Published in final edited form as:
Circulation. 2012 July 3; 126(1): 126–132. doi:10.1161/CIRCULATIONAHA.111.087213.

Energy Balance and Obesity

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Abstract

This paper describes the interplay among energy intake, energy expenditure and body energy stores and illustrates how an understanding of energy balance can help develop strategies to reduce obesity. First, reducing obesity will require modifying both energy intake and energy expenditure and not simply focusing on either alone. Food restriction alone will not be effective in reducing obesity if human physiology is biased toward achieving energy balance at a high energy flux (i.e. at a high level of energy intake and expenditure). In previous environments a high energy flux was achieved with a high level of physical activity but in today's sedentary environment it is increasingly achieved through weight gain. Matching energy intake to a high level of energy expenditure will likely be more a more feasible strategy for most people to maintain a healthy weight than restricting food intake to meet a low level of energy expenditure. Second, from an energy balance point of view we are likely to be more successful in preventing excessive weight gain than in treating obesity. This is because the energy balance system shows much stronger opposition to weight loss than to weight gain. While large behavior changes are needed to produce and maintain reductions in body weight, small behavior changes may be sufficient to prevent excessive weight gain. In conclusion, the concept of energy balance combined with an understanding of how the body achieves balance may be a useful framework in helping develop strategies to reduce obesity rates.

Keywords

Obesity; physical activity; energy flux; energy balance

Framing the Issue

Obesity is often considered to be a result of either excessive food intake or of insufficient physical activity. There is a great debate about which behavior deserves the most responsibility, but this approach has not yet produced effective or innovative solutions. We believe that obesity can best be viewed in energy balance terms. The first law of

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Conflict of Interest/Disclosures
None of the authors have any conflicts to disclose.

thermodynamics assures that body weight cannot change if, over a specified time, energy intake and energy expenditure are equal. This way of thinking puts the blame not just on one or the other behavior but on both. If the problem is that too many people are in positive energy balance, then the solution must involve changing a combination of energy intake and energy expenditure to achieve balance. Efforts to develop effective strategies to reduce obesity rates could benefit from an understanding of how energy balance is achieved by the body.

Energy Balance: Definitions

The basic components of energy balance include energy intake, energy expenditure and energy storage (1). Body weight can change only when energy intake is not equal to energy expenditure over a given period of time. Humans take in energy in the form of protein, carbohydrate, fat and alcohol (energy in (E_{IN})). Humans expend energy (energy out (E_{OUT})) through resting metabolic rate (RMR)—which is the amount of energy necessary to fuel the body at rest; the thermic effect of food (TEF)—which is the energy cost of absorbing and metabolizing food consumed; and the energy expended through physical activity (EE_{PA}). RMR is proportional to body mass, particularly the amount of fat-free mass. TEF is proportional to the total food consumed and on a typical mixed diet, comprises eight to 10 percent of total energy ingested. Physical activity associated energy expenditure (EE_{PA}) is the most variable component of energy expenditure and consists of the amount of physical activity performed multiplied by the energy cost of that activity.

When energy intake equals energy expenditure, the body is in energy balance and body energy (generally equivalent to body weight) is stable. However, the time period over which energy balance may be controlled or regulated is not well understood. Differences in the time frame over which energy balance occurs between individuals may be important and may also explain the large variability in individual responses to weight loss interventions and other perturbations to the energy balance system. When energy intake exceeds energy expenditure, a state of positive energy balance occurs and the consequence is an increase in body mass, of which 60 to 80 percent is usually body fat (2). Conversely, when energy expenditure exceeds energy intake, a state of negative energy balance ensues and the consequence is a loss of body mass (again with 60 to 80 percent from body fat). Any genetic or environmental factor that impacts body weight must act through one or more component of energy balance.

How the Body Achieves Energy Balance

Our understanding of the mechanisms by which the body acts to achieve and maintain energy balance is incomplete, but the available evidence suggests that a complex physiological control system is involved. This system includes afferent signals from the periphery about the state of energy stores and efferent signals that affect energy intake and expenditure (3). Furthermore, we know that the components of energy balance can be influenced by changes in each other as a consequence of positive or negative energy balance (4-10), which act to defend body energy stores, maintain energy balance and preventing shifts in body mass. If energy balance was not controlled by such a system and were subject only to behavioral mechanisms controlling food intake and volitional energy expenditure most people would routinely experience wide swings in body weight over short periods of time. The relative stability of body weight from day to day is consistent with the view that energy balance is subject to physiological control.

In practical terms, assessment of energy balance is usually accomplished by assessment of body weight or body composition (to estimate total energy content). Energy balance itself, is not something that is measured, but rather various surrogates are measured that represent the sum total of energy inputs and outputs and the state of body energy stores. However, we do not have the ability to measure the small changes in energy balance that could impact body weight. Given this, great care should be taken in making predictions about changes in body weight from measures of either energy intake or energy expenditure.

Obesity is not a Problem in only one Component of Energy Balance

Despite the evidence for a control system, most people in today's environment gain significant escess body weight and body fat over their adult years. This does not argue against an energy balance control system, but suggests there may be limits to the body's ability to match intake and expenditure under the prevailing conditions in the modern environment. For example, one can develop some crude estimates of the extent to which food intake has increased and physical activity has decreased over the past decades. Analysis of the NHANES data (11) suggests that the average daily energy intake increased from 1971 to 2000. The average increase was 168 kcal/day for men and 335 kcal/day for women. With no active regulation or adaptation of energy balance, this increase theoretically could explain a yearly weight gain of 18 pounds for men and 35 pounds for women.

On the energy expenditure side, Basset et al (12) examined physical activity patterns in an Old Order Amish population who are living an agrarian lifestyle typical of a large fraction of the population in the U.S. early in the 20th century. Using pedometers, they found that Amish men walked an average of about 18,000 steps per day and women an average of about 14,000 per day. Basset et al (13) also reported that in 2003, the average American adult walked about 5,000 steps per day. Compared to the Amish lifestyle, this is a difference of 13,000 steps/day for men and 9,000 steps/day for women. Without taking account of physiological adaptation, this decline in physical activity over the past century could explain a yearly weight gain of 68 pounds for men and 47 pounds for women. Similarly Church et al. (14) recently estimated that occupational physical activity has declined by an average of about 142 kcal/day since 1960. This alone could explain a substantial amount of weight gain in the population.

Although these estimates are crude, the point is that taken together, the changes in reported energy intake and energy expenditure over the past decades would predict more weight gain (by 30-80 fold) in adults than actually has occurred if there were not some physiological processes attempting to maintain energy balance. Further, because alterations in one component of energy balance affect the others (4-10), it is not realistic or helpful to attribute obesity solely to energy intake or energy expenditure. A great example of the way that components of energy balance interact is demonstrated by Hall et al. (15) who modeled changes in components of energy balance with food restriction. They showed that the traditional estimate of a pound of weight loss with each 3500 kcal of negative energy balance was not true because of reductions in energy expenditure in response to decreases in energy intake, and that the actual weight loss would be less than expected. The same would hold true for weight gain – the expected weight gain would be less than predicted from the degree of positive energy balance because of the interaction among components of energy balance.

Does it Matter How Energy Balance is Achieved?

Theoretically, an individual can achieve energy balance in multiple ways. Energy balance can be achieved at different levels of body weight and body composition and it can be achieved at different levels of energy intake and energy expenditure (as long as the two are equal over a period of time). However, the way energy balance is achieved may be affected by characteristics of human physiology.

A Physiological Drive for High Energy Expenditure

A person who is very physically active might maintain energy balance and a healthy body weight by eating and expending 3,000 kcal/day. That same person, if adopting a sedentary lifestyle, could maintain energy balance and the same healthy body weight by eating and expending 2,000 kcal/day. Finally, if that sedentary person failed to sufficiently reduce energy intake to match reduced energy expenditure over time, they would gain weight and could end up achieving energy balance at 3,000 kcal/day by becoming obese.

Based on our review of the energy balance literature and information about how our modern lifestyle differs from decades ago, we hypothesize that human physiology developed under circumstances that conferred a advantage for achieving energy balance at a relatively high (compared to resting metabolic rate) level of energy expenditure--a high energy throughput—or high energy flux. The idea that energy balance is best regulated at high (but not excessive) levels of physical activity was first proposed by Jean Mayer and colleagues in the 1950s (16). Mayer observed that energy intake was better matched to energy expenditure when people were physically active. While these studies in man were cross sectional in nature, other prospective studies published by Mayer and colleagues conducted in rats established the linearity of coupling between food intake and energy expenditure only within certain limits (17). In rats, matching of energy intake to expenditure was poor at either very low expenditure or very high levels of expenditure. Similarly, in humans, matching of intake and expenditure was less accurate when people were very inactive (apparently, food intake does not decline when energy demand declines) or when they were exercised to exhaustion. This is consistent with the view that the physiology is suited to regulate energy balance best under conditions in which physical activity (energy expenditure) “pulls” appetite. The concept of high energy flux where energy intake is pulled by energy expenditure is illustrated in Figure 1. Mayer further hypothesized that there may be a minimum threshold of either physical activity or energy throughput above which adaptive adjustments in energy intake and expenditure to achieve balance are more sensitive to changes in the other. One hallmark feature of this system bias would be a constant drive to consume energy. This would have been necessary in order to maintain body weight under ancestral lifestyle conditions that undoubtedly demanded a relatively high level of physical activity for survival. Given this hypothesized system bias for optimal control under high energy throughput conditions, this means that an individual having a low energy throughput is constantly at risk for weight gain. A low energy throughput is a prominent feature of sedentary American life today.

There is considerable debate in the literature today about whether physical activity has any role whatsoever in the epidemic of obesity that has swept the globe since the 1980's (18). The timing of the secular rise in body weight fits so well with the expansion of food availability and marketing it seems reasonable to assign significant blame to the food environment. Several arguments are made for this point of view. First, measures of leisure time physical activity have not changed significantly over time (19). Second, measures of total energy expenditure have not declined over the time period during which obesity rates increased (20). This view, however, does not consider the necessary, but not sufficient, effect of the decline in physical activity that occurred in our society (and in those countries undergoing rapid urbanization and industrialization) during the first half of the 20th century. The decline in daily activity that came from industrialization, mechanized transportation, urbanization and other aspects of technology created the largest decline in activity and created the right conditions under which an increase in food access, availability and decreased cost could have a major impact on body weight. In effect, the decline in the daily energy expenditure necessary for subsistence prevalent over a century ago was the “permissive” factor that allowed the effect of the changing food environment to become apparent. Further, as physical activity levels declined, body weight increased, which would have increased total energy expenditure due to increases in RMR and the energy cost of movement (1). It is not surprising that total energy expenditure has not changed, since becoming obese is a way to increase energy expenditure in a sedentary population.

Blundell (personal communication) refers to the zone above the theoretical energy expenditure threshold first proposed by Mayer as the “regulated zone” and the zone below as the “unregulated zone”. Being in the regulated zone would mean having high sensitivity for matching energy intake to energy expenditure and being in the unregulated zone would mean being at much greater risk for positive energy balance and obesity.. Although not definitive, some research supports this view. Blundell et al. (21) demonstrated that at low levels of physical activity, energy intake does not adjust quickly and accurately to changes in energy expenditure, with the result being an increased propensity to gain weight. Similarly, Stubbs et al. (9) reduced physical activity from 1.8 × RMR to 1.4 × RMR in normal weight men studied in a whole room calorimeter, they found that there was not a compensatory reduction in energy intake. This led to positive energy balance and weight gain.

Flatt (22) recently reviewed a compendium of concepts about control of body weight and concluded that there is little evidence that a “low” metabolism plays a significant role in weight gain. Thus, the main contributor to low energy throughput that puts people at risk of weight gain is a low level of physical activity. Increasing energy throughput (i.e increasing energy expenditure) to promote energy balance can be produced either by increasing physical activity or by increasing body mass (i.e., becoming obese)(1). Additional support for this notion comes from many studies showing that a high level of physical activity is associated with low weight gain over time and comparatively low levels of physical activity are associated with high weight gain over time (23-26). Over the past century, the physical activity level of most of the population has declined substantially. While it is theoretically possible to avoid weight gain in this situation, the fact that few people have accomplished this suggests that it is difficult to maintain energy balance at a low energy throughput.

One could hypothesize that the drop in physical activity related energy expenditure over the past century may have pushed a larger and larger fraction of the population into the “unregulated zone”. Much of the dramatic decline in daily activity (and hence, daily energy expenditure) occurred during the first part of the last century as industrialization and urbanization changed typical lifestyles and this may have been a pre-requisite for enabling the increase in obesity seen over the last 30 years. Unfortunately there are no objective measures of physical activity patterns during this period. In the latter part of the 20th century as food price relative to income declined (27) and access, availability (28) and convenience all increased, the physiological system had already been primed for weight gain. Under the prevailing sedentary lifestyle conditions today, gaining weight serves to increase resting metabolic rate and the energy cost of physical activity, thus increasing energy throughput which balances the higher level of energy intake. In this respect, becoming obese is simply an adaptive response to the modern environment, but it is also a “trade-off” for maintaining a low level of physical activity. Indeed, we speculate that becoming obese may be the only way to achieve energy balance when living a sedentary lifestyle in a food abundant environment.

It is important to emphasize that this does not mean that physical activity is the only component of energy balance to focus on in addressing obesity. In fact, the physiological and environmental drivers of food intake are so powerful that we currently have a very poor ability to oppose such forces and produce significant, sustained reductions in energy intake. This does not mean we shouldn't continue to push against these forces, but rather to compliment efforts to change the food environment with strategies to increase energy expenditure. This is a very different strategy than promoting widespread food restriction as the foundational tactic for combatting obesity.

A healthy body weight is maintained with a high level of physical activity and a high energy intake. This would be the well regulated zone where energy intake and energy expenditure are very sensitive to changes in the other. At low levels of physical activity, substantial food restriction would be needed to maintain a healthy body weight. This would be the unregulated zone where energy intake and expenditure are only weakly sensitive to changes in each other. This seems to be an unsustainable situation for most people and the result is weight gain and obesity which returns the system to a high energy throughput.

Food Restriction alone is not the Answer

Food restriction is a common strategy for treating obesity (29). Food restriction does produce weight loss but it also produces compensatory decreases in other components of energy balance, ie. decreases in energy expenditure and body energy stores (1,8,30), and an increase in hunger (31). Because energy requirements fall with weight loss, a common strategy for weight loss maintenance is trying to match a lower level of energy expenditure with a lower energy intake. The lack of success in weight loss maintenance (32) suggests this may not be an optimum strategy. Lowering energy intake is opposed by biology (1,8,30) and the environment (33). Increasing physical activity serves to increase total energy expenditure, allowing for a higher energy intake for a given level of body weight and requiring less food restriction. In fact, individuals who are successful in long-term weight loss maintenance report engaging in high amounts of physical activity (34). Just as restricting food intake is difficult, it is not easy to produce sustained increases in physical activity, but from an energy balance point of view, including physical activity in the strategy would improve the likelihood of successfully matching energy intake and expenditure at a lower body weight.

Energy Balance Implications for Addressing Obesity: Treatment vs Prevention

Two thirds of adults and ~20% of children and adolescents are overweight or obese and could benefit from weight loss (35). Further, much of the population seems to be continuing to gain weight or in the case of children, gain weight at an excessive rate (36,37). Thus there is need for both prevention and treatment of obesity. From an energy balance point of view it should be easier to prevent obesity than to reverse it once it is present. This is because the biological compensatory mechanisms defending body weight appear to respond much more strongly to negative energy balance than to prevention of positive energy balance (8,30). In effect, the system is biased toward preserving existing body weight but does not appear to strongly defend against body weight that has not yet been acquired. Thus, an energy balance framework would predict that it would be easier to prevent weight gain than to produce sustained reductions in body weight in those already obese.

Because metabolism declines with loss of body mass (7,8) (one component of energy balance affects another), energy requirements are greatly reduced following intentional weight loss. The reductions can be from 170-250 kcal/day for a 10% weight loss and 325-480 for a 20% weight loss (38,39). Thus substantial weight loss and subsequent maintenance requires substantial and permanent behavior change. The lack of success in long-term weight loss maintenance (32) suggests most people are not able to sustain the degree of behavior change they need to keep weight off.

Compensatory reductions in RMR and increases in hunger occur with caloric restriction and weight loss (1,31). However, simply preventing positive energy balance should not produce significant compensation through increased energy intake or reduction in RMR. A reasonable starting point in addressing obesity is to develop behavior goals for primary prevention of weight gain. In energy balance terms, this would require less change than producing and maintaining weight loss since the degree of positive energy balance producing this gradual weight gain seems to be relatively small.

Hill et al. reported (36), using longitudinal and cross sectional data sets, that the average weight gain of the population over the past two decades (when obesity increased most rapidly) has been about one to two pounds per year. Using a very conservative analysis of the distribution of weight gain over time, they estimated that the average weight gain was due to about 15 kcal/day of positive energy balance. At the 90th percentile of weight gain, this was 50 kcal/day. By assuming that excess energy is stored with a 50% efficiency, they predicted that weight gain in 90 percent of the adult population could be prevented by reducing positive energy balance by 100 kcal/day. We termed this the “enegy gap”. Wang et al. (37) estimated that excessive weight gain could be prevented in children and adolescents by reducing positive energy balance by about 150 kcal/day.

A population weight gain prevention strategy need only advocate small changes in physical activity and energy intake to be successful. Such a program could concentrate on increasing lifestyle physical activity and on helping focus people on reducing energy density and portion size of some foods consumed. One program based on this concept is the America on the Move (AOM) program (40; www.americaonthemove.org), a national weight gain prevention program that advocates walking 2,000 more steps each day and eating 100 kcal less each day. Evidence indicates this program is effective in increasing total physical activity, reducing energy intake, and reducing excessive weight gain (41-44). In particular, the AOM small changes approach was used to reduce weight gain in overweight and obese children when delivered as part of a family-based intervention (42,43). As compared to the control group, the group receiving the small changes intervention reduced relative body mass index over time. The small changes intervention involved increasing walking as measured by pedometers and making small changes in food intake such as eating breakfast or substituting foods/beverages with non-caloric sweeteners for those containing sugar. Other researchers have demonstrated the effectiveness of a small change approach for promoting weight loss when compared to a standard didactically based nutrition and physical activity program (45-48). The main features of the small change model that distinguish it from other models of behavior change are: 1) the starting point is a change from an individual's baseline, 2) the individual is involved in setting their own goal vs. being given a goal by the program, and 3) the changes required are small and manageable so that the individual does not feel restricted or overburdened (48).

It is sometimes suggested in the popular media that the small changes strategy will be effective for substantial weight loss versus its intention as a means to eliminate primary weight gain. For example, it has been suggested that cutting 100 kcal/day from energy intake could result in losing 10 pounds per year and 50 pounds over 5 years. This argument fails to recognize the interrelatedness of components of energy balance. In fact, cutting 100 kcal/day would produce some weight loss but far less than 10 pounds per year (15), because as the body loses mass its energy requirements fall and the 100 kcal cut from the diet becomes a smaller and smaller energy deficit each day. This is why the small changes approach is designed as a means to prevent weight gain rather than promote weight loss and a daily effort to increase activity and decrease intake by 100 kcal does not lose its power to reduce positive energy balance over time.

It is especially important that we apply weight gain prevention strategies to children. Many children are also gaining weight at excessive rates (37) due to the same factors that promote increased energy intake and decreased physical activity in adults. The same tactics that influence energy intake and expenditure in adults have an impact on children. The RMR and TEF may be greater for growing children per kg body mass than in adults, but low levels of physical activity still promote positive energy balance. This impact may be even greater because historically high levels of physical activity were common for children and youth in activities of daily life. The establishment of healthy weight in early life is particularly important for long-term health. The responsibility of parents, caregivers and teachers to facilitate healthy eating and regular physical activity is greater in today's society. Young children should be active more than they are sedentary (49) during their waking hours which may be a significant challenge in our contemporary sedentary society. Pediatricians regularly provide guidance about nutritional needs of children, however physical activity guidance is much less specific. Recent guidelines (50) suggest that appropriate physical activity levels for young children are greater than for adolescents or adults.

How to Produce Behavior Changes in the Population

Even if we agree on population strategies and on the type and amount of behavior change needed to address obesity, we still need quantitative goals for behavior change and we still have the enormous challenge of producing this behavior change in the population. There is increasing recognition that the physical environment impacts behavior (33), and there are increasing efforts to understand and modify the physical environment to help people achieve healthier lifestyles (51). However, it seems unlikely that we can modify the environment sufficiently so that most people would maintain a healthy lifestyle without conscious effort. If we are asking individuals to take some personal responsibility in making these behavior changes, we should make sure they have the cognitive skills needed to move toward healthier lifestyles. We believe there is a great need to evaluate the potential impact of teaching our children about energy balance (i.e. how energy in food interacts with energy expenditure to determine body weight) and about how food and physical activity choices impact energy balance.

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Summary and Recommendations

Looking at reducing obesity through the lens of the energy balance framework provides the opportunity to recommend specific strategies to reduce obesity. First, by increasing physical activity in the population we can get more people in the regulated zone of energy balance and maximize the intrinsic biological mechanisms for managing energy balance. Accomplishing this would allow us to focus on promoting smarter eating and reduce the need for dramatic food restriction. Second, we are likely going to be more effective in preventing weight gain than in producing and maintaining weight loss. This is because components of energy balance compensate to oppose weight loss in response to negative energy balance. Finally, in our current environment, maintaining a healthy body weight for most people requires using cognitive skills to help match energy intake with energy expenditure and to overcome biological tendencies to overeat and underexercise. Teaching those skills to people and particularly to children could empower them with better tools to be active participants in managing their own body weight. Simultaneously we should intensity efforts to modify the physical environment to make healthier choices both more available and accessible while increasing their perceived value by consumers.

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Acknowledgments

Funding Sources

The work described in this manuscript was supported in part by NIH grants DK42549 and DK48520.

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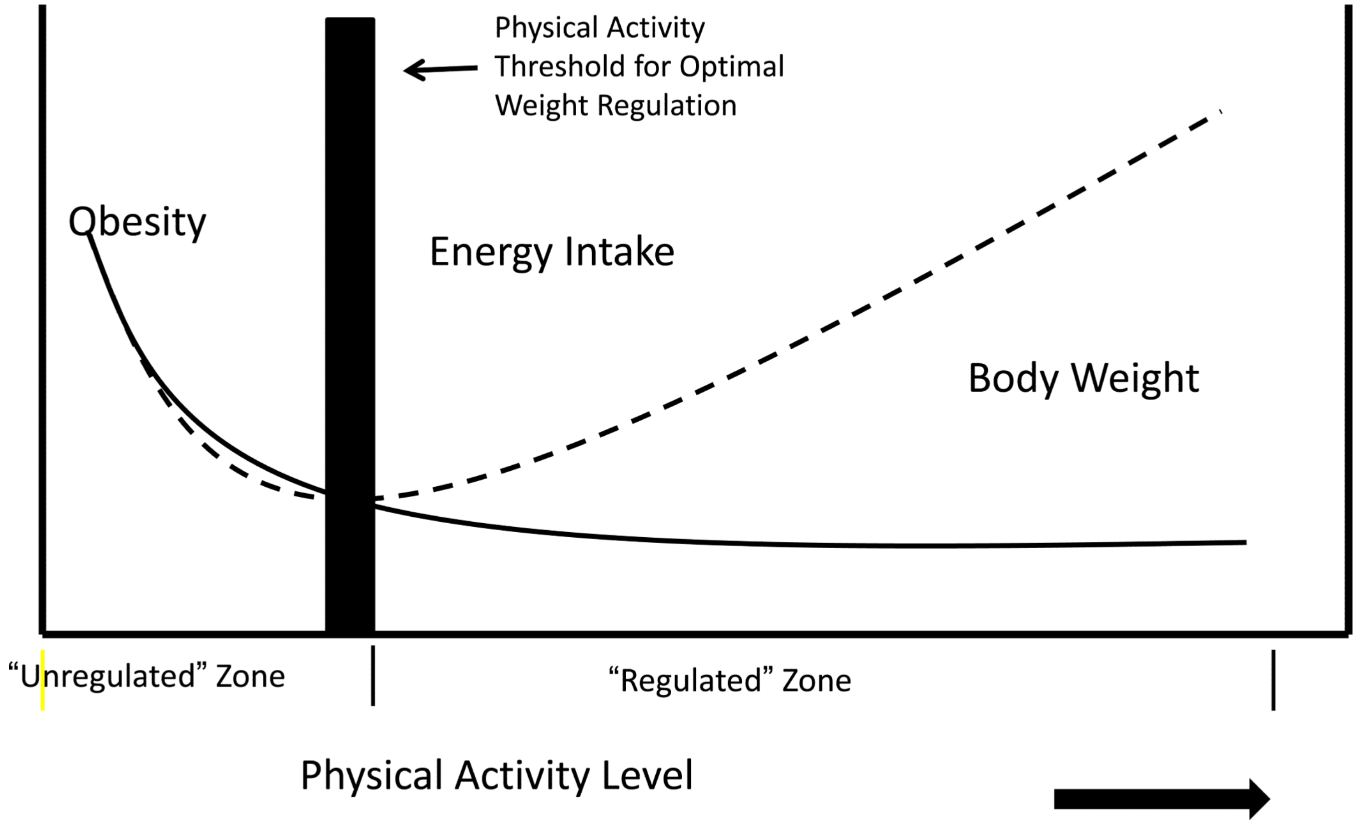

Figure 1.
This figure, modified from the work of Jean Mayer and colleagues, illustrates the hypothesis that energy balance may be easier to achieve at high energy throughput (ie. high energy expenditure). We illustrate the concept to a threshold for physical activity, above which people are in the regulated zone of energy balance and below which they are in the unregulated zone. In the regulated zone energy intake is “pulled along” to meet high energy needs, and energy intake and expenditure are very sensitive to changes in each other. At low energy throughput, energy intake and expenditure are only weakly sensitive to changes in each other and maintaining a healthy body weight requires sustained food restriction.