 ± 6.3[7,8]	<0.001	<0.001	<0.001	<0.001
TDEE (kcal/d)	2421 ± 426[4]	2412 ± 440[5]	2204 ± 333[4,5]	3243 ± 675[6,7]	3119 ± 534[6,8]	2909 ± 521[7,8]	<0.001	<0.001	<0.001	<0.001

Values are presented as mean ± SD.
Abbreviations: FM, fat mass; FFM, fat-free mass; TDEE, total daily energy expenditure.
[1] Significance between sex per age group by the univariate general linear model.
[2] Significance between sex with age as a continuous variable in a univariate general linear model.
[3] $P < 0.001$ young females different from middle-aged and old females.
[4] $P < 0.001$ young females different from middle-aged and old females.
[5] $P < 0.001$, middle-aged females different from old females (within sex between age-group difference by Tukey's post hoc test in univariate general linear model).
[6] $P < 0.001$ young males different from middle-aged and old males.
[7] $P < 0.001$ young males different from middle-aged and old males.
[8] $P < 0.001$, middle-aged males different from old males (within sex between age-group difference by Tukey's post hoc test in univariate general linear model).

± SE. Statistical significance was set at the $\alpha = 0.05$. Statistical tests were conducted using SPSS (Version 26, IBM Armonk) and SAS (Version 9.4).

Results

Participant demographics

For the total sample, females were older, had a higher BMI (in kg/m^2), fat mass, and percent body fat, and lower fat-free mass and absolute TDEE than males (Supplementary Table 1). In a subsample of participants, females had lower REE (mean ± SD: 1425 ± 235 kcal/d compared with 1820 ± 262 kcal/d; $P <$ 0.001) and PAL (1.7 ± 0.2 compared with 1.8 ± 0.3) compared with males, yet the overall sample was active (1.8 ± 0.2) (Supplementary Table 3). Within sex, middle-aged males (1.9 ± 0.4) had a higher average PAL than older males (1.7 ± 0.3; $P =$ 0.017). Between sexes, younger and middle-aged males were more active than younger and middle-aged females ($P < 0.05$) (Supplementary Table 4).

Changes in percent body fat and fat-free mass between age groups

As shown in Table 1 and Figure 2, percent body fat, fat-free mass, and fat mass were different between females and males within each age group with the older groups having greater fat mass and lower fat-free mass than middle-aged and young groups.

In females, the older group had higher percent body fat than the younger (mean difference ± SE: +5.6 ± 0.5%; $P < 0.001$) and middle-aged groups (+3.1 ± 0.5%; $P < 0.001$), whereas the middle-aged group had higher percent body fat than the younger group (+2.5 ± 0.6%; $P < 0.001$). As such, the younger group had lower fat mass than the middle-aged (−2.9 ± 1.0 kg; P = 0.010) and older groups (−3.6 ± 0.9 kg; $P < 0.001$), but values were similar between middle-aged and older groups ($P =$ 0.599). Younger females had similar fat-free mass compared with the middle-aged group (+0.9 ± 0.5 kg; $P = 0.212$), but both groups had higher fat-free mass compared with older females (+4.1 ± 0.5 kg; $P < 0.001$ and +3.2 ± 0.4 kg; $P < 0.001$, respectively) (Table 1 and Figure 2).

Similarly, in males, the older group had higher percent body fat than younger (+6.1 ± 0.7%; $P < 0.001$) and middle-aged groups (+2.9 ± 0.7%; $P < 0.001$), whereas the middle-aged group had higher percent body fat than the younger group (+3.2 ± 0.7%; $P < 0.001$). Fat mass was similar between younger and middle-aged groups ($P = 0.060$) and middle-aged and older groups ($P = 0.085$). However, the younger group had significantly lower fat mass than older group (−4.7 ± 1.2 kg; $P < 0.001$). Conversely, the younger group had greater fat-free mass compared with middle-aged (+2.8 ± 0.8 kg; $P <$ 0.001) and older groups (+4.9 ± 0.9 kg; $P < 0.001$). The middle-aged group had greater fat-free mass compared with the older group (+2.1 ± 0.8 kg; $P < 0.001$) (Table 1 and Figure 2).

Absolute TDEE and adjusted TDEE between age groups and in a sex-dependent way

In females, absolute TDEE was similar between the younger and middle-aged groups ($P = 0.943$). However, the older group had lower TDEE than the younger (−217 ± 26 kcal/d; $P <$ 0.001) and the middle-aged groups (−208 ± 22 kcal/d; $P <$ 0.001) (Table 1). The same trends were observed when TDEE was adjusted for fat-free mass and fat mass using multiple regression analysis. The older group had lower adjusted TDEE than both the younger (−71 ± 24 kcal/d; $P = 0.003$) and middle-aged groups (−93 ± 20 kcal/d; $P < 0.001$), without differences between younger and middle-aged females (+22 ± 24 kcal/d; $P = 0.360$) (Figure 3).

In males, absolute TDEE was progressively lower with each age group. Thus, the middle-aged group had lower TDEE than the younger group (−124 ± 50 kcal/d; $P = 0.036$), whereas the older group had lower TDEE than both the younger (−334 ± 57 kcal/d; $P < 0.001$) and middle-aged groups (−210 ± 50 kcal/d; $P < 0.001$). When adjusting TDEE for fat-free mass and fat mass, the difference between the younger and middle-aged group disappeared (+13 ± 30 kcal/d; $P = 0.661$), but the older group still had lower adjusted TDEE than both the younger (−93 ± 35

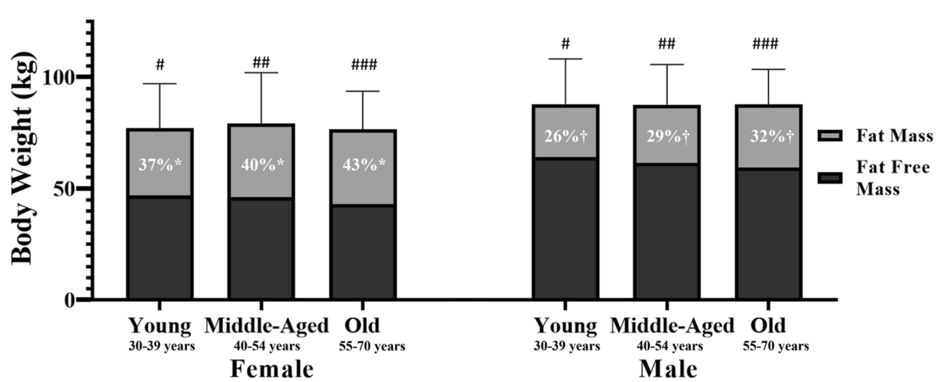

FIGURE 2. Body weight represented with fat mass, fat-free mass, and %fat mass values per age group indicative of the menopause transition in females with males as the comparator group. *, indicates significance in females for %fat between each age group; †, indicates significance in males for %fat between age groups; #, indicates significant difference between young females and males for fat mass, fat-free mass, and %fat; ##, indicates significant differences between middle-aged females and males for fat mass, fat-free mass, and %fat; ###, indicates significant differences between old females and males for fat mass, fat-free mass, and %fat.

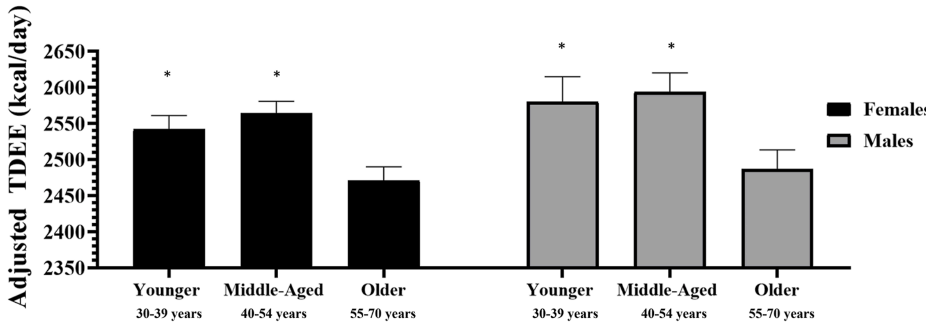

FIGURE 3. Adjusted total daily energy expenditure (TDEE) values per age groups indicative of the menopause transition in females with males as a comparator group. *, indicates significant difference from older group. There were no significant differences between sex for the magnitude of change in adjusted TDEE between groups [females (younger compared with middle-aged) compared with males (younger compared with middle-aged): −9 kcal/d ± 38 kcal/d; $P = 0.821$; females (middle-aged compared with older) compared with males (middle-aged compared with older): −14 kcal/d ± 36 kcal/d; $P = 0.698$].

kcal/d; $P = 0.008$) and the middle-aged group (−107 ± 30 kcal/d; $P < 0.001$) (Figure 3).

After adjusting for fat-free mass and fat mass, TDEE was not different between females and males in the younger (−38 ± 40 kcal/d; $P = 0.336$), middle-aged (−30 ± 31 kcal/d; $P = 0.342$) or the older groups (−16 ± 34 kcal/d; $P = 0.639$). Importantly, the difference in adjusted TDEE between younger and middle-aged groups was not different between sexes [females (younger compared with middle-aged) compared with males (younger compared with middle-aged): −9 ± 38 kcal/d; $P = 0.821$]. Neither were the differences in adjusted TDEE between middle-aged and older groups [females (middle-aged compared with older) compared with males (middle-aged compared with older): −14 ± 36 kcal/d; $P = 0.698$] (Figure 3). Adjusted TDEE and REE both declined with age in both sexes, whereas percent body fat increased, and PAL showed a modest decline across the lifespan. The slopes of these relationships differed significantly between females and males for all outcomes when age was a continuous variable ($P < 0.01$) (Supplementary Figures 1–4).

Discussion

Our study used the DLW method to directly assess how age affects energy expenditure and body composition—factors that are rarely compared between males and females within the same cohort. By leveraging the largest global dataset of free-living TDEE measurements, our analysis provides novel insight into sex-specific changes in body composition and energy expenditure using age groups that are reflective of the menopause transition. Our findings demonstrate that there was a higher percentage of body fat in middle-aged and older females despite no significant changes in weight. Absolute values of TDEE were similar between young and middle-aged females, but largely different from older females. When observing within sex differences, older males demonstrated a significantly lower absolute TDEE compared with young and middle-aged males. Our adjusted TDEE results in both females and males demonstrate how body composition changes across the lifespan largely influence TDEE. These findings enhance our understanding of how aging influences metabolism and body composition, providing a foundation to develop sex-specific health interventions, such as tailored nutrition plans and physical activity programs accounting for age-related changes in body composition and energy expenditure.

Previous cross-sectional studies suggest divergent patterns of change in fat mass in aging males and females [27–29]. Typically, older males have an equal or greater amount of fat mass compared with younger males [27,29,30]. Females experience body composition alterations in midlife when fat mass exponentially increases with consequential deleterious metabolic implications (e.g., increased risk of cardiovascular disease) [15,31–33]. In the present study, percent body fat was higher in middle-aged and older females and males despite no significant differences in body weight, suggesting similar trajectories in fat mass gain with age. Cross-sectional and longitudinal studies indicate that fat-free mass declines most rapidly during perimenopause [6,15,17]. Our data suggest older females demonstrated clinically meaningful lower fat-free mass compared with young and middle-aged females (Δ −4.1 kg and Δ −3.2 kg, respectively). Although reports of the pattern of changes in fat-free mass in males are more limited, our data show a similar pattern of body composition change between sexes (i.e., greater fat mass and lower fat-free mass), suggesting aging has a commonality that surpasses divergent sex-hormone differences [34].

Many existing linear regression models examining the effects of aging on TDEE do not include sex, limiting the interpretation of sex differences during critical periods such as menopause [16,35–37]. Importantly, in the present study, adjusted TDEE was not significantly different between sexes in any age group, suggesting that the differences in TDEE between sexes across the lifespan are mostly explained by differences in body composition. We stratified our analysis of TDEE by sex, thus providing objective measures and predictive equations for young, middle-aged, and older females and males (Supplementary Figures 1–4). When adjusting for fat-free mass and fat mass in our sample, adjusted TDEE remained stable between young and middle-aged females (Δ−22 kcal/d), but largely lower between middle-aged and older females (Δ−93 kcal/d). Adjusted TDEE was also similar between young and middle-aged males (Δ−13 kcal/d) but was significantly lower between middle-aged to older males (Δ−107 kcal/d). When sex was combined as reported by Pontzer et al. [22], age did not affect adjusted TDEE (the model included fat-free mass, fat mass, and sex) in individuals who were 20–60 y of age. However, in individuals over 60 y, age did affect adjusted TDEE ($\beta = -24$ kcal/d per extra year of age) [22]. Taken together with our data, the transition between middle-aged and older adulthood is likely where the greatest decreases in adjusted TDEE occur. Such observation is novel and important as it extends our understanding of the dataset. Energy balance, and thus body weight, is maintained by matching energy intake with expenditure, whereas chronic excess intake leads to fat gain.

This cross-sectional study provided a robust comparison between males and females across well-defined age categories. Strengths of this secondary outcome analysis include the use of the reference standard method of DLW to measure TDEE and body composition, as well as the inclusion of participants across 9 European countries and the United States, allowing for a generalizable sample. We obtained REE in a subsample of participants that allowed us to characterize PAL, demonstrating no significant differences between age groups in females. Yet, our study has limitations related to defining menopausal stage, heterogeneity in participant characteristics, and lack of dietary recall data. First, menopause status was not confirmed (e.g., self-report, hormonal profiles, etc.), making it difficult to isolate the effects of menopause from age-related changes in body composition and energy expenditure. Although we based our age ranges on Stages of Reproductive Aging Workshop (STRAW) guidelines to try to account for menopause stages, to address this limitation, we used terms like “younger,” “middle-aged,” and “older” to transparently reflect age-related findings without assuming menopausal status. Second, the IAEA database includes participants from diverse studies with varying activity levels, potential medication use (e.g., hormonal contraception), and lifestyle factors that can contribute to variability in TDEE. These variables were not consistently reported, so we were unable to account for these variables in our statistical analyses. Finally, energy intake was not measured. Yet, the DLW method accounts for the thermic effect of food and substrate oxidation, indirectly capturing the influence of energy intake on energy balance and body composition [38].

In conclusion, with human life expectancy continually increasing [39], understanding the differences in body composition and energy expenditure across the lifespan presents important opportunities for investigations into factors that can impact the main determinants of energy expenditure. Our analysis stratified TDEE measures by sex, providing empirical measurements and predictive equations for both females and males across the aging spectrum. Our analyses suggest there is a substantially lower energy expenditure associated with changes in body composition across the lifespan, which may impact energy balance and cardiometabolic health for both males and females.

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Author contributions

The authors’ responsibilities were as follows – HEC, RFF-V, RB, ER, KLM, LMR, YY, DAS, BW, HP, HS: contributed to writing; HEC, RFV, RB, ER, YY, HS, AHL, HP, JR, DAS, KRW, WWW, JRS: contributed to discussion and analysis; YY, HS, PNA, LFA, LJA, LA, IB, KB-A, EEB, SB, AGB, CVCB, PB, MSB, NFB, SGC, GLC, JAC, RC, SKD, LRD, UE, SE, TF, BWF, AHG, MG, CH, AEH, MBH, SH, NJ, AMJ, PK, KPK, MK, WEK, RFK, EVL, WRL, NL, CM, ACM, EPM, JCM, JPM, MLN, TAN, RMO, KHP, YPP, JP-R, GP, RLP, RAR, S.B. Racette, DAR, ER, RNR, S.B. Roberts, AJS, AMS, ES, SSU, GV, LMVE, EAVM, JCKW, GW, BMW, JY, TY, XY, AHL, HP, JR, DAS, KRW, WWW, JRS: contributed data; JRS, CL, AHL, AJ M-A, HP, JR, DAS, HS, KRW, WWW, YY: assembled and managed the database; and all authors: read and approved the final manuscript.

Conflict of interest

The authors report no conflicts of interest.

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Data availability

All data used in these analyses are freely available via the IAEA DLW Database, which can be found at https://doubly-labelled-water-database.iaea.org/home and www.dlwdatabase.org.

Declaration of generative AI in scientific writing

During the preparation of this work, the author(s) used ChatGPT to improve readability and language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cdnut.2025.107614.

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