

1 Daily Energy Expenditure through the Human Life Course

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119 **Abstract:** Total daily energy expenditure (“total expenditure”) reflects daily energy needs and is
120 a critical variable in human health and physiology, but its trajectory over the life course is poorly
121 studied. We analyzed a large, diverse database of total expenditure measured by the doubly
122 labeled water method for males and females aged 8 days to 95 yr. Total expenditure increased
123 with fat free mass in a power-law manner, with four distinct life stages. Fat free mass-adjusted
124 expenditure accelerates rapidly in neonates to ~50% above adult values at ~1 yr, declines slowly
125 to adult levels by ~20 yr, remains stable in adulthood (20-60 yr) even during pregnancy, then
126 declines in older adults. These changes shed light on human development and aging and should
127 help shape nutrition and health strategies across the lifespan.

128 **One Sentence Summary:** Expenditure varies as we age, with four distinct metabolic life stages
129 reflecting changes in behavior, anatomy, and tissue metabolism.

130 **Main Text:** All of life’s essential tasks, from development and reproduction to maintenance and
131 movement, require energy. Total expenditure (MJ/d) is thus central to understanding both daily
132 nutritional requirements and the body’s investment among activities. Yet we know surprisingly
133 little about total expenditure in humans or how it changes over the lifespan. Most large ($n > 1,000$)
134 analyses of human energy expenditure have been limited to basal expenditure, the metabolic rate
135 at rest (1), which accounts for only a portion (usually ~50-70%) of total expenditure, or have
136 estimated total expenditure from basal expenditure and daily physical activity (2-5). Doubly
137 labeled water studies provide measurements of total expenditure in free-living subjects, but have
138 been limited in sample size ($n < 600$), geographic and socioeconomic diversity, and/or age (6-9).

139 Body composition, size, and physical activity change over the life course, often in
140 concert, making it difficult to parse the determinants of energy expenditure. Total and basal
141 expenditures increase with age as children grow and mature (10, 11), but the relative effects of

142 increasing physical activity and age-related changes in tissue-specific metabolic rates are unclear
143 (12-16). Similarly, the decline in total expenditure beginning in older adults corresponds with
144 declines in fat free mass and physical activity but may also reflect age-related reductions in
145 organ metabolism (9, 17-19).

146 We investigated the effects of age, body composition, and sex on total expenditure using
147 a large (n = 6,421; 64% female), diverse (n = 29 countries) database of doubly labeled water
148 measurements for subjects aged eight days to 95 years (20), calculating total expenditure from
149 isotopic measurements using a single, validated equation for all subjects (21). Basal expenditure,
150 measured *via* indirect calorimetry, was available for n = 2,008 subjects, and we augmented the
151 dataset with additional published measures of basal expenditure in neonates and doubly labeled
152 water-measured total expenditure in pregnant and post-partum women (Methods; Table S1).

153 We found that both total and basal expenditure increased with fat free mass in a power-
154 law manner (Figures 1, S1, S2, Table S1), requiring us to adjust for body size to isolate potential
155 effects of age, sex, and other factors. Notably, due to the power-law relation with size, the ratio
156 of (energy expenditure/mass) does not adequately control for body size because the ratio trends
157 lower for larger individuals (Figure S1). Instead, we used regression analysis to control for body
158 size (22). A general linear model with *ln*-transformed values of energy expenditure (total or
159 basal), fat free mass, and fat mass in adults 20 – 60 y (Table S2) was used to calculate residual
160 expenditures for each subject. We converted these residuals to “adjusted” expenditures for clarity
161 in discussing age-related changes: 100% indicates an expenditure that matches the expected
162 value given the subject’s fat free mass and fat mass, 120% indicates an expenditure 20% above
163 expected, *etc.* Using this approach, we also calculated the portion of adjusted total expenditure

164 attributed to basal expenditure (Figure 2D; Methods). Segmented regression analysis (Methods)
165 revealed four distinct phases of adjusted total and basal expenditure over the lifespan.

166 *Neonates (0 to 1 y)*: Neonates in the first month of life had size-adjusted energy expenditures
167 similar to adults, with adjusted total expenditure of $99.0 \pm 17.2\%$ (n = 35) and adjusted basal
168 expenditure of $78.1 \pm 15.0\%$ (n = 34; Figure 2). Both measures increased rapidly in the first year.
169 In segmented regression analysis, adjusted total expenditure rose $84.7 \pm 7.2\%$ per year from birth
170 to a break point at 0.7 years (95% CI: 0.6, 0.8); a similar rise and break point were evident in
171 adjusted basal expenditure (Table S4). For subjects between 9 and 15 months, adjusted total and
172 basal expenditures were nearly ~50% elevated compared to adults (Figure 2).

173 *Juveniles (1 to 20 y)*: Total and basal expenditure continued to increase with age throughout
174 childhood and adolescence along with fat free mass (Figure 1), but size-adjusted expenditures
175 steadily declined. Adjusted total expenditure declined at a rate of $-2.8 \pm 0.1\%$ per year from
176 $147.8 \pm 22.6\%$ for subjects 1 – 2 y to $102.7 \pm 18.1\%$ for subjects 20 – 25 y (Tables S2, S4).
177 Segmented regression analysis identified a breakpoint in adjusted total expenditure at 20.5 y
178 (95% CI: 19.8, 21.2), after which it plateaued at adult levels (Figure 2); a similar decline and
179 break point were evident in adjusted basal expenditure (Figure 2, Table S4). No pubertal
180 increases in adjusted total or basal expenditure were evident among subjects 10 – 15 (Figure 2,
181 Table S3). In multivariate regression for subjects 1 to 20 y, males had a higher total expenditure
182 and adjusted total expenditure (Tables S2, S3), but sex had no detectable effect on the rate of
183 decline in adjusted total expenditure with age (sex:age interaction p=0.30).

184 *Adults (20 to 60 y)*: Total and basal expenditure and fat free mass were all stable from age 20 to
185 60 (Figure 1, 2; Tables S1, S2). Sex had no effect on total expenditure in multivariate models
186 with fat free mass and fat mass, nor in analyses of adjusted total expenditure (Tables S2, S4).

187 Adjusted total and basal expenditures were stable even during pregnancy, the elevation in
188 unadjusted expenditures matching those expected from the gain in mothers' fat free mass and fat
189 mass (Figure 2C). Segmented regression analysis identified a break point at 63.0 y (95% CI:
190 60.1, 65.9), after which adjusted TEE begins to decline. This break point was somewhat earlier
191 for adjusted basal expenditure (46.5, 95% CI: 40.6, 52.4), but the relatively small number of
192 basal measures for 45 – 65 y (Figure 2D) reduces our precision in determining this break point.

193 Older adults (>60 y): At ~60 y, total and basal expenditure begin to decline, along with fat free
194 mass and fat mass (Figures 1, S3, Table S1). Declines in expenditure are not only a function of
195 reduced fat free mass and fat mass, however. Adjusted total expenditure declined by $-0.7 \pm 0.1\%$
196 per year, and adjusted basal expenditure fell at a similar rate (Figure 2, Figure S3, Text S1, Table
197 S4). For subjects 90+ y, adjusted total expenditure was ~26% below that of middle-aged adults.

198 Our analyses provide empirical measures and predictive equations for total and basal
199 expenditure from infancy to old age (Tables S1, S2), and bring to light major metabolic changes
200 across the life course. To begin, we can infer fetal metabolic rates from maternal measures
201 during pregnancy: if body size-adjusted expenditures were elevated in the fetus, then adjusted
202 expenditures for pregnant mothers, particularly late in pregnancy when the fetus accounts for a
203 substantial portion of a mother's weight, would be likewise elevated. Instead, the stability of
204 adjusted total and basal expenditures at ~100% during pregnancy (Figure 2B) indicates that the
205 growing fetus maintains a fat free mass- and fat mass-adjusted metabolic rate similar to adults,
206 which is consistent with adjusted expenditures of neonates (both ~100%; Figure 2) in the first
207 weeks after birth. Total and basal expenditures, both absolute and size-adjusted values, then
208 accelerate rapidly over the first year. This early period of metabolic acceleration corresponds to a

209 critical period in early development in which growth often falters in nutritionally-stressed
210 populations (23). Increasing energy demands could be a contributing factor.

211 After rapid acceleration in total and basal expenditure during the first year, adjusted
212 expenditures progressively decline thereafter, reaching adult levels at ~20 yr. Elevated adjusted
213 expenditures in this life stage may reflect the metabolic demands of growth and development.
214 Adult expenditures, adjusted for body size and composition, are remarkably stable, even during
215 pregnancy and post-partum. Declining metabolic rates in older adults could increase the risk of
216 weight gain. However, neither fat mass nor percentage increased in this period (Figure S3),
217 consistent with the hypothesis that energy intake is coupled to expenditure (24).

218 Following previous studies (15, 16, 19, 25, 26), we calculated the effect of organ size on
219 basal expenditure over the lifespan (Methods). Organs with a high tissue-specific metabolic rate,
220 particularly the brain and liver, account for a greater proportion of fat free mass in young
221 individuals. Thus organ-based basal expenditure, estimated from organ size and tissue-specific
222 metabolic rate, follows a power-law relationship with fat free mass, roughly consistent with
223 observed basal expenditures (Methods, Figure S6). Still, observed basal expenditure exceeded
224 organ-based estimates by ~30% in early life (1 – 20 y) and was ~20% lower than organ-based
225 estimates in subjects over 60 y (Figure S6), consistent with studies indicating that tissue-specific
226 metabolic rates are elevated in juveniles (15, 16) and reduced in older adults (19, 25, 26).

227 We investigated the contributions of daily physical activity and changes in tissue-specific
228 metabolic rate to total and basal expenditure using a simple model with two components: activity
229 and basal expenditure (Figure 3; Methods). Activity expenditure was modeled as a function of
230 physical activity and body mass, assuming activity costs are proportional to weight, and could
231 either remain constant over the lifespan or follow the trajectory of daily physical activity

232 measured *via* accelerometry, peaking at 5 – 10 y and declining thereafter (12, 17, 18) (Figure 3).
233 Similarly, basal expenditure was modeled as a power function of fat free mass (consistent with
234 organ-based basal expenditure estimates; Methods) multiplied by a “tissue specific metabolism”
235 term, which could either remain constant at adult levels across the lifespan or follow the
236 trajectory observed in adjusted basal expenditure (Figure 2). For each scenario, total expenditure
237 was modeled as the sum of activity and basal expenditure (Methods).

238 Models that hold physical activity or tissue-specific metabolic rates constant over the
239 lifespan do not reproduce the observed patterns of age-related change in absolute or adjusted
240 measures of total or basal expenditure (Figure 3). Only when age-related changes in physical
241 activity and tissue-specific metabolism are included does model output match observed
242 expenditures, indicating that variation in both physical activity and tissue-specific metabolism
243 contribute to total expenditure and its components across the lifespan. Elevated tissue-specific
244 metabolism in early life may be related to growth or development (15, 16). Conversely, reduced
245 expenditures in later life may reflect a decline in organ level metabolism (25-27).

246 Metabolic models of life history commonly assume continuity in tissue-specific
247 metabolism over the life course, with metabolic rates increasing in a stable, power-law manner
248 (28, 29). Measures of humans here challenge this view, with deviations from the power-law
249 relationship for total and basal expenditure in childhood and old age (Fig. 1, 2). These changes
250 present a potential target for investigating the kinetics of disease, drug activity, and healing,
251 processes intimately related to metabolic rate. Further, inter-individual variation in expenditure is
252 considerable even when controlling for fat free mass, fat mass, sex, and age (Figure 1, 2, Table
253 S2). Elucidating the processes underlying metabolic changes across the life course and variation
254 among individuals may help reveal the roles of metabolic variation in health and disease.

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263 **Conflict of interest**

264 The authors have no conflicts of interest to declare.

265 **Data Availability**

266 All data used in these analyses is freely available via the IAEA Doubly Labelled Water Database
267 (<https://doubly-labelled-water-database.iaea.org/home> or <https://www.dlwdatabase.org/>).

268 **Supplementary Material**

269 Materials and Methods

270 Figures S1-S10

271 Tables S1-S4

272 References (30-54)

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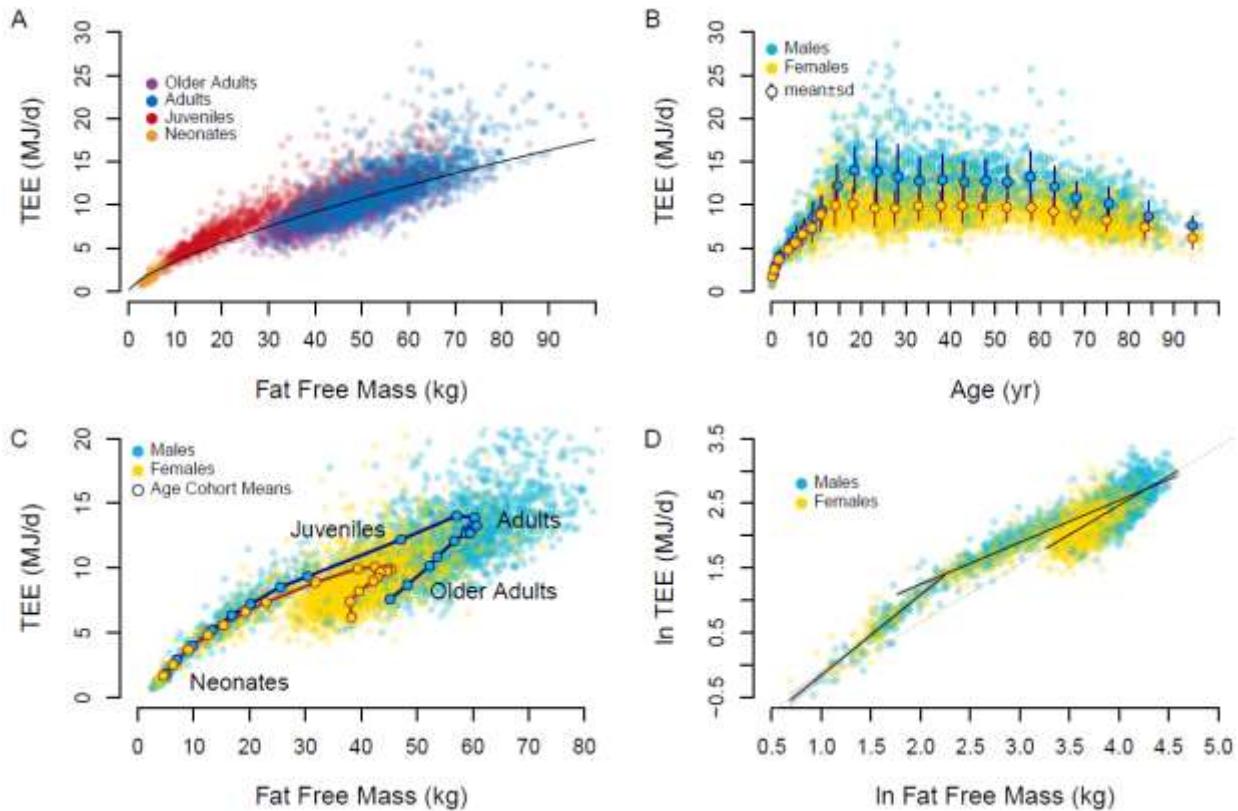
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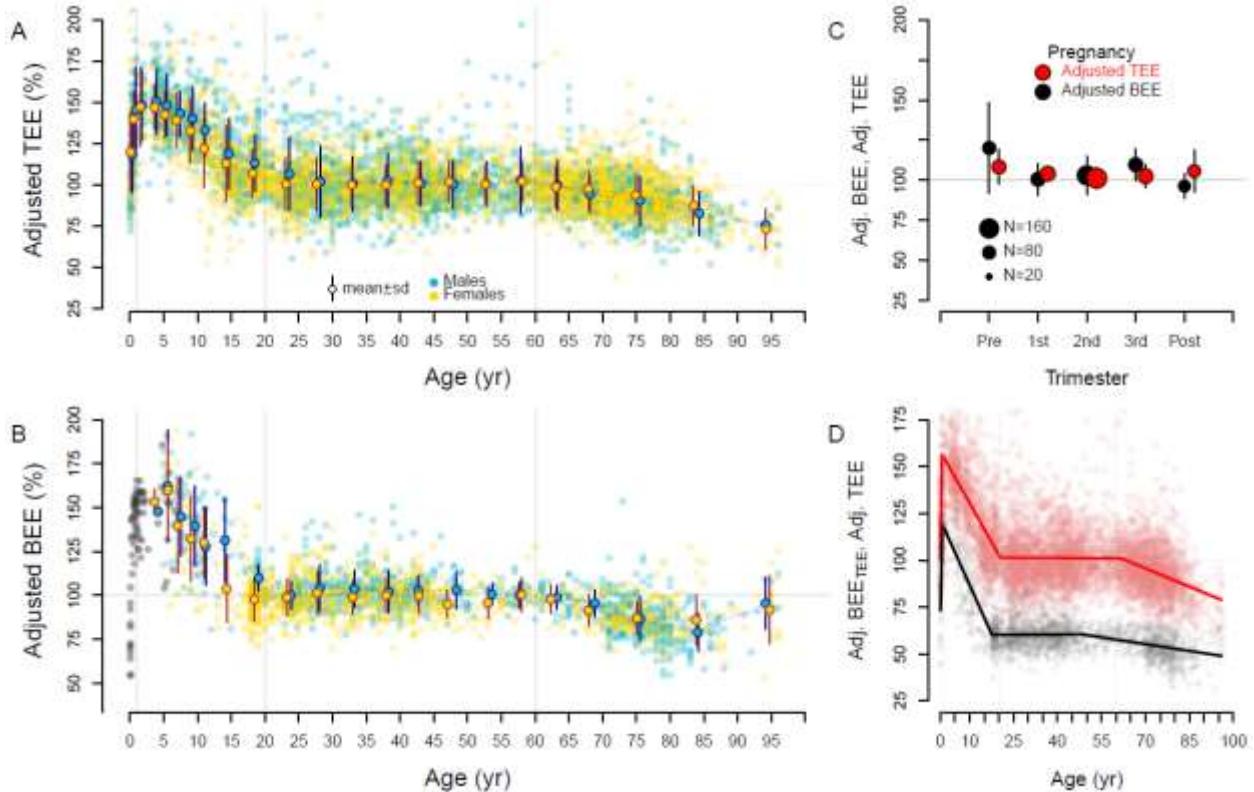
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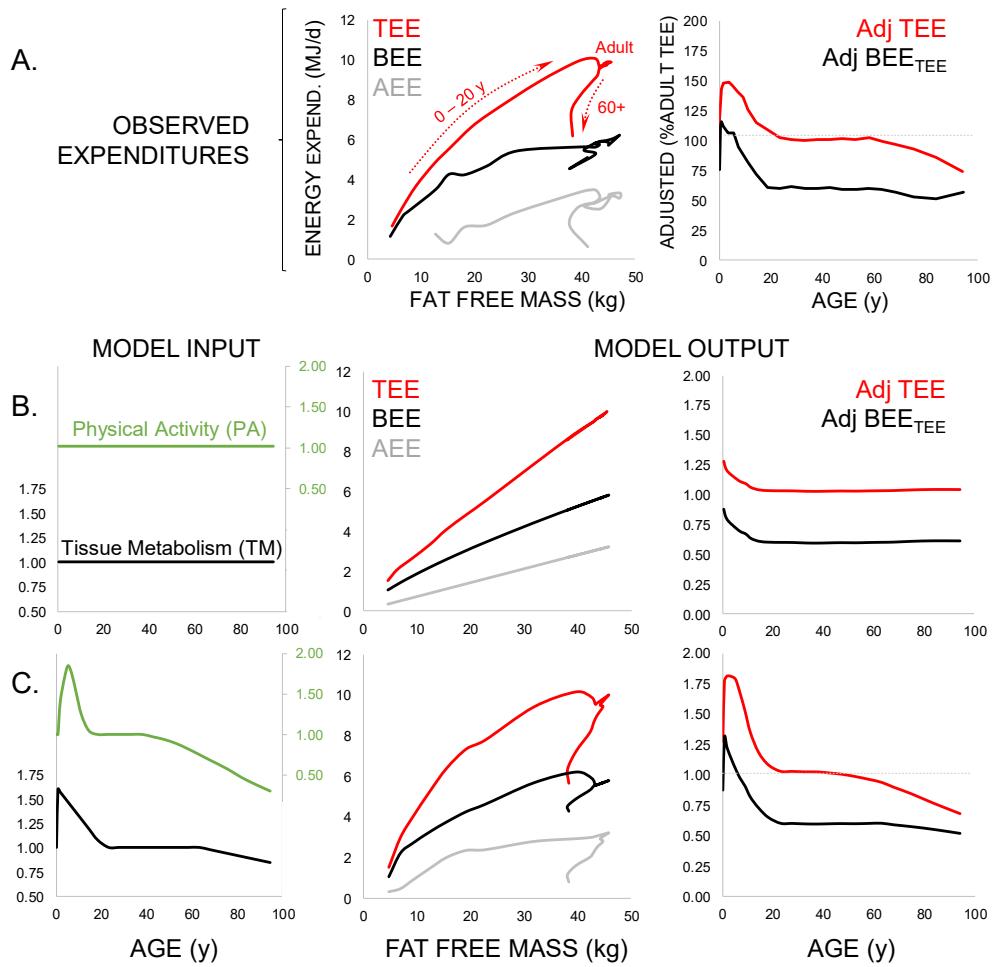
389

390 **Figure 1. A.** Total expenditure (TEE) increases with fat free mass in a power-law manner (black line: $TEE = 0.677FFM^{0.708}$, $r^2 = 0.83$, $p < 0.0001$; Table S2) but age groups cluster about the trend line differently. **B.** Total 391 expenditure rises in childhood, is stable through adulthood, and declines in older adults. Means \pm SD for age- 392 sex cohorts are shown. **C.** Age-sex cohort means show a distinct progression of total expenditure and fat 393 free mass over the life course. **D.** Neonate, juveniles, and adults exhibit distinct relationships between fat 394 free mass and expenditure. The dashed line, extrapolated from the regression for adults, approximates the 395 regression used to calculate adjusted total expenditure. 396



397

398 **Figure 2.** Fat free mass- and fat mass-adjusted expenditures over the life course. Individual subjects and
 399 age-sex cohort mean \pm SD are shown. For both total (Adj. TEE) (A) and basal (Adj. BEE) expenditure (B),
 400 adjusted expenditures begin near adult levels (~100%) but quickly climb to ~150% in the first year. Adjusted
 401 expenditures decline to adult levels ~20y, then decline again in older adults. Basal expenditures for infants
 402 and children not in the doubly labeled water database are shown in gray. C. Pregnant mothers exhibit
 403 adjusted total and basal expenditures similar to non-reproducing adults (Pre: prior to pregnancy; Post: 27
 404 weeks post-partum). D. Segmented regression analysis of adjusted total (red) and adjusted basal
 405 expenditure (calculated as a portion of total; Adj. BEE_{TEE}; black) indicates a peak at ~1 y, adult levels at
 406 ~20 y, and decline at ~60 y (see text).



407

408 **Figure 3.** Modeling the contribution of physical activity and tissue-specific metabolism to daily expenditures.

409 **A.** Observed total (TEE, red), basal (BEE, black), and activity (AEE, gray) expenditures (Table S1) show
 410 age-related variation with respect to fat free mass (see Figure 1C) that is also evident in adjusted values
 411 (Table S3; see Figure 2D). **B.** These age effects do not emerge in models assuming constant physical
 412 activity (PA, green) and tissue-specific metabolic rate (TM, black) across the life course. **C.** When physical
 413 activity and tissue-specific metabolism follow the life course trajectories evident from accelerometry and
 414 adjusted basal expenditure, respectively, model output is similar to observed expenditures.

415 **Supplementary Materials:**

416 Pontzer et al. *Daily Energy Expenditure through the Human Life Course*

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430 **Material and Methods**

431 1. Doubly Labeled Water Database

432 Data were taken from IAEA Doubly Labelled Water (DLW) Database, version 3.1,

433 completed April, 2020 (20). This version of the database comprises 6,743 measurements of total

434 expenditure using the doubly labeled water method. Of these, a total of 6,421 had valid data for

435 total expenditure, fat free mass, fat mass, sex, and age. These 6,421 measurements were used in

436 this analysis. This dataset was augmented with published basal expenditure measurements for

437 n=136 neonates and infants (30-35) that included fat free mass and fat mass. Malnourished or

438 preterm infants were excluded. For sources that provided cohort means rather than individual
439 subject measurements (32, 35) means were entered as single values into the dataset without
440 reweighting to reflect sample size. This approach resulted in 77 measures of basal expenditure,
441 fat free mass, and fat mass for n=136 subjects. We also added to the dataset published basal and
442 total expenditure measurements of n=141 women before, during, and after pregnancy (36-38)
443 that included fat free mass and fat mass. These measurements were grouped as pre-pregnancy, 1st
444 trimester, 2nd trimester, 3rd trimester, and post-partum for analysis.

445 In the doubly labeled water method (5), subjects were administered a precisely measured
446 dose of water enriched in $^2\text{H}_2\text{O}$ and H_2^{18}O . The subject's body water pool is thus enriched in
447 deuterium (^2H) and ^{18}O . The initial increase in body water enrichment from pre-dose values is
448 used to calculate the size of the body water pool, measured as the dilution space for deuterium
449 (N_d) and ^{18}O (N_o). These isotopes are then depleted from the body water pool over time: both
450 isotopes are depleted *via* water loss, whereas ^{18}O is also lost *via* carbon dioxide production.
451 Subtracting the rate (%/d) of deuterium depletion (k_d) from the rate of ^{18}O depletion (k_o), and
452 multiplying the size of the body water pool (derived from N_d and N_o) provided the rate of carbon
453 dioxide production, $r\text{CO}_2$. Entries in the DLW database include the original k and N values for
454 each subject, which were then used to calculate CO_2 using a common equation that has been
455 validated in subjects across the lifespan (21). The rate of CO_2 production, along with each
456 subject's reported food quotient, was then used to calculate energy expenditure (MJ/d) using the
457 Weir equation (39). We used the food quotients reported in the original studies to calculate total
458 energy expenditure from $r\text{CO}_2$ for each subject.

459 The size of the body water pool, determined from N_d and N_o , was used to establish FFM,
460 using hydration constants for fat free mass taken from empirical studies. Other anthropometric

461 variables (age, height, body mass, sex) were measured using standard protocols. Fat mass was
462 calculated as (body mass) – (fat free mass).

463 2. Basal Expenditure, Activity Expenditure, and Physical Activityl Level (PAL)

464 A total of 2,008 subjects in the database had associated basal expenditure, measured *via*
465 respirometry. For these subjects, we analyzed basal expenditure, activity expenditure, and
466 “physical activity level” (PAL). Activity expenditure was calculated as [0.9(total expenditure) –
467 (basal expenditure)] which subtracts basal expenditure and the assumed thermic effect of food
468 [estimated at 0.1(total expenditure)] from total expenditure. The PAL ratio was calculated as
469 (total expenditure)/(basal expenditure). As noted above, the basal expenditure dataset was
470 augmented with measurements from neonates and infants, but these additional measures do not
471 have associated total expenditure and could not be used to calculate activity expenditure or PAL.

472 3. Predictive Models for Total, Basal, and Activity Expenditures and PAL

473 We used general linear models to regress measures of energy expenditure against
474 anthropometric variables. We used the base package in R version 4.0.3 (40) for all analyses.
475 General linear models were implemented using the `lm` function. These models were used to
476 develop predictive equations for total expenditure for clinical and research applications, and to
477 determine the relative contribution of different variables to total expenditure and its components.
478 Given the marked changes in metabolic rate over the lifespan (Figure 1, Figure 2) we calculated
479 these models separately for each life history stage: infants (0 – 1 y), juveniles (1 – 20 y), adults
480 (20 – 60 y), and older adults (60+ y). These age ranges were identified using segmented
481 regression analysis. Results of these models are shown in Table S2.

482 4. Adjusted Expenditures

483 We used general linear models with fat free mass and fat mass in adults (20 – 60 y) to
484 calculate adjusted total expenditure and adjusted basal expenditure. The 20 – 60 y age range was
485 used as the basis for analyses because segmented regression analysis consistently identified this
486 period as stable with respect to size-adjusted total expenditure (see below).

487 We used models 2 and 5 in Table S2, which have the form $\ln(\text{Expenditure}) \sim \ln(\text{FFM}) +$
488 $\ln(\text{Fat Mass})$ and were implemented using the `lm` function in base R version 4.0.3 (40). We
489 used \ln -transformed variables due to the inherent power-law relationship between body size and
490 both total and basal expenditure (ref. 2; see Figure 1, Figure S1). Predicted values for each
491 subject, given their fat free mass and fat mass, were calculated from the model using the
492 `pred()` function; these \ln -transformed values were converted back into MJ as `exp(Predicted)`.
493 Residuals for each subject were calculated as (Observed – Predicted) expenditure, and were then
494 used to calculate adjusted expenditures as:

495
$$\text{Adjusted Expenditure} = 1 + \text{Residual} / \text{Predicted} \quad [1]$$

496 The advantage of expressing residuals as a percentage of the predicted value is that it allows us
497 to compare residuals across the range of age and body size in the dataset. Raw residuals (MJ) do
498 not permit direct comparison because the relationship between size and expenditure is
499 heteroscedastic; the magnitude of residuals increases with size (see Figure S1). Ln-transformed
500 residuals ($\ln(\text{MJ})$) avoid this problem but are more difficult to interpret. Adjusted expenditures,
501 used here, provide an easily interpretable measure of deviation from expected values. An
502 adjusted expenditure value of 100% indicates that a subject's observed total or basal expenditure
503 matches the value predicted for their fat free mass and fat mass, based on the general linear
504 model derived for adults. An adjusted expenditure of 120% indicates an observed total or basal

505 expenditure value that exceeds the predicted value for their fat free mass and fat mass by 20%.
506 Similarly, an adjusted expenditure of 80% means the subject's measured expenditure was 20%
507 lower than predicted for their fat free mass and fat mass using the adult model. Adjusted total
508 expenditure and adjusted basal expenditure values for each age-sex cohort are given in Table S3.
509 Within each metabolic life history stage we used general linear models (`lm` function in R) to
510 investigate the effects of sex and age on adjusted total and basal expenditure.

511 This same approach was used to calculate adjusted basal expenditure as a proportion of
512 total expenditure (Figure 2D), hereafter termed adjusted BEE_{TEE}. Residual_{BEE-TEE}, the deviation
513 of observed basal expenditure from the adult total expenditure regression (eq. 2 in Table S2),
514 was calculated as (Observed Basal Expenditure – Predicted Total Expenditure) and then used to
515 calculate adjusted BEE_{TEE} as

516
$$\text{Adjusted BEE}_{\text{TEE}} = 1 + \text{Residual}_{\text{BEE-TEE}} / \text{Predicted Total Expenditure} \quad [2]$$

517 When adjusted BEE_{TEE} = 80%, observed basal expenditure is equal to 80% of predicted total
518 expenditure given the subject's fat free mass and fat mass. Adjusted BEE_{TEE} is equivalent to
519 adjusted basal expenditure (Figure S4) but provides some analytical advantages. The derivation
520 of adjusted BEE_{TEE} approach applies identical manipulations to observed total expenditure and
521 observed basal expenditure and therefore maintains them in directly comparable units. The ratio
522 of (adjusted total expenditure)/(adjusted basal expenditure) is identical to the PAL ratio of (total
523 expenditure)/(basal expenditure), and the difference (0.9adjusted total expenditure – adjusted
524 basal expenditure) is proportional to activity expenditure (Figure S4). Plotting adjusted total
525 expenditure and adjusted BEE_{TEE} over the lifespan (Figure 2D) therefore shows both the relative
526 magnitudes of total and basal expenditure and their relationship to one another in comparable
527 units.

528 5. Segmented Regression Analysis

529 We used segmented regression analysis to determine the change points in the relationship
530 between adjusted expenditure and age. We used the *Segmented* (version 1.1-0) package in R
531 (41). For adjusted total expenditure, we examined a range of models with 0 to 5 change points,
532 using the `npsi`= term in the `segmented()` function. This approach does not specify the
533 location or value of change points, only the number of them. Each increase in the number of
534 change points from 0 to 3 improved the model $adj. R^2$ and standard error considerably.
535 Increasing the number of change points further to 4 or 5 did not improve the model, and the
536 additional change points identified by the `segmented()` function fell near the change points for
537 the 3-change point model. We therefore selected the 3-change point model as the best fit for
538 adjusted total expenditure in this dataset. Segmented regression results are shown in Table S4. A
539 similar 3-change point segmented regression approach was conducted for adjusted basal
540 expenditure (Figure S4) and adjusted BEE_{TEE} (Figure 2D). We note that the decline in adjusted
541 basal expenditure and adjusted BEE_{TEE} in older adults begins earlier (as identified by segmented
542 regression analysis) than does the decline in adjusted total expenditure among older adults.
543 However, this difference may reflect the relative paucity of basal expenditure measurements for
544 subjects 40 – 60 y. Additional measurements are needed to determine whether the decline in
545 basal expenditure does in fact begin earlier than the decline in total expenditure. Here, we view
546 the timing as essentially coincident and interpret the change point in adjusted total expenditure
547 (~60 y), which is determined with a greater number of measurements, as more accurate and
548 reliable.

549 Having established that 3 break points provided the best fit for this dataset, we examined
550 whether changes in the age range used to calculate adjusted total energy expenditure affected the

551 age break-points identified by segmented regression. When the age range used to calculate
552 adjusted expenditure was set at 20 – 60 y, the set of break point (95% CI) was: 0.69 (0.61-0.76),
553 20.46 (19.77-21.15), 62.99 (60.14-65.85). When the age range was expanded to 15 – 70 y, break
554 points determined through segmented regression were effectively unchanged: 0.69 (0.62 – 0.76),
555 21.40 (20.60-22.19), 61.32 (58.60-64.03). Break points were also unchanged when the initial age
556 range for adjusted expenditure was narrowed to 30 – 50 y: 0.69 (0.62-0.77), 20.56 (19.84-21.27),
557 62.85 (59.97-65.74).

558 6. Organ Size and Basal Expenditure

559 Measuring the metabolic rate of individual organs is notoriously challenging, and the
560 available data come from only a small number of studies. The available data indicate that organs
561 differ markedly in their mass-specific metabolic rates at rest (42). The heart (1848 $\text{kJ kg}^{-1} \text{d}^{-1}$),
562 liver (840 $\text{kJ kg}^{-1} \text{d}^{-1}$), brain (1008 $\text{kJ kg}^{-1} \text{d}^{-1}$), and kidneys (1848 $\text{kJ kg}^{-1} \text{d}^{-1}$) have much greater
563 mass-specific metabolic rates at rest than do muscle (55 $\text{kJ kg}^{-1} \text{d}^{-1}$), other lean tissue (50 kJ kg^{-1}
564 d^{-1}), and fat (19 $\text{kJ kg}^{-1} \text{d}^{-1}$). Consequently, the heart, liver, brain, and kidneys combined account
565 for ~60% of basal expenditure in adults (15, 19, 43, 44). In infants and children, these
566 metabolically active organs constitute a larger proportion of body mass. The whole body mass-
567 specific basal expenditure [i.e., (basal expenditure)/(body mass), or (basal expenditure)/(fat free
568 mass)] for infants and children is therefore expected to be greater than adults' due to the greater
569 proportion of metabolically active organs early in life adults (15, 19, 43, 44). Similarly, reduced
570 organ sizes in elderly subjects may result in declining basal expenditure (19).

571 To examine this effect of organ size on basal expenditure in our dataset, we used
572 published references for organ size to determine the mass of the metabolically active organs
573 (heart, liver, brain, and kidneys) as a percentage of body mass or fat free mass for subjects 0 – 12

574 y (15, 43-45), 15 to 60 y (15, 19), and 60 to 100 y (19, 46). We used these relationships to
575 estimate the combined mass of the metabolically active organs (heart, liver, brain, kidneys) for
576 each subject in our dataset. We then subtracted the mass of the metabolically active organs from
577 measured fat free mass to calculate the mass of “other fat free mass”. These two measures, along
578 with measured fat mass, provided a three-compartment model for each subject: metabolically
579 active organs, other fat free mass, and fat (Figure S6A).

580 Following previous studies (15, 16, 19, 25, 26), we assigned mass-specific metabolic
581 rates to each compartment and estimated basal expenditure for each subject. We used reported
582 mass-specific metabolic rates for the heart, liver, brain, and kidneys (see above; (42)) and age-
583 related changes in the proportions of these organs for subjects 0 – 12 y (15, 45), 15 to 60 y (15,
584 16, 19, 25, 26), and 60 to 100 y (19, 25, 26, 46) to calculate an age-based weighted mass-specific
585 metabolic rate for the metabolically active organ compartment. We averaged the mass-specific
586 metabolic rates of resting muscle and other lean tissue (see above; (15, 19)) and assigned a value
587 of $52.5 \text{ kJ kg}^{-1} \text{ d}^{-1}$ to “other fat free mass”, and we used a mass-specific metabolic rate of 19 kJ
588 $\text{kg}^{-1} \text{ d}^{-1}$ for fat.

589 Results are shown in Figure S6. Due to the greater proportion of metabolically active
590 organs in early life, the estimated basal expenditure from the three-compartment model follows a
591 power-law relationship with FFM (using age cohort means, $\text{BEE} = 0.38 \text{ FFM}^{0.75}$; Figure S6B)
592 that is similar to that calculated from observed basal expenditure in our dataset (see Table S2 and
593 7. *Modeling the Effects of Physical Activity and Tissue Specific Metabolism*, below). Estimated
594 BEE from the three-compartment model produced mass-specific metabolic rates that are
595 considerably higher for infants and children than for adults and roughly consistent with observed
596 age-related changes in (basal expenditure)/(fat free mass) (Figure S6C). Thus, changes in organ

597 size can account for much of the variation in basal expenditure across the lifespan observed in
598 our dataset.

599 Nonetheless, observed basal expenditure was ~30% greater early in life, and ~20% lower
600 in older adults, than estimated basal expenditure from the three-compartment model (Figure
601 S6D). The departures from estimated basal expenditure suggest that the mass-specific metabolic
602 rates of one or more organ compartments are considerably higher early in life, and lower late in
603 life, than they are in middle-aged adults, consistent with previous assessments (15, 16, 19, 25,
604 26). It is notable, in this context, that observed basal expenditure for neonates is nearly identical
605 to basal expenditure estimated from the three-compartment model, which assumes adult-like
606 tissue metabolic rates (Figure S6B,C,D). Observed basal expenditure for neonates is thus
607 consistent with the hypothesis that the mass-specific metabolic rates of their organs are similar to
608 those of other adults, specifically the mother.

609 7. Modeling the Effects of Physical Activity and Tissue Specific Metabolism

610 We constructed two simple models to examine the contributions of physical activity and
611 variation in tissue metabolic rate to total and basal expenditure. In the simplest version, we used
612 the observed relationship between basal expenditure and fat free mass for all adults 20 – 60 y
613 determined from linear regression of $\ln(\text{basal expenditure})$ and $\ln(\text{fat free mass})$ (untransformed
614 regression equation: basal expenditure = 0.32 (fat free mass) $^{0.75}$, adj. $r^2 = 0.60$, df = 1684, $p <$
615 0.0001) to model basal expenditure as

616 $\text{Basal expenditure} = 0.32 \text{ TM}_{\text{age}} (\text{fat free mass})^{0.75}$ [3]

617 The TM_{age} term is tissue metabolic rate, a multiplier between 0 and 2 reflecting a relative
618 increase ($\text{TM}_{\text{age}} > 1.0$) or decrease ($\text{TM}_{\text{age}} < 1.0$) in organ metabolic rate relative that expected
619 from the power-law regression for adults. Note that, even when $\text{TM}_{\text{age}} = 1.0$, smaller individuals

620 are expected to exhibit greater mass-specific basal expenditure (that is, a greater basal
621 expenditure per kg body weight) due to the power-law relationship between basal expenditure
622 and fat free mass. Further, we note that the power-law relationship between basal expenditure
623 and fat free mass for adults is similar to that produced when estimating basal expenditure from
624 organ sizes (see *Organ Size and Basal Expenditure*, above). Thus, variation in TM_{age} reflects
625 modeled changes in tissue metabolic rate *in addition* to power-law scaling effects, and also, in
626 effect, in addition to changes in basal expenditure due to age-related changes in organ size and
627 proportion. To model variation in organ activity over the lifespan, we either 1) maintained TM_{age}
628 at adult levels ($TM_{age} = 1.0$) over the entire lifespan, or 2) had TM_{age} follow the trajectory of
629 adjusted basal expenditure with age (Figure S8).

630 To incorporate effects of fat mass into the model, we constructed a second version of the
631 model in which basal expenditure was modeled following the observed relationship with FFM
632 and fat mass for adults 20 – 60 y,

633
$$\text{Basal expenditure} = 0.32 TM_{age} (\text{fat free mass})^{0.7544} (\text{fat mass})^{0.0003} \quad [4]$$

634 As with the fat free mass model (eq. 3), we either maintained TM_{age} at 1.0 over the life span or
635 modeled it using the trajectory of adjusted basal expenditure.

636 Activity expenditure was modeled as a function of physical activity and body mass
637 assuming larger individuals expend more energy during activity. We began with activity
638 expenditure, calculated as $[0.9(\text{total expenditure}) - (\text{basal expenditure})]$ as described above. The
639 observed ratio of (activity expenditure)/(fat free mass) for adults 20 – 60 y was $0.07 \text{ MJ d}^{-1} \text{ kg}^{-1}$.
640 We therefore modeled activity expenditure as

641
$$\text{Activity expenditure} = 0.07 PA_{age} (\text{fat free mass}) \quad [5]$$

642 To incorporate effects of fat mass, we constructed a second version using the ratio of (activity
643 expenditure)/(body weight) for adults 20 – 60y,

644
$$\text{Activity expenditure} = 0.04 \text{ PA}_{\text{age}} \text{ (body weight)} \quad [6]$$

645 In both equations, PA_{age} represents the level of physical activity relative to the mean value for 20
646 – 60 y adults. PA_{age} could either remain constant at adult levels ($\text{PA}_{\text{age}}=1.0$) over the lifespan or
647 follow the trajectory of physical activity measured *via* accelerometry, which peaks between 5 –
648 10 y, declines rapidly through adolescence, and then declines more slowly beginning at ~40 y
649 (12-14, 17, 18, 47-50). Different measures of physical activity (*e.g.*, moderate and vigorous PA,
650 mean counts per min., total accelerometry counts) exhibit somewhat different trajectories over
651 the lifespan, but the patterns are strongly correlated; all measures show the greatest activity at 5-
652 10 y and declining activity in older adults (Figure S7). We chose total accelerometry counts (12,
653 17), which sum all movement per 24-hour period, to model age-related changes in PA_{age} . We
654 chose total counts because activity energy expenditure should reflect the summed cost of all
655 activity, not only activity at moderate and vigorous intensities. Further, the amplitude of change
656 in moderate and vigorous activity over the lifespan is considerably larger than the observed
657 changes in adjusted total expenditure or adjusted activity expenditure (Figure S10). Determining
658 the relative contributions of different measures of physical activity to total expenditure is beyond
659 the scope of the simple modeling approach here and remains an important task for future
660 research.

661 8. Physical Activity, Activity Expenditure and PAL

662 To further interrogate our simple model of expenditure and the contribution of physical
663 activity, we examined the agreement between accelerometry-measured physical activity,
664 adjusted activity expenditure, and modeled PAL over the lifespan. First, as noted in our

665 discussion of the simple expenditure model (see above; Figures 3, S8, S9), moderate and
666 vigorous physical activity and total accelerometry counts show a similar shape profile when
667 plotted against age, but moderate and vigorous physical activity shows a greater amplitude of
668 change over the lifespan (Figure S10). Moderate and vigorous physical activity reach a peak ~4-
669 times greater than the mean values observed for 20 – 30 y men and women, far greater than the
670 amplitude of change in adjusted total expenditure.

671 We used adjusted total and basal expenditures to model activity expenditure and PAL
672 over the lifespan for comparison with published accelerometry measures of physical activity.
673 Modeling activity expenditure and PAL was preferable because our dataset has no subjects less
674 than 3 y with measures of both total and basal expenditure, and only 4 subjects under the age of 6
675 y with both measures (Table S1). Using values of adjusted total expenditure and adjusted
676 BEE_{TEE} (basal expenditure expressed as a percentage of total expenditure) for age cohorts from
677 Table S3 enabled us to model activity expenditure and PAL for this critical early period of
678 development, in which both physical activity and expenditure change substantially. We modeled
679 adjusted activity expenditure as [(adjusted total expenditure) – (adjusted BEE_{TEE})] and PAL as
680 [(adjusted total expenditure) / (adjusted BEE_{TEE})], which as we show in Figure S4 correlate
681 strongly with unadjusted measures of activity expenditure and PAL, respectively.

682 Modeled adjusted activity expenditure and PAL showed a somewhat different pattern of
683 change over the lifecourse than either total counts or moderate and vigorous activity measured via
684 accelerometry (Figure S10). Modeled activity expenditure was most similar to total counts, rising
685 through childhood, peaking between 10 and 20 y before falling to a stable adult level; the adult
686 level was stable from ~30 – 75 y before declining (Figure S10). Modeled PAL rose unevenly
687 from birth through age 20, then remained largely stable thereafter.

688 The agreement, and lack thereof, between the pattern of accelerometry-measured physical
689 activity and modeled activity expenditure and PAL must be assessed with caution. These
690 measures are from different samples; we do not have paired accelerometry and energy
691 expenditure measures in the present dataset. The life course pattern of accelerometry-measured
692 physical activity, particularly total counts, is broadly consistent with that of modeled activity
693 expenditure. However, more work is clearly needed to determine the effects of physical activity
694 and other factors to variation in activity expenditure and PAL over the lifecourse.

695 9.IAEA DLW database consortium

696 This group authorship contains the names of people whose data were contributed into the
697 database by the analysis laboratory but they later could not be traced, or they did not respond to
698 emails to assent inclusion among the authorship. The list also includes some researchers who did
699 not assent inclusion because they felt their contribution was not sufficient to merit authorship.

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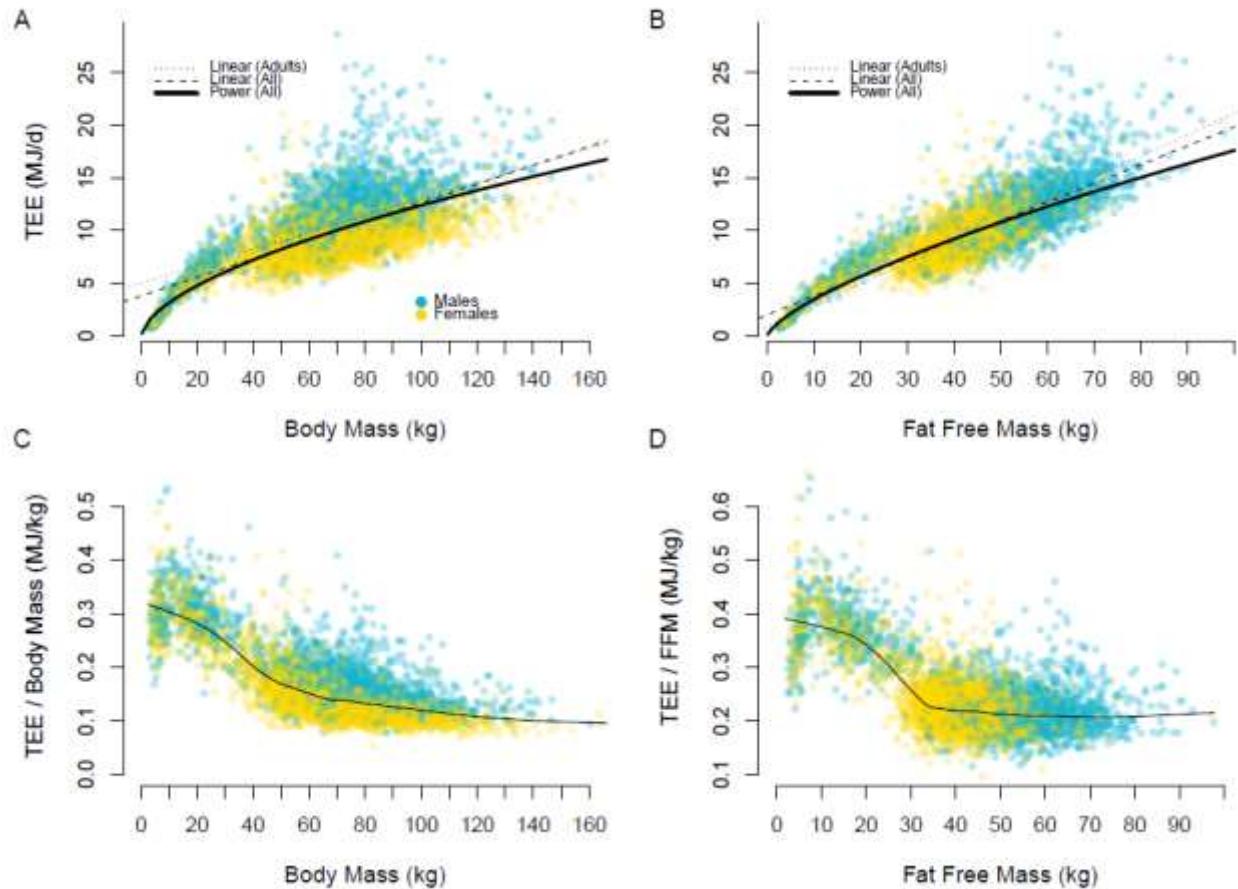
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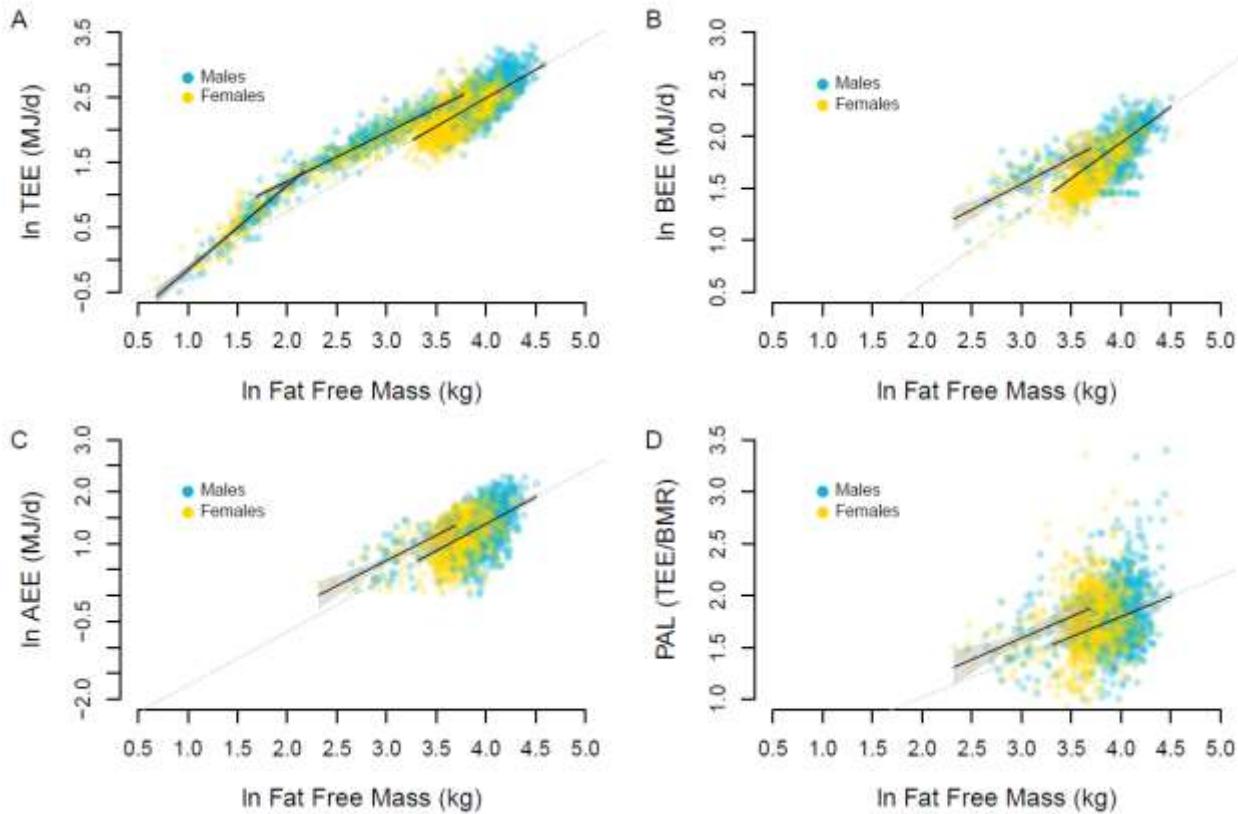
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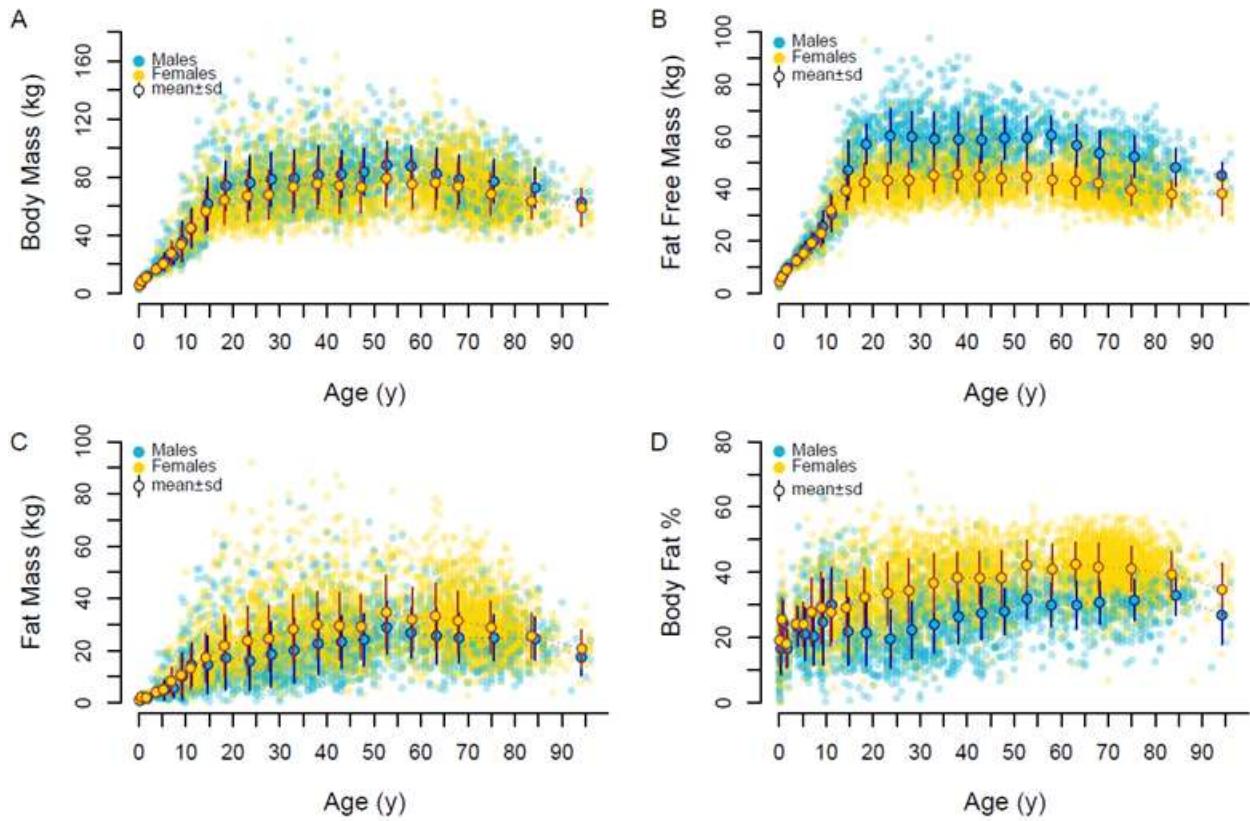
783

784 **Figure S1.** Total expenditure (TEE) increases with body size in a power-law manner. For the entire dataset
 785 ($n = 6,407$): **A.** the power-law regression for total body mass ($\ln\text{TEE} = 0.593 \pm 0.004 \ln\text{Mass} - 0.214 \pm$
 786 0.018 , $p < 0.001$, adj. $r^2 = 0.73$, model std. err. = 0.223 , df = 6419) is less predictive than the regression for
 787 **B.** fat free mass ($\ln\text{TEE} = 0.708 \pm 0.004 \ln\text{FFM} - 0.391 \pm 0.015$, $p < 0.001$, adj. $r^2 = 0.83$, model std. err. =
 788 0.176 , df = 6419). For both body mass and fat free mass regressions, power-law regressions outperform
 789 linear models, particularly at the smallest body sizes. For all models, for both body mass and fat free mass,
 790 children have elevated total expenditure, clustering above the trend line. Children also exhibit elevated
 791 basal and activity expenditures (Figure S2). Power-law regressions have an exponent < 1.0 , and linear
 792 regressions (dashed: linear regression through all data; dotted: linear regression through adults only) have
 793 a positive intercept, indicating that simple ratios of **C.** (total expenditure)/(body mass) or **D.** (total
 794 expenditure)/(fat free mass) do not adequately control for differences in body size (22) as smaller individuals
 795 will tend to have higher ratios. Lines in **C** and **D** are lowess with span $1/6$. In body mass regressions (panel
 796 **A**, power and linear models) and the ratio of (total expenditure)/(body mass) (**C**), adult males cluster above
 797 the trend line while females cluster below due to sex differences in body composition. In contrast, males
 798 and females fit the fat free mass regressions (**B**) and ratio (**D**) equally well.



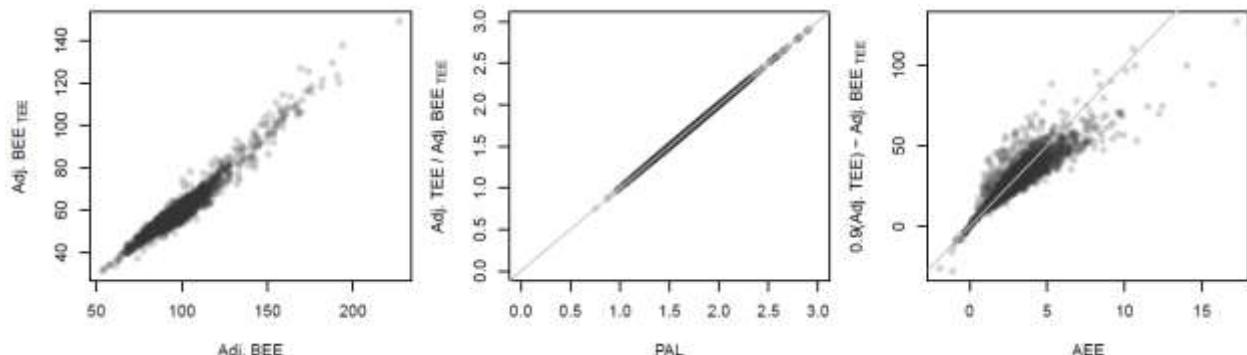
799

800 **Figure S2.** Infants and children exhibit different relationships between fat free mass and expenditure and
 801 the PAL ratio. **A:** For total expenditure (TEE), regressions for infants (age <1 y, left regression line) and
 802 adults (right regression line) intersect for neonates, at the smallest body size. However, the slopes differ,
 803 with the infants' regression and 95% CI (gray region) falling outside of that for adults (age 20 – 60 y,
 804 extrapolated dashed line). Juvelines (age 1 – 20 y, middle regression line) are elevated, with a regression
 805 outside the 95% CI of adults. Juvenile (1 – 20 y) regressions (with 95%CI) are also elevated for basal
 806 expenditure (BEE) (**B**), activity expenditure (AEE) (**C**), and PAL (**D**) compared to adults (20 – 60 y). Sex
 807 differences in expenditure (**A-D**) are attributable to differences in fat free mass. Note that total and basal
 808 expenditures are measured directly. Activity expenditure is calculated as (0.9TEE – BEE), and PAL is
 809 calculated as (TEE/BEE); see Methods.



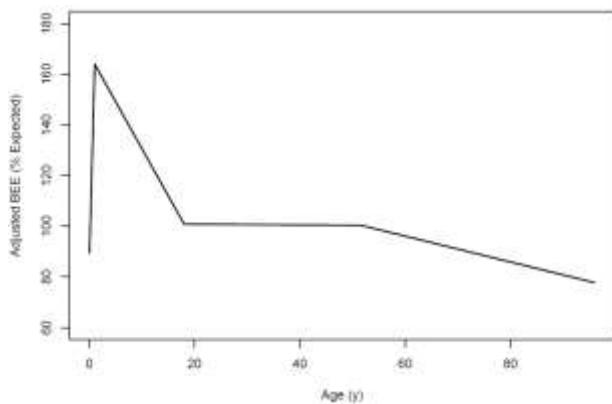
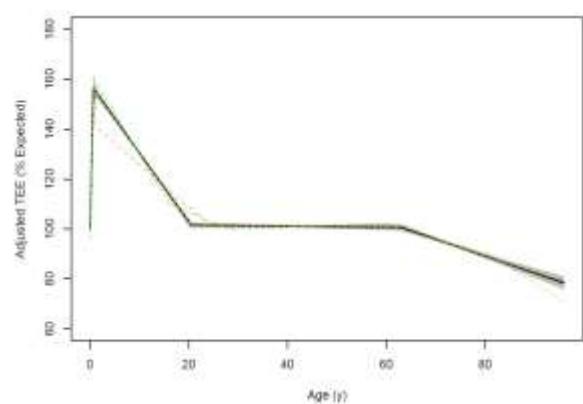
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811 **Figure S3.** Changes in body composition over the lifespan: **A.** Body mass; **B.** Fat free mass; **C.** Fat Mass;
812 and **D.** Body fat percentage.

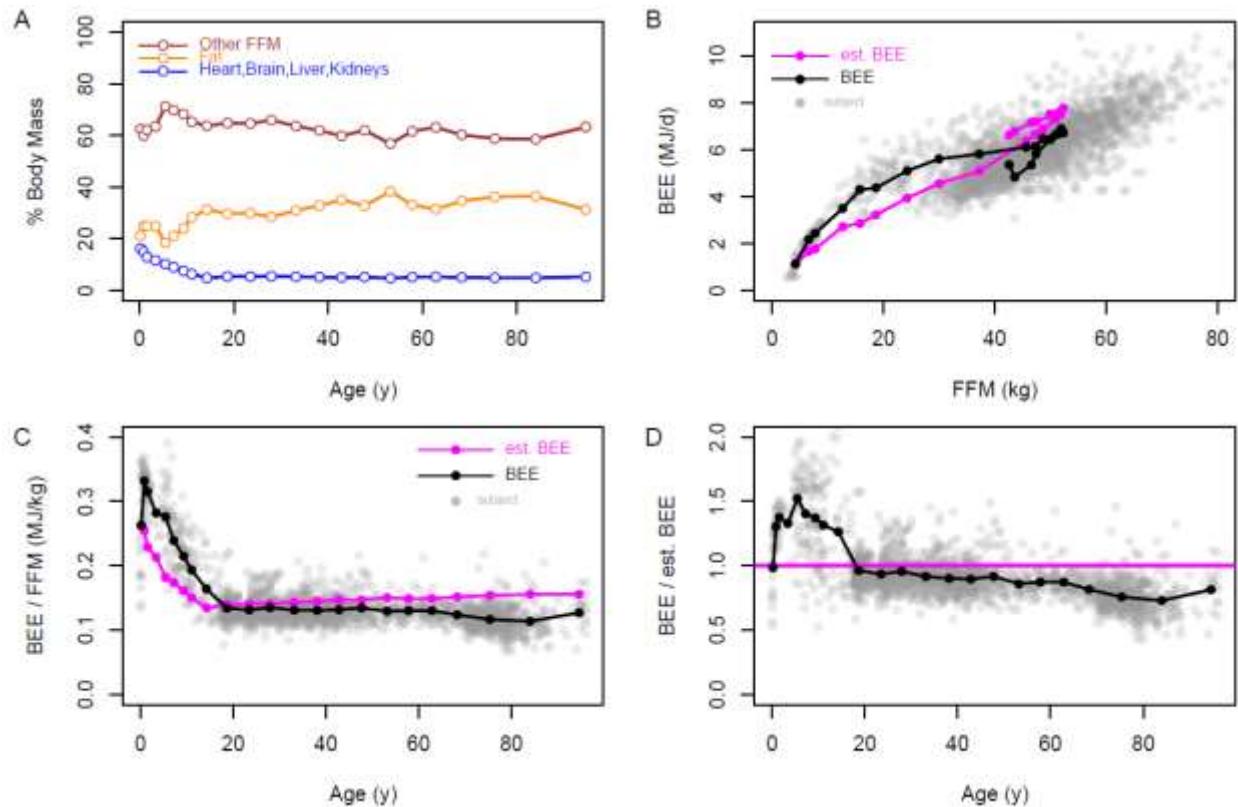


813

814 **Figure S4.** Left: Adjusted BEE_{TEE} corresponds strongly to adjusted basal expenditure (Adj. BEE). Center:
 815 The ratio of adjusted total expenditure (adj. TEE) to adjusted BEE_{TEE} is identical to the PAL ratio. Right: The
 816 difference (0.9adjusted total expenditure – adjusted BEE_{TEE}) is proportional to activity energy expenditure
 817 (AEE). Gray lines: center panel: y = x, right panel: y = 10x.

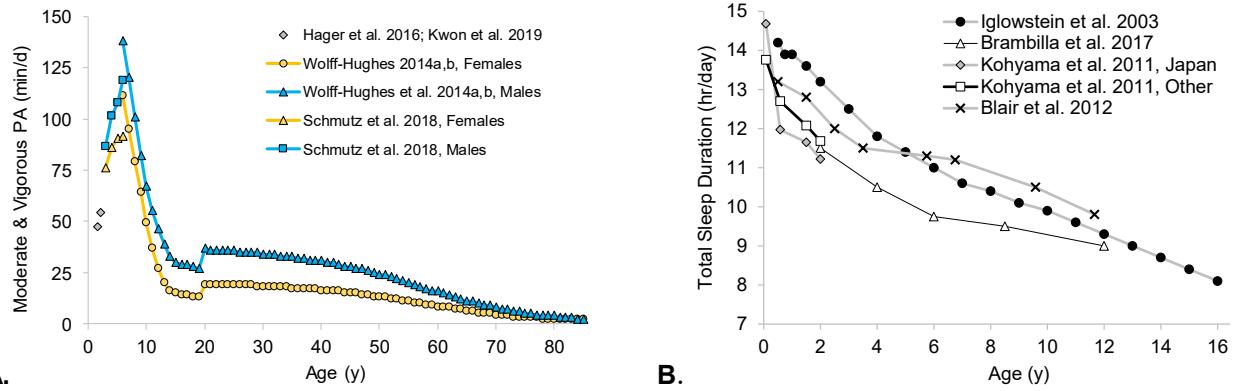


820 **Figure S5.** Segmented regression analysis of adjusted TEE (A) and adjusted BEE (B). In both panels,
821 the black line and gray shaded confidence region depicts the 3 change-point regression. For adjusted
822 TEE, segmented regressions are also shown for 2 change points (red), 4 change points (yellow), and 5
823 change points (green). Segmented regression statistics are given in Table S4.



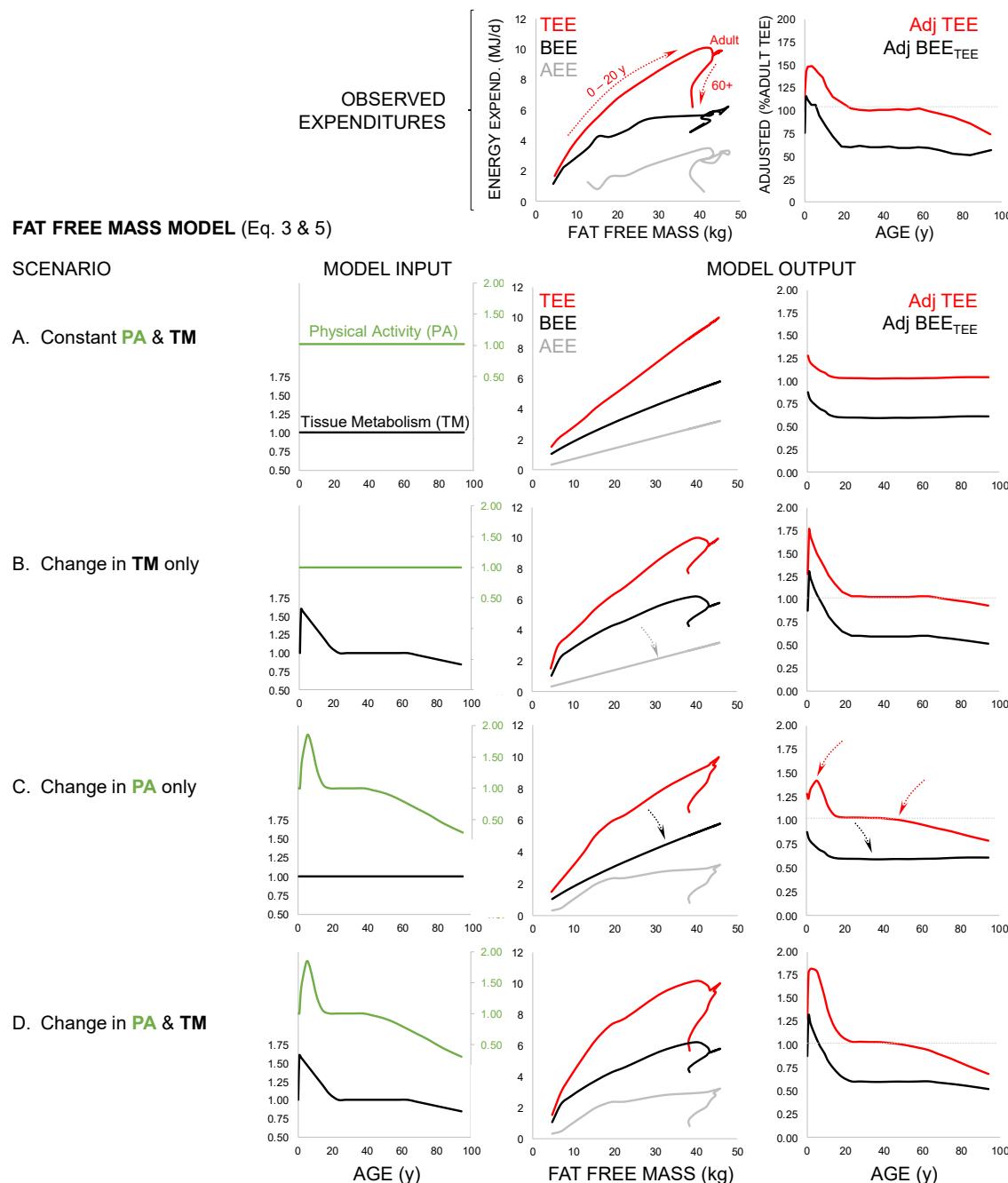
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825 **Figure S6. Organ sizes and BEE.** **A.** The relative proportions of metabolically active organs (heart,
 826 brain, liver, kidneys), other fat free mass (FFM), and fat changes over the life course. Age cohort means
 827 are shown. **B.** Consequently, estimated basal expenditure (BEE) from the three-compartment model
 828 increases with fat free mass (FFM) in a manner similar to observed basal expenditure, with **C.** greater
 829 whole body mass-specific basal expenditure (BEE/FFM) early in life. **D.** Observed basal expenditure is
 830 ~30% greater early in life, and ~20% lower after age 60 y, than estimated basal expenditure from the
 831 three-compartment model (shown as the ratio of BEE/est.BEE). In panels **B**, **C**, and **D**, age-cohort means
 832 for observed (black) and estimated (magenta) basal expenditure are shown.



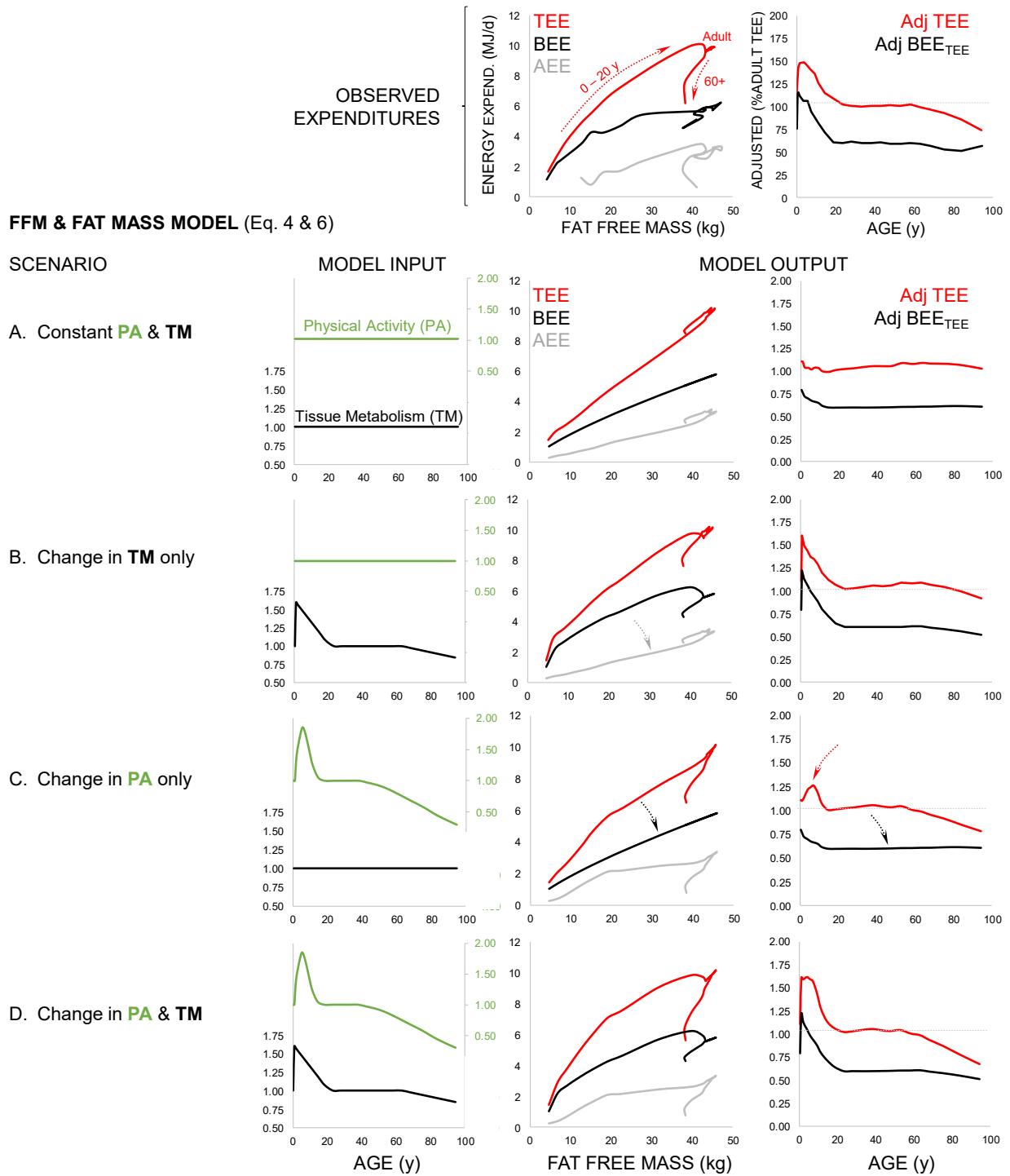
833 **A.**

834 **Figure S7.** Modeling physical activity across the lifespan. **A.** Across studies and countries,
 835 accelerometer-measured physical activity rises through infancy and early childhood, peaking between 5
 836 and 10y before declining to adult levels in the teenage years (12-14, 17, 18, 47-50). Physical activity
 837 declines again, more slowly, in older adults. The onset of decline in older adults varies somewhat across
 838 studies, beginning between ~40 y and ~60 y. Here, physical activity is shown as minutes/day of moderate
 839 and vigorous physical activity. Other measures (e.g., total accelerometer counts; mean counts/min, vector
 840 magnitude) follow a similar pattern of physical activity over the life span (12, 17). **B.** The increase in
 841 physical activity from 0 to ~10 y is mirrored by the steady decline in total daily sleep duration during this
 842 period (51-54).



843

844 **Figure S8.** Results of the fat free mass model. Observed expenditures exhibit a marked age effect on the
 845 relationship between expenditure and fat free mass that is evident in both absolute (Figure 1C) and adjusted
 846 (Figure 2D) measures. **A.** If physical activity (PA) and cellular metabolism (TM) remain constant at adult
 847 levels, age effects do not emerge from the model. **B.** When only TM varies, age effects emerge for total
 848 expenditure (TEE) and basal expenditure (BEE), but not activity expenditure (AEE; gray arrow). **C.**
 849 Conversely, if only physical activity varies age effects emerge for AEE and TEE but not BEE (black arrow).
 850 Adjusted TEE also peaks later in childhood and declines earlier in adulthood (red arrows) than observed.
 851 **D.** Varying both PA and TM gives model outputs similar to observed expenditures.

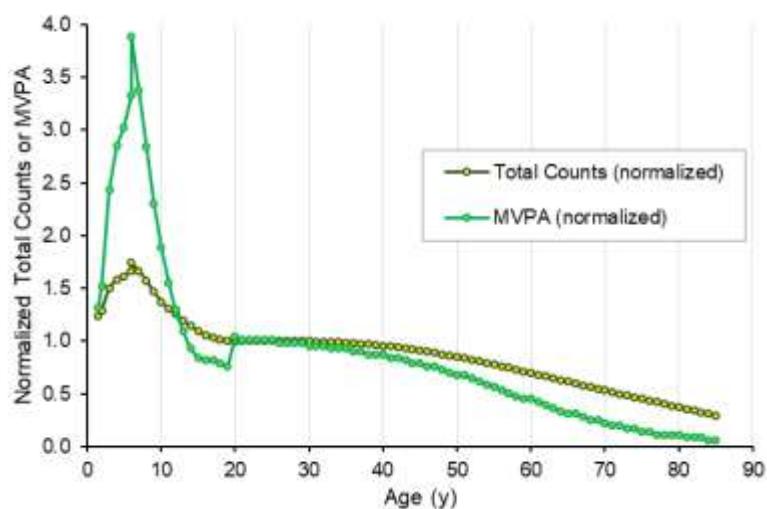


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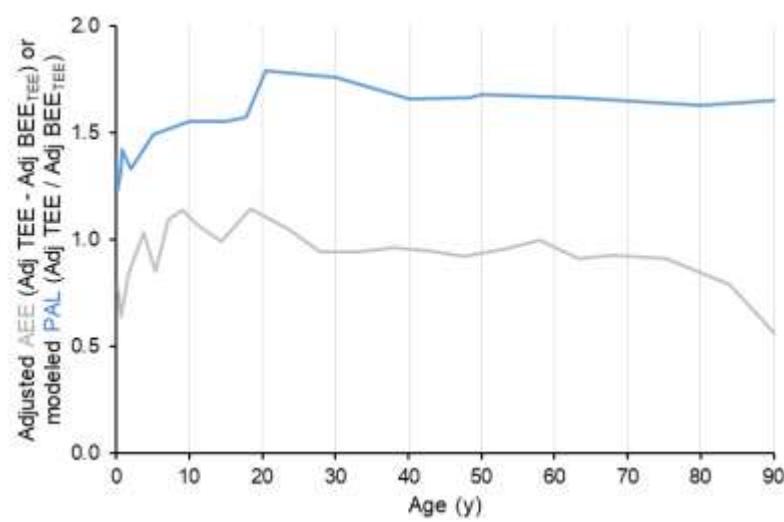
853 **Figure S9.** Results of the fat free mass and fat mass model. Model outputs are similar to those of the fat
 854 free mass model (Figure S8). The scenario that best matches the observed relationships between fat free
 855 mass, age, and expenditure is D, in which AEE is influenced by age-related variation in both physical activity
 856 and cellular metabolism. Abbreviations as in Fig S8.

857

A

858
859

B



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861 **Figure S10. A.** Physical activity measured via accelerometry from published analyses (12-14, 17, 18,
 862 47-50) and **B.** modeled activity expenditure and PAL calculated from cohort means for adjusted total
 863 expenditure and adjusted BEE_{TEE} in Table S3. Accelerometry measures and modeled activity expenditure
 864 are normalized to mean values for 20 – 30 y subjects.

Table S1. Key characteristics by age-sex cohort for A. Total expenditure (TEE) from the DLW database and B. subjects with basal expenditure (BEE) measurements. Activity expenditure (AEE) = 0.9TEE - BEE. *Infant data from the literature, males and females pooled. N values for infant BEE (0 to 2 years) indicate number of entries and (number of individuals). See Methods.

		Age (y)				Height (cm)				Mass (kg)				BMI		Fat Free Mass (kg)		Fat Mass (kg)		Fat%		TEE (MJ/d)		
		F	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	
Age group	N	N	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
(0.0-5]	102	93	0.24	0.13	0.24	0.13	59.7	46	60.4	54	5.71	128	6.12	152	15.8	16	16.4	119	4.56	0.87	5.03	109	1.14	0.63
(0.5-1]	18	23	0.68	0.18	0.72	0.20	69.1	43	71.8	46	8.54	140	9.17	133	17.8	21	17.7	13	6.32	0.91	6.94	118	2.23	0.80
(1-2]	33	35	1.70	0.46	1.64	0.48	82.3	50	83.2	53	11.06	141	11.69	195	16.3	10	16.8	110	9.04	1.32	9.74	141	2.12	0.87
(2-4]	54	48	3.81	0.58	3.78	0.31	101.2	46	102.1	61	16.66	338	17.38	303	15.9	17	16.6	24	12.51	185	13.24	185	4.15	1.91
(4-6]	99	121	5.34	0.63	5.31	0.66	112.7	67	113.7	75	20.41	336	21.74	573	16.0	20	16.6	23	15.34	231	16.83	232	5.06	2.43
(6-8]	42	43	7.03	0.65	7.25	0.62	122.5	10.2	125.2	88	27.62	84.8	25.71	54.9	18.0	39	16.2	24	19.28	3.97	20.14	2.75	8.34	5.33
(8-10]	79	75	9.10	0.48	9.14	0.55	133.5	9.3	136.9	10.0	33.62	11.50	35.76	13.69	18.2	45	18.4	48	22.96	5.01	25.53	6.09	10.66	7.74
(10-12]	69	34	11.14	0.58	11.01	0.47	148.5	8.6	147.8	9.6	44.91	13.45	31.41	21.24	31.85	6.35	30.42	6.63	13.30	7.90	14.50	18.3	30.11	112
(12-16]	227	129	14.37	1.18	14.53	1.14	160.6	8.4	168.4	12.1	56.72	14.67	61.73	16.36	21.9	4.8	21.5	5.6	39.37	7.27	47.15	1142	17.34	9.25
(16-20]	211	103	18.32	0.98	18.37	1.11	163.9	7.4	177.9	7.7	64.31	16.34	74.36	16.73	23.5	4.9	42.49	7.26	57.11	7.58	21.82	1176	17.25	12.26
(20-25]	257	128	23.23	1.40	23.48	1.38	164.6	7.4	177.6	9.3	67.08	17.92	76.35	16.80	24.8	6.4	24.14	4.9	43.26	6.35	60.29	10.53	23.92	13.08
(25-30]	281	186	27.77	1.48	28.05	1.40	164.1	6.9	177.4	8.9	67.99	16.72	78.56	18.51	25.2	5.4	24.9	4.8	43.85	6.81	24.53	12.51	18.58	12.54
(30-35]	238	149	32.99	1.36	32.88	1.41	164.5	6.2	177.2	8.0	73.39	17.78	79.14	19.56	27.2	6.3	25.14	5.4	45.20	6.63	59.07	10.23	28.18	12.56
(35-40]	232	167	38.05	1.45	38.01	1.42	164.2	6.5	176.7	7.6	75.50	17.68	81.55	19.88	28.0	6.6	26.0	5.4	45.47	6.82	58.91	10.51	30.03	12.59
(40-45]	301	165	42.81	1.36	42.92	1.37	163.7	7.2	176.3	7.7	74.23	18.78	82.12	15.90	27.6	6.3	26.4	4.3	44.76	7.56	58.79	8.91	29.47	12.78
(45-50]	172	144	47.43	1.46	47.76	1.46	164.6	6.1	176.8	7.2	73.18	17.40	83.74	15.81	27.4	6.3	27.4	4.3	44.02	6.44	59.52	8.15	29.15	12.40
(50-55]	105	93	52.80	1.48	52.59	1.48	163.5	5.9	177.1	6.7	74.66	16.71	88.16	15.51	29.7	7.0	28.4	4.8	43.66	6.51	59.54	8.29	34.72	13.08
(55-60]	111	76	58.24	1.48	57.76	1.38	163.6	6.2	177.3	7.6	75.35	17.07	87.53	13.91	28.3	5.7	27.8	3.7	43.42	6.06	60.67	7.13	31.93	12.22
(60-65]	252	90	63.22	1.47	63.16	1.55	161.5	7.1	174.5	7.4	76.21	18.34	82.34	17.11	29.3	6.8	27.2	4.5	42.92	6.83	56.70	8.07	33.29	12.58
(65-70]	387	90	68.04	1.47	67.98	1.37	161.4	6.7	172.4	7.3	73.67	15.55	78.50	16.64	28.3	5.7	26.2	4.5	42.20	5.85	53.61	8.62	31.47	11.13
(70-80]	682	232	75.05	2.79	75.40	2.92	159.4	6.7	171.3	8.0	68.10	14.29	77.19	14.92	26.9	5.2	29.62	5.65	52.79	7.86	24.88	10.72	41.6	7.42
(80-90]	149	66	83.65	2.40	84.20	2.50	157.5	7.2	168.7	7.5	63.61	12.29	72.76	13.80	25.7	4.7	25.42	5.42	38.02	5.22	48.22	7.07	25.59	8.10
(90-100]	22	8	94.36	1.79	94.00	1.85	158.0	9.1	168.8	8.0	58.98	12.81	62.60	9.47	23.6	4.1	22.0	3.4	38.26	8.50	45.18	4.93	20.72	7.23
B.		Age (y)				Mass (kg)				Fat Free Mass (kg)				Fat Mass (kg)		Fat%		BEE (MJ/d)		AEE (MJ/d)		PAL (TEE/BEE)		
Age Group	N	N	mean	sd	mean	sd	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M
(0.0-5]*	22	111	0.21	0.27	0.21	0.27	5.45	1.56	4.76	1.52	6.55	1.73	2.2	2.25	24.97	3.94	2.17	0.29	1.14	0.52	1.14	0.52	1.14	0.52
(1-2]*	18	86	0.85	0.44	0.85	0.44	1.56	0.32	1.03	0.32	7.72	1.22	2.6	2.63	24.96	3.27	2.44	0.44	1.50	0.50	1.50	0.50	1.50	0.50
(2-4]	3	1	3.80	0.35	4.00	NA	216	8.3	18.0	NA	14.87	4.25	14.96	NA	6.7	4.0	30	NA	29.54	6.26	39.91	NA	4.07	0.67
(4-6]	9	11	5.74	0.34	5.41	0.47	19.1	2.9	19.9	3.7	15.16	2.78	16.81	2.61	3.9	1.8	3.11	1.5	20.41	8.91	15.04	4.77	4.26	0.82
(6-8]	18	13	7.19	0.58	7.38	0.72	24	5.65	24.7	4.6	18.07	3.75	20.01	2.50	6.4	4.4	4.6	3.8	24.29	11.13	17.41	10.59	4.24	0.85
(8-10]	22	21	9.19	0.64	9.49	0.61	31.6	13.0	35.6	12.9	22.19	4.08	26.32	6.07	9.4	10.4	9.2	7.8	25.80	13.20	22.67	13.20	4.67	0.87
(10-12]	5	18	11.12	0.61	11.07	0.28	36	2.6	32	6.3	30.77	3.42	30.56	6.44	8.4	4.4	14.7	5.5	22.44	8.32	29.96	10.88	5.43	0.87
(12-16]	18	11	14.47	1.33	13.95	0.87	65.8	26.5	64.0	14.0	40.05	11.53	32.51	7.19	25.7	16.8	11.5	7.5	35.77	12.72	24.17	8.02	5.65	1.18
(16-20]	154	41	18.57	0.83	18.92	0.75	63.7	15.9	74.8	12.5	42.43	7.32	57.96	7.28	21.3	11.2	16.8	9.2	31.95	8.30	21.65	8.25	5.63	0.95
(20-25]	135	42	23.41	1.40	23.70	1.37	66.4	18.2	77.5	18.3	43.32	7.03	60.09	11.38	23.1	13	17.7	11.0	32.62	9.55	21.25	8.61	5.77	0.81
(25-30]	114	71	27.98	1.44	27.55	1.74	75.5	20.3	77.6	18.3	45.46	6.95	58.52	9.23	29.3	14.6	18.9	11.8	33.15	16.71	35.93	17.07	5.80	0.81
(30-35]	95	71	33.18	1.34	33.10	1.47	74.8	20.3	77.5	18.3	45.46	6.95	58.52	9.23	31.5	14.9	22.0	12.3	38.29	9.00	25.86	8.49	6.22	0.83
(35-40]	112	87	38.10	1.45	38.17	1.45	78.5	20.6	80.1	20.2	46.96	7.57	58.10	9.33	31.5	14.9	22.0	12.3	38.29	9.00	25.86	8.49	7.32	1.17
(40-45]	99	53	42.92	1.33	42.57	1.29	80.8	18.5	47.08	18.20	59.28	9.50	33.8	15.3	23.0	12.5	39.94	8.82	26.35	9.81	6.24	1.02		
(45-50]	37	30	47.19	1.27	48.20	1.37	75.5	20.7	92.9	16.6	45.01	7.42	63.72	6.48	30.5	14.5	29.1	13.7	38.08	10.35	29.89	8.78	5.73	0.82
(50-55]	32	13	53.16	1.57	53.46	1.20	80.5	18.2	82.18	16.6	51.65	7.44	35.3	16.7	30.6	13.5	41.92	8.73	31.79	8.78	7.97	1.16		
(55-60]	22	23	58.18	1.40	57.52	1.24	71.0	12.6	87.0	10.2	43.40	4.84	61.72	6.29	27.6	8.9	25.3	7.2	38.09	5.81	28.68	5.83	5.92	0.83
(60-65]	22	37	62.50	1.44	63.11	1.66	65.7	10.1	79.9	12.6	40.40	5.51	56.76	5.89	23.2	8.2	38.16	4.80	28.22	6.25	5.49	0.82		
(65-70]	40	29	68.05	1.64	68.66	1.45	71.2	16.3	76.4	15.1	42.61	5.56	53.98	9.37	28.6	11.7	38.6	11.7	38.78	5.58	5.30	0.61		
(70-80]	187	192	75.42	2.87	67.1	14.6	80.2	14.0	39.22</td															

Table S2. Model parameters for Total, Basal, and Activity Expenditure and PAL (p<0.0001 for all models)

Total Expenditure (TEE)		Neonates (0 - 1y)				Juveniles (1 - 20y)				Adults (20 - 60y)				Older Adults (60+ y)			
Model	Factors	β	std. err.	t-value	p	β	std. err.	t-value	p	β	std. err.	t-value	p	β	std. err.	t-value	p
1. TEE~Body Mass+Sex+Age	Intercept (MJ/d)	0.255	0.111	2.304	0.022	2.592	0.118	22.032	0.000	5.984	0.197	30.427	0.000	0.917	0.375	29.130	0.000
	Body Mass (kg)	0.205	0.025	8.061	0.000	0.080	0.004	22.494	0.000	0.065	0.002	30.274	0.000	0.048	0.002	24.701	0.000
	Sex(M)	0.090	0.046	1.953	0.052	1.436	0.095	15.145	0.000	2.669	0.081	33.036	0.000	1.659	0.070	23.672	0.000
	Age (y)	0.951	0.205	4.632	0.000	0.183	0.015	11.832	0.000	-0.025	0.004	-6.635	0.000	-0.080	0.004	-18.451	0.000
	model	N	SEE	df	adjR2	N	SEE	df	adjR2	N	SEE	df	adjR2	N	SEE	df	adjR2
		235	0.343	231	0.733	1403	1.719	1399	0.726	2805	2.032	2801	0.482	1978	1.311	1974	0.509
		β	std. err.	t-value	p	β	std. err.	t-value	p	β	std. err.	t-value	p	β	std. err.	t-value	p
2. In(TEE)~In(FFM)+In(FM)	Intercept (MJ/d)	-1.270	0.074	-17.130	0.000	-0.121	0.028	-4.259	0.000	-1.102	0.050	-22.038	0.000	-0.773	0.062	-12.403	0.000
	In(Fat Free Mass; kg)	1.163	0.046	25.311	0.000	0.696	0.011	67.758	0.000	0.916	0.013	71.248	0.000	0.797	0.018	44.723	0.000
	In(Fat Mass; kg)	0.053	0.014	3.862	0.000	-0.041	0.007	-5.714	0.000	-0.030	0.005	-5.986	0.000	-0.016	0.009	-1.828	0.068
	model	N	SEE	df	adjR2	N	SEE	df	adjR2	N	SEE	df	adjR2	N	SEE	df	adjR2
		235	0.160	232	0.796	1403	0.154	1400	0.842	2805	0.142	2802	0.646	1978	0.139	1975	0.533
		β	std. err.	t-value	p	β	std. err.	t-value	p	β	std. err.	t-value	p	β	std. err.	t-value	p
3. In(TEE)~In(FFM)+In(FM)+Sex+Age	Intercept (MJ/d)	-1.122	0.089	-12.619	0.000	-0.348	0.044	-7.956	0.000	-1.118	0.069	-16.129	0.000	0.092	0.089	1.032	0.302
	In(Fat Free Mass; kg)	1.025	0.067	15.215	0.000	0.784	0.021	38.119	0.000	0.920	0.020	45.942	0.000	0.736	0.025	29.883	0.000
	In(Fat Mass; kg)	0.034	0.015	2.294	0.023	-0.019	0.007	-2.622	0.009	-0.032	0.006	-5.149	0.000	-0.030	0.010	-3.118	0.002
	Sex(M)	-0.014	0.021	-0.644	0.520	0.067	0.009	7.592	0.000	-0.002	0.009	-0.249	0.803	0.011	0.010	1.042	0.298
	Age (y)	0.254	0.082	3.104	0.002	-0.012	0.002	-6.630	0.000	0.000	0.000	0.765	0.444	-0.008	0.000	-19.038	0.000
	model	N	SEE	df	adjR2	N	SEE	df	adjR2	N	SEE	df	adjR2	N	SEE	df	adjR2
		235	0.157	230	0.804	1403	0.147	1398	0.857	2805	0.142	2800	0.646	1978	0.128	1973	0.606
Basal Expenditure (BEE)		Juveniles (1 - 20y)				Adults (20 - 60y)				Older Adults (60+ y)							
4. BEE~Body Mass+Sex+Age	Factors	β	std. err.	t-value	p	β	std. err.	t-value	p	β	std. err.	t-value	p	β	std. err.	t-value	p
	Intercept (MJ/d)	2.965	0.158	18.785	0.000	3.649	0.104	34.943	0.000	5.905	0.379	15.571	0.000				
	Body Mass (kg)	0.034	0.003	11.004	0.000	0.036	0.001	32.494	0.000	0.031	0.002	14.277	0.000				
	Sex(M)	1.185	0.101	11.733	0.000	1.263	0.045	27.915	0.000	0.724	0.066	10.939	0.000				
	Age (y)	0.033	0.015	2.212	0.028	-0.008	0.002	-3.487	0.001	-0.041	0.004	-9.501	0.000				
	model	N	SEE	df	adjR2	N	SEE	df	adjR2	N	SEE	df	adjR2	N	SEE	df	adjR2
		345	0.848	341	0.581	1036	0.694	1032	0.682	621	0.761	617	0.520				
		β	std. err.	t-value	p	β	std. err.	t-value	p	β	std. err.	t-value	p	β	std. err.	t-value	p
5. In(BEE)~In(FFM)+In(FM)	Intercept (MJ/d)	0.055	0.078	0.700	0.480	-0.954	0.059	-16.176	0.000	-0.923	0.099	-9.350	0.000				
	In(Fat Free Mass; kg)	0.535	0.028	19.103	0.000	0.707	0.016	45.353	0.000	0.656	0.027	24.640	0.000				
	In(Fat Mass; kg)	-0.095	0.014	-6.784	0.000	0.019	0.006	3.408	0.001	0.028	0.015	1.819	0.069				
	model	N	SEE	df	adjR2	N	SEE	df	adjR2	N	SEE	df	adjR2	N	SEE	df	adjR2
		345	0.153	342	0.573	1036	0.103	1033	0.688	621	0.135	618	0.530				
		β	std. err.	t-value	p	β	std. err.	t-value	p	β	std. err.	t-value	p	β	std. err.	t-value	p
6. In(BEE)~In(FFM)+In(FM)+Sex+Age	Intercept (MJ/d)	-0.270	0.100	-2.704	0.007	-0.497	0.079	-6.281	0.000	-0.089	0.151	-0.587	0.557				
	In(Fat Free Mass; kg)	0.663	0.044	15.167	0.000	0.561	0.023	24.008	0.000	0.549	0.040	13.663	0.000				
	In(Fat Mass; kg)	-0.054	0.014	-4.005	0.000	0.054	0.007	7.809	0.000	0.042	0.016	2.619	0.009				
	Sex(M)	0.090	0.019	4.780	0.000	0.086	0.010	8.297	0.000	0.037	0.016	2.288	0.022				
	Age (y)	-0.018	0.003	-5.102	0.000	-0.001	0.000	-2.124	0.034	-0.006	0.001	-8.814	0.000				
	model	N	SEE	df	adjR2	N	SEE	df	adjR2	N	SEE	df	adjR2	N	SEE	df	adjR2
		345	0.137	340	0.658	1036	0.100	1031	0.708	621	0.128	616	0.582				
Activity Expenditure (AEE)		Juveniles (1 - 20y)				Adults (20 - 60y)				Older Adults (60+ y)							
7. AEE~Body Mass+Sex+Age	Factors	β	std. err.	t-value	p	β	std. err.	t-value	p	β	std. err.	t-value	p	β	std. err.	t-value	p
	Intercept (MJ/d)	-0.481	0.237	-2.030	0.043	1.822	0.252	7.231	0.000	5.835	0.604	9.663	0.000				
	Body Mass (kg)	0.032	0.005	6.774	0.000	0.023	0.003	8.870	0.000	0.014	0.003	4.111	0.000				
	Sex(M)	0.999	0.152	6.581	0.000	1.308	0.109	11.983	0.000	0.661	0.105	6.264	0.000				
	Age (y)	0.113	0.022	5.133	0.000	-0.012	0.006	-2.216	0.027	-0.058	0.007	-8.354	0.000				
	model	N	SEE	df	adjR2	N	SEE	df	adjR2	N	SEE	df	adjR2	N	SEE	df	adjR2
		345	1.275	341	0.476	1036	1.675	1032	0.201	621	1.212	617	0.219				
		β	std. err.	t-value	p	β	std. err.	t-value	p	β	std. err.	t-value	p	β	std. err.	t-value	p
8. In(AEE)~In(FFM)+In(FM)	Intercept (MJ/d)	-3.330	0.231	-14.447	0.000	-4.124	0.248	-16.627	0.000	-2.556	0.401	-6.381	0.000				
	In(Fat Free Mass; kg)	1.301	0.082	15.776	0.000	1.476	0.065	22.614	0.000	0.952	0.108	8.807	0.000				
	In(Fat Mass; kg)	-0.099	0.044	-2.414	0.016	-0.142	0.023	-6.130	0.000	-0.042	0.062	-0.685	0.494				
	model	N	SEE	df	adjR2	N	SEE	df	adjR2	N	SEE	df	adjR2	N	SEE	df	adjR2
		338	0.445	335	0.550	1023	0.423	1020	0.333	612	0.546	609	0.116				
		β	std. err.	t-value	p	β	std. err.	t-value	p	β	std. err.	t-value	p	β	std. err.	t-value	p
9. In(AEE)~In(FFM)+In(FM)+Sex+Age	Intercept (MJ/d)	-3.437	0.332	-10.366	0.000	-5.194	0.342	-15.187	0.000	0.222	0.625	3.355	0.723				
	In(Fat Free Mass; kg)	1.349	0.145	9.298	0.000	1.816	0.100	18.079	0.000	0.674	0.165	4.088	0.000				
	In(Fat Mass; kg)	-0.093	0.044	-2.097	0.037	-0.221	0.029	-7.598	0.000	-0.010	0.066	-0.151	0.880				
	Sex(M)	0.006	0.062	0.090	0.928	-0.198	0.044	-4.480	0.000	0.079	0.067	1.181	0.238				
	Age (y)	-0.005	0.011	-0.474	0.636	0.002	0.001	1.162	0.246	-0.025	0.003	-7.852	0.000				
	model	N	SEE	df	adjR2	N	SEE	df	adjR2	N	SEE	df	adjR2	N	SEE	df	adjR2
		338	0.446	333	0.547	1023	0.420	1018	0.345	612	0.521	607	0.195				
PAL (TEE/BEE)		Juveniles (1 - 20y)				Adults (20 - 60y)				Older Adults (60+ y)							
10. PAL~Body Mass+Sex+Age	Factors	β	std. err.	t-value	p	β	std. err.	t-value	p	β	std. err.	t-value	p	β	std. err.	t-value	p
	Intercept (MJ/d)	1.290	0.048	26.913	0.000	1.668	0.041	40.739	0.000	2.209	0.144	15.348	0.000				
	Body Mass (kg)	0.002	0.001	2.035	0.037	0.001	0.000	2.058	0.040	0.000	0.001	-0.239	0.811				
	Sex(M)	0.050	0.031	1.641	0.102												

Table S3. Adjusted total expenditure (TEE), Adjusted basal expenditure (BEE), and Adjusted BEE_{TEE}. *Infant data from the literature, males and females pooled. N values for infant BEE (0 to 2 years) indicate number of entries and (number of individuals).

Adjusted TEE - Female & Male Cohorts										Adjusted BEE and Adjusted BEE _{TEE}										
Age	N		mean Age		Adjusted TEE		N		mean Age		Adjusted BEE		N		mean Age		Adjusted BEE _{TEE}			
	F	M	F	M	mean	sd	mean	sd	F	M	mean	sd	mean	sd	mean	sd	mean	sd		
(0,0.5]	103	93	0.2	0.2	120.0	23.2	118.4	23.2	22	(111)*	0.2		100.47	33.89			86.03	28.9		
(0.5,1]	18	23	0.7	0.7	139.8	17.0	145.5	25.7	20	(88)*	0.9		142.89	11.62			115.47	9.2		
(1,2]	33	35	1.7	1.6	147.4	23.9	148.2	21.6	18	(86)*	1.6		142.02	13.52			111.94	9.6		
(2,4]	54	48	3.8	3.8	147.0	13.4	150.3	19.6	3	1	3.8	4.0	150.2	6.0	144.3	NA	108.6	7.4	100.7	NA
(4,6]	99	121	5.3	5.3	142.5	14.0	148.2	18.5	9	5	5.7	5.4	156.4	26.3	158.8	30.9	110.1	19.9	108.1	19.9
(6,8]	42	42	7.0	7.2	139.2	16.7	143.2	13.6	18	12	7.2	7.4	136.9	25.8	141.9	21.8	94.6	17.7	94.6	15.1
(8,10]	79	75	9.1	9.1	132.8	19.2	140.2	18.7	22	16	9.2	9.5	130.0	23.4	137.3	21.8	87.2	15.2	88.8	14.2
(10,12]	68	34	11.1	11.0	122.0	23.4	133.4	16.3	5	5	11.1	11.1	128.3	19.9	126.3	21.2	82.6	12.3	81.8	15.0
(12,16]	229	128	14.4	14.5	113.1	22.9	118.9	21.4	18	16	14.4	13.9	103.1	18.6	130.0	23.3	64.9	12.2	82.4	15.7
(16,20]	209	103	18.3	18.4	107.1	14.4	113.3	17.1	155	148	18.5	18.9	97.5	12.9	109.3	7.5	60.2	8.1	62.9	5.3
(20,25]	252	123	23.2	23.5	100.6	15.5	106.7	21.9	135	116	23.4	23.8	98.3	10.5	99.6	8.1	60.6	7.1	57.0	5.2
(25,30]	280	182	27.8	28.0	100.5	15.3	102.0	21.2	115	104	27.9	27.9	100.8	11.5	104.0	13.4	62.5	7.8	59.6	8.3
(30,35]	235	146	33.0	32.8	100.0	11.9	100.7	16.5	96	94	33.2	33.1	98.7	9.7	103.3	10.4	60.9	6.3	59.7	7.0
(35,40]	231	165	38.0	38.0	100.0	11.9	102.3	16.3	112	110	38.1	38.2	99.7	10.2	101.6	11.7	61.4	6.9	59.1	7.2
(40,45]	301	165	42.8	42.9	101.3	12.6	100.8	13.2	100	96	42.9	42.6	99.8	10.4	102.9	9.1	61.6	6.9	59.7	6.1
(45,50]	171	144	47.4	47.8	102.0	12.4	100.5	14.3	42	41	47.3	48.1	99.0	14.7	108.1	14.6	61.4	9.6	62.7	8.9
(50,55]	105	93	52.8	52.6	100.5	11.4	100.8	13.2	33	33	53.1	53.4	96.1	9.1	103.1	9.2	59.8	5.5	60.3	5.9
(55,60]	111	76	58.2	57.8	102.2	11.7	102.9	20.0	23	23	58.1	57.5	100.3	9.5	100.0	7.1	62.5	6.1	57.9	4.5
(60,65]	252	90	63.2	63.2	98.8	12.4	99.8	15.3	23	21	62.4	63.1	99.5	12.8	99.2	8.5	62.6	8.3	58.3	5.2
(65,70]	387	90	68.0	68.0	97.6	10.9	94.4	11.1	40	40	68.0	68.7	91.0	8.6	95.2	7.6	56.9	5.9	56.4	4.8
(70,80]	681	232	75.1	75.4	93.9	12.1	90.6	14.6	188	173	75.2	75.4	86.8	9.9	86.4	12.9	55.2	6.6	51.5	8.0
(80,90]	149	66	83.6	84.2	87.6	12.2	82.8	13.0	47	38	84.1	84.0	86.5	16.0	78.6	10.8	55.3	10.8	47.6	6.8
(90,100]	22	8	94.4	94.0	73.2	12.4	76.0	9.6	14	5	94.9	94.0	91.2	19.1	94.8	14.6	57.1	12.9	57.3	8.6

868 **Table S4.** Segmented Regression Analyses

adjTEE	Segments				Break Points		
	<i>beta</i>	<i>SE</i>	<i>CI_lower</i>	<i>CI_upper</i>	<i>Estimate</i>	<i>CI_lower</i>	<i>CI_upper</i>
	84.70	7.15	70.69	98.71	0.69	0.61	0.76
	-2.77	0.07	-2.91	-2.63	20.46	19.77	21.15
	-0.02	0.02	-0.07	0.03	62.99	60.13	65.85
	-0.68	0.06	-0.79	-0.57			

adjBEE	Segments				Break Points		
	<i>beta</i>	<i>SE</i>	<i>CI_lower</i>	<i>CI_upper</i>	<i>Estimate</i>	<i>CI_lower</i>	<i>CI_upper</i>
	75.51	5.59	64.55	86.46	1.04	0.94	1.14
	-3.75	0.22	-4.17	-3.33	18.00	16.82	19.18
	0.02	0.05	-0.07	0.12	46.46	40.57	52.35
	-0.45	0.04	-0.53	-0.37			