Descriptive epidemiology of energy expenditure in the UK: Findings from the National Diet and Nutrition Survey 2008 – 2015

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Abstract

Background Little is known about population levels of energy expenditure as national surveillance systems typically employ only crude measures. The National Diet and Nutrition Survey (NDNS) in the UK measures energy expenditure in a 10% subsample by gold-standard doubly-labelled water (DLW).

Methods DLW-subsample participants from NDNS (383 males, 387 females) aged 4-91years were recruited between 2008 and 2015 (Rolling Programme). Height and weight were measured, and bodyfat percentage estimated by deuterium dilution.

Results Absolute Total Energy Expenditure (TEE) increased steadily throughout childhood, ranging from 6.2 and 7.2 MJ/day in 4-7yr-old to 9.7 and 11.7 MJ/day for 14-16yr-old girls and boys, respectively. TEE peaked in 17-27yr-old women (10.7 MJ/day) and 28-43yr-old men (14.4 MJ/day), before decreasing gradually in old age. Physical Acitivty Energy Expenditure (PAEE) declined steadily with age from childhood (87 kJ/day/kg in 4-7yr olds) through to old age (38 kJ/day/kg in 71-91yr olds). No differences were observed by time, region, and macronutrient composition. Bodyfat percentage was strongly inversely associated with PAEE throughout life, irrespective of expressing PAEE relative to bodymass or fat-free mass. Compared to females with <30% bodyfat, females >40% recorded 29 kJ/day/kg and 18 kJ/day/kg fat-free mass less PAEE in analyses adjusted for age, geographical region, and time of assessment. Similarly, compared to males with <25% bodyfat, males >35% recorded 26 kJ/day/kg and 10 kJ/day/kg fat-free mass less PAEE.

Conclusions This first nationally representative study reports levels of human energy expenditure as measured by gold-standard methodology; values may serve as reference for other population studies. Age, sex and body composition are the main determinants of energy expenditure.

Keywords: Energy expenditure, physical activity, epidemiology, population

Key messages:

- First nationally representative study of human energy expenditure, covering the UK in the period 2008-2015
- Total Energy Expenditure (MJ/day) increases steadily with age thoughout childhood and adolescence, peaks in the 3rd decade of life in women and 4th decade of life in men, before decreasing gradually in old age
- Physical Acitivty Energy Expenditure (kJ/day/kg or kJ/day/kg fat-free mass) declines steadily with age from childhood to old age, more steeply so in males
- Bodyfat percentage is strongly inversely associated with physical activity energy expenditure
- We found little evidence that energy expenditure varied by geographical region, over time, or by dietary macronutrient composition

Introduction

Little is known about population levels of energy expenditure (EE) as most national surveys use proxy methods for assessment, typically questionnaires. These may take the form of either self-reported dietary energy intake combined with measures of weight change[1], or self-reported physical activity combined with estimates of resting EE[2]. The former approach is challenged not only by the necessary correction for any weight changes but also by possible underreporting of energy intake by overweight or obese individuals[3]. The latter approach does not need to make assumptions about energy balance as it is directly assessing the expenditure side; however, self-report methods for physical activity also have limited accuracy, and this applies particularly to derivatives such as estimates of energy expenditure[4]. The use of objective methods in the form of wearable sensors such as accelerometers and heart rate monitors is typically preferred as the objective methods for large-scale population studies, since these provide information about intensity patterns as well as more precise estimates of energy expenditure when coupled with appropriate inference models[5–9]. Irrespective of the success of such inference models, feasibility is somewhat limited for methods using heart rate monitoring due to its requirement for individual calibration using an exercise test[10,11], whereas the main limitation of accelerometry-based estimation of energy expenditure depends on the mix of specific behaviours in which the population under study is engaged as this relationship varies by activity type[12,13].

Preferably, one would therefore employ more direct, yet highly feasible, measurements of the quantity of interest for the surveillance of population trends in energy expenditure. The doubly-labeled water (DLW) technique is the gold-standard for measurement of energy expenditure during free-living[14]. This technique uses the stable isotopes deuterium (^{2}H) and Oxygen-18 (^{18}O) to directly measure rate of carbon dioxide production (rCO_2) over a period of 1-2 weeks, from which average total energy expenditure (TEE) can be calculated with high precision. Combined with simple anthropometric measurements, estimates of physical activity energy expenditure (PAEE) can also be derived. The DLW method is highly feasible in terms of low participant burden but it is unfortunately also expensive and hence is only seldom used in large studies.

The National Diet and Nutrition Survey (NDNS) employs a nationally representative sampling frame to assess the diet and nutritional status of the general population aged 1.5 years or older living in private households in the UK[15]. One of the unique features of the NDNS is that a 10% subsample of all age groups 4 years or older also had energy expenditure assessed using the DLW technique over 10 days of free-living. The aim of this study was to describe the variation in components of energy expenditure by key personal characteristics, geographical location, and over time.

Methods

Participants

This is a repeat cross-sectional survey. Participants were recruited to the rolling programme in NDNS by stratified and clustered random sampling of households in the UK. NDNS data are weighted to account for any selection or response biases to ensure results are representative of the UK population[15]. A total of 15,583 households were selected to take part between 2008 and 2015, and 8,974 households agreed (58% household response rate). From those households, 10,727 individuals agreed to take part and a subsample of these NDNS participants were invited to take part in the DLW substudy, within which individuals were sampled according to pre-specified age/sex strata (4-10, 11-15, 16-49, 50-64, and 65+ years). The DLW sub-study field work was carried out in two waves; for the first wave

(2008-11), targets were 40 participants in each of the age/sex groups but for the second wave (2013-15), these were changed to 30 participants for each stratum for those aged 4-10 and those 65+ years, and to 50 participants for those aged 16-49 years. A total of 808 were invited to take part in the DLW substudy, of whom 770 participants provided sufficient data to derive valid EE estimates and they constitute the sample included in the present analysis. This subsample does not differ from the main NDNS (excluding children <4 years) in terms of sex, body mass index (BMI), total energy intake, fruit and vegetable intake in g/day, free sugar intake (% total energy intake), and saturated fat intake (% total energy intake) but it was 2.6 years older[15].

All adult participants provided informed written consent and all children provided assent with written consent from their legal guardian. The study was approved by the Oxfordshire A Research Ethics Committee (#07/H0604/113) and Cambridge South NRES Committee (#13/EE/0016).

Measurements

Anthropometric measurements were performed in participants' homes. Height was measured to the nearest millimeter using a portable stadiometer and bodymass was measured to the nearest 100g in light clothing using calibrated scales[15]. BMI (kg/m^2) was calculated from these measures.

Food and drink intake was captured using a four-day unweighed (estimated) paper diary. Average nutrient intakes were calculated using DINO (Diet In, Nutrients Out, DINO)[16], which incorporates Public Health England's NDNS nutrient databank, from which total energy intake and macronutrient composition (fat, carbohydrate, protein, and alcohol) was determined. This method was selected following a comparison study prior to the start of the NDNS Rolling Programme which evaluated two candidate methods, the estimated food diary and the repeat 24-hour recall. Both methods were feasible and provided similar information on food, energy and nutrient intake. The diary was selected based on continuity with past NDNS surveys and flexibility with a wide range of age groups[17].

For the measurement of TEE, a baseline (pre-dose) urine sample was first collected to establish the natural abundance of the ^2H and ^{18}O isotopes in body water. Next, a dose of $^2H_2{}^{18}O$ proportional to the participant's bodymass (80mg per kg bodymass of ^2H_2O and 150mg per kg bodymass of $H_2{}^{18}O$) was prepared in a dose bottle. The full dose was drunk using a straw following which the bottle was re-filled with local tap water and again fully drunk by the participant. Participants collected single daily spot urine samples for the next ten days, representing about 2.5 half-lives of peak enrichment. The urine samples were analysed for isotopic enrichment by mass spectrometry (^{18}O enrichment: AP2003, Analytical Precision Ltd, Northwich, Cheshire, UK; ^2H enrichment: Isoprime, GV Instruments, Wythenshaw, Manchester, UK or Sercon ABCA-Hydra 20-22, Sercon Ltd, Crewe, UK). Rate of carbon dioxide production was measured using the method of Schoeller[18] and converted to TEE using the energy equivalents of CO_2 of Elia and Livesey[19] using the food quotient as an approximation of the respiratory exchange quotient. Total bodywater was assessed using the zero-time intercept of deuterium turnover[20] and fat-free bodymass calculated using a hydration factor of 73%[21]. Bodyfat percentage was calculated as total bodymass minus fat-free mass, expressed as percentage of total.

Resting metabolic rate was estimated from anthropometry variables by averaging three prediction equations; one based on age, sex, height, and total bodymass derived in a large database[22], and two based on smaller studies which also take into account body composition[23,24]. In order to calculate 24-hour resting energy expenditure (REE), we integrated this resting metabolic rate value over time, but with a small adjustment for the 5% lower metabolic rate observed during sleep[25] applied using age-specific sleep durations ranging from 8-12 hours/day[26]. The diet-induced thermogenesis (DIT) was calculated from the macro-nutrient composition of the diet as previously described[7,27], and PAEE was calculated as the residual energy expenditure which sums with REE and DIT to make up TEE, according to the equation PAEE = TEE - REE - DIT.

Statistics

We expressed daily TEE in absolute units (MJ/day) and both TEE and PAEE in relative units (kJ/day/kg bodymass). In sensitivity analyses, we also expressed energy expenditure in units scaled to fat-free bodymass and in allometrically-scaled units of kJ/day/kg$^{2/3}$ bodymass, the latter based on the theoretical principle that absolute energy expenditure scales to bodily dimensions to the power of 2 and bodymass scales to bodily dimensions to the power of 3[28,29]. We present summary statistics (mean and standard deviation) of all estimates of energy expenditure by recruitment strata, ie age and sex groups. In addition, we present box plots (box denoting median and interquartile ranges) by expanded age-groups (deciles), as well as by survey year (2008-11 and 2012-15) and main geographical regions of North England, South England, and Scotland/Wales/North-Ireland combined. North England included the following Government Office Regions; North East, North West, Yorkshire and The Humber, East Midlands and West Midlands, and South England comprised the East, South West, London and South East as used previously[30]. We examine the association with obesity status by both body mass index (BMI) and bodyfat groups, stratified by sex and age groups. To examine independent associations, we performed a multiple linear regression analysis with mutual adjustment for all above factors, and with additional adjustment for season of measurement (expressed as two orthogonal sine functions; "winter" (with max=1 on January 1st and min=-1 on July 1st) and "spring" (with max=1 on April 1st and min=-1 on October 1st). A sensitivity analysis to the BMI association was performed using fat mass index (FMI) and fat-free mass index (FFMI) in age- and sex-specific tertiles, and finally a supplementary analysis describing energy expenditure by macronutrient composition groups was performed to investigate possible behavioural associations.

Results

Of the 770 participants with valid DLW data included in this analysis, the four constituent countries of the United Kingdom were represented with 568 participants from England, 50 from Scotland, 72 from Wales and 80 from Northern Ireland (Table 1).

Mean (SD) TEE was 10.6 (2.8) $MJ \bullet day^{-1}$ or 185 (63) $kJ \bullet day^{-1} \bullet kg^{-1}$, REE was 5.9 (1.2) $MJ \bullet day^{-1}$, and PAEE was 64 (28) $kJ \bullet day^{-1} \bullet kg^{-1}$. Across these estimates of energy expenditure, after adjustment for age, time and region of measurement, male sex was associated with higher values ($p<0.001$). When TEE and PAEE were expressed relative to fat-free mass, only PAEE was higher in males ($p=0.010$).

Figure 1 shows TEE, PAEE, and bodymass across age deciles and stratified by sex. Median TEE and PAEE were higher in males than females across all age groups; bodymass was similar in boys and girls up to age 16 years but higher in men above that age. Absolute TEE ($MJ \bullet day^{-1}$) was highest in 17-27-year old women and 28-43-year old men, respectively. In contrast, TEE and PAEE relative to bodymass ($kJ \bullet day^{-1} \bullet kg^{-1}$) was highest in the youngest individuals and displayed a consistent downward trend with advancing age into adulthood. TEE had a less steep association with age from early to later adulthood. The bodymass-scaled

EE associations partially mirrored the positive trend in bodymass from childhood into young adulthood, which levelled off across adult ages. Similar age associations were observed in the sensitivity analyses (Supplementary Figure S1-S2), although the age association for allometrically scaled TEE ($kJ \cdot day^{-1} \cdot kg^{-2/3}$) was more linear across the whole age range, and 8-11-year olds had the highest PAEE of all groups in these analyses.

There were no significant differences in TEE, PAEE or bodymass among those participants surveyed between 2008-2011 and those surveyed between 2013-2015 (Figure 2), nor were there any discernible differences between constituent geographical regions (Figure 3). These observations were confirmed in the multi-variable adjusted analyses which were additionally adjusted for season of measurement, an effect which was only apparent in males, with slightly higher values in spring (Table 2).

Across the sample, absolute TEE ($MJ \cdot day^{-1}$) was higher in individuals with higher BMI. Overweight participants had higher TEE ($MJ \cdot day^{-1}$) than normal-weight participants, and obese participants accumulated higher TEE levels than overweight participants, a trend that was observed within nearly all age- and sex strata (Figure 4). However, this relationship was inverse when TEE was expressed in relative terms. Obese males and females in all age groups recorded the lowest relative TEE and PAEE ($kJ \cdot day^{-1} \cdot kg^{-1}$), whereas normal-weight individuals recorded the highest.

A similar relationship was also observed for TEE and PAEE across groups of differing bodyfat percentage, although the clear positive trend for absolute TEE was absent in the two adult age groups (Figure 5). For relative TEE and PAEE ($kJ \cdot day^{-1} \cdot kg^{-1}$), those with the highest bodyfat percentage recorded the lowest energy expenditure, whereas the slimmest individuals recorded the highest. The sole exception to this were men aged 65-91y with medium bodyfat who as a group accumulated slightly more PAEE than their slimmer counterparts. The multivariable regression analysis confirmed associations with BMI and body fatness in both sexes (Table 2). Fat-free mass index, however, was only positively associated with absolute TEE and inversely associated with relative TEE but not related to relative PAEE in neither males nor females.

In sensitivity analyses modelling PAEE per kg fat-free mass (supplement table S1), individuals in the third tertile of fat mass index were less active; this inverse association was also observed for bodyfat percentage groups. This sensitivity analysis also suggested a possible regional difference in activity levels, with women in Wales, Scotland and Northern Ireland expending more activity energy per kg fat-free mass, independent of other covariates.

Associations between macronutrient compostion and energy expenditure were generally weak but trending towards higher PAEE in groups consuming a lower proportion of their energy intake from carbohydrate or protein. However, young girls who consumed low-carbohydrate diets were less active than their counterparts, as were older men who consumed low-protein diets (Figure 6).

Discussion

Here, we report gold-standard measured energy expenditure from a nationally representative cross-sectional UK survey. Our results show how TEE and PAEE vary according to age, sex and body composition but no differences were observed by geographical region of the UK or over time in the period between 2008 and 2015.

Our results demonstrate that males accumulate higher overall levels of TEE and PAEE than females across all ages, a finding that is consistent with other British cohort studies investigating energy expenditure by objective methods[31–36]. Age was an important correlate of PAEE and TEE in both sexes, with similar patterns across the lifespan for all EE measures; absolute TEE peaks in the early adult years, before dropping off around retirement age, whereas relative TEE and PAEE are highest in the earliest years of life before gradually declining steeply at first and reflecting in part natural growth and development, and then more shallowly after the age when adult height is typically attained.

There are no previous reports of nationally representative DLW-based estimates of energy expenditure from the UK, nor from other countries. However, within the UK, some preparatory NDNS work in 1989 measuring 81 children from Cambridgeshire aged 1.5 – 4.5 years old reported TEE levels of 4.9 MJ•day^{-1} (333 kJ•day^{-1}•kg^{-1}) in the whole group and 5.4 MJ•day^{-1} (320 kJ•day^{-1}•kg^{-1}) in 4-yr olds (n=27)[35]. Assuming a diet-induced thermogenesis of 10% TEE and estimating REE[22,26] suggests PAEE around 77 kJ•day^{-1}•kg^{-1} (79 kJ•day^{-1}•kg^{-1} for 4-yr olds). The 2008 to 2015 NDNS DLW subsample does not include children younger than 4 years but the eight 4-yr old children included had TEE of 5.9 MJ•day^{-1} (314 kJ•day^{-1}•kg^{-1}) and PAEE of 86 kJ•day^{-1}•kg^{-1}.

A sample of 78 children aged 3-18 years from Belfast (Northern Ireland) measured in 1991 (or earlier) had TEE values of 7.1 MJ•day^{-1} (313 kJ•day^{-1}•kg^{-1}) in 3-10 yr olds (n=44) and 11.8 MJ•day^{-1} (211 kJ•day^{-1}•kg^{-1}) in 12-18 yr olds (n=34)[36]; estimating PAEE as above yields values of 81 and 108 kJ•day^{-1}•kg^{-1} in 3-10 yr old girls and boys, and 67 and 90 kJ•day^{-1}•kg^{-1} in 12-18 yr old girls and boys, respectively.

Overall, these historical UK estimates of energy expenditure are not very different to what we report here from the most recent NDNS survey but no firm conclusions on secular trends in energy expenditure in UK children can be drawn owing to regional differences in population sampling and small sample sizes.

Considering more contemporary UK data, 1397 British 6-yr olds measured by combined heart rate and movement sensing recorded PAEE of 95 $kJ•day^{-1}•kg^{-1}$ which is almost identical to NDNS values[37]. In fact several British cohort studies using this technique observe comparable PAEE levels across the age range, with 66 and 84 $kJ•day^{-1}•kg^{-1}$ in 825 adolescent girls and boys (aged 15 years) attending schools in Cambridge[31], and 50 and 59 $kJ•day^{-1}•kg^{-1}$ in a sample of 12002 English adult women and men aged between 29 and 64 years (mean 49 years)[34]; the latter cohort also reported a DLW-measured PAEE of 50 $kJ•day^{-1}•kg^{-1}$ in a subsample of 100 men and women (mean age 54 years)[9]. In older adults, PAEE by combined sensing was reported as 34 and 36 $kJ•day^{-1}•kg^{-1}$ in 1787 women and men of the nationally representative UK 1946 birth cohort assessed at ages 60-64 years[33]; this compares to PAEE of 32 $kJ•day^{-1}•kg^{-1}$ observed in 23 Cambridge men aged 76 to 88 years measured some time before 1995, with TEE of 9.2 $MJ•day^{-1}$ (129 $kJ•day^{-1}•kg^{-1}$)[38].

Internationally, only limited DLW data are available from large single studies but pooled analyses from multiple smaller studies have been reported. Torun reported TEE of 7.5 $MJ•day^{-1}$ (259 $kJ•day^{-1}•kg^{-1}$) in 657 girls and 8.0 $MJ•day^{-1}$ (287 $kJ•day^{-1}•kg^{-1}$) in 483 boys aged 1-18 years, including data from UK studies reported above; the remaining studies were mostly from North America, followed by Northern Europe and Latin America[39]. Comparing estimates from Latin America vs other countries, TEE was 6.5 vs 6.7 $MJ•day^{-1}$ (292 vs 275 $kJ•day^{-1}•kg^{-1}$) in 3-11 yr old girls and 7.1 vs 7.2 $MJ•day^{-1}$ (295 vs 296 $kJ•day^{-1}•kg^{-1}$) in boys, respectively. In parallel, PAEE 86 vs 77 $kJ•day^{-1}•kg^{-1}$ in girls and 87 vs 86 $kJ•day^{-1}•kg^{-1}$ in boys. In older children, TEE was 10.5 $MJ•day^{-1}$ (193 $kJ•day^{-1}•kg^{-1}$) in girls and 13.0 $MJ•day^{-1}$ (225 $kJ•day^{-1}•kg^{-1}$) in boys, and PAEE was 71 and 84 $kJ•day^{-1}•kg^{-1}$, respectively; these estimates did not include any studies from Latin America. Combined, these studies show similar TEE but varying levels of PAEE, although direct comparisons should bear in mind notable differences between studies, including participant selection, setting, and era.

In adults, male NDNS participants accumulated a mean TEE and PAEE of 12.9 MJ•day^{-1} and 55 kJ•day^{-1}•kg^{-1}, whereas adult women accumulated 10.1 MJ•day^{-1} and 48 kJ•day^{-1}•kg^{-1}, respectively. This is comparable to levels of TEE and PAEE in other DLW studies in comparable populations, e.g. mean TEE of 12.7 MJ•day^{-1} for men and 10.0 MJ•day^{-1} for women, and PAEE of approximately 54 kJ•day^{-1}•kg^{-1} and 44 kJ•day^{-1}•kg^{-1} were reported in a meta-analysis of 1575 men and 2914 women aged over 19 years from high-development index countries[40]. This analysis included published DLW data upto 2011, and although studies in special populations were excluded, again caution is warranted as to the representativeness of the participants included.

More recently, Matthews et al reported DLW results from a study of 461 American men and 471 women in a convenience sample with mean ages of 64 and 62 years, respectively. In that study, mean TEE was 11.6 and 9.1 MJ•day^{-1} and mean PAEE was 39 and 38 kJ•day^{-1}•kg^{-1}, for men and women respectively[41]. Again, these figures are very similar to those found for TEE in the oldest category of NDNS participants (>64 years), and only about 10% lower for PAEE although we note mean age was 72 years in our sample. Overall, the results therefore suggest that British men and women expend a similar amount of total and physical activity energy as their counterparts in the developed world, with a similar age-related decline.

This is partially in contrast to EE levels in populations residing in less developed countries, where only absolute EE levels are similar but activity levels are higher. For example, absolute TEE in studies from countries with low-to-medium development scores was reported to be 12.3 and 9.3 MJ•day^{-1} but relative PAEE estimated at 69 and 49 kJ•day^{-1}•kg^{-1}, for men and women respectively[40]. With respect to PAEE, these high levels seem particularly pronounced in rural dwellers in these countries, with values around 60 kJ•day^{-1}•kg^{-1} in Cameroon[42] and even higher in rural Luo, Kamba, and Masai in Kenya[43] as assessed with individually calibrated combined heart rate and movement sensing.

BMI and bodyfat percentage were also important correlates of TEE and PAEE, and there is an ongoing debate over how to best express energy expenditure with respect to body size, particularly when examining associations with overweight and obesity[44,45] In the NDNS sample, larger body size was associated with higher absolute levels of TEE (MJ•day^{-1}) but irrespective of how energy expenditure was expressed relative to body weight (kJ•day^{-1}•kg^{-1} or kJ•day^{-1}•kg$^{-2/3}$), BMI displayed an inverse relationship. This was also observed when body fatness was assessed in terms of total bodyfat % or fat mass index. Multivariate analysis demonstrated that, when corrected for age, geographical region, survey year and season of measurement, overweight women accumulated 30 kJ•day^{-1}•kg^{-1} less TEE and 13 kJ•day^{-1}•kg^{-1} less PAEE than their normal-BMI counterparts. Continuing this trend, obese females accumulated 43 kJ•day^{-1}•kg^{-1} less TEE and 19 kJ•day^{-1}•kg^{-1} less PAEE than normal-weight female participants. This was replicated in males with TEE and PAEE lower in groups with higher BMI.

This finding highlights the role that absolute body size plays in the accumulation of absolute energy expenditure, but also underlines obesity's inverse association with physical activity energy expenditure. This relationship was apparent regardless of the measure of obesity and of the measure of physical activity, with those with higher absolute bodyfat levels and those in the highest FMI category accumulating less physical activity than slimmer counterparts. However, the association with fat-free mass index was non-significant in both males and females, as also observed in a pooled analysis of 529 Dutch adults[46], many of whom were included in the meta-analysis by Dugas et al who reported non-significant associations between Physical Activity Level (TEE/REE) and body weight.[40] This highlights the complex interplay between physical activity, energy expenditure, body mass, and diet. Despite a recent observation suggesting that low carbohydrate diets were associated with higher energy expenditure[47], we did not find any significant associations for macronutrient composition of the diet in NDNS.

This study has several notable strengths. Firstly, the NDNS is nationally representative and with no observed selection bias for the DLW subsample; therefore the estimates for TEE and PAEE can serve as national reference values for this period. Secondly, DLW is the gold standard method for measuring energy expenditure during free-living conditions. Thirdly, our analyses include the main components and common expressions of energy expenditure, including both absolute and various relative measures, and within the limitations of the sample also reasonable stratification and multivariable adjustment analyses to test the robustness of observed differences across specific population subgroups.

This study also has some limitations. The study as a whole is not large, with only 770 individuals included in the present analyses. In addition, the majority of the sample came from England, with very few participants included in certain subgroup analyses. The generalisability of these small groups to the wider Northern Irish, Scottish and Welsh populations is therefore less certain. It is also possible that non-participating households may differ from participating households. Another limitation is that data are cross-sectional and effectively snap-shot assessments taken at relatively short time intervals between 2008 and 2015 which with this sample size is unlikely to be sufficient to detect secular trends even if they truly occurred in the UK over this time period; given the slight increase in national obesity levels in the same period[48], we suspect that absolute TEE levels may have also increased but that relative EE levels may have decreased in line with the observed associations with such indicators in our study. Finally, some misclassification of the habitual diet cannot be ruled out, owing to only sampling 4 days of intake and using estimated portion sizes, rather than weighed quantitites, but the method provides similar estimates of intake as the commonly used repeat 24-hour recall method, both of which compare reasonably well with biomarkers, particularly when normalised for energy intake as we have done here[17,49,50].

In conclusion, age, sex and body composition are the main determinants of human energy expenditure. Results from this nationally representative sample using gold-standard methodology may serve as reference values for other population studies.

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Table 1. Participant characteristics. National Diet and Nutrition Survey DLW subsample (2008-2015)

	Females					Males				
Age group	4-10	11-15	16-49	50-64	65-91	4-10	11-15	16-49	50-64	65-91
Age (y)	7.5 (2)	13.4 (1)	31.9 (11)	57.0 (5)	72.9 (6)	7.1 (2)	12.8 (1)	29.2 (11)	56.4 (5)	73.3 (6)
N	*73*	*80*	*91*	*79*	*64*	*74*	*76*	*89*	*83*	*61*
Survey Year (n)										
2008-2011	41	38	40	37	32	41	34	38	41	29
2013-2015	32	42	51	42	32	33	42	51	42	32
Region (n)										
South England	28	24	28	26	25	23	26	23	24	20
North England	31	34	36	32	23	34	23	41	44	23
Scotland	4	9	4	6	5	4	5	3	5	5
Wales	4	6	7	8	9	6	11	9	5	7
North Ireland	6	7	16	7	2	7	11	13	5	6
Anthropometry										
Height (cm)	127 (13)	159 (8)	164 (7)	162 (6)	160 (7)	126 (11)	159 (10)	178 (6)	175 (7)	172 (6)
Weight (kg)	28.5 (9)	54.7 (13)	70.0 (17)	76.5 (16)	73.5 (14)	26.6 (6)	53.0 (13)	82.7 (19)	86.7 (15)	82.8 (14)
BMI (kg/m^2)	17.2 (3)	21.4 (4)	26.2 (6)	29.3 (6)	28.7 (5)	16.6 (2)	20.6 (4)	26.2 (6)	28.2 (4)	28.0 (4)
FFMI (kg/m^2)	12.6 (1)	14.4 (2)	16.1 (2)	16.4 (2)	16.0 (2)	13.0 (1)	15.1 (2)	18.7 (3)	19.1 (2)	18.2 (2)
FMI (kg/m^2)	4.6 (2)	7.0 (3)	10.1 (5)	12.9 (4)	12.7 (4)	3.6 (2)	5.6 (3)	7.5 (4)	9.1 (3)	9.8 (3)
Bodyfat (%)	26 (7)	31 (8)	37 (8)	43 (6)	43 (6)	21 (7)	26 (9)	27 (9)	32 (7)	34 (7)
Diet										
Carbohydrate intake (% energy)	54 (4)	52 (5)	49 (8)	46 (7)	47 (7)	53 (4)	54 (5)	49 (7)	47 (7)	46 (7)
Fat intake (% energy)	32 (4)	34 (4)	32 (6)	33 (6)	34 (6)	33 (4)	32 (4)	32 (6)	32 (6)	33 (6)
Protein intake (% energy)	14 (2)	14 (3)	15 (4)	16 (4)	17 (3)	14 (2)	14 (3)	15 (4)	16 (3)	16 (3)
Alcohol intake (% energy)	0 (.0)	0 (.4)	3 (7)	4 (5)	2 (4)	0 (.0)	0 (.0)	4 (7)	6 (7)	5 (6)
Energy Expenditure										
Diet-induced thermogenesis (MJ/d)	.6 (.1)	.8 (.1)	1.0 (.2)	1.0 (.2)	.9 (.2)	.7 (.1)	1.0 (.2)	1.3 (.3)	1.2 (.3)	1.1 (.3)
REE (MJ/d)	4.3 (.5)	5.6 (.6)	6.0 (.7)	5.8 (.6)	5.3 (.6)	4.5 (.4)	6.1 (.8)	7.5 (.9)	7.1 (.8)	6.5 (.7)
TEE (MJ/d)	7.2 (1)	9.8 (2)	10.8 (2)	10.3 (1)	9.2 (1)	7.7 (1)	11.3 (2)	13.9 (3)	13.0 (2)	11.4 (2)
TEE (kJ/d/kg)	263 (42)	185 (33)	158 (29)	138 (25)	127 (23)	300 (47)	221 (40)	173 (32)	152 (25)	138 (22)
PAEE (kJ/d/kg)	82 (19)	64 (21)	56 (21)	48 (18)	42 (16)	99 (31)	84 (27)	64 (24)	55 (20)	46 (17)

Data are N or mean (SD). Acronyms: BMI: body mass index, FFMI: fat-free mass index, FMI: fat mass index, REE: resting energy expenditure, TEE: total energy expenditure, PAEE: physical activity energy expenditure.

Table 2. Mutually adjusted associations with energy expenditure. National Diet and Nutrition Survey DLW subsample (2008-2015)

Females

	Total Energy Expenditure (MJ / day)	95% C.I.	Total Energy Expenditure (kJ / day / kg)	95% C.I.	Physical Activity Energy Expenditure (kJ / day / kg)	95% C.I.
Age						
4-10y	Reference		Reference		Reference	
11-15y	2.41***	1.92; 2.90	-73.3***	-82.0; -64.6	-17.1***	-22.9; -11.2
16-49y	3.07***	2.58; 3.57	-91.2***	-100.0; -82.4	-20.6***	-26.5; -14.7
50-64y	2.08***	1.52; 2.64	-98.5***	-108.4; -88.5	-23.1***	-29.7; -16.4
65-91y	1.05***	0.47; 1.62	-110.8***	-121.0; -100.6	-30.5***	-37.3; -23.7
Year of Study						
2008-2011	Reference		Reference		Reference	
2013-2015	0.03	-0.28; 0.34	3.5	-2.0; 9.0	1.0	-2.7; 4.7
Season						
Spring	0.02	-0.20; 0.24	-0.1	-4.0; 3.7	0.0	-2.6; 2.6
Winter	0.10	-0.12; 0.33	0.2	-3.7; 4.2	0.9	-1.7; 3.6
Region						
South England	Reference		Reference		Reference	
North England	-0.08	-0.43; 0.28	-3.4	-9.7; 2.9	-1.6	-5.8; 2.6
Scotland, Wales, Northern Ireland	0.16	-0.24; 0.56	5.0	-2.1; 12.1	3.9	-0.9; 8.6
BMI Category						
<25 kg/m^2	Reference		Reference		Reference	
25-30 kg/m^2	0.73***	0.30; 1.15	-30.2***	-37.8; -22.6	-12.8***	-17.9; -7.7
>30 kg/m^2	1.78***	1.32; 2.23	-43.2***	-51.3; -35.2	-18.8***	-24.2; -13.4
Constant	7.16***	6.74; 7.58	262.6***	255.1; 270.0	82.4***	77.4; 87.4
Model 2 (BF% instead of BMI category)						
F: <30% M: <25%	Reference		Reference		Reference	
F: 30-40% M: 25-35%	0.09	-0.39; 0.57	-31.1***	-38.3; -23.9	-14.3***	-19.3; -9.3
F: >40% M: >35%	0.71***	0.20; 1.23	-61.2***	-68.9; -53.6	-29.0***	-34.3; -23.7
Model 3 (FFMI instead of BMI category)						
Tertile 1	Reference		Reference		Reference	
Tertile 2	0.92***	0.60; 1.25	-13.9***	-21.3; -6.5	-1.4	-6.2; 3.4
Tertile 3	2.50***	2.16; 2.84	-24.6***	-32.4; -16.8	-2.1	-7.1; 3.0

Males

	Total Energy Expenditure (MJ / day)	95% C.I.	Total Energy Expenditure (kJ / day / kg)	95% C.I.	Physical Activity Energy Expenditure (kJ / day / kg)	95% C.I.
Age						
4-10y	Reference		Reference		Reference	
11-15y	3.27***	2.62; 3.91	-75.0***	-85.6; -64.4	-13.7***	-21.5; -5.8
16-49y	5.03***	4.36; 5.71	-107.7***	-118.8; -96.5	-27.1***	-35.4; -18.8
50-64y	3.56***	2.81; 4.31	-122.1***	-134.4; -109.7	-33.8***	-42.9; -24.7
65-91y	1.80***	0.99; 2.61	-135.4***	-148.8; -122.1	-42.7***	-52.5; -32.8
Year of Study						
2008-2011	Reference		Reference		Reference	
2013-2015	-0.16	-0.57; 0.25	-4.1	-10.9; 2.7	-3.0	-8.0; 2.1
Season						
Spring	0.36**	0.09; 0.64	2.1	-2.5; 6.7	2.7	-0.7; 6.1
Winter	0.20	-0.10; 0.50	-0.2	-5.1; 4.8	-0.5	-4.1; 3.2
Region						
South England	Reference		Reference		Reference	
North England	0.21	-0.26; 0.69	-1.1	-8.9; 6.7	0.0	-5.7; 5.8
Scotland, Wales, Northern Ireland	0.21	-0.33; 0.75	3.5	-5.3; 12.3	4.3	-2.3; 10.8
BMI Category						
<25 kg/m^2	Reference		Reference		Reference	
25-30 kg/m^2	1.49***	0.93; 2.06	-27.6***	-36.9; -18.3	-11.0***	-17.9; -4.1
>30 kg/m^2	2.87***	2.22; 3.52	-40.8***	-51.5; -30.1	-15.8***	-23.7; -7.9
Constant	7.74***	7.18; 8.31	301.7***	292.5; 311.0	99.4***	92.5; 106.2
Model 2 (BF% instead of BMI category)						
F: <30% M: <25%	Reference		Reference		Reference	
F: 30-40% M: 25-35%	0.57**	0.03; 1.10	-36.1***	-43.4; -28.8	-16.3***	-22.1; -10.6
F: >40% M: >35%	0.90***	0.27; 1.53	-54.5***	-63.0; -46.0	-25.6***	-32.3; -18.9
Model 3 (FFMI instead of BMI category)						
Tertile 1	Reference		Reference		Reference	
Tertile 2	1.47***	1.02; 1.92	-12.95***	-21.39; -4.52	1.28	-4.77; 7.32
Tertile 3	2.96***	2.48; 3.44	-17.35***	-26.31; -8.39	1.89	-4.53; 8.31

C.I: confidence intervals
*** p<0.01, ** p<0.05, * p<0.1

Figure 1. Total and Physical Activity-related Energy Expenditure by age (approximate deciles) and sex groups (Females= light grey; Males= dark grey). Bottom panel shows stratified body mass.

Figure 2. Age and sex-specific Total and Physical Activity-related Energy Expenditure by survey year (2008-2011= light grey; 2013-2015= dark grey). Bottom panel shows stratified body mass.

Figure 3. Age and sex-specific Total and Physical Activity-related Energy Expenditure by geographical region (South England = light grey; North England = medium-grey; Scotland, Wales, and North Ireland = dark-grey). Bottom panel shows stratified body mass.

Figure 4. Age and sex-specific Total and Physical Activity-related Energy Expenditure by BMI category (Normal-weight (<25kg/m^2) = light grey; Overweight (25-30kg/m^2) = medium grey; Obese (>30kg/m^2) = dark grey).

Figure 5. Age and sex-specific Total and Physical Activity-related Energy Expenditure by bodyfat% groups (Slimmest = light grey; medium body composition = medium grey; fattest = dark grey).

Figure 6. Total and Physical Activity-related Energy Expenditure by dietary intake groups of carbohydrate (<45%, 45-55%, >55% energy, left panels), fat (<30%, 30-35%, >35% energy, middle panels), and protein (<14%, 14-17%, >17% energy, right panels), stratified by age and sex groups.

Supplement:

Figure S1. Total and Physical Activity-related Energy Expenditure per kg fat-free mass by age (approximate deciles) and sex groups (Females= light grey; Males= dark grey). Bottom panel shows stratified fat-free mass.

Figure S2. Allometrically scaled Total and Physical Activity-related Energy Expenditure per kg$^{2/3}$ total body mass by age (approximate deciles) and sex groups (Females= light grey; Males= dark grey). Bottom panel shows stratified allometrically scaled body mass.

Supplement Table S1: Sensitivity analysis modelling PAEE per kg fat-free mass from stratifying variables (mutually adjusted)

Outcome: PAEE (kJ / day / kg FFM)

	Females		Males	
	PAEE (kJ / day / kg FFM)	C.I.	PAEE (kJ / day / kg FFM)	C.I.
Model 1				
Age				
4-10y	Reference		Reference	
11-15y	-15.3***	-23.8; -6.9	-10.6**	-20.2; -0.9
16-49y	-23.2***	-31.0; -15.4	-36.2***	-45.3; -27.2
50-64y	-25.0***	-33.3; -16.6	-43.3***	-52.7; -33.9
65-91y	-37.6***	-46.2; -29.0	-55.0***	-65.2; -44.8
Year of Study				
2008-2011	Reference		Reference	
2012-2015	0.8	-4.4; 5.9	-1.7	-7.8; 4.5
Season				
Spring	1.1	-2.5; 4.7	4.7**	0.6; 8.8
Winter	1.5	-2.2; 5.1	-0.2	-4.6; 4.3
Region				
South England	Reference		Reference	
North England	-1.7	-7.6; 4.2	-0.9	-8.0; 6.2
Scotland, Wales, Northern Ireland	5.6*	-1.0; 12.2	3.8	-4.2; 11.9
FMI Category				
1st Tertile	Reference		Reference	
2nd Tertile	-5.5*	-11.8; 0.9	-4.0	-11.3; 3.3
3rd Tertile	-11.9***	-18.5; -5.3	-8.3**	-15.7; -0.9
Constant	114.3***	107.0; 121.7	128.0***	118.7; 137.2
Model 2 (with BF% instead of FMI)				
F: <30% M: <25%	Reference		Reference	
F: 30-40% M: 25-35%	-7.1*	-14.5; 0.2	-6.1	-13.5; 1.3
F: >40% M: >35%	-17.9***	-25.8; -10.0	-9.7**	-18.3; -1.1

95% confidence intervals in parentheses
*** p<0.01, ** p<0.05, * p<0.1

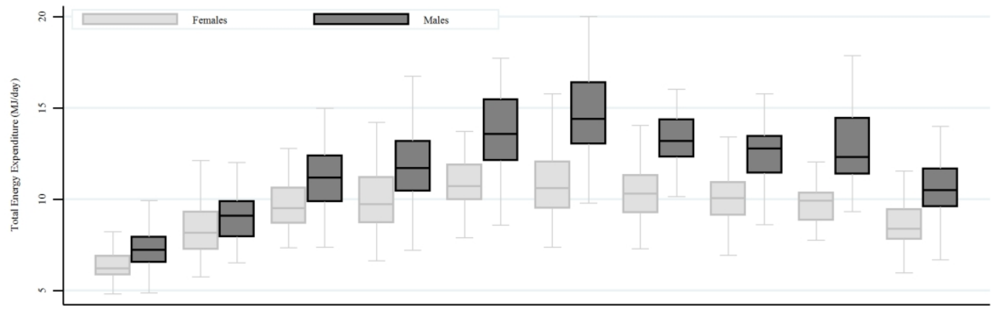

Figure 1A

705x211mm (72 x 72 DPI)

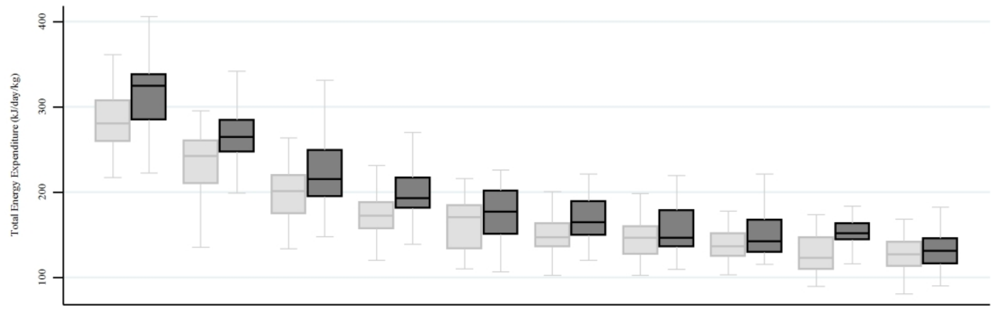

Figure 1B

705x211mm (72 x 72 DPI)

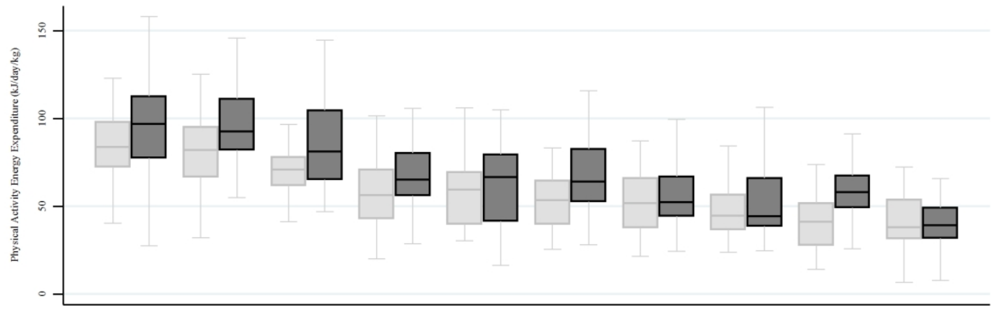

Figure 1C

705x211mm (72 x 72 DPI)

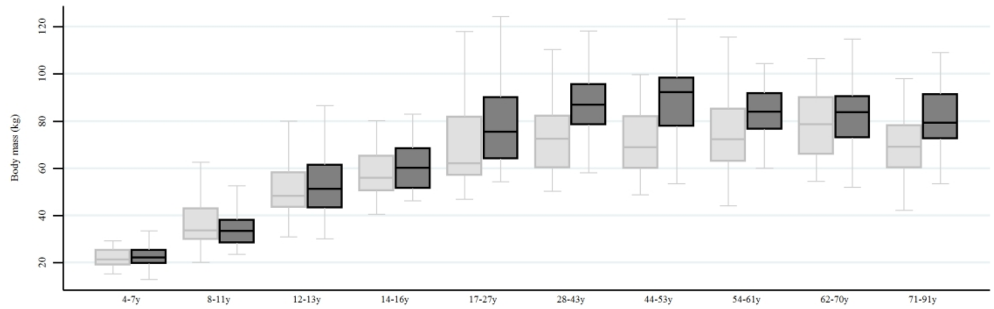

Figure 1D

705x211mm (72 x 72 DPI)

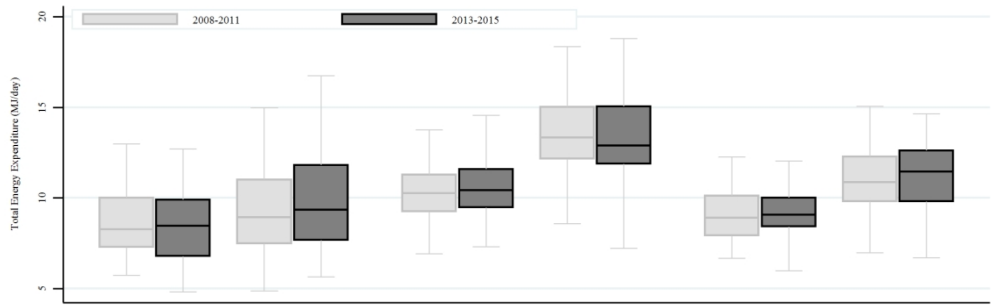

Figure 2A

705x211mm (72 x 72 DPI)

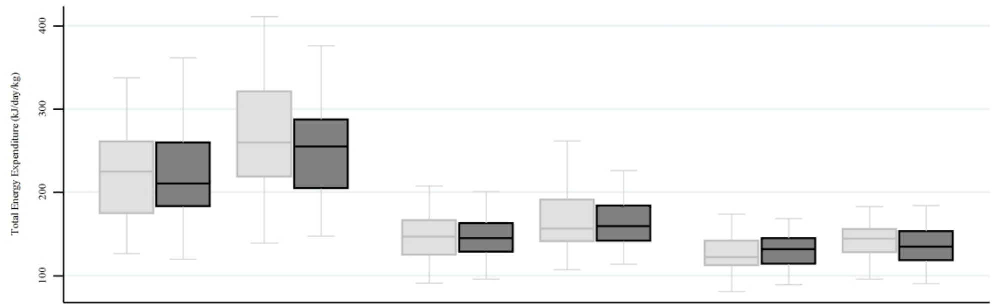

Figure 2B

705x211mm (72 x 72 DPI)

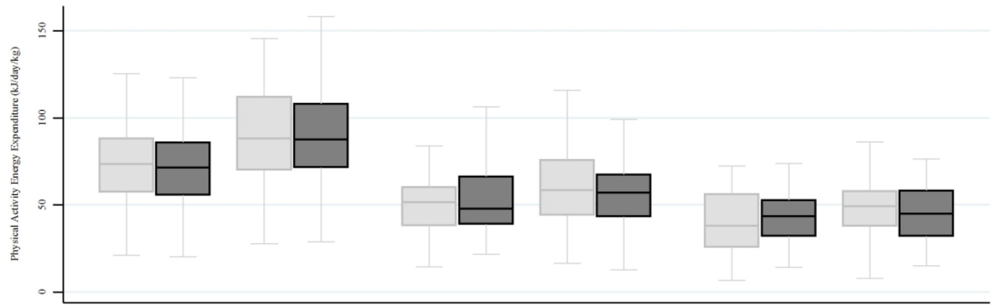

Figure 2C

705x211mm (72 x 72 DPI)

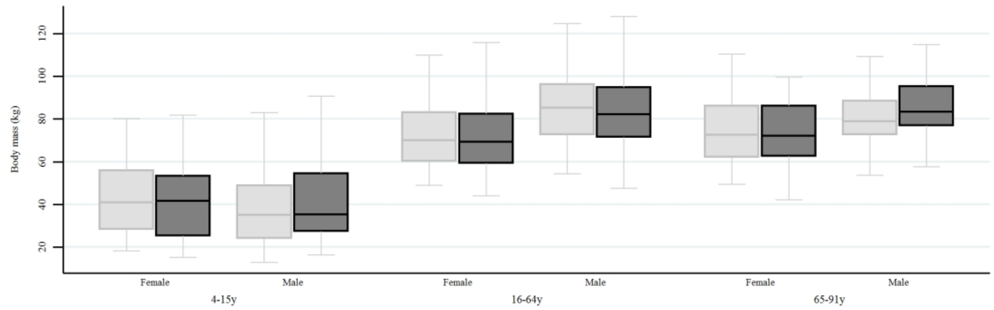

Figure 2D

705x211mm (72 x 72 DPI)

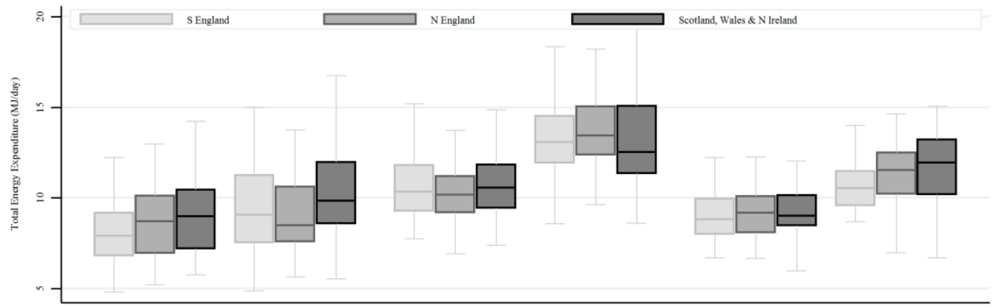

Figure 3A

705x211mm (72 x 72 DPI)

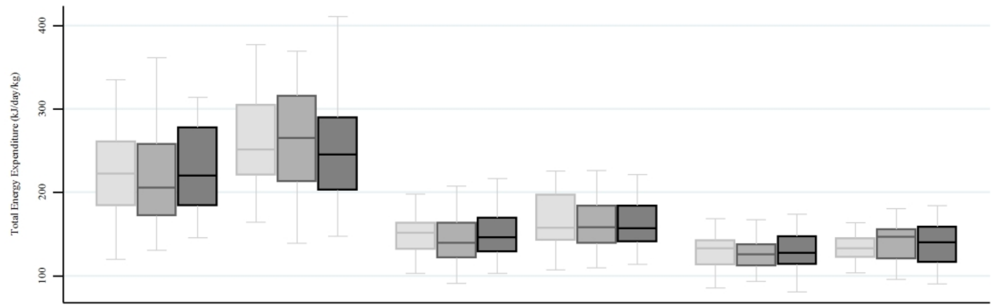

Figure 3B

705x211mm (72 x 72 DPI)

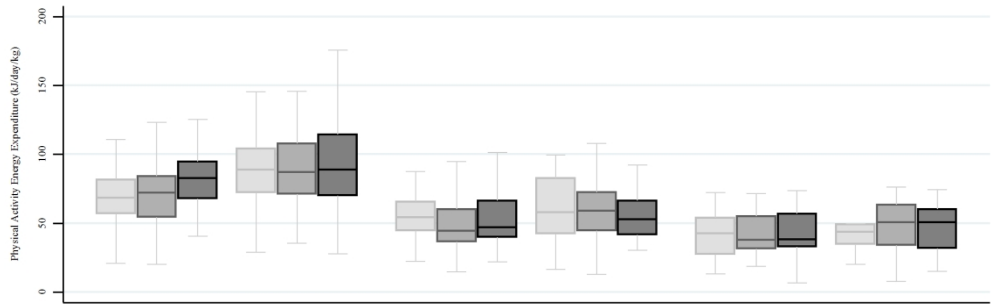

Figure 3C

705x211mm (72 x 72 DPI)

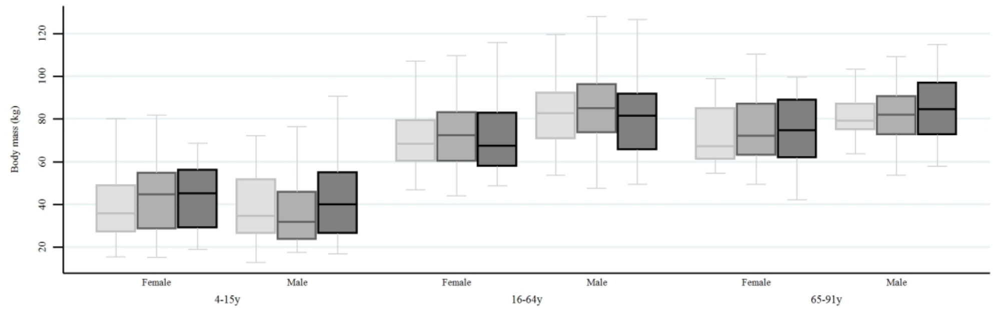

Figure 3D

705x211mm (72 x 72 DPI)

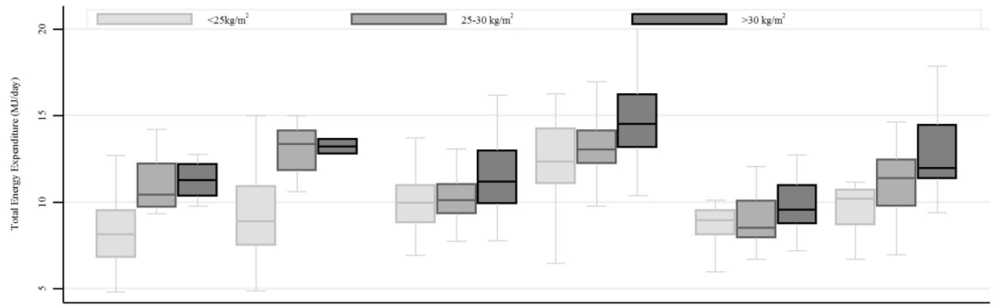

Figure 4A

705x211mm (72 x 72 DPI)

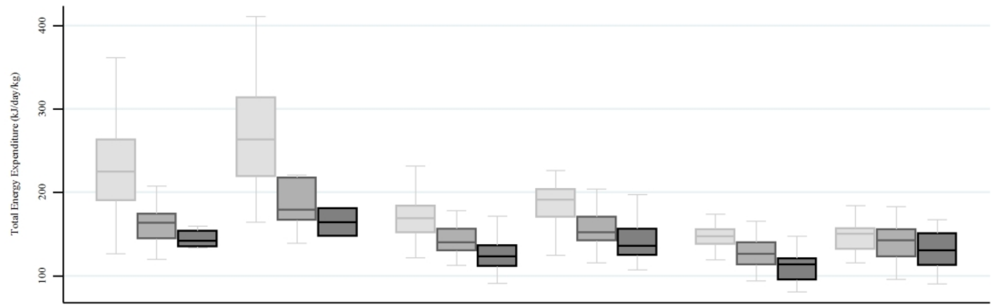

Figure 4B

705x211mm (72 x 72 DPI)

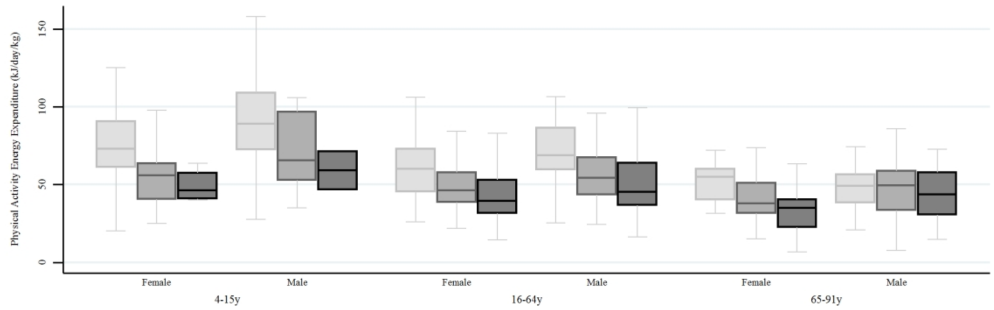

Figure 4C

705x211mm (72 x 72 DPI)

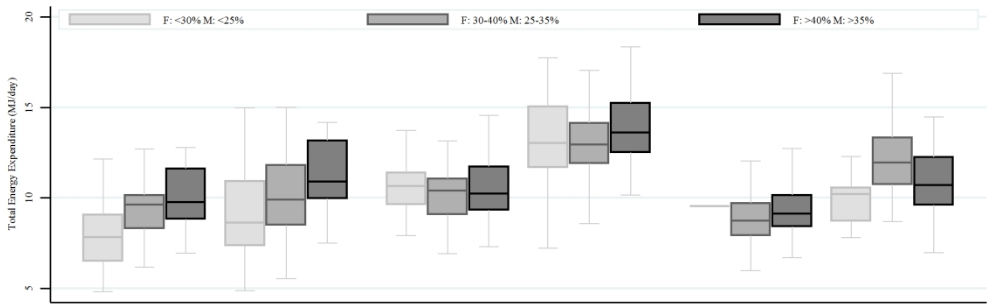

Figure 5A

705x211mm (72 x 72 DPI)

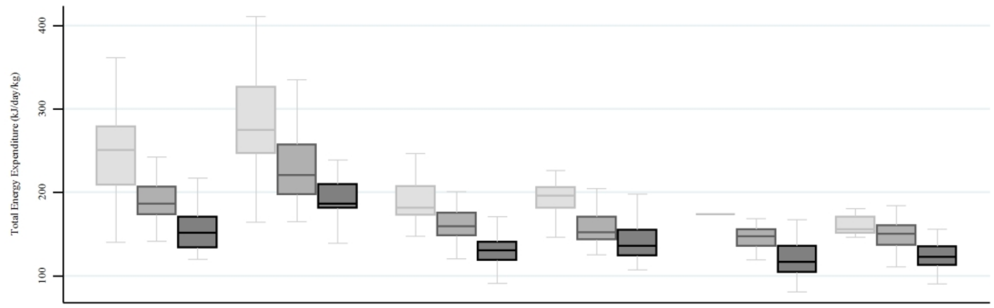

Figure 5B

705x211mm (72 x 72 DPI)

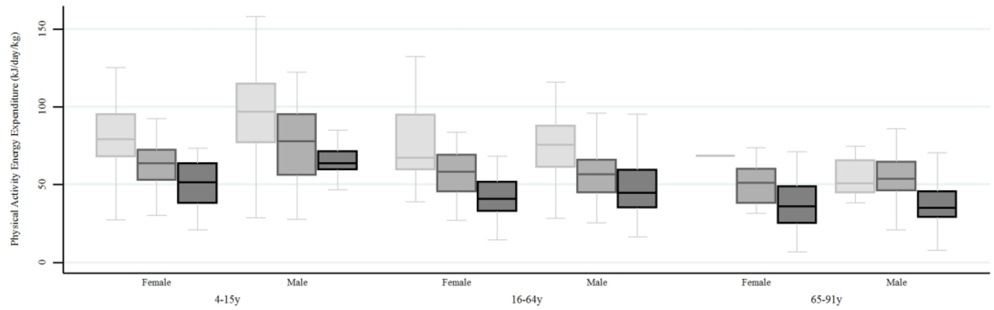

Figure 5C

705x211mm (72 x 72 DPI)

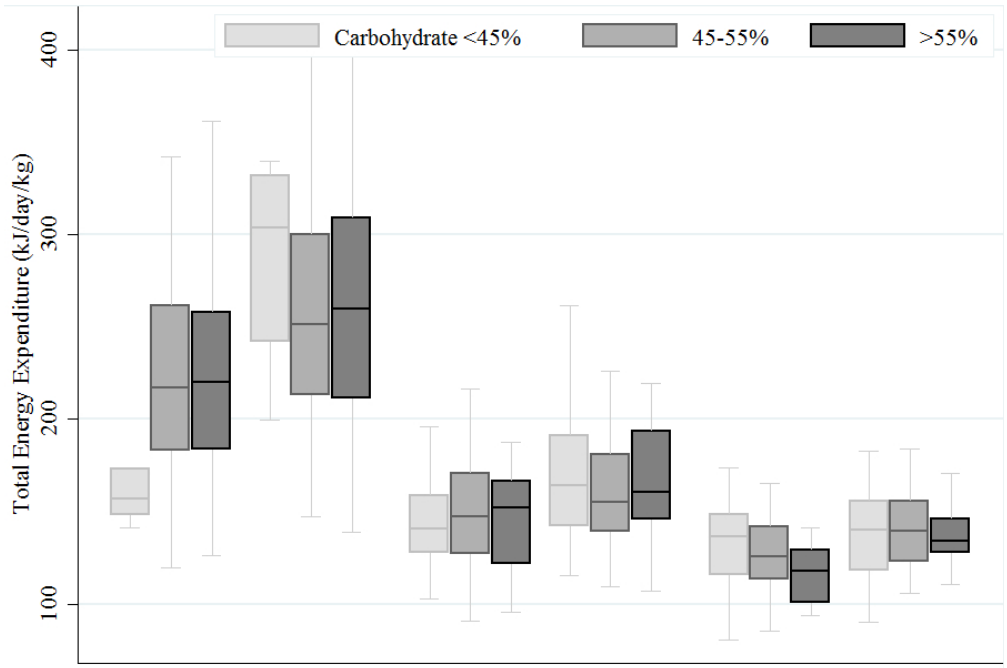

Figure 6A

317x211mm (72 x 72 DPI)

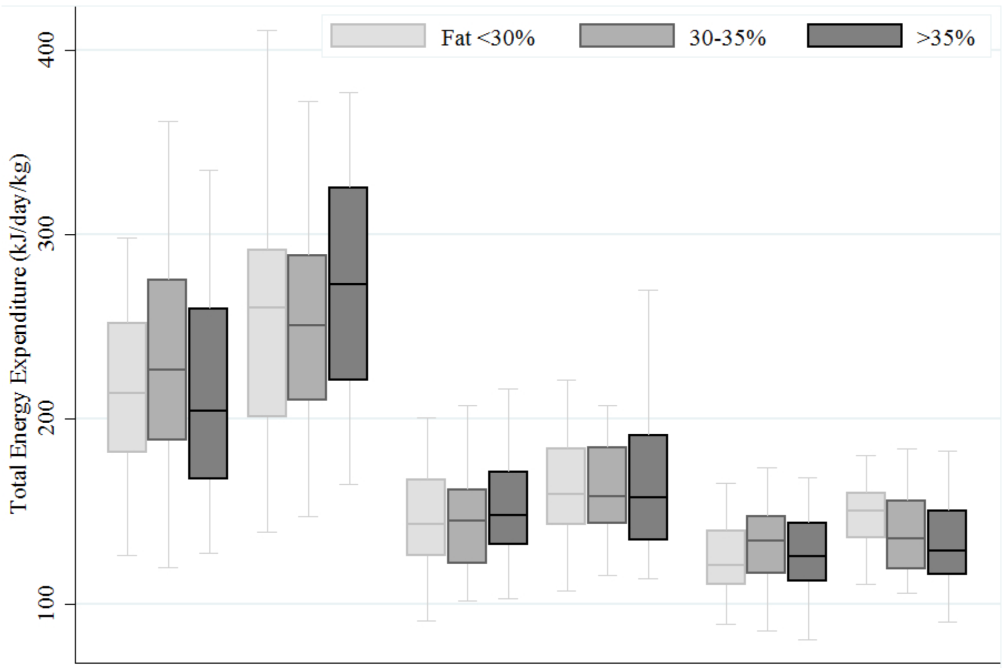

Figure 6B

317x211mm (72 x 72 DPI)

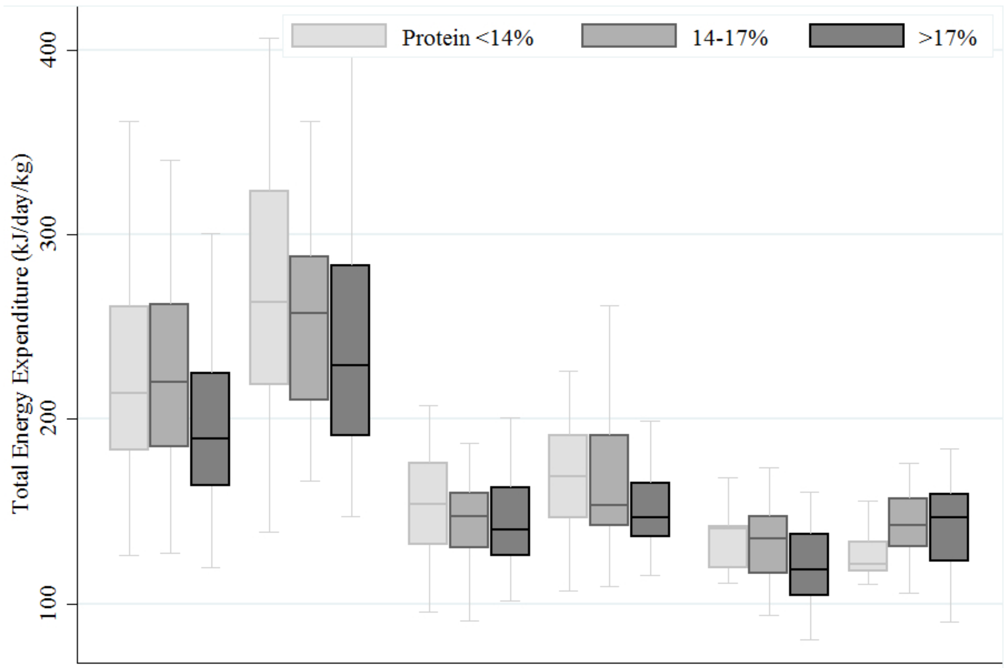

Figure 6C.

317x211mm (72 x 72 DPI)

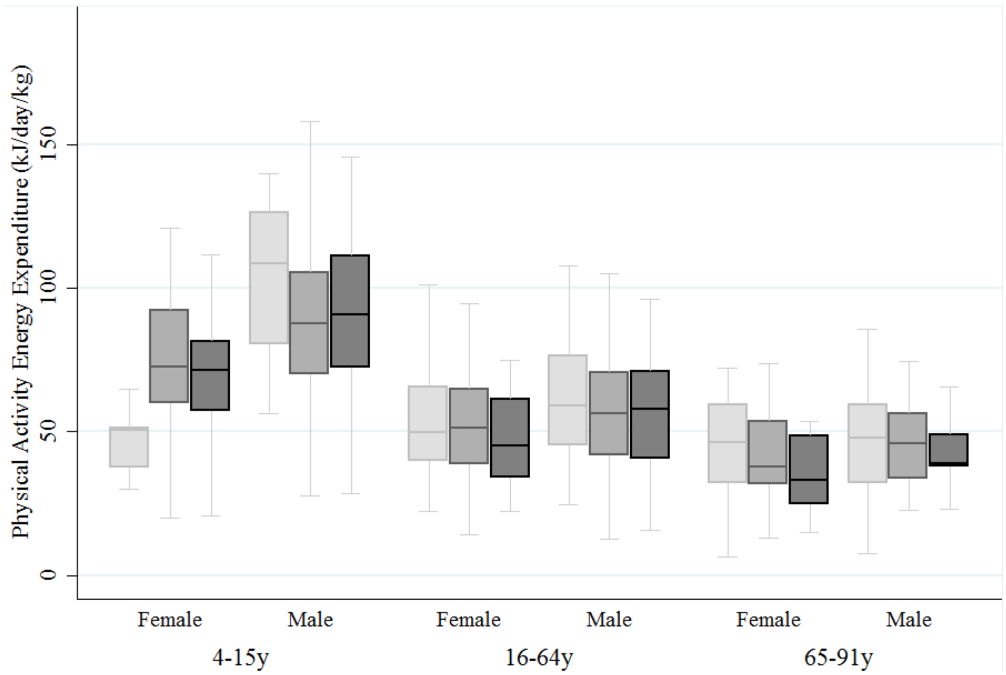

Figure 6D.

317x211mm (72 x 72 DPI)

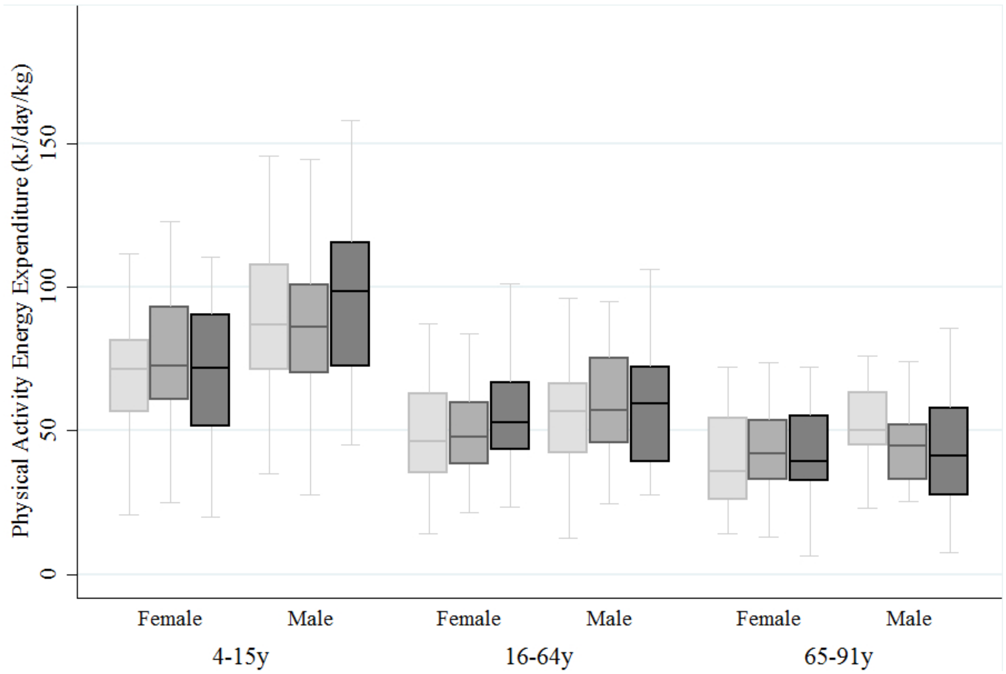

Figure 6E.

317x211mm (72 x 72 DPI)

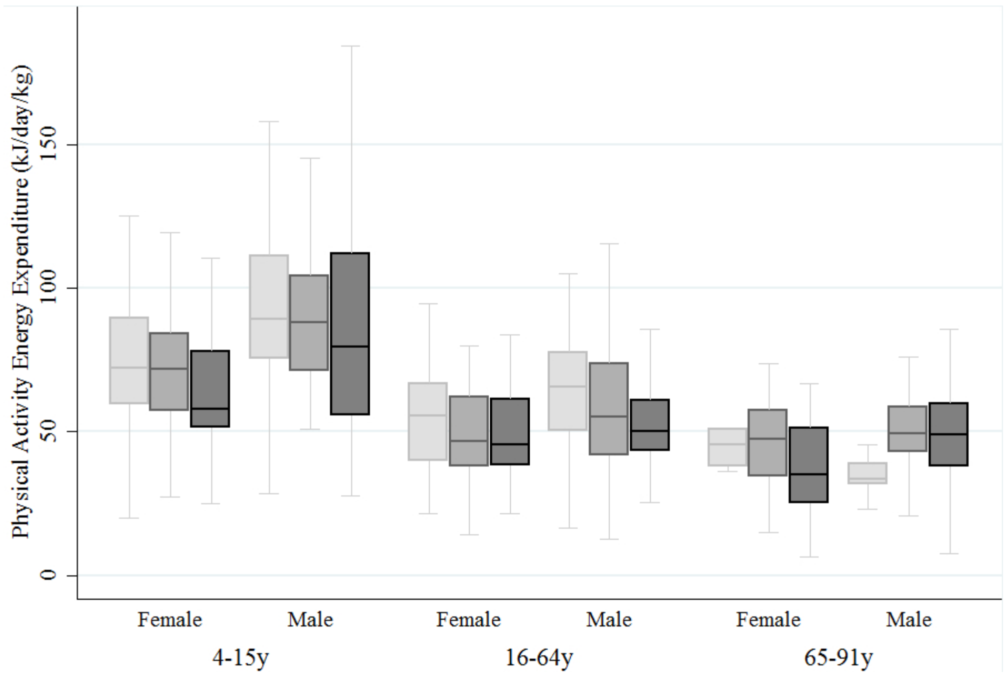

Figure 6F.

317x211mm (72 x 72 DPI)