LETTER

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Metabolic acceleration and the evolution of human brain size and life history

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Humans are distinguished from the other living apes in having larger brains and an unusual life history that combines high reproductive output with slow childhood growth and exceptional longevity[1]. This suite of derived traits suggests major changes in energy expenditure and allocation in the human lineage, but direct measures of human and ape metabolism are needed to compare evolved energy strategies among hominoids. Here we used doubly labelled water measurements of total energy expenditure (TEE; kcal day^{-1}) in humans, chimpanzees, bonobos, gorillas and orangutans to test the hypothesis that the human lineage has experienced an acceleration in metabolic rate, providing energy for larger brains and faster reproduction without sacrificing maintenance and longevity. In multivariate regressions including body size and physical activity, human TEE exceeded that of chimpanzees and bonobos, gorillas and orangutans by approximately 400, 635 and 820 kcal day^{-1}, respectively, readily accommodating the cost of humans' greater brain size and reproductive output. Much of the increase in TEE is attributable to humans' greater basal metabolic rate (kcal day^{-1}), indicating increased organ metabolic activity. Humans also had the greatest body fat percentage. An increased metabolic rate, along with changes in energy allocation, was crucial in the evolution of human brain size and life history.

Variation in life history reflects evolved differences in energy expenditure. Each organism must allocate its available metabolic energy, which is largely a function of body size, to the competing needs of growth, reproduction and maintenance, resulting in fundamental trade-offs among these vital tasks[2–5]. For example, species that reproduce faster than expected for their body mass generally have shorter maximum lifespans, as energy is directed towards reproductive output and away from maintenance[2–5]. Among primates, this trade-off framework has been expanded to consider the energy needed to grow and maintain large brains[6,7].

In this light, humans present an energetic paradox. Humans in natural fertility populations reproduce more often, and produce larger neonates, than any other living hominoid, yet humans also have the longest lifespans and the largest, most metabolically costly brains[1] (Extended Data Fig. 1). This uniquely human suite of derived, metabolically costly traits suggests a lifting of energetic constraints in the hominin lineage, but the critical underlying mechanisms remain largely unknown. Some have hypothesized that a reduced gut[8] or increased locomotor efficiency[9] provided the extra energy needed for brain expansion. However, phylogenetically informed analyses suggest that gut reduction is insufficient to explain increased human brain size[1], and, although human walking is more economical[10], traditional hunter–gatherers travel so much farther per day[11] that their daily ranging costs are no lower than wild chimpanzees' (Supplementary Discussion and Supplementary Table 1). Similarly, provisioning of young offspring and their mothers helps to shorten human inter-birth intervals and increase the pace of reproduction[1], but reproduction remains relatively costly for human mothers (Supplementary Discussion, Supplementary Fig. 1 and Supplementary Table 2). Furthermore, it is unclear whether food sharing or other dietary changes are sufficient to fuel larger brains, larger neonates and longer lifespans without an acceleration in metabolic rate to harness increased energy acquisition.

Here, we test the hypothesis that humans have evolved an accelerated metabolic rate and larger energy budget, accommodating larger brains, greater reproductive output and longer lifespans without the expected energetic trade-offs. Increased TEE (kcal day^{-1}) has previously been discounted as an explanation for the human energetic paradox[1,8], in part because human basal metabolic rate (BMR; kcal day^{-1}) is broadly similar to that of other primates[8,11]. However, variation in TEE and BMR among humans and the great apes, our closest evolutionary relatives, is largely unstudied. Lacking sufficient data on TEE and BMR in apes, previous analyses have been unable to compare metabolic rates across the entire hominoid clade and test for metabolic acceleration in humans.

We used the doubly labelled water method[12] to measure TEE in mixed-sex samples of adult chimpanzees (*Pan troglodytes*; $n = 27$), bonobos (*Pan paniscus*; $n = 8$), Western lowland gorillas (*Gorilla gorilla*; $n = 10$) and orangutans (*Pongo* spp.; $n = 11$), and compared these data to similar measures of TEE in a large, adult human sample[13] (*Homo sapiens*; $n = 141$); this method also provides a measure of body composition (Methods and Table 1). TEE was measured over 7–10 days while individuals followed their normal daily routine. We also compared published measurements of BMR in humans, chimpanzees and orangutans, and we estimated daily locomotor energy expenditure and BMR for adults in our TEE sample to assess their contribution to variation in TEE. Comparisons were performed at the genus level, both to avoid the issue of close phylogenetic relatedness for chimpanzees and bonobos, and because no metabolic differences were apparent between these two species.

Humans exhibited greater TEE than other hominoids, with larger daily energy budgets than all apes except adult male gorillas

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Table 1 | Age, body size and composition, and TEE

Genus	Sex	*n*	Age (years) (s.d.)	Mass (kg) (s.d.)	FFM (kg) (s.d.)	Body fat* (%) (s.d.)	TEE† (kcal day^{-1}) (s.d.)	BMR‡	Walk and climb‡
Homo	Female	76	33.5 (6.0)	80.1 (19.8)	46.1 (7.4)	41.1 (7.1)	2,190 (381)	1,474	183
	Male	65	32.6 (5.4)	73.8 (15.2)	56.1 (7.9)	22.9 (7.6)	2,721 (569)	1,640	226
Pan	Female	17	25.8 (11.3)	46.4 (8.1)	43.3 (7.8)	9.0 (5.5)	1,722 (363)	1,214	102
	Male	18	22.3 (10.7)	57.9 (13.4)	53.8 (11.7)	8.4 (4.9)	2,145 (546)	1,401	120
Gorilla	Female	6	19.7 (4.1)	73.7 (7.3)	63.3 (7.0)	13.9 (6.4)	2,030 (527)	-	110
	Male	4	24.5 (11.7)	166.4 (42.5)	148.3 (27.0)	15.2 (4.6)	3,630 (839)	-	253
Pongo	Female	5	27.6 (5.3)	58.2 (4.0)	44.3 (2.5)	23.4 (8.8)	1,476 (268)	984	88
	Male	6	20.0 (10.8)	76.7 (34.1)	62.4 (23.3)	16.4 (8.6)	1,617 (289)	1,090	163

s.d., standard deviation.
*Excludes $n = 6$ *Pan* subjects with negative calculated body fats (Methods).
†Calculated for *Pan*, *Gorilla*, and Pongo using equation 7.17 in ref. 12.
‡Estimated BMR and locomotion costs were calculated from body mass and daily activity (Methods).

(Table 1). Fat-free mass (FFM) explained 34% of the variance in TEE ($t(195) = 10.18$, $r^2 = 0.34$, $P < 0.001$; Fig. 1 and Supplementary Table 3). Differences among genera accounted for an additional 27% of the variance in TEE, with humans having the highest TEE, followed in order by *Pan*, *Gorilla* and *Pongo* ($P \leq 0.001$ for all comparisons; Fig. 1 and Supplementary Table 3). For comparison, mean FFM was similar for *Homo*, *Pan* and *Pongo* cohorts, yet mean human TEE was ~27% greater than *Pan* and ~58% greater than *Pongo*. Body fat was weakly, negatively correlated with TEE ($\beta = -0.04 \pm 0.02$, $P = 0.02$); age ($P = 0.70$) and sex ($P = 0.26$) were not significant covariates in TEE models including FFM, fat mass and genus (Supplementary Table 3). Results were robust across different models for calculating TEE from isotope enrichment (Supplementary Table 3).

Together, BMR and daily locomotor expenditure accounted for much of the variation in TEE among genera. The mean estimated daily energy cost of walking and climbing among apes in our sample was similar across genera and ~100 kcal day^{-1} below estimated daily walking cost in our human sample (Table 1). Our analyses of published measurements[14–16] indicate that BMR is lower in *Pan* than in comparably aged humans, in analyses controlling for sex, age and body mass ($P < 0.001$; Methods and Extended Data Fig. 2). The few measurements of *Pongo* BMR[16,17] appear to be lower still (Extended Data Fig. 2); no data for the *Gorilla* BMR are available. For cohorts in the TEE data set, estimated BMR for *Homo* was ~200 kcal day^{-1} greater than *Pan* and ~500 kcal day^{-1} greater than *Pongo* (Table 1). Estimated physical activity levels (PALs: TEE/estimated BMR; see Table 1), were similar across genera (*Homo*: female 1.5, male 1.7; *Pan*: female 1.4, male 1.5; *Pongo*: female 1.5, male 1.5), indicating that organ activity contributed more than physical activity to variations in TEE.

Body fat percentage, measured from isotope dilution[12], was markedly higher in humans than other hominoids in our TEE sample, and only humans exhibited a significant sex difference (Table 1). Body fat percentage was remarkably low for *Pan*, consistent with measures from dissection[18], and somewhat higher for *Gorilla* and *Pongo*. Indeed, body fat percentages for captive apes were comparable to, or even below, average body fat percentages for humans in physically active, traditional hunter–gatherer populations[19].

Together, these results indicate substantial metabolic evolution across the hominoid clade and a previously uncharacterized diversity in TEE, BMR and body fat percentage (Fig. 2). For a given FFM, humans have greater TEE, BMR and fat mass than other hominoids. Chimpanzees and bonobos have the next largest energy budgets but carry the least amount of body fat. Gorillas have lower TEE and greater body fat than *Pan*. Orangutans have exceptionally low TEE and BMR, and fat percentages similar to gorillas (Table 1).

Comparisons of BMR and TEE indicate that hominin brain and life history evolution were fuelled in large part by increased mass-specific organ metabolic rates (kcal g^{-1} h^{-1}), and not solely through anatomical or physiological trade-offs. BMR reflects the summed metabolic activity of the organs at rest and is largely shaped by organs with high mass-specific metabolic rates such as the brain, liver and gastrointestinal tract[20]. If, as assumed in previous studies, organ-mass-specific metabolic rates were similar across hominoids, then humans and apes with the same FFM should have similar BMRs — the cost of humans' larger brain offset by a reduced gastrointestinal tract[8]. Instead, BMR and TEE are substantially greater for humans, controlling for FFM (Table 1, Figs 1, 2 and Extended Data Fig. 2), indicating an evolutionary increase in the metabolic activity of at least some organ systems. Humans' greater BMR and TEE could readily accommodate the marginal cost of increased reproductive output, estimated at ~130 kcal day^{-1} over the course of a woman's reproductive career in natural fertility populations (Supplementary Discussion, Supplementary Table 2 and Supplementary Fig. 3). Greater metabolic activity could also support humans' derived brain metabolism[21] and increased somatic maintenance and longevity[1], but more comparative analyses are needed to identify specific mechanisms and associated metabolic costs.

Analysing relatively sedentary human and ape populations allowed us to compare cohorts with similar FFMs, PALs and locomotor expenditures (Table 1), but the pattern of TEE, BMR and body composition variation among genera is expected to hold across more physically active populations. When controlling for body size, TEE is remarkably consistent across populations within a species, regardless of activity level[22]: traditional hunter–gatherers have similar size-corrected TEEs to people living in cities[19], and zoo-housed populations of primates and other mammals are similar to their counterparts in the wild[22–24]. Humans in traditional foraging and farming populations and apes in the wild will generally have lower body fat percentages[19] than the cohorts in the TEE sample (Table 1), but again the pattern of differences seen here is expected to persist: even in captivity,

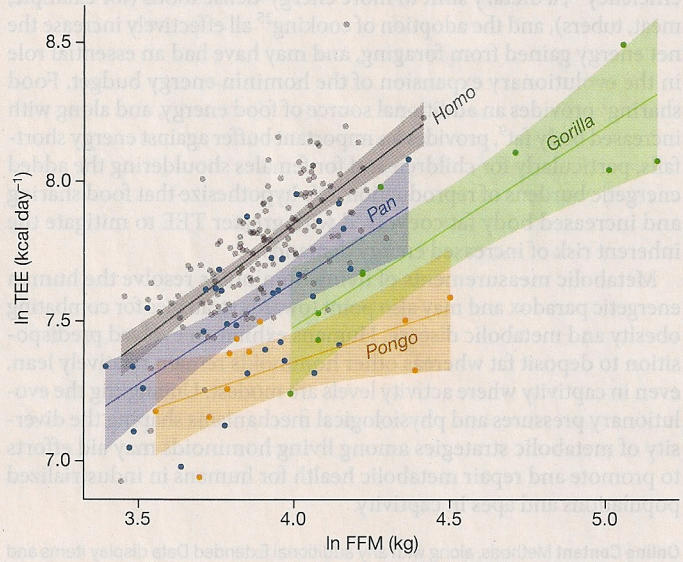

Figure 1 | TTE and FFM for hominoids. Humans (*Homo*, grey, $n = 141$), chimpanzees and bonobos (*Pan*, blue, $n = 35$), gorillas (*Gorilla*, green, $n = 10$), and orangutans (*Pongo*, orange, $n = 11$). Lines and shaded regions indicate least squares regressions and 95% confidence intervals for each genus. TEE for *Homo* exceeds other genera in a general linear model accounting for FFM, fat mass and other variables ($P < 0.001$; Table 1 and Supplementary Table 3).

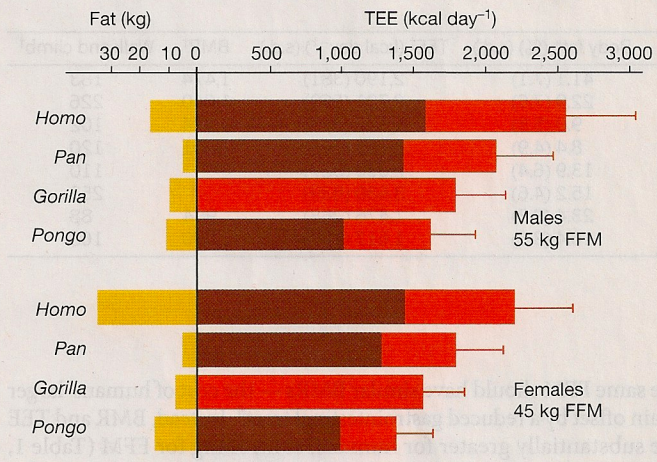

Figure 2 | Predicted TEE, BMR and fat mass for adult hominoids. Values are estimated for males (55 kg FFM) and females (45 kg FFM), using the same FFM across genera. TEE (red bars) is estimated from FFM, fat mass and genus using model C in Supplementary Table 3; error bars represent model standard error. BMR (darker red regions) is estimated from body mass (Methods and Extended Data Fig. 2); no BMR data are available for *Gorilla*. Fat mass (yellow bars) is calculated from FFM using body fat percentages in Table 1.

body fat percentage in *Pan* is remarkably low and fat percentages for *Pongo* and *Gorilla* fall near the very lowest ranges for healthy, physically active human populations[19].

Expansion of the hominin energy budget challenges current models of life history and brain evolution predicated on metabolic stasis and constraint[1,2,5–9]. Evolved increases in BMR and TEE do not diminish the importance of gut reduction, efficient walking, dietary change and maternal provisioning in the hominin lineage, but rather place these critical adaptations within a different energetic framework. Increased TEE exposes individuals to a greater likelihood of energy shortfalls, providing strong selection for behavioural and anatomical adaptations to mitigate this risk. Gut reduction[8] allows for greater energy allocation to reproduction and maintenance (including larger brains) while limiting the increase in BMR and TEE. Improved walking efficiency[10], a dietary shift to more energy-dense foods (for example, meat, tubers), and the adoption of cooking[25] all effectively increase the net energy gained from foraging, and may have had an essential role in the evolutionary expansion of the hominin energy budget. Food sharing[1] provides an additional source of food energy, and along with increased body fat[9], provides an important buffer against energy shortfalls, particularly for children and for females shouldering the added energetic burdens of reproduction. We hypothesize that food sharing and increased body fat coevolved with greater TEE to mitigate the inherent risk of increased energy demands.

Metabolic measurements of living hominoids resolve the human energetic paradox and may also point towards strategies for combating obesity and metabolic disease. Humans exhibit an evolved predisposition to deposit fat whereas other hominoids remain relatively lean, even in captivity where activity levels are modest. Untangling the evolutionary pressures and physiological mechanisms shaping the diversity of metabolic strategies among living hominoids may aid efforts to promote and repair metabolic health for humans in industrialized populations and apes in captivity.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Supplementary Information is available in the online version of the paper.

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