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Age-Related Changes in Energy Expenditure

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Abstract

BACKGROUND: Total Daily Energy Expenditure (TDEE) is a dynamic parameter influenced by basal metabolic rate (BMR), thermic effect of food (TEF), and activity-related energy expenditure (AEE). With aging, all components of TDEE undergo measurable declines due to changes in body composition, hormonal regulation, and physical activity. Understanding these age-related changes is critical for addressing malnutrition, sarcopenia, frailty, and metabolic diseases in older adults.

AIM: This review synthesizes current knowledge on the physiological, cellular, and behavioral determinants of energy expenditure across the lifespan, with an emphasis on elderly populations.

METHODS: A comprehensive literature analysis was conducted, including randomized controlled trials, observational cohort studies, and mechanistic research, focusing on age-related trends in BMR, TEF, AEE, non-exercise activity thermogenesis (NEAT), and organ-specific metabolic rates.

RESULTS: Aging is associated with reductions in fat-free mass (FFM) and specific metabolic rates of major organs. Mitochondrial dysfunction, decreased Na^+/K^+ ATPase activity, and diminished protein synthesis contribute to lower BMR. TEF declines due to reduced sympathetic responsiveness. AEE and NEAT are significantly impacted by behavioral, neurological, and structural limitations, leading to a progressive fall in total energy expenditure. Notably, higher AEE is independently associated with reduced mortality risk and better physiological resilience in older adults.

CONCLUSION: Age-related energy expenditure decline is multifactorial and partially modifiable. Preservation of physical activity and metabolic health through targeted interventions may mitigate the adverse effects of aging on energy balance and overall health.

Introduction

Feeding is essential for our survival and represents a multisensory experience that integrates gustatory, visual, auditory, and olfactory stimuli, all of which converge on brain centers involved in the regulation of appetite and satiety. Nutrition in older individuals is critical for preserving age-appropriate muscle strength and must be adapted to the physiological changes of aging. The burden of multimorbidity and comorbidities directly impacts both the quality and duration of life.

Recognizing age-related changes in energy expenditure is essential to understanding the mechanisms of appetite regulation. These two processes, energy intake and expenditure, are interdependent facets of the same metabolic coin, and their balance is vital for maintaining body weight and integrity, as well as influencing the onset and course of many diseases. A complex network of interconnected physiological systems orchestrates energy intake and expenditure to regulate body weight and ensure species survival.

Key hormones such as ghrelin stimulate appetite and food intake, while others such as glucagon-like peptide-1 (GLP-1), peptide YY (PYY), amylin, and cholecystokinin (CCK) suppress appetite and energy intake. Along with adipokines and pancreatic hormones, these signals are integrated by the central nervous system (CNS) to regulate feeding behavior. Humans eat to meet their total daily energy expenditure (TDEE), the majority of which is composed of resting metabolic rate (RMR), while the most variable and behavior-dependent component is activity-related energy expenditure (AEE). Brown adipose tissue (BAT) also contributes to TDEE, though its long-term effect on energy balance remains uncertain.

The obesogenic environment typical of industrialized countries promotes excessive caloric intake and low physical activity, resulting in weight gain.

However, weight regulation is not simply a matter of "eat less and exercise more" because both appetite and TDEE undergo adaptive changes that facilitate weight regain after loss. Over recent decades, lifestyle changes have led to food intake far exceeding physiological needs. This, combined with our metabolic regulation shaped by millennia of evolution in energy-scarce environments, has resulted in habitual overeating beyond our true energy requirements—arguably the primary driver of the global obesity epidemic. Maintaining energy balance requires equilibrium between caloric intake and expenditure. This balance is fundamental to overall homeostasis. However, how the main components of energy balance, food intake and TDEE, change with age remains incompletely understood.

With aging, energy intake and output decline. Limited literature exists on age-related changes in these mechanisms, primarily due to the logistical and ethical challenges of conducting randomized controlled trials in older and very old adults. Consequently, much of the available data derives from observational population studies, which carry inherent methodological limitations. A deeper understanding of these processes is crucial. It may help determine whether the observed changes represent adaptive responses to an aging body or are linked to the development of pathological conditions that directly affect life expectancy and quality of life. As global life expectancy continues to rise, answering these questions becomes increasingly vital.

Components of the total daily energy expenditure

Total Daily Energy Expenditure (TDEE) is determined by three components:1)Basal Metabolic Rate (BMR); 2) Physical Activity Energy Expenditure (PAEE); 3) Thermic Effect of Food (TEF). (See Figure 1).

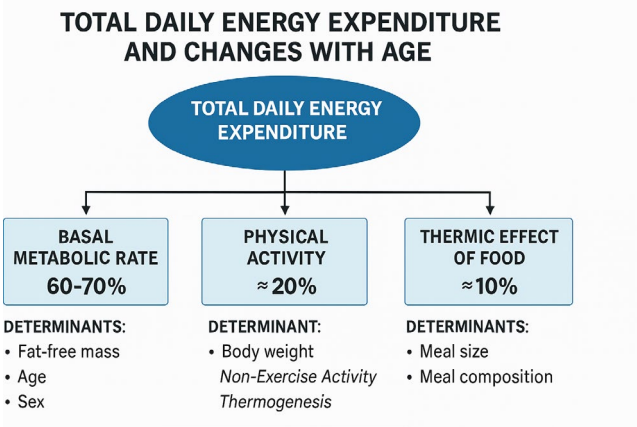

Figure 1: Main components and determinants of total daily energy expenditure

Basal Metabolic Rate

Basal metabolic rate (BMR) represents the energy required to sustain vital physiological processes (e.g., cellular function, respiration, circulation) at complete rest and accounts for approximately 60–70% of TDEE in sedentary individuals. BMR can be divided into sleeping metabolic rate and awake resting metabolic rate, the latter being approximately 10% higher [1]. BMR is ideally measured under strict standardized conditions in a thermoneutral environment [2]. Due to the difficulty in maintaining these conditions, *Resting Energy Expenditure* (REE) is often measured in clinical settings and is about 5% higher than BMR. Although BMR and REE are used interchangeably, REE is more commonly assessed in clinical practice and research. REE is measured by *indirect calorimetry*, an open-circuit method where the patient inhales ambient air and the difference in oxygen (O_2) and carbon dioxide (CO_2) concentrations between inhaled and exhaled air is used to calculate energy expenditure (EE) [3] and substrate oxidation (e.g., fats and carbohydrates).

In clinical settings, REE is measured in the morning after at least an 8-hour fast, and subjects should refrain from moderate to intense physical activity for 24–48 hours beforehand. When these conditions are followed, the coefficient of variation in repeat measurements is approximately 5% [4]. Portable indirect calorimeters exist but typically measure only O_2 consumption and not substrate oxidation, making them less accurate [5], [6]. When determining REE, factors like height, weight, sex, and ethnicity are considered. The most used formulas of *Harris–Benedict* [7] and *Mifflin–St. Jeor* [8] are applicable at the population level but may under- or overestimate REE by more than 10% in 30–40% of adults [9].

REE largely depends on body size and composition, particularly *fat-free mass* (FFM), which includes total body water, proteins, carbohydrates, soft tissues, and bone minerals. FFM accounts for 50–70% of REE variability between individuals. Although often considered synonymous with muscle mass, FFM includes metabolically heterogeneous tissues. For example, the brain, heart, kidneys, and liver, which make up only 5–6% of body weight, account for approximately 60% of REE [10], [11]. In contrast, skeletal muscles, adipose tissue, and bone comprise a larger portion of body mass but contribute only 20–30% of REE. Despite its lower metabolic rate per gram, skeletal muscle is a strong predictor of REE due to its volume [10]. Adipose tissue, although energetically sparse (4 kcal/kg/day), also contributes, especially in obesity [12]. REE declines with age, mainly due to reductions in FFM [13].

Age-related decreases in organ and tissue metabolic rates are also observed, likely due to reductions in cellular mass, decreased Na^+/K^+-ATPase activity, and lower norepinephrine levels, reflecting decreased physical activity, dietary intake, and protein synthesis [14]. In general, men have higher absolute REE than women, but this difference is less

pronounced when adjusted for body fat [15]. In adulthood, growth no longer contributes to BMR, making physical activity and body composition the primary factors influencing energy needs. The diversity of body size, composition, and habitual activity across populations with different geographic, cultural, and economic backgrounds makes it difficult to define universal energy requirements based on average TDEE. To account for variation in physical activity, TDEE is often calculated using factor-based estimations that combine time spent on routine tasks and the energy expenditure associated with those activities.

Thermic Effect of Food

The thermic effect of food (TEF) represents the energy expended for the digestion, absorption, and storage of nutrients. In adults consuming a mixed diet, TEF accounts for approximately 10% of total daily energy expenditure (TDEE) [16]. TEF is proportional to the energy and micronutrient content of food. Protein intake generates a higher TEF compared to fats or carbohydrates [16]. The decline in TEF with age [17], [18] may be attributed to changes in β-adrenergic sensitivity, resulting in reduced postprandial sympathetic stimulation [19]. Data on changes in TEF with weight gain or loss in individuals with or without obesity are inconsistent [20]. Some studies suggest that low TEF may serve as a predictive factor for future weight gain [21].

Activity Energy Expenditure

Activity energy expenditure (AEE) is the most variable component of TDEE and depends on body size and movement. AEE is sometimes expressed as the Physical Activity Level (PAL), which represents the ratio of TDEE to basal metabolic rate (BMR). In the absence of physical limitations, PAL varies significantly among individuals. For example, PAL values around 1.2 are typical for sedentary individuals, while values exceeding 4.0 have been recorded in elite athletes during competition (e.g., Tour de France cyclists, Arctic sled haulers, or Nordic skiers). However, such high levels cannot be sustained long-term [22]. PAL values of 2.8 to 3.0 can be maintained for short periods during intense athletic training but are unlikely to reflect annual averages [22]. In the general population: AEE can be further categorized into exercise thermogenesis and non-exercise activity thermogenesis (NEAT), which includes energy expenditure from occupational tasks, sitting, standing, and other daily activities (see Figure 1).

Measuring AEE in laboratory or everyday settings is challenging. In research, AEE can be assessed via whole-room indirect calorimetry—experimental chambers resembling small hotel rooms where individual components of TDEE can be measured during exercise, rest, and sleep. However, due to the confined space and scheduling limitations, such measurements may not accurately reflect AEE and TDEE under real-life conditions. The doubly labeled water (DLW) method is the most accurate approach for measuring TDEE [23], [24]. This method involves the intake of stable (non-radioactive) isotopes of hydrogen (2H, deuterium) and oxygen (18 O). The labeled 2H is excreted from the body as water (primarily in urine and to a lesser extent through respiration and sweat), while 18O is eliminated both as water and as CO_2 in exhaled air. Thus, the difference in elimination rates reflects CO_2 production over the measurement period (typically 7–14 days), which is used to estimate TDEE [23], [25]. AEE can then be calculated as: *AEE* = *TDEE* – *BMR* and *PAL* can be calculated as**:** TDEE/BMR.

The limitation of this method is that it does not provide information about the type or intensity of physical activity. Therefore, portable activity monitors are more suitable for this purpose. Although most devices demonstrate reasonable accuracy, they estimate AEE as a percentage of TDEE using predictive equations, and significant variability exists among both commercial and research-grade monitors [26]. Activity monitors that incorporate additional biosignals (e.g., heart rate) may improve the accuracy of AEE and TDEE estimations [26].

Changes in Total Daily Energy Expenditure with Age

In attempts to theoretically explain aging, considerable attention has been paid to the role and significance of total daily energy expenditure (TDEE), due to the observed correlation between high TDEE in short-lived mammals and lower TDEE in long-lived species. Some have proposed that TDEE is biologically capped over the lifespan of a given species, and that excessive short-term expenditure may accelerate aging processes [27]. However, other studies strongly criticize and challenge the so-called "rate of living theory" (ROLT) related to TDEE [28], [29]. Energy expenditure is often assumed to be a driver of aging without a full understanding of the age-related changes in the individual components of TDEE.

A deeper understanding of these changes could reveal potential interventions to support healthy longevity. For example, it remains unclear why activity energy expenditure (AEE) declines with age across all mammalian phylogenies. While many aging hypotheses implicate metabolic rate, debate continues around the role of TDEE changes and their potential effects on lifespan extension [30]. With age, TDEE follows an inverted U-shaped trajectory. In the first two decades of life, TDEE approximately doubles, mainly due to increases in body mass. In the following two decades (ages 17 to 40), TDEE plateaus, corresponding with relatively stable body weight during this life stage. After age 40, TDEE begins to decline. By age 75, individuals show TDEE levels like those of

children aged 7–11 years, despite having significantly greater body mass [31]. This pattern is reflected in the current dietary guidelines issued by FAO/WHO/UNU [2]. For example, a person aged 18–29.9 years weighing 70 kg is recommended a daily caloric intake of 2550 kcal/day, whereas a person over the age of 60 with the same body weight is advised to consume 2050 kcal/day. This represents an approximate reduction of 500 kcal/day in TDEE after the age of 40 and highlights the overall decline in energy expenditure that accompanies aging and changes in body composition.

A dynamic balance exists between body mass and the components of total daily energy expenditure (TDEE). The ratio of energy intake to TDEE regulates body weight. An increase in energy intake without a corresponding rise in resting energy expenditure (REE) and activity energy expenditure (AEE) leads to weight gain. Similarly, an increase in TDEE without dietary compensation results in weight loss. Aging is associated with reductions in all components of this equation: body mass, REE, AEE, and the thermic effect of food (TEF). However, it remains unclear which of these is the primary driver of the observed change. One possibility is that a reduction in energy intake alone leads to weight loss. Another hypothesis suggests that a decline in the energy intake-to-(REE + AEE) ratio may compensate for the reduced body mass [32]. The decline in TDEE with age is driven by a combined reduction in both REE and AEE. Potential contributors to this decrease include:

1. Changes in Resting Metabolic Rate with age

Basal metabolic rate (BMR) accounts for 60–80% of total daily energy expenditure (TDEE). As previously noted, of all TDEE components, resting energy expenditure (REE) is the most frequently measured due to the accessibility and affordability of the equipment required, and the relatively short time required for assessment in humans (around 30–60 minutes). REE measurement is typically combined with assessments of body fat percentage and fat-free mass (FFM). Since FFM accounts for more than 60% of daily REE, its quantity is used to adjust the obtained REE values. This adjustment helps account for many individual differences in REE, though it is important to note that REE is not constant among older adults. For example, higher body mass in young adults, when adjusted for FFM, is associated with lower REE [33].

Animal studies suggest that weight gain is associated with an increase in tissues with low energy demands (fat) without a proportional increase in highly metabolically active tissues (e.g., brain, liver, kidneys) [34]. Thus, when body weight increases but skeletal muscle mass (which has lower metabolic activity) increases disproportionately compared to other FFM components, total REE decreases because the mass of highly active tissues remains unchanged [33]. In aging, body mass typically decreases. Aging is associated with a progressive decline in whole-body REE at a rate of 1–2% per decade after age 20.[35] This decrease is closely linked to the reduction in FFM, which consists of metabolically active tissues and organs [36]. However, there is ongoing debate as to whether the decrease in REE is entirely due to changes in FFM, as some evidence suggests that body composition adjustments do not fully account for the REE differences between young and older adults [37].

In other words, REE remains significantly lower in older adults even after correcting for differences in body composition. A more accurate estimate of REE can be calculated using the equation: $REE=\sum(M_i \times Met_i)$. Where M_i represents the mass of a given organ, and Met_i is the specific metabolic rate of that organ, expressed in kcal/kg/day, reflecting the metabolic rate of the cells within that organ. Age-related changes in organ mass (M_i) were first evaluated in 1926 based on autopsy studies involving approximately 2200 men and women [38]. These studies found that from age 20 to 80, there is a 32% reduction in liver mass, a 23% reduction in kidney mass, a 55% reduction in spleen mass, and a 10% increase in heart mass. While this and other studies demonstrate age-related reductions in most organ masses [38], [39], [40], they have been criticized for lacking information about cause of death and for potential fluid shifts that may have occurred between time of death and organ measurement. However, in vivo data support these findings. He Q et al. analyzed whole-body magnetic resonance imaging results and confirmed that most organs decline in mass with age [41]. The estimated percentage change in organ mass from age 20 to 80 was calculated using equations. The results showed that the mass of the brain, bones, kidneys, liver, and muscles decreases at relatively similar rates—between 10–20%—over that period, while the spleen exhibited a dramatic 38% loss of tissue mass [41]. These findings indicate that the reduction in organ mass with age clearly contributes to the age-related decline in REE (Figure 2).

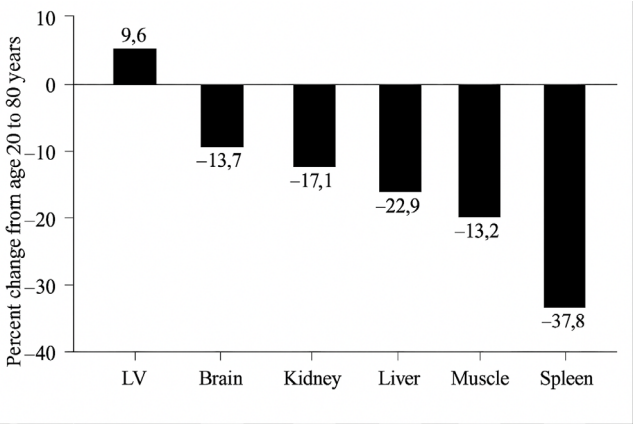

Figure 2: Percent change in organ mass between ages 20 and 80 [41]. Adapted from He Q, Heshka S, et al. Smaller Organ Mass with Greater Age, Except for Heart. J Appl Physiol. 2009

The other component of the equation for calculating resting metabolic rate (RMR), the specific metabolic rate (Meti), depends on factors such as the

cellular fraction within a given tissue, mitochondrial proton leak, protein turnover rate, and Na^+/K^+-ATPase activity [42]. As a result, Meti cannot be easily determined in vivo. Most of the existing literature relies on approximations based solely on organ mass or total body fat-free mass (FFM), under the assumption that specific metabolic rates remain constant across the lifespan. Until recently, this assumption went largely unchallenged. Wang Z et al. conducted a comprehensive study of organ mass and estimated specific metabolic rate across adults aged 23 to 88 [43]. Organ volumes were measured using whole-body magnetic resonance imaging (MRI), excluding low-energy tissues like adipose tissue. The cellular fraction of organs was also assessed, based on the premise that aging increases extracellular components, which do not contribute to heat production.

The precision of this method depends on accurate estimation of body cell mass and extracellular water. Researchers used total body potassium to estimate cellular mass, deuterium dilution for total body water, and a combination of both to determine extracellular water. Their findings showed that the model predicted RMR accurately up to age 50 but significantly underestimated it beyond that. This underestimation likely reflects a lower cellular fraction in FFM in older adults, which reduces metabolic rate per unit of tissue. Therefore, assuming homogeneous metabolic activity across age groups may lead to inaccuracies when estimating age-related declines in RMR.

a) The Protective Role of Physical Activity on Age-Related RMR Decline

Physical activity plays a key role in slowing the age-related decline in RMR due to its significant influence on maintaining body composition in highly active older adults [44]. Aerobic capacity and total exercise volume are positively correlated with RMR, suggesting that activity level contributes to resting energy expenditure. Numerous studies indicate sex-specific effects of chronic physical activity on RMR [45], [46]. In older physically active women—particularly those who had trained in endurance running for approximately 18 years—RMR adjusted for FFM did not decline. Similarly, prior engagement in athletics or swimming was associated with preserved FFM-adjusted RMR in elderly women [45]. These data suggest that endurance exercise helps maintain RMR. Interestingly, older active women also maintained FFM comparable to younger women. In contrast, among highly active older men, RMR adjusted for FFM was lower than in younger counterparts. Subgroup analysis showed that both exercise volume and energy intake were positively correlated with FFM-adjusted RMR. When younger and older groups were matched for either weekly training hours or energy intake, the difference in RMR disappeared. This suggests that RMR in men declines with age despite regular endurance exercise, but the reduction is closely tied to decreased exercise volume and energy intake. Men who are able to sustain high levels of physical activity and caloric intake as they age may be able to preserve their RMR.

b) Energy Balance, Physical Training, and RMR: Insights from Experimental Studies

Bullough RC et al. investigated the potential mechanisms underlying increased resting metabolic rate (RMR) in physically trained individuals [47]. Using a set of controlled experiments, the researchers evaluated the effects of four energy balance states: high energy balance (high intake + exercise), low energy balance (low intake + no exercise), negative energy balance (low intake + exercise), and positive energy balance (high intake + no exercise) in both trained and untrained individuals. They found that RMR was higher in trained individuals only under conditions of high energy balance, in which caloric intake matched the energy expended through physical activity. This increase in RMR was partially attributed to elevated norepinephrine levels. Notably, a reduction in norepinephrine levels was observed in all trained individuals who transitioned from high to low energy balance. Correlation analysis revealed that norepinephrine was strongly associated with the change in RMR during this transition. In contrast, levels of triiodothyronine (T3), glucose, insulin, and epinephrine remained unchanged, suggesting they do not significantly affect RMR in this context. These findings suggest that overall energy intake contributes to RMR even in states of energy balance, and that age-related reductions in RMR may be partly due to attenuated norepinephrine release during chronic physical training in older adults.

c) The Impact of Disease States on RMR in Aging

Aging is accompanied by various diseases that may increase or decrease RMR. Conditions such as Alzheimer's disease, chronic obstructive pulmonary disease (COPD), congestive heart failure, Parkinson's disease, diabetes mellitus, malnutrition, and cancer are all associated with altered RMR [48]. Diseases that typically elevate RMR include COPD [49], lung cancer [50], and diabetes [51]. Conversely, RMR tends to decline in conditions linked with negative energy balance and weight loss, such as Alzheimer's disease [52], renal failure [53], and malnutrition [54]. Although hypermetabolism has been proposed as a driver of clinical deterioration in chronic diseases, most studies conclude that reduced energy intake is the main mediator of negative energy balance and weight loss in such conditions [55]. It is important to note that many studies have not adjusted RMR measurements for fat-free mass (FFM), which may confound interpretations. Moreover, it remains unclear whether changes in cellular composition or shifts in specific organ

metabolic rates contribute to the observed alterations in RMR in aging and chronic illness.

d) Tissue-Specific Metabolic Rates and Their Role in Age-Related Decline in RMR

As previously noted, tissue-specific metabolic rates are determined by processes such as mitochondrial proton leak, protein metabolism, and Na^+/K^+ ATPase activity at both the cellular and tissue levels. Changes in these processes support the notion that tissue-specific metabolic rates contribute to the age-associated decline in resting metabolic rate (RMR). When cellular ATP demand is low, mitochondrial proton leak may account for approximately 16–21% of RMR [56]. Paradoxically, aging is associated with increased proton leak, which would theoretically elevate RMR [57]. However, this process may also explain the observed decrease in specific metabolic rate per unit of tissue, as the energy lost through proton leak is not utilized for useful biological work. Na^+/K^+ ATPase is a critical enzyme found in all cells, responsible for maintaining the sodium and potassium gradient across the plasma membrane. Its activity is linked to interspecies differences in RMR, correlating with variations in body size across mammals and reptiles [58], [59]. Multiple animal studies have demonstrated age-related declines in Na^+/K^+ ATPase activity in cardiac [60] and brain tissues [61]. Similar changes have been reported in human erythrocytes [62] and lymphocytes [63]. Although some studies offer conflicting findings [64], the predominant body of evidence suggests that reduced Na^+/K^+ ATPase activity contributes to the decrease in RMR observed with aging.

e) Protein Turnover and Age-Related Changes in Metabolic Rate

Maintaining protein balance through energy-dependent processes governing amino acid synthesis and degradation is a key determinant of resting metabolic rate (RMR) [56]. Overall, aging in both humans and animals leads to a reduction in whole-body and tissue-specific protein turnover [65], [66], [67]. However, some studies report no significant effect of altered protein turnover on RMR after adjusting for fat-free mass (FFM) [68]. Most investigations rely on tissue models, particularly skeletal muscle, due to its relevance in sarcopenia. It is widely accepted that muscle protein breakdown rates remain stable with age, while protein synthesis—both in the fasting and postprandial states—declines with aging [69]. Older adults show a blunted increase in muscle protein synthesis following the ingestion of essential amino acids [70]. The mechanisms behind reduced protein synthesis are not fully elucidated but may involve decreased levels of anabolic hormones and impaired nutrient uptake. Testosterone levels correlate with myosin heavy chain synthesis, and testosterone replacement in hypogonadal men has been shown to restore muscle protein synthesis [71], [72]. In contrast, long-term growth hormone administration in older adults does not significantly affect muscle protein synthesis [73]. Altered nutrient uptake in skeletal muscle may also contribute to age-related declines in protein synthesis. In older individuals without overt type 2 diabetes, insulin resistance at the muscle level impairs protein synthesis, potentially due to defects in endothelial-dependent vasodilation [74]. Supporting this, aerobic exercise—which enhances vasodilation—reduces insulin resistance and improves muscle protein synthesis in the elderly [75]. In summary, the observed age-related decline in tissue-specific metabolic rates appears to be associated with decreased Na^+/K^+ ATPase activity and reduced protein synthesis.

2. Age-Related Changes in Physical Activity Energy Expenditure

With aging, physical activity levels and mobility decline across species—including humans, non-human primates, dogs, rodents, and insects [76]. Physical activity energy expenditure (AEE) includes two categories: energy expended during structured exercise and that expended during routine daily activities (see Figure 1). AEE is highly variable [77] and remains the most difficult component of total daily energy expenditure (TDEE) to measure, and therefore the least studied in the context of aging. AEE ranges broadly in humans—from 262 kcal/day in older adults with dementia [78] to 1434 kcal/day in Mount Everest climbers [79]. Like other TDEE components, AEE is influenced by body mass, though the effect is weaker compared to resting metabolic rate (RMR). While fat-free mass (FFM) accounts for over 60% of RMR, it only explains ~10% of AEE [80]. Thus, AEE is largely independent of FFM, and its age-related decline primarily reflects reductions in movement frequency and intensity (e.g., walking, household chores, standing, and sedentary behavior). Studies in families and monozygotic twins suggest that AEE has a genetic basis [81]. Stronger evidence comes from animal studies, where a 72% reduction in spontaneous physical activity was observed before significant weight gain in obesity-prone mice [82]. Moreover, mutations in the foraging gene are associated with reduced motor behavior in adult Drosophila [83] Joosen et al. [84] evaluated physical activity levels and AEE using respiratory chambers and free-living assessments in monozygotic and dizygotic twins. They found that genetics accounted for 72% of AEE variation and 78% of variability in physical activity levels. These associations were attenuated but remained significant after adjusting for anthropometric traits (e.g., body fat mass). Conversely, a similar study in children reported weaker genetic influence on AEE, which disappeared after adjusting for anthropometric and demographic factors [85]. Although physical activity originates from higher-order brain centers, these results suggest that

the decision to be active is modulated by genetic predisposition. Despite the genetic component, AEE consistently declines with age. Using doubly labeled water and indirect calorimetry, Johannsen et al. [86] measured TDEE and RMR and calculated AEE with the formula: *AEE = TDEE − [RMR + (0.1 × TDEE)]*. They studied 206 men and women across three age groups: 20–34, 60–74, and ≥90 years. Interestingly, only the ≥90 group showed a significant reduction in AEE when adjusted for body mass [86]. A separate longitudinal study [87] followed 316 individuals for 25 years, showing AEE reductions of 9% and 25% in the 60–74 and >75-year groups, respectively. This decline was the primary determinant of age-related reductions in TDEE. Importantly, reductions in FFM—a normal biological adaptation to aging—did not fully explain the observed decrease in AEE. A number of epidemiological studies have shown that physical activity declines with advancing age. However, most of these studies rely on self-reported data, which introduces significant discrepancies compared to actual physical activity levels [88], [89], [90], [91]. Accurately quantifying activity energy expenditure (AEE) is challenging, which is why there is limited literature on AEE in older adults. Troiano et al. [92] conducted a large-scale study in which accelerometers were placed on the thighs of 4,867 individuals across different age groups. The device functioned as a small (2.0 × 1.6 × 0.6 inch), lightweight (42.5 g) accelerometer capable of measuring accelerations ranging from 0.05 to 2 G and frequencies from 0.25 to 2.5 Hz—corresponding to most types of human motion. An analog-to-digital converter collected data at a frequency of 10 Hz, with the values aggregated into one-minute epochs. A key feature of these accelerometers was their ability to count the number of accelerations, where a higher count over a given period indicated higher intensity activity. Thresholds for these counts were established and used to classify activity intensity as moderate or vigorous.

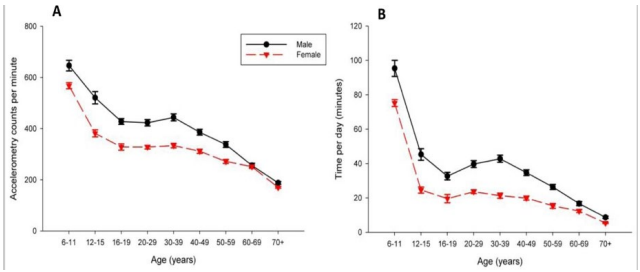

Figure 3. Age-related decline in physical activity across the lifespan. Panel A: Accelerometry counts per minute, a proxy for physical activity intensity, decrease progressively with age in both sexes. Panel B: The duration of daily moderate-to-vigorous physical activity also declines significantly, especially after early adulthood. Data derived from NHANES accelerometer study (Troiano et al., 2008) including 4,867 individuals aged 6 to 70+ years.[92]

The data showed that moderate-to-vigorous physical activity declined sharply after age 11, with another noticeable drop after age 39. Both men and women exhibited a ~55% decrease in accelerometer-recorded counts of moderate-to-vigorous activity between the ages of 39 and 70+. In terms of time spent in moderate or vigorous activity, men's daily activity decreased from 42 minutes per day (21 min/day in women) to just 8.7 minutes per day (5.4 min/day in women) between the ages of 39 and 70+. This represents an approximate 75% reduction in time spent in moderate-to-vigorous physical activity for both sexes. These findings underscore the substantial decline in AEE with increasing age (Figure 3).

3. Non-Exercise Activity Thermogenesis changes with age

In addition to voluntary physical activity, AEE includes involuntary movements known as non-exercise activity thermogenesis (NEAT) (see Fig. 1). In its strictest definition, NEAT encompasses unconscious, spontaneous, and non-volitional movements only [93]. While volitional AEE is a major component of TDEE, under normal conditions it has a smaller determining effect on total expenditure compared to NEAT [94]. NEAT is even more challenging to quantify, as standard equipment such as hip-mounted accelerometers fails to capture many movements contributing to it (e.g., seated or standing postural adjustments). To address these challenges, Harris AM et al. conducted a case–control study comparing healthy older adults (>70 years) with younger adults (30–40 years) in terms of fat-free mass (FFM) and physical activity levels.[95] The researchers measured NEAT using specially designed triaxial accelerometers and inclinometers, which detect acceleration relative to gravitational force. These devices assessed posture allocation, tracking time spent lying, sitting, standing, and moving over a 10-day period. The results showed that older adults walked 3 miles less per day, spent 131 minutes more per day sitting, and 110 minutes less standing than their younger counterparts [95]. These findings suggest that NEAT—as reflected by time spent in seated, standing, and ambulating postures—is markedly reduced even in older individuals with FFM levels comparable to those of young adults.

4. Age-Related Changes in the Biological Regulation of Activity-Related Energy Expenditure

Aging increases the tendency toward physical inactivity. However, it remains unclear whether biological changes associated with aging drive a person's desire to be less active—and whether this tendency is inherently part of aging and shaped by evolution. The answer is not yet definitive. In humans, it likely involves a complex interplay of biological, psychological, and social factors [96]. Nevertheless, the potential role of biological factors should not be overlooked. AEE is closely linked to body weight regulation. Prolonged caloric restriction reduces

physical activity levels [97], while overfeeding increases activity in lean individuals [98]. A study by Martin et al. supports the connection between body mass and activity: using the doubly labeled water method, they found that AEE was significantly reduced in overweight adults following a 25% reduction in caloric intake over three months [97]. These findings align with anecdotal reports of apathy and decreased movement in individuals undergoing semi-starvation, suggesting that reduced physical activity serves as a survival mechanism for conserving energy [99]. Interestingly, in non-human primates, caloric restriction may increase physical activity, possibly due to behavioral changes related to intensified food-seeking [100]. However, such behavior is unlikely to affect AEE in humans given the readily available food in modern environments. Thus, caloric restriction suppresses AEE and may be a protective mechanism against excessive loss of body weight [97]. Given the close association between body weight and AEE, it is plausible that the age-related reduction in AEE serves as a compensatory strategy to mitigate losses in both total body mass [101] and fat-free mass (FFM) [102]. In other words, declining AEE with age may help conserve energy and protect against tissue wasting. It is tempting to interpret this link as a possible explanation for the reduction in physical activity observed with aging.

5. The Relationship Between Longevity and Energy Expenditure

The role of total daily energy expenditure (TDEE) as a key predictor of lifespan is actively debated. A substantial body of literature supports both sides of the argument regarding the importance of energy expenditure in the aging process. This discussion is centered on the so-called “Rate of Living Theory” (ROLT) [103]. Rubner was the first to document a relationship between metabolic rate and body size in animals [104]. He noted that TDEE, when expressed as a function of body size and lifespan, appears relatively fixed. From this, he hypothesized that energy expended more rapidly leads to a shorter lifespan. Further support came from Loeb and Northrop, who demonstrated that cold-blooded animals exposed to elevated ambient temperatures experienced shortened lifespans [105]. Pearl later expanded on these ideas in two key publications, forming the foundation of ROLT [106]. He stated, “Life expectancy is determined by two variables: the constitution of the individual (genetically determined), and the average metabolic rate or energy expenditure.” ROLT has been supported by studies in mammals exposed to manipulated environmental temperatures [107]. However, birds and bats live several times longer than similarly sized mammals with comparable resting metabolic rates (RMR0) [108]. Moreover, rats chronically exposed to cold environments increase their TDEE but do not experience shortened lifespans [109]. Despite criticism, ROLT provides a conceptual framework for exploring how energy metabolism may contribute to aging through cumulative damage caused by byproducts of oxidative metabolism [110], [111]. The theory remains controversial due to several methodological challenges, including the need to adjust for body size, the lack of standardized lifespan definitions, appropriate interspecies comparison methods, and the selection of the most relevant TDEE component—RMR or activity energy expenditure (AEE). Unlike RMR, which shows low variability within species after adjustment for fat-free mass (FFM), TDEE is highly variable both within and across species, even after correcting for body mass [112]. Thus, TDEE may be a more appropriate metric than RMR when testing the validity of ROLT. Speakman presented comprehensive data on energy expenditure (EE), calculated using the doubly labeled water method in mammals and birds, and examined its relationship with lifespan [113]. Among small mammals (<4 kg), EE was inversely proportional to lifespan—even after adjusting for body mass and environmental temperature influences—supporting the Rate of Living Theory (ROLT), as higher EE rates correlated with shorter lifespan. However, human data provides a contrasting perspective. In a study by Manini et al. [30], total daily energy expenditure (TDEE) and resting metabolic rate (RMR) were measured in 302 older adults (70+ years) using doubly labeled water and indirect calorimetry, respectively. The activity-related energy expenditure (AEE) was calculated using the equation***:(TDEE*** × *0.90) – RMR.* Participants were followed over eight years to assess mortality risk. Neither resting EE nor tissue-specific EE predicted mortality. However, once AEE was isolated, individuals in the lowest AEE quartile had nearly three times the mortality risk compared to those in the highest quartile. Expressed per standard deviation, a 287 kcal/day increase in AEE was associated with a 32% reduction in mortality risk. Adjustments for sex, health status, and body composition did not alter this association. Comorbidity profiles were similar across AEE quartiles, minimizing potential bias from preexisting illness. While such studies cannot assess lifelong AEE, these findings support the broader conclusion that higher AEE is linked to reduced mortality and better preserved health [114]. This suggests AEE may serve as a strong predictor of longevity.

6. Energy Balance and Its Impact on Long-Term EE

Maintaining energy balance across the lifespan is crucial for physiological function. Energy balance—achieved when energy intake equals expenditure—ensures homeostasis. Deviations result in shifts in body energy stores, primarily through changes in the mass of certain tissues, [115]. which in turn affect EE. With positive energy balance, RMR increases due to the

growth of fat-free mass (FFM); conversely, RMR decreases with weight loss during negative energy balance. If energy intake remains constant after a body mass change, EE will eventually realign with intake, stabilizing weight at a new equilibrium. However, persistent deviations can result in disproportional shifts in EE unrelated to metabolic mass. Several studies [116], [117], [118] have shown that post-weight loss, 24-hour EE may drop by as much as 15% more than predicted based on changes in body composition—a phenomenon known as *metabolic adaptationor a daptive thermogenesis.* Conversely, overfeeding results in higher-than-expected EE [119]. In severely obese individuals, one study noted a persistent decline in RMR following an intense diet and exercise program, with reductions of 275–499 kcal/day observed even six years post-intervention, despite substantial recovery of both FFM and fat mass [120]. This suggests disproportionate changes in EE not only during but long after dynamic weight changes. Beyond changes in body composition, altered efficiency of movement and physical activity with different body weights also affects 24-hour EE. Variations in food intake impact the thermic effect of food (TEF), contributing to overall EE fluctuations. Moreover, RMR does not scale linearly with metabolic mass [121], [122] potentially due to changes in FFM composition. As noted earlier, both weight loss and aging are associated with relatively larger reductions in high-metabolic-rate organs (e.g., liver, heart, kidneys) compared to overall FFM loss. [123].

Conclusion

Age-related changes in total daily energy expenditure (TDEE) are multifactorial and involve progressive reductions in basal metabolic rate (BMR), thermic effect of food (TEF), and activity energy expenditure (AEE). These changes are primarily driven by: Alterations in body composition, notably the loss of fat-free mass (FFM) and disproportionate atrophy of metabolically active organs such as the liver, kidneys, and heart. Declines in tissue-specific metabolic rates, due to reduced Na^+/K^+ ATPase activity, increased mitochondrial proton leak, and impaired protein turnover. Decreased physical activity, both volitional and non-volitional (NEAT), resulting from sarcopenia, reduced mobility, and behavioral adaptations, including lower motivation or opportunity for physical engagement.Metabolic adaptation, which may persist long after weight loss or in the context of chronic illness, further lowering resting energy demands. Importantly, AEE emerges as a strong, independent predictor of longevity. Higher AEE is consistently associated with reduced mortality and better preservation of physiological function in older adults. Physical activity not only mitigates the decline in resting metabolic rate but also supports muscle mass retention and metabolic resilience.Understanding these dynamics is crucial for developing personalized strategies to maintain energy balance, prevent frailty, and delay the onset of age-associated chronic diseases. Interventions promoting sustained physical activity, nutritional adequacy, and metabolic health across the lifespan are essential pillars of healthy aging.

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