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Evolutionary origins of obesity

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Summary

Although it appeared relatively suddenly, the current obesity epidemic – largely manifest in industrialized societies but now spreading to the rest of the world – is the result of interaction between human biology and human culture over the long period of human evolution. As mammals and primates, humans have the capacity to store body fat when opportunities to consume excess energy arise. But during the millions of years of human evolution such opportunities were rare and transient. More commonly ancestral hominins and modern humans were confronted with food scarcity and had to engage in high levels of physical activity. In tandem with encephalization, humans evolved elaborate and complex genetic and physiological systems to protect against starvation and defend stored body fat. They also devised technological aids for increasing energy consumption and reducing physical effort. In the last century, industrialization provided access to great quantities of mass-produced, high-calorie foods and many labour-saving and transportation devices, virtually abolishing starvation and heavy manual work. In the modern obesogenic environment, individuals possessing the appropriate combination of ancestral energy-conserving genes are at greater risk for overweight and obesity and associated chronic diseases.

Keywords: Energetics, hominins, human evolution, primates.

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Introduction

An epidemic of obesity has gripped industrial nations and is rapidly spreading to less developed countries (1–3). The ultimate cause of this epidemic is a series of biological and cultural adaptive responses to energy scarcity during the long course of human evolution (4) which operate today in an environment of energy abundance. Recent technological and economic developments in the industrial world created the modern obesogenic environment which is being adopted by the rest of the world as well. The World Health Organization predicts a 'globesity' epidemic (5).

The biological adaptations consist of the genetic and neurophysiological components of a complex metabolic system for accumulating and defending energy stores. Increasing energy needs for maintenance, physical activity and fertility were met with increasing energy efficiency (6–10) in a series of energetic transitions which maximized dietary quality and flexibility and minimized the effort to acquire nutrients. While some ancient hominin groups were eventually unable to balance their energy budgets and became extinct (11), the ancestors of modern humans survived the rigours of the past by exploiting new foods, developing effective food processing technologies and evolving an efficient metabolic system that protected against starvation while providing the energy required by the extraordinarily large human brain. This review of human evolutionary energetics aims to complement the rapidly growing appreciation of human energy-conserving biology and its interaction with the modern toxic environment to generate the globesity epidemic.

Our genetic legacy

While two-thirds of Americans are overweight or obese, the rest are of normal, healthy weight. Body mass variation is now known to have a large genetic component, with heritability estimates ranging from 30% to 70% (12). The

majority of Americans seem to possess some combination of obesity-susceptibility genes, while the rest are relatively resistant to overweight or obesity despite living in the same obesogenic environment. The genetic component of variations in body mass became evident only after development of the modern, post-World War II environment and the sudden onset and increase of obesity rates in the USA and other industrialized nations. Today it is also becoming evident among populations in less developed societies.

More than 40 years ago, James Neel (13,14) proposed that a 'thrifty genotype' had evolved to protect human populations from starvation by facilitating quick release of insulin, efficient conversion of sugar, and storage of excess energy as body fat during exceptional times of food abundance. While stored fat served as an energy reservoir during times of famine, in the modern commercialized world of continuous and ubiquitous food abundance and persistent physical inactivity, the energy conserving function of these genes has become a liability by promoting continuous fat storage, high rates of obesity, overproduction of insulin, and development of insulin resistance and diabetes mellitus – the modern 'diabesity' epidemic (15,16).

Today there is overwhelming evidence for the heritability of adiposity and obesity levels. Studies of monozygotic twins showing greater within-pair correlation of weight gain and lipoprotein levels after overfeeding than between-pair similarities strongly support a genetic component in obesity (17,18), as does the finding that adiposity levels and body fat distributions are more similar in monozygotic than dizygotic twins (19).

Over a decade of studies examining the human genome have produced the Human Obesity Gene Map (20). To date, 253 quantitative trait loci (QTL) and 135 candidate genes associated with obesity phenotypes have been identified. Every human chromosome except Y contains one or more of these loci. Identification of specific gene combinations and their interactions with environmental factors is still needed, but recent advances have begun to elucidate these linkages in the determination of obesity risk.

Several major genes contribute to obesity by disrupting the hypothalamic pathways controlling satiety and food intake (21). These include the very rare *LEP* and *LEPR* genes and the somewhat more common *MC4R* gene. The most common forms of obesity, however, are polygenic in origin and are associated with biological functions such as energy expenditure, lipid and glucose metabolism, adipose tissue development, and inflammation (12,22–25). Some recently identified genes are involved in complex gene–gene and gene–environment interactions (24–30).

Genetic factors have also been found to be associated with physical activity levels (31–35). Spontaneous physical activity is negatively associated with weight gain and least influenced by volition (36,37). The Human Gene Map for Performance and Health-Related Fitness Phenotypes locates 165 autosomal genes and QTL, five X-chromosome genes, and 17 mitochondrial genes associated with various forms of physical activity or inactivity (38).

Factors related to thinness are also influenced by genes (39). These include high metabolic rates, a decreased preference for high-fat, high-carbohydrate foods, and effective satiety processes. A β_2-adrenoceptor haplotype was associated with lower body mass index and percentage body fat in Swedish women (40). Loos *et al.* (41) found two variants in the Agouti-related protein gene that are associated with lower fat and carbohydrate intake. And weight loss interventions had more favourable prognoses in individuals with specific genotypes (42).

The precise evolutionary origin of these and other genes associated with energetics and body mass is unknown. But recent developments in comparative genomics can be expected to provide such information. Several genes influencing human brain development evolved rapidly after evolutionary divergence from other hominoids (43). The HAR1F gene expressed in the human neocortex during fetal development, evolved rapidly, with 18 substitutions accumulating in the human lineage since the human-chimpanzee common ancestor (44). Continuing work to compare human and non-human primate genomes will produce similar results for the evolution of human obesity-promoting genes.

As brain development involves phospholipids-associated organization of synapses, it is not unreasonable to consider that genes promoting greater energy efficiency may have co-evolved with those influencing evolution of the large human brain (45). If co-evolution is shown to be the case, the current obesity epidemic may constitute one price humans have had to pay for their remarkable cognitive abilities.

The primate prologue

Humans belong to the Order Primates, a mammalian taxon noted for its eclectic diets. In contrast to more specialized carnivores or herbivores, primates seek out a variety of nutrient-dense, high-quality foods to support their active lives, relatively large brains, and long gestation and lactation periods (10,46). Similarities in adiposity, metabolism and genetics of obesity (47–50) reflect the common evolutionary ancestry of humans and other primates.

Humans and their closest relatives, the African and Asian great apes, are the extant descendants of a once very large and diverse group of forest-dwelling hominoid species which lived during the Miocene Epoch 23–5 million years ago (51). By the end of the Miocene, global climatic changes had reduced the once continuous tropical forest cover extending over much of Africa, Asia and Europe to patches interspersed with woodlands, grassy savannas and deserts. The loss of their natural habitat and growing com-

petition with monkey species which thrived in this novel environment brought an end to the Age of Apes. The few survivors, including the last common ancestor of humans and the African great apes, took refuge in the remaining forests and relied on a diet of energy-rich fruits and diverse forest vegetation.

The first primates had appeared more than 40 million years ago as descendants of small terrestrial insectivorous mammals. They adopted an arboreal life and a diet of fruits, tree gum, flowers, nectar, seeds and foliage to supplement the protein-rich insects they preyed upon in the treetops (10,52). Extant prosimians, the direct descendants of these early primates, continue these dietary habits. The smallest prosimians are virtually exclusive insect-eaters, obtaining most of their food energy from protein (53).

Monkeys and apes, also descendants of those early prosimians, prefer a diet of young leaves and fruits (54). These high-quality foods provide plant proteins and simple carbohydrates but little indigestible fibre and plant toxin. Small amounts of animal foods – insects, grubs, eggs, birds, small mammals – add protein and fat to the diet (55).

Some monkey species are endowed with specialized digestive tracts to accommodate low-quality mature leaves, which are difficult to digest but are more readily available than the preferred plant foods. Leaf-eating monkeys have sacculated stomachs with special fermentation chambers for bacterial breakdown of cellulose to produce energy-rich carbohydrates (56). Gorillas and orangutans, the largest of the great apes dependent on leafy diets, possess long colons constituting almost half the entire volume of their digestive tracts (57,58) for slow food passage and maximum nutrient absorption. They slowly digest and ferment fibrous leaves, bark, pith, stems and shoots of various plants, which they eat in huge quantities throughout the day. In order to aid digestion and conserve energy, gorillas move slowly through their territory and rest often, gently playing, grooming each other, and napping. Because of the lack of edible fruits at high altitudes, the diet of mountain gorillas consists almost entirely of herbal vegetation and is even more limited than that of gorillas living at lower altitudes, where fruit, aquatic vegetation, insects and earthworms are available, but unevenly dispersed (59,60).

Chimpanzees and bonobos are the great apes genetically most similar to humans. They consume richer, more easily digested foods and avoid extremely fibrous plants and fruits or stashed then as wadges in the cheek until every bit of juice and pulp has been extracted. The remaining fibrous mass is spit it out (61). Chimpanzees are smaller and more active in their food search than gorillas because of the patchy distribution of fruit, their preferred food, and they more often include animal protein in their diets. Although plants are their primary source of protein (10,62), adult males hunt singly or in groups to aggressively pursue and capture small mammals such as bushpigs, bushbucks and monkeys (61,63). As much as 5% of the diet of common chimps consists of meat from red colobus monkeys and small African antelopes (64). From such small animals a chimpanzee can derive as much protein and fat as from 3000 of the figs that are its main carbohydrate source (65). Meat is a highly prized but rarely eaten food, densely packed with essential nutrients and fats. Unlike more readily available fruits and vegetables, it also has an important social function. It is the only food that is regularly shared with others or bartered for future cooperation and support (64).

Bonobos, the very rare chimpanzees of central Africa, have not been observed to hunt, but they are opportunistic meat eaters (66,67). They share the common chimpanzees' taste for meat but seem to lack the aggressive drive to pursue prey. Perhaps because their rainforest environment provides more fruit and tender terrestrial vegetation as well as grubs and other small protein sources than the typical chimpanzee habitat, they have no need to hunt.

Insects and nuts also provide protein, but require special skills to exploit. Adult female chimpanzees are highly skilled in using tools in their quest for termites and ants, from which they obtain significant amounts of fat and protein (61,68). They carefully prepare fishing wands by removing leaves from a twig or by breaking a strong grass stem to the appropriate length. Dipping their tools into a termite mound or anthill, they quickly strip off the clinging insects with hands and lips and pop them into their mouths. Tools also aid in cracking open nuts that are too hard to be opened with teeth and jaws. Wild chimps in the Taï Forest of western Africa prepare an anvil (a large rock, log, or branch), find an appropriate hammer (a stone or piece of wood), collect a supply of nuts and crack them open one after another (63). Chimpanzees seem to crave variety, eating a large number of different plant foods – 184 vegetable foods from 141 species of trees and other plants at the Gombe Reserve (61). Of these foods, about half are fruits and a fourth are leaves. On any given day, an individual chimp eats an average of 13 different food types.

Monkeys and apes expend a great deal of energy in their constant quest for high-energy food (69–71), spending as much as 30% of each day in their search. As food sharing is rare and food storage unknown, they forage individually every day. Even recently weaned youngsters can count on their mothers to do no more than lead them to appropriate food sources. Gorillas virtually live within their larder and readily find plenty of edible vegetation on the ground and in trees, but they have to travel to fresh food sources after exhausting the supply in one area (72,73). Lowland gorillas travel more than 1 kilometer per day and venture even farther when they know that fruit is available. The fruits preferred by chimpanzees, while higher in nutrient quality than leafy vegetation, mature intermittently and are also

more unevenly and widely dispersed (65,70). Chimpanzees know when and where to find ripe fruit and travel considerable distances to feeding sites, spending less time in their search when plenty of ripe fruit is available, but more when forced to rely on leafy fallback foods (69). The Gombe chimpanzees trek one to 5 kilometers per day in search of food, and spend 35% to 65% of their day feeding (61). Chimpanzee travel involves climbing trees and other strenuous activities such as brachiation, leaping and quadrupedal knuckle-walking for long distances. And occasionally energetic displays and attacks are necessary to defend food sources from intruders and competitors (74). In general, the caloric return for physical effort is low for most monkeys and apes. Nutritional stress indicators such as linear enamel hypoplasia are not infrequent in chimpanzees and other primates (75–77).

While the normal optimum body composition for most mammals includes 5% body fat, primates have the potential for greater energy storage and the development of unique subcutaneous and abdominal fat depots, both of which increase disproportionately with adiposity through adipocyte proliferation (78). Primates also manifest sexual dimorphism in body composition (79). A rare longitudinal study of captive baboons (80) revealed that sex differences in skinfold thicknesses appear early and become more pronounced during development. Adult male baboons weigh twice as much as females, but females have thicker subcutaneous adipose tissue deposits at the neck, suprailiac and triceps sites. Energy storage supports the high cost of primate reproduction, which involves extended periods of gestation, lactation and transporting of youngsters (70). For highly endangered, wild great apes, energy availability is crucial to their survival. All great apes have low fertility rates (81), which are severely limited by low-energy return for the physical exertion of foraging.

Even though they eat almost continuously, wild chimpanzees and gorillas do not become obese (6). Primates are susceptible to obesity in captive environments, however (82). Captive monkeys and apes which do not have to forage and whose physical activity is severely constrained may become obese and develop metabolic abnormalities and comorbidities such as cardiovascular disease and diabetes mellitus (83–86).

A study of 53 species of anthropoid primates found that some species of captive animals, such as orangutans, weighed more than non-captive (wild) ones, although others manifested little weight difference (87). Captive gorilla females were heavier than wild females, possibly because of richer diets and lower activity levels. Dissection of four adult captive lowland gorillas documented the consequences of inactivity in captivity (88). One of the four was an old, obese female with hip arthritis that left her relatively immobile. She had half the muscle mass and twice the adipose tissue of the other three.

When food is abundant, even some wild primates can become obese. Wild baboon females with access to garbage dumps averaged 50% greater body mass, and had 23.2% body fat compared with 1.9% for their wild-feeding counterparts (89). Linear dimensions were the same in the two groups, but skinfolds and upper arm circumferences were significantly greater in the privileged females. Not only did the garbage dump promote greater energy intake, but it also reduced energy expenditure associated with foraging. One group of wild garbage-eating baboons was found to have elevated levels of low-density lipoprotein and insulin, but did not manifest cardiovascular disease or diabetes (90).

Orangutans are mainly frugivorous and travel widely through their territories in search of this scarce, high-energy food. On the rare occasions of mast fruiting, when large amounts of fruit ripen simultaneously and contain more calories and less fibre than usual, orangutans gorge on fruit instead of eating their usual variety of leaves, bark and some fruit (91). Calorie consumption more than doubles during this time, and they develop fat deposits. Urine analysis during subsequent fruit-poor times indicates the presence of ketones, byproducts of lipid breakdown and utilization of energy reserves. Bonobos, chimpanzees and gorillas apparently do not have such a pronounced fat storage mechanism (6). Fat accumulation in orangutans seems to be an adaptation to periodic food scarcity and is linked to the long gestation period and extremely slow development of orangutan infants who depend on maternal lactation for many years.

Temporary fattening also occurs during the reproductive cycle of some male primates which become fattened before the breeding season (92,93) and have more mating opportunities than their thinner competitors. The stored energy sustains their competitive mating efforts during a period when feeding has low priority. The extra fat is lost during the breeding season.

Variety and flexibility are common to diets of both humans and their primate relatives. A preference for sweet, carbohydrate-rich fruits as well as for highly prized but rare, nutrient-rich meat is shared by humans and some non-human primates. Like other primates, humans have the potential to store energy and develop subcutaneous and abdominal adipose tissue deposits, but apes have little opportunity to do so because of their high activity levels and the relatively high energetic costs of reproduction. Human fat depots are unique in their size and distribution, especially among females whose breast, hip and thigh subcutaneous depots are mobilized for pregnancy and lactation (94). Retention of these depots is greater than the more metabolically active abdominal fat reserves predominating in males. Thus, humans in general and human females in particular have a selective advantage over non-human primates in the ability to store, retain and utilize energy reserves for reproduction.

The hominin heritage

During the hominoid extinction of the Late Miocene Epoch, an African hominin group diverged from the dwindling hominoid stock to establish the human lineage that evolved through the Pliocene and Pleistocene Epochs (95). Except for one outstanding feature, these early hominins resembled their ape-like relatives and shared their forest habitats. While the ancestors of modern great apes continued to inhabit the forests, hominins eventually moved to open woodlands and savanna grasslands and adopted new dietary and activity patterns. Fossil remains of the earliest hominins include *Sahelanthropus tchadensis* from Chad dating to nearly 7 million years ago (96), 4.2-million-year-old *Australopithecus anamensis* from Kenya (97), and other gracile australopithecine species discovered in association with forest and woodland floral and faunal remains (98,99). Their diets consisted of a large variety of folivorous and frugivorous foods possibly supplemented with nuts, insects and small animals (100).

Habitual bipedality distinguished these early hominins (here collectively referred to as Australopithecines) from quadrupedal apes. A two-legged gait is slow in comparison with quadrupedal locomotion, but it is more energy-efficient than quadrupedal walking at the same speed (101,102), reducing energy needed for locomotion by as much as 35%. Bipedalization, indicated by the configuration of broad, short pelvis, fully extendable knees and arched feet with convergent great toes (103), was literally the first step in human energetic evolution, conserving locomotor energy for diversion to maintenance and reproduction. Early hominins retained curved finger bones and other skeletal features associated with arboreal climbing and brachiation for finding food and shelter in the trees. They subsisted on a variety of foods from multiple microenvironments, including hard, abrasive foods like nuts and seeds rich in vegetable fats (104).

Despite locomotor efficiency, Australopithecines had to expend more energy than modern apes in their wider search for food (105,106). Pronounced sexual dimorphism may have been their strategy to conserve energy and enhance reproductive fitness. Large males used their bulk and strength to defend against predators and compete with each other for mates, but the size of females was constrained by energetic needs for gestation, lactation and infant transport, much as in highly sexually dimorphic gorillas and orangutans (107). But unlike infant apes which cling to their mothers' body hair with prehensile feet, hominin infants were supported and carried by their mothers. The very recent discovery of a nearly complete fossil skeleton of a 3-year-old *Australopithecus afarensis* child (108) suggests another energy-conserving strategy. Delayed brain growth reduces daily requirements of this very energy-expensive tissue by extending the development period (109,110).

Two hominin genera descended from the Australopithecines – *Paranthropus* and *Homo* (98,111). The former, consisting of at least three exclusively African species, were stocky, robust and sexually dimorphic. Their unique megadont dentition is indicative of an extreme plant-based diet consisting of tough, gritty vegetation, hard seeds and nuts, and fibrous stems and roots. These food items were processed with massive, thickly enameled premolars and molars well adapted for crushing and grinding (112,113) and robust mandibles and large chewing muscles attached to sagittal crests. The diminutive incisors and canines of *Paranthropus* suggest that slicing foods and peeling fruits were not important dental functions (114), and the inverted cone-shaped rib cage of *Paranthropus* hints at a large, gorilla-like digestive system for processing great amounts of bulky, low-quality vegetation (115,116). *Paranthropus*, however, expanded the hominin diet to include a wide array of savanna plant items not consumed by apes or the earliest hominins.

Although archaeological evidence is sparse, *Paranthropus* probably used simple tools much like chimpanzees to retrieve termites and open nuts that were too hard to crack with even the most powerful chewing apparatus. Seeds and nuts contained vegetable oils and fats that provided essential energy for active hominins. Perhaps they also used digging sticks to uncover buried roots and tubers, something chimpanzees are unable to do. Such underground storage organs (117) are rich in carbohydrates and micronutrients and contain few toxins and little indigestible fibre.

Dental microwear patterns and bone isotope analyses (118) indicate that *Paranthropus* consumed at least some animal foods, possibly insects, grubs, eggs, and the flesh of birds and small animals, along with tough plant foods. *Paranthropus* species achieved a new level of dietary diversity but were forced to travel over greater distances in their food quest than forest-dwellers. As energy-efficient bipeds, they had several additional advantages over other woodland and savanna animals. Erect posture increased visibility over great distances, freed hands for carrying infants and food supplies, and minimized exposure to ultraviolet radiation (119). Stout bodies prevented excessive loss of body water in the tropical heat. Nevertheless, daily foraging for widely dispersed food and water sources and confrontations with savanna-dwelling predators must have had a high energetic cost. The distribution of subcutaneous adipose tissue, known to be more extensive in bipedal than in quadrupedal mammals (120), cannot be determined in any of the ancestral hominins. Despite the potential ability to do so, it is unlikely that *Paranthropus* had the opportunity to accumulate this energy reservoir. After more than 1 million years of survival on the African savanna, *Paranthropus* was no longer able to mobilize adequate energy for both body maintenance and reproduction on a largely plant-based diet. Linear enamel hypoplasia indicative of

nutritional stress has been identified in the dentition of both *Australopithecus* and *Paranthropus* species (121). *Paranthropus* became extinct without leaving descendants about 1 million years ago.

The palaeolithic pattern

The presence of a contemporary and sympatric hominin species probably also indirectly contributed to the extinction of *Paranthropus* (122). Resource competition with early *Homo* undoubtedly challenged the adaptive strategies of *Paranthropus*. Although no taller than its Australopithecine ancestor, *Homo* had a significantly larger brain than apes, *Australopithecus* or *Paranthropus* (95). The first fossil human, named *Homo habilis* by Leakey for its ability to manufacture and utilize stone tools for food processing, had developed a novel adaptation for improving dietary quality on the African savanna (123). Ancient animal bones with cut marks and fractures indicate that meat was sliced from skeletons, and limb bones were smashed to expose the fatty marrow inside (124). Cutting and crushing with stone tools softened foods, reduced stress on teeth, jaws and enhanced nutrient extraction. The stone tools were used to butcher animal carcasses abandoned by predators or obtained through power scavenging (125–127). Group collaboration enabled small humans to drive away dangerous predators such as saber-toothed cats to confiscate their prey (128). As among hunting chimpanzees, sharing the highly prized and nutritious meat may have sustained and promoted further cooperation and social behaviour (129).

Humans were socially and technologically better equipped than *Paranthropus* for the savanna foraging life and were more efficient energy procurers. Their small molar teeth with sharp cusps and thin enamel were not adapted for a diet of tough vegetation and hard seeds and nuts. Theirs were the teeth of true omnivores who intentionally and routinely consumed more animal foods than *Paranthropus* and thereby greatly enhanced their dietary flexibility and adaptive versatility in a mosaic of microenvironments and climatic fluctuations (130).

It is no coincidence that brain size expansion began with *Homo*. These early humans were able to tap the richest source of energy and nutrition available and complement their plant-based diet with significant amounts of animal protein and fat. Meat supplied all the amino acids, along with many essential vitamins and minerals (131) and must have given humans a tremendous energetic advantage over herbivorous hominins and apes (132). The meat and fat obtained with the aid of stone tools were rich sources of lipid energy and polyunsaturated fatty acids essential for encephalization (133).

The dietary innovations of early *Homo* prepared the way for its African descendant, *Homo erectus*. This long-lived human species, with an even larger brain, more modern body proportions, and a more sophisticated set of stone tools for food procurement and processing came to dominate the savanna almost 2 million years ago and persisted for more than 1.5 million years to witness the extinction of *Paranthropus*. *Homo erectus* tool makers produced bifacially flaked stone tools with sharp edges that were used for a variety of tasks, including butchery (123). The handaxe, a multipurpose tool with sharp edges and a pointed tip for cutting, scraping, smashing and digging was the hallmark of *Homo erectus* technology. It was designed for more efficient processing of meat and other animal products, some of it obtained by cooperative hunting of dangerous but high-yield game such as giant baboons or elephants.

These humans were significantly longer-legged than their predecessors. They had a great, energy-saving stride for extremely efficient walking and great endurance during the long distances covered in their food quest (134). Their foraging territories were many times larger than those of earlier hominins (135), and their estimated physical activity levels were significantly higher (136). The increased energetic cost of hunting and scavenging was offset by the high quality of meat and fat from the variety of ungulates that were readily available on the expanding savanna grasslands.

Homo erectus individuals were significantly taller and heavier than their predecessors. Female body size increased by 50%, effectively reducing the sexual dimorphism of earlier hominins (137). Increased body size is associated with larger *Homo erectus* neonates with larger brains, but infants were quite helpless at birth and completely dependent on adult care during their greatly extended period of post-natal brain development and growth (138). A larger developing fetus and a longer period of infant dependency increased total reproductive energy requirements for *Homo erectus* females, but slow development reduced daily energy needs (137,139). Significant amounts of animal protein and fat consumed by mothers and accumulation of large maternal fat stores buffered energy demands. It is likely that the sexually dimorphic pattern of human body composition originated with *Homo erectus* (94). This may also have been the origin of the relatively high level of human fetal adiposity. Human neonates have a higher proportion of body fat than all other mammals and continue to accumulate fat at a higher rate during infancy (140), protecting against disabling loss of muscle protein and supporting and protecting human brain development and functioning during periods of famine.

Homo erectus brains were larger than those of earlier hominins, both absolutely and relative to body size. Human brains require five times more energy than those of other mammals of the same size, and 20–25% of human metabolic energy is committed to brain function (105,136). The plant-based diets of apes and early hominins could not have sustained large-brained, physically active humans. A

more high-quality, meat-based diet provided adequate energy for muscular activity and brain functioning and also reduced the need for a large digestive system (7,88). This dietary shift changed the configuration of the rib cage from the funnel-shape of early hominins to the barrel-shaped rib cage associated with a shorter colon and longer intestine of modern humans.

In addition to its early stages, the life of *Homo erectus* was extended post-reproductively as well. Grandparents provided care, food and protection for growing children, helping to boost child survival and relieving mothers from the sole responsibility for child care (137,141). Like hunting and scavenging, successful child rearing required collaboration and cooperation by adult members of society, and was rewarded by higher fertility rates and population survival.

Homo solved the metabolic problem of sustaining a large body and brain through technology and meat consumption (115). Stone tools for dissecting and processing carcasses and the many bony remains of large animals are clear evidence for increased meat-eating by *Homo erectus*. Based on known consumption rates among contemporary foraging populations, human hunters ate up to 10 times more meat than chimpanzees and earlier hominins (135), who lacked the human level of collaborative hunting skills and sophisticated tools for capturing and butchering animals.

Eventually, *Homo* developed the use of fire for cooking and warmth (142). Remains of hearths, fireplaces and burned bones appear frequently in the archaeological record, suggesting that meat and probably also tubers and other vegetables were cooked. Heat destroys cell walls, making the tough more tender, the indigestible more accessible and the toxic more tolerable. Cooked foods are more palatable and digestible and thus higher in nutritional quality than raw items. Cooking also enhanced sociality. There may have been a division of labour in which some individuals ranged far to find food which they carried back to others. Perhaps elderly individuals who could no longer travel great distances became responsible for preparing and overseeing the sharing of cooked food among members of a family, including very young children who were unable to feed themselves. Much more than a simple cooking facility and source of warmth, the hearth may have been the place to rest and socialize, share food and stories and plan future activities (143).

A meat-based diet enabled some *Homo erectus* groups to emigrate from tropical Africa to Europe and Asia, where they were faced with a more variable climate and food availability (144). Seasons of cold and plant food scarcity forced them to subsist almost exclusively on meat and fat from wild game during part of the annual cycle. They were nomadic hunters and could not put food in storage or accumulate heavy supplies and equipment. Daily life in cold climates, carrying tools and children on long annual treks, and the hunting, butchering and transporting of game must have had a high energetic cost (145).

Homo had established an effective energetic system to maintain larger bodies and brains, support sustained physical activity in colder climates and increase fertility rates. Manufacture and use of Palaeolithic tools and control of fire, cooperative hunting, and collaborative child rearing required greater intellectual complexity and the learning of new skills (135). Early *Homo* had achieved an optimal level of foraging efficiency, obtaining more nutrients and energy at less energetic cost (146).

Contemporary humans (*Homo sapiens*) and Neanderthals (*Homo neanderthalensis*) descended from *Homo erectus*. Both followed the meat-based foraging strategy and used elaborate stone tool kits. In both species, brain size increased relative to *Homo erectus* without any further increase in body size (95).

Isolated from other human populations in Ice Age Europe, Neanderthals were the first humans to adapt to extreme arctic conditions as intelligent, active and successful hunters of large game which included reindeer, bear, mammoth, bison, horses and wild cattle (11,118). They produced a variety of sophisticated stone tools to work with wood and hides as well as animal carcasses, using the efficient Levallois technique to prepare stone cores before striking off flakes (123). Bone isotope analyses show that, like carnivorous predators of the highest level, their diet consisted mainly of meat, fat and marrow to meet the metabolic demands of their cold climate, highly active lifestyle and extreme phenotype (large brains, robust skeletons and heavy muscularity).

Their daily energy needs, estimated to be as high as 4000 calories, were extreme (11,147), and may have contributed to their ultimate demise after more than 250 000 years of survival in Europe and western Asia. When the European climate became even colder during the last glacial maximum, metabolic demands finally outstripped the ability to supply adequate energy for maintenance and reproduction, despite their use of caves, rock shelters and fire for protection and warmth. Large game animals, the primary food sources, had become more difficult to find. Neanderthals were forced to move to southern Europe and western Asia, their final habitats before they completely disappeared (148).

Nutritional stress among Neanderthals is indicated by a high prevalence of linear enamel hypoplasia and archaeological evidence for survival cannibalism among some groups (149–151). Human remains at cave sites in France and Spain have cutmarks and percussion scars that are identical to those on butchered animal bones. Unlike Neanderthal remains elsewhere which were deliberately buried in graves, these human remains had received the same treatment as bones of food animals and were left unburied.

Despite the stresses of their environment, the Neanderthals might have survived longer, perhaps even until the return of a warmer interglacial period, except for one additional challenge – the arrival in Europe about 40 000 years ago of the Cro-Magnons, anatomically modern humans. For nearly 10 000 years Neanderthals coexisted and competed with these immigrants for the increasingly scarce resources so essential to their survival. The newcomers possessed tall and slim physiques that betrayed their tropical African origins and scaled down their metabolic requirements. Demographic modelling of modern human and Neanderthal populations has shown that a very small disadvantage in mortality rates, less than 2%, could have led to total extinction of Neanderthals within 1000 years after the arrival of *Homo sapiens* (152). Neanderthal populations dwindled and finally disappeared without any trace of intergroup violence, leaving the world solely to modern humans.

The oldest fossil evidence of modern humans comes from Ethiopia and dates to 195 000 years ago (153). About 100 000 years ago, they began to emigrate to Asia, Europe to replace more ancient human populations, and finally made their way to Australia and the Americas. These Upper Palaeolithic peoples developed new hunting weapons, such as bows and arrows and long-handled spears and spear-throwers that enabled them to kill prey from a safe distance. Marine mammals and fish were caught with bone hooks and barbed harpoons and enriched the diet along with shellfish and small mammals previously avoided. They constructed sturdy, heated shelters with hearths and ovens for heating and cooking, wore warm, closely fitting clothing sewed with bone needles, and created the earliest forms of artistic expression – cave paintings of animals, humans and many mysterious markings.

They left behind numerous small ivory, bone and stone sculptures of female figures. One example, the 'Venus of Willendorf', manifests extreme adiposity of breasts, hips and buttocks (154). She may have represented a well-nourished woman with abundant fat stores, an ideal of feminine beauty and fertility of her day. This little sculpture and others like it signify that at least some individuals had the opportunity to develop sizeable adipose tissue deposits.

The diet of Palaeolithic foragers was probably the most nutrient-dense and healthful in all of human history. The 'Palaeolithic Diet' has been reconstructed and its nutritional impact evaluated by combining archaeological data with observations of the few remaining modern foraging peoples (155,156). Daily calorie consumption was high, an average of 3000 calories per day, and meat constituted a significant 35–50% of the diet, with wild plant foods making up the remainder. Wild game contains much less saturated fat and up to five times more healthful polyunsaturated fat than meat from domestic farm animals (157). The Palaeolithic combination of lean meat, wild nuts, fruits and vegetables was lower in carbohydrates and higher in protein and micronutrients, including cancer-preventing antioxidants, than the modern industrial diet. It also contained less sodium, more fibre, and more of virtually every vitamin and mineral – potassium, calcium, Vitamin B, Vitamin C, iron and folate. Sugar, salt and alcohol were unknown. Skeletal remains of Upper Palaeolithic populations indicate their tall stature and generally good skeletal and dental health (158).

The Palaeolithic Diet is characterized by alternating periods of feast and famine. Throughout their evolutionary history, humans adapted to a highly nutritious but limited, unpredictable food supply and a regular cycle of accumulation and depletion of fat reserves. Palaeolithic foraging enabled humans to establish permanent populations in virtually all of the world's ecological niches. But it is marked by conditions of extreme fluctuation – alternating abundance and scarcity of food, seasonal and geographical variations in food availability, and varying levels of physical effort required to obtain adequate energy. The enhanced ability to store body fat during periods of plenty provided adequate energy for high-level physical activity, ensured survival during times of scarcity, and supported the energetic needs of the large human brain and its development during infancy and childhood. Foragers enjoyed generally good nutritional health, even though their subsistence-related physical exertion involved three times the energy expenditure of typical modern human workers who have access to labour-saving technology and a more sedentary lifestyle (159).

The neolithic transition

A global shift from foraging to farming began about 10 000 years ago during a warmer climatic phase after the last great glacial period. In at least nine centres of origin foragers began to raise crops and domesticate animals. They developed new, smoothly ground stone implements and pottery for processing and containing their food (160–169). The warmer climate drove many large game animals away or contributed to their extinction and forced reliance on fallback foods that included wild cereals. Increasing population pressure made foraging for wild foods impractical and impossible and necessitated planting and cultivation. Whatever the reason or reasons, the human subsistence pattern underwent a universal transformation from foraging and wild food collection to domestication and food production and a dramatic dietary change.

Farming may have grown quite naturally out of foraging as hunters began to partially control the migration of game animals, sow a few wild seeds in convenient locations, and leave portions of tubers and roots to sprout where they lay (Harlan 1995). In each of the world's agricultural centres local plants and animals were cultivated and raised,

depending on the specific indigenous wild forms present and their domesticability. Thus, domesticated wheat, barley, sheep and goats appeared in the Fertile Crescent, dogs, maize, and beans in the Americas, cattle in Africa, and bananas in New Guinea (161). Domestic plants and animals became genetically distinct from their wild forms, were dependent on human action for survival and reproduction, and yielded large amounts of energy. By 3000 years ago, farmers had replaced foragers in nearly all regions of the world and established a more dependable, high-energy subsistence base which eventually spurred the development of villages, towns, cities, and finally nations with their large sedentary populations and stratified societies.

But agriculture had a high energetic price. Plant cultivation and animal husbandry required rigourous and constant, year-round labour. Energy expenditures of early farmers are estimated to be as high as those of modern farmers in non-industrial societies (159). Crops sometimes failed and animals died prematurely or did not reproduce as expected. Pests and natural disasters destroyed stored food surpluses. Food shortages and starvation were not uncommon. Domestic animals transmitted bacteria and parasites to humans in densely populated farming villages and towns, causing epidemics of infectious diseases not experienced by nomadic foragers (170).

Agriculture changed the global environment permanently and irreversibly. Plowing and cultivation encouraged weed growth and promoted soil erosion. High-density, sedentary agricultural populations dispersed in villages and towns over the landscape, and their conversion of forested and grass-covered lands into great expanses of fields and gardens severely reduced the natural habitat of wild animals and plants. Foraging as a major subsistence strategy was lost forever.

Although it provided a storable, high-energy food supply, agriculture greatly reduced dietary diversity and permanently altered food preferences. All important seed crops of today were derived from once low-priority, but easily domesticated food plants that were converted into meals through newly developed food processing techniques such as grinding and baking. World-wide, of the more than 200 000 seed-bearing plant species known, 3000 had been used for food by Palaeolithic foragers, 200 were domesticated, 13 became important food plants, but only four dominate today in plant agriculture (171,172). These are all grasses – maize, wheat, rice and sugar cane. Of the wide variety of animal species hunted and collected by Palaeolithic foragers, about 50 were domesticated, and only a few of these were used for food in each region (llama, alpaca, pig, turkey, chicken, horse, buffalo, cattle, goat, sheep, dog). Selective breeding produced domesticated seeds that were larger and more productive than their wild forms, but domesticated animals became more docile and smaller, reducing their absolute food yield. To augment the animal protein supply, early farmers developed a variety of legumes to provide plant proteins (pea, lentil, bean, peanut, soybean), and root crops such as potato, sweet potato, taro and yam for additional sources of carbohydrates. The dietary focus shifted from animal protein and fat to plant carbohydrates.

Wherever farming replaced foraging, there was a general decline in human health (173–180). Unequivocal signs of nutritional deficiencies, growth disturbances and increasing disease burdens are evident in the skeletal remains of farmers, from the earliest beginnings of agriculture to historic times (181,182). The most detailed studies of health decline come from early agricultural communities in North America (183,184), where skeletal lesions document iron deficiency anaemia and tubercular bone infections in populations that adopted maize as the primary food crop. Chronic protein-energy malnutrition, and a high prevalence of dental caries, abscesses and tooth loss were related to high-carbohydrate diets (185,186). Average adult stature was significantly lower, and life expectancy decreased relative to preceding foraging populations.

The development of agricultural was also accompanied by the first signs of social stratification, marked by variation in the value of grave goods (187,188). In post-agricultural urban and industrial societies, elites are not only wealthier and more powerful but also better nourished, healthier and longer-lived, largely because of greater access to animal protein and overall improved nutrition.

Agriculture created dependence on cereal grains that replaced lean meat and fresh fruits and vegetables as primary sources of energy. Food allergies and deficiencies related to animal milk and cereal diets reflect the still incomplete human adaptation to these relatively new food sources (171). Lactase persistence is perhaps the only human genetic adaptation to an agricultural diet, but the ability to digest lactose is varies considerably in frequency among the world's populations (189). Food security and efficiency in food production evolved at the cost of overall declining nutritional health, especially among the world's poor.

Modern agriculture, like other human subsistence activities in industrialized societies, uses labour-saving technology and less human energy expenditure than farming in less developed societies and nomadic foraging in the present and in the past. Today's industrial-agricultural environment is an obesogenic one. Modern societies have achieved the ultimate in foraging strategies by optimizing energy intake with minimal physical effort and energy expenditure. The tradeoff is a decline in nutritional health, an increase in obesity rates, and epidemics of diabetes (15) and cardiovascular disease (190). Not only has energy intake increased in industrialized nations through modern food processing and marketing techniques, but energy

Table 1 Energetic transitions in human evolution

	Hominoids	Hominins	Palaeolithic humans	Neolithic humans	Industrialized humans
100 ya					**High obesity prevalence** --
					Industrialization + ----------
					Mechanization + ----------
					Hi energy consumption + --
					Lo physical activity + -----
					Increased body size – ----
					Sleep deprivation & stress +
10 kya				**Low obesity prevalence** ----------┤	
				Reduced body size + ----------┤	
				Social stratification –/+ ----------	
				Sedentism + ----------	
				Animal domestication: lo protein, hi saturated fat + ----------	
				Plant domestication: lo nutrient, hi carbohydrate + ----------	
2 mya			Meat/fat based diet + ----------┤		
			Cooking + ----------		
			Stone tool technology + ----------┤		
			Increased locomotor efficiency + ----------┤		
			Extended infant development/lifespan + ----------		
			Encephalization – ----------┤		
			Increased body size, especially females – ----------┤		
			Increased territory/big game hunting – ----------┤		
			Population expansion to northern latitudes – ----------		
4 mya		Relatively small females + --┤			
		Bipedalization + ----------			
		Increased dietary variety + ----------┤			
20 mya	Proteinenhanced diet + ----------┤				
	Plant–based diet – ----------┤				
	Hi physical activity levels – ----------┤				

+, increased energy intake or conservation; –, increased energy expenditure; mya, million years ago; kya, thousand years ago; ya, years ago.

expenditure has declined because of automation, mechanized transport, and increases in sedentary occupations and leisure pursuits (159,191–194), which apparently do not induce compensation by reduction of energy consumption (195).

Other aspects of the modern environment contribute to obesity rates and related health risks as well. Plasma organochlorine concentration is positively related to adiposity, and obese individuals have higher levels of these lipophilic pollutants in their adipose tissue (196). Weight loss releases these pesticide compounds from storage in adipose tissue, concentrates them in plasma and exposes target organs to their carcinogenic effects. Plasma organochlorines are negatively correlated with thyroxine levels and may help to account for reduced energy expenditure and decreased thermogenesis during body weight loss (197). In addition, the modern lifestyle is often characterized as stressful and less than conducive to restful sleep. Both stress and sleep deprivation have been associated with increased rates of obesity (198,199), although causal links have not been identified.

Conclusion

Table 1 summarizes energetic transitions during the course of human evolution. Modern industrial societies have achieved the ultimate foraging strategy by maximizing energy intake and minimizing physical effort and energy expenditure, but the tradeoff is a decline in nutritional health. Combined with the strong genetic endowment (20) and efficient metabolic system for energy accumulation, storage and defense (200) which evolved over the long period of evolution in energy-poor environments, the modern human environment contributes to high rates of obesity. Biological mechanisms to protect against nutritional deficiencies, excessive energy storage and their health consequences have not yet evolved in human populations. Biologically adapted to cope with the worst case scenario of food shortage and potential starvation, humans have created a modern obesogenic environment that has overwhelmed the body's energy balance system.

Conflict of Interest Statement

No conflict of interest was declared.

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