

Chapter 2

Physiological Bases of Physical Limitations During Exercise

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Abstract During the execution of physical activity, obese individuals suffer from considerable functional limitations which are principally related to the excess of their body mass, more than to other morbid conditions co-occurring with obesity. Important changes in body composition are associated with the rise in body adiposity, so that obese persons, and women in particular, result with a lower amount of fat-free mass and leg muscle volume per unit body mass, but with absolute larger quantities. Therefore, motor performance of obese individuals during anaerobic activity, which includes the execution of short and intense efforts, is largely reduced by the imbalance between the size of available skeletal muscle and the disproportionate accumulation of fat tissue, although the capacity of strength and absolute leg power output production are increased. Differently, activities relying upon aerobic metabolism, such as bicycle ergometer exercise or walking, are limited in obese subjects principally due to the greater metabolic energy required to move the heavier body, or single body segments involved in movements, which may ultimately exceed the limits of the aerobic capacity. The physiological mechanisms underlying these functional limitations during exercise in obesity should be considered when devising protocols of physical activity and rehabilitation aiming to cure the body mass excess.

2.1 Engines, Fuel, and Performance

In much the same way as cars do, humans move in the space, perform mechanical work, consume fuel, and achieve a power performance. It is remarkable that Dorothy M. Needham, one of the most eminent biochemists of the past century, titled *Machina Carnis* [i.e. muscle machine] her comprehensive book considering the nature of the biochemical processes fuelling the muscle engine and the complex regulation of its energy supply (Needham 1971).

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Indeed, muscles accomplish the essential task to produce force and motion taking energy from the chemical fuel originally coming from foods, not so different from the combustion engines of ordinary cars. To this end, the energy contained in chemical bonds of the high-energy phosphate substance adenosine triphosphate (ATP), considered as the ultimate energy source for muscle contraction, is made available as free energy by chemical splitting and is used to produce mechanical work, while part is degraded as heat. For a detailed account of the biochemical pathways supporting muscle energetics, the readers are referred to the excellent review by Pietro E. di Prampero (di Prampero 1981), which links with clearness the energy processes at cellular level with physiological phenomena detectable at whole organism level in the exercising individual.

In a concise formulation, all energy required for muscle shortening is provided by the breakdown of ATP at cellular level. Nevertheless, energy supply provided by ATP stores within the muscle is relatively limited, and the process of ATP refurnishing takes place concomitant with utilization.

When exercise has an intensity requiring an amount of energy compatible with the kinetics of the refurnishing process, ATP is restored by means of oxidative mechanisms consuming oxygen and utilizing the body stores of carbohydrates and fats as substrate, and exercise can be maintained for a long duration (several minutes or longer) in a steady-state condition (aerobic exercise). Differently, when exercise has an intensity which outbalances the capability of the mechanisms for energy restoration, it is supported for a limited period (several seconds) by the ATP sources at muscular level (anaerobic exercise).

The great deal of physiological responses intervening in the course of aerobic exercise substantially represent the functional adjustment of the elements belonging to the oxygen transport pathway from ambient air to mitochondria to the increased oxygen flow required by exercising muscles. In conditions of metabolic steady-state during exercise at constant intensity, the pulmonary inflow of oxygen measured by assessing the respiratory gas exchanges with the technique of indirect calorimetry does correspond to the oxygen consumed at cellular level. Thus, due to the stoichiometric nature of the relation between utilized oxygen and ATP yield, the amount of oxygen consumed during aerobic submaximal exercise corresponds to the actual energy required to sustain that physical activity. In fact, depending on the oxidized substrate, 1 L of oxygen consumed has an energy equivalent ranging from 4.7 kcal (or 19.6 kJ), when lipid oxidation is the sole source of energy, to 5.1 kcal (or 21.1 kJ), when carbohydrates are the sole source of energy.

Therefore, during exercise when muscles actively shorten producing mechanical work under aerobic conditions, the rate of oxygen consumption (VO_2) increases progressively as exercise intensity rises. Figure 2.1 illustrates the relation between VO_2 and exercise intensity for a young man running on a treadmill. Data shown in the figure are taken from a historical record obtained by Rodolfo Margaria in Pavia in the late 1930s (Margaria 1938), but they are fairly representative of the physiological responses associated with the energetics of exercise which can also be investigated with modern technologies.

Figure 2.1 represents the common knowledge of how VO_2 relates substantially linearly to exercise intensity during a typical incremental test (region between

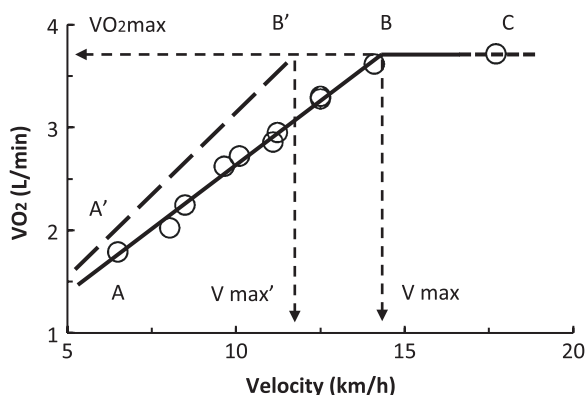


Fig. 2.1 The relationship between the rate of oxygen consumption (VO_2) and running velocity on treadmill. The single data points are obtained in a young man exercising at steady-state conditions and enable the determination of the individual's maximal aerobic capacity ($\text{VO}_{2\text{max}}$) and the maximal aerobic performance (V_{max}). The prediction of exercise energetics performed while wearing an added weight is represented by the broken line, which also indicates maximal aerobic performance during loaded running (V'_{max}). See text for details. (Data from Margaria 1938)

points A and B) and ignores the upward deviation in VO_2 occurring during prolonged exercise at high workloads. Above point B, the relation levels off (region between points B and C) and the plateau in VO_2 represents the individual's maximal capacity to transfer oxygen from the ambient air to the mitochondria ($\text{VO}_{2\text{max}}$), either determined by metabolic oxidative capacity limitation in muscle mitochondria or by oxygen supply limitation at some step in the oxygen transport pathway, depending on the ongoing physiological scenario. For an integrative view of the factors limiting maximal oxygen transfer, the readers may enjoy a recent comprehensive review by Wagner (2006).

To a first approximation, point B also indicates the maximal exercise performance (V_{max}) which could be sustained aerobically. Below point B, in conditions corresponding to submaximal exercise, VO_2 increases with exercise intensity and in steady-state conditions exactly matches the amount of oxygen required by exercising muscles to perform that kind and intensity of mechanical work. The incline of the line for the relation between VO_2 and exercise intensity is dependent on the energy required for that specific activity (i.e. running on treadmill, for the case depicted in Fig. 2.1). For individuals with similar body mass, structure, and shape, moving their body segments according to the same biomechanical paradigm and to the same physiological coordination pattern of skeletal muscles involvement, the energy cost of a given physical activity is expected to be similar (Taylor et al. 1982), so that VO_2 required for running at a given submaximal velocity is the same for different individuals, independent of their $\text{VO}_{2\text{max}}$.

Nevertheless, the overall energy required for exercise performance is also strongly influenced by the mass of the body or the body segments involved in motion during the specific exercise activity under consideration. During terrestrial locomotion, humans have to perform at each step a given amount of mechanical

work to propel forward their body mass, so that the subject's own weight is an important determinant of the energy required for locomotion. From several experiments performed with the application to the trunk of an external weight in healthy lean subjects during locomotion, it can be predicted that the costs of supporting and accelerating body mass could be increased in direct proportion to the extra mass supported by the exercising muscles (Taylor et al. 1980). Thus, according to this model, we could imagine that the subject represented in Fig. 2.1 would display a left shift in the relation VO_2 -velocity if wearing a weight jacket with a load of about 15 % of his body weight while running on the treadmill under aerobic conditions. In Fig. 2.1, the broken line with a steeper slope shown in the region A'-B' indicates a higher energy requirement for the loaded running, which implies the consequence of attaining the plateau of $\text{VO}_{2\text{max}}$ at a lower maximal velocity ($V_{\text{max'}}$). Therefore, it appears that the individual's maximal performance in aerobic conditions depends upon both his maximal aerobic capacity and the energy cost of exercise.

It is relevant to understand the interplay between the variables such as the individual's aerobic capacity, the metabolic energy required for exercise, and the maximal aerobic performance since in obesity these reference parameters undergo changes which may seriously interfere with the individual's capability to sustain the execution of specific physical exercise and, in certain cases, even of simple movements associated with everyday life activities.

2.2 Muscle Engine and Muscle Functioning: Implications for Maximal Strength, Power Output, and Anaerobic Performance

2.2.1 Body Composition

The most self-evident structural body change in obesity is an enormous global increase in fat tissue accumulation, which greatly affects body composition in obese people, with important consequences for motor activity.

The main parameters characterizing body composition according to a two-compartment model (see Ellis 2000, for a comprehensive review of models and methods for the estimate of body composition) in a typical sample of young seriously obese men and women ($\text{BMI} > 35 \text{ kg/m}^2$) are shown in Table 2.1 and compared with those coming from a sample of normal weight individuals of the same age and body frame. Apart from the striking difference in the amount of fat tissue between the two groups, it is interesting to note the trend of fat-free mass (FFM). It can be appreciated that, in normal weight individuals, FFM constitutes the largest share of body mass (although with significant differences between men and women), and this percent is to a great extent reduced in obese individuals and even outbalanced by fat mass. By contrast, when considered in absolute terms of mass units, FFM is actually significantly increased in obese men and women in comparison with their respective normal weight counterpart.

Table 2.1 Average values (\pm SD, in parentheses) of anthropometric and body composition parameters in two healthy groups of normal weight (NW) and obese (OB) young men and women, matched for age and height

	NW ($n = 22$) ^a		OB ($n = 22$) ^b	
	Males	Females	Males	Females
Age (years)	27.3 (4.3)	27.9 (3.8)	27.2 (3.2)	27.9 (3.6)
Height (m)	1.75 (0.05)	1.64 (0.06)	1.75 (0.07)	1.64 (0.05)
Body mass (kg)	68.0 (6.6)	57.8 (7.1)	130.6 ^c (12.3)	113.7 ^c (12.1)
Body mass index (kg/m ²)	22.2 (1.7)	21.6 (2.0)	42.6 ^c (3.3)	42.1 ^c (2.9)
Fat mass (kg)	7.3 (3.7)	16.6 (5.1)	59.2 ^c (6.0)	58.9 ^c (7.3)
Fat-free mass (kg)	60.7 (4.7)	44.2 (3.8)	71.4 ^c (8.0)	54.9 ^c (5.8)
Fat-free mass (%)	89.6 (4.7)	77.0 (6.5)	54.6 ^c (2.7)	48.3 ^c (2.5)

^aUnpublished data from the Laboratory of Biomechanics at Istituto di Bioimmagini e Fisiologia Molecolare del CNR, Segrate (MI); ^bdata selected from the cohort published in Lafortuna et al. (2012) to match the NW group; ^csignificantly different from the NW counterpart ($p < 0.001$, Student's t test for unpaired data)

Bearing in mind that FFM is an indicator, though rather crude, of skeletal muscle mass, it can be easily realized that these very simple relations have relevant repercussions on the performance of the different motor activities powered by the muscle action. In fact, during brisk movements entailing body displacement which require a considerable power output under anaerobic conditions (such as stepping up a ramp of stairs or performing short sprints) the determinant of actual performance is the ratio between the muscle mass and total body mass, which dictates the power output per unit body mass (Lafortuna et al. 2002).

Differently, during static (or quasi static) actions with a relevant development of strength, the performance is mainly determined by the absolute size of involved muscles (Maughan et al. 1983; Fukunaga et al. 2001b).

2.2.2 Skeletal Muscle Size

In spite of a relative abundance of studies which report body composition trends in relation with body adiposity and provide evidence of a definite increase of FFM as a function of BMI (Norgan 1994; Schutz et al. 2002; Lafortuna et al. 2004, 2005), investigations addressing the effects of obesity on muscle characteristics are surprisingly scanty.

Indeed, skeletal muscle can be characterized by quantitative (size) and qualitative (composition) structural attributes which concur in determining functional

performance. A recent study, conducted on a sample of men and women with different body adiposity, investigated these structural characteristics in lower limb muscles with computed tomography (CT) and image analysis (Lafortuna et al. Influence of body adiposity on structural characteristics of skeletal muscle in men and women. unpublished data). The volume of muscle, after accounting for limb length and age, resulted to increase significantly with the degree of body adiposity in both genders, although at a lower rate in women, a trend similar to that observed for FFM. In fact, from these results it can be established that overall leg muscle volume increases on average by about 2.4 kg every 5 BMI units in man and about 1.3 kg in females, when variations due to age are accounted for. This muscle enlargement can be viewed as an adaptive response to increased body mass which acts as a chronic training load during everyday motor activity. Indeed skeletal muscle is an adaptable tissue actively responding to mechanical loading, in addition to growth factors and nutrients, and is finely regulated by a complex and not completely understood cellular signalling network ultimately controlling protein synthesis and sarcomere addition [for a recent review of muscle responses to mechanical loading of exercise the reader may (see Miyazaki and Esser 2009)]. Unfortunately, at present no study has been performed to detect the involvement of any regulatory process specifically controlling the muscle response to the obesity-related mechanical overload.

Otherwise, when the volume of muscle in lower limbs is expressed per unit body mass, which may be considered as an indicator of leg muscle amount available for the displacement of each kilogram of the whole body during the movements relying upon leg action, adiposity plays a negative role, particularly in women.

2.2.3 Muscle Structure: Function Relationships

Thus, most importantly, these variations of muscle size due to the effect of body adiposity closely influence the individual's functional capabilities for movements, both in relation to its absolute quantity or relative to body mass, according to the relevant function considered. In Fig. 2.2 leg muscle volume normalized by limb length (panel *a*), representing the average muscle cross-sectional area (CSA) through the whole limb, or normalized by body mass (panel *b*), representing the limb muscle available per unit body mass, is plotted against BMI in men and women over a range of body adiposity. In the lower panels of the figure, the functional correlates of these parameters obtained in obese individuals are plotted against BMI. Panel *c* shows the trend of peak force expressed during the push phase of a vertical jump performed under conditions of maximal effort, whereas average power output per unit body mass developed during a Margaria stair climbing test (Margaria et al. 1966), which correlates directly with the real performance such as the ascending velocity, is illustrated in panel *d*. Overall, the figure shows how motor functions parallel the structural changes intervening at different degrees of obesity. A similar relationship between body composition and muscle performance has been observed also among obese children and adolescent in whom FFM was a positive

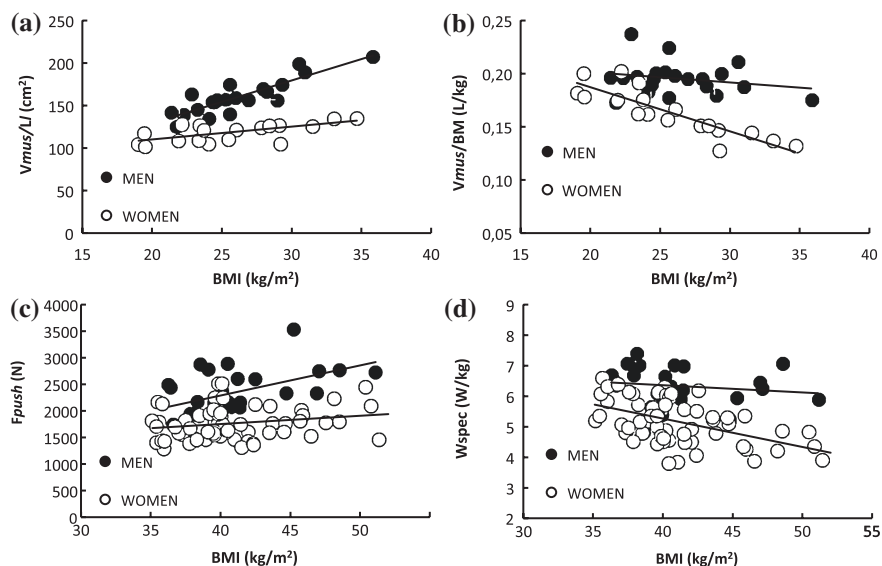


Fig. 2.2 The effect of body adiposity on skeletal muscle structure and performance in men and women. The volume of leg muscle normalized per limb length (V_{mus}/LI) and per body mass (V_{mus}/BM) is plotted as a function of BMI (panels *a* and *b*). Peak force expressed during the push phase (P_{push}) of a vertical jump performed under conditions of maximal effort (panel *c*) and average mass-specific maximal power output (W_{spec}) during a stair climbing test (panel *d*) are plotted against BMI. *Closed circles* males; *open circles* females. Regression lines through the data are shown as continuous lines. (Data in panels *a* and *b* from Lafortuna et al. Influence of body adiposity on structural characteristics of skeletal muscle in men and women. unpublished data; in panels *c* and *d* from Lafortuna et al. 2005)

linear correlate of absolute lower limb power output, independent of the different body composition ensuing between boys and girls at puberty (Sartorio et al. 2006).

Contrasting a group of extremely obese young men with a counterpart of lean individuals matched by age and stature, Maffiuletti et al. (2007) found that obese subjects display significantly more elevated absolute but lower relative (per unit body mass) muscle torque and power output during isometric and isokinetic knee extensions. Pescatello et al. (2007) reported similar results concerning peak isometric and isotonic elbow strength in a quite large sample of overweight/obese and normal weight individuals, detecting also a significantly larger CSA of biceps muscle in overweight/obese group. Such trends in absolute and relative strength for effect of obesity have been found also among male adolescents performing isometric knee extensions (Abdelmoula et al. 2012).

Interestingly, in obese subjects the stronger muscle groups during isotonic exercise, in comparison with normal weight persons, were those mainly involved in movements against the force of gravity (Lafortuna et al. 2004), as similarly reported by Hulens et al. (2001a, b) who observed higher strength in obese women than in the lean counterpart during isokinetic knee extension, but not during knee

flexion and isometric handgrip, reflecting the gravity-related nature of the training effect of obesity overload. Taken as a whole, these results indicate that muscle strength scales with the size of the muscles involved in its production, but a careful allometric model of elbow isometric strength recently suggested that muscle area may not completely determine muscle strength (Zoeller et al. 2008), since other factors such as structural arrangement of fibers within the muscle (i.e. the pennation angle) and the presence of different amounts of intramuscular fat may act as confounding bias.

While it is not known whether obesity-related changes in skeletal muscle attributes involve also modifications of pennation angle, with significant effect on the externally measured strength in relation to muscle CSA, different degrees of fat infiltration in skeletal muscles has been detected with imaging technique in obese individuals. In fact, muscle attenuation on CT images, which is a correlate of tissue density and inversely reflects the extent of lipid infiltration in muscles (Goodpaster et al. 2000), has been observed to decrease with the rise of body adiposity (Lafortuna et al. Influence of body adiposity on structural characteristics of skeletal muscle in men and women. unpublished data). By means of a quantitative evaluation of muscle attenuation, several investigations detected a higher degree of such infiltration within muscles in obesity and older age (Kelley et al. 1991; Ryan and Nicklas 1999) and found it to be associated with reduced motor performances (Hilton et al. 2008; Goodpaster et al. 2001; Visser et al. 2005), besides an increased metabolic risk (Kelley et al. 1991; Goodpaster et al. 1997). Hence, although muscle size is known to be the major predictor of force and power production in the general context (Maughan et al. 1983; Fukunaga et al. 2001b), qualitative attributes of muscle composition such as fat infiltration may be important in determining the association between muscle mass and its function, and, especially in obesity during older age, may be of value to characterize the functional limitation of motor capabilities.

Thus, mainly due to a larger muscle mass, muscle strength and power output in absolute terms have been reported to be substantially higher in obese people under different experimental conditions, although their motor performance during anaerobic tasks requiring brief and intense efforts results considerably reduced. This functional condition is summarized in Fig. 2.3, which compares the value of peak vertical force attained during the push phase of a vertical jump performed under maximal effort by lean and obese young men and shows the relationship resulting between BMI and the vertical displacement of the center of body mass (an indicator of the anaerobic performance) during the same experimental conditions. In spite of the remarkably higher strength developed during this maneuver, the actual performance of obese individuals is fairly lower and decreases with their degree of adiposity.

Finally, a last issue concerning the different effect exerted by body adiposity on muscle size in the two genders should be addressed, in view of the clinical relevance and the potential impact on rehabilitation strategies. As reported above, men and women undergo different changes in body composition along with the increase in body adiposity (see also panel *a* in Fig. 2.2). Due to the lower increase of muscle mass with rising adiposity, the muscle volume per unit body mass (structural correlate of anaerobic performance) decreases considerably in women as a function of

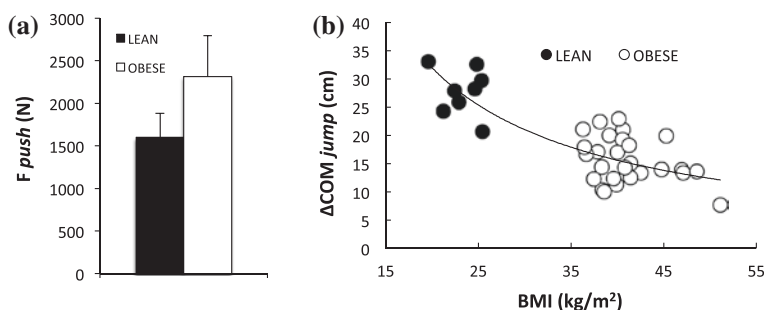


Fig. 2.3 Strength and performance during maximal anaerobic effort in obese and lean young men. Average peak force ($\pm\text{SD}$) expressed during the push phase (P_{push}) of a vertical jump (panel *a*) and effect of BMI on the vertical displacement of body center of mass (ΔCOM) attained during the same test (panel *b*). *Closed symbols* lean subjects; *open symbols* obese subjects. (Data from Lafortuna et al. 2002)

BMI (see panel *b* in Fig. 2.2), with important practical implications. Similar trends have also been reported in the variation of FFM/BM with the degree of obesity (Lafortuna et al. 2005). This raises the hypothesis that different mechanisms may intervene in men and women to regulate muscle size as a function of body adiposity. In fact, it has been observed that even a prolonged heavy strength training stimulus induces a significantly greater increase of muscle volume in males than in females (Ivey et al. 2000). Besides a possible role of the higher levels of masculine testosterone, several gender-related differences in the regulation of growth hormone, as differences in body composition and fat distribution (Roelen et al. 1997), and in leptin plasma concentration (Llopis et al. 1998), may participate in determining such a gender-dependent response of muscle mass to the increase of body adiposity among obese individuals. Moreover, due to the loss of muscle size with advancing age, the concomitance of obesity and older age in females appears to involve a particularly unfavorable condition which exposes them to functional derangements of dynamic performance. Thus, as also evidenced with functional testing in a clinical context (Lafortuna et al. 2004), older women with high degree of obesity are prone more than men to suffer from major reductions in anaerobic leg power output induced by obesity, which may interfere with everyday locomotor abilities and even ultimately lead more rapidly toward thresholds for disabled mobility.

2.3 The Energy Expenditure for Body Movements: Implications for Aerobic Performance

In spite of the definite increase in the size of muscle engine under the effect of body adiposity, which permits the production of higher strength and absolute power, besides a diminished anaerobic performance, as discussed in the previous

section, also the motor performance during the execution of aerobic activity is considerably reduced in obese people.

2.3.1 Maximal Aerobic Capacity

Indeed, the absolute volume of skeletal muscle is a major determinant of the individual's maximal aerobic capacity by providing a greater amount of oxidative machinery, as evidenced by Davies (1973) in a pioneering study on African subjects with a different condition of nutrition and involvement in physical activity. More recently, Tolfrey et al. (2006) showed with an allometric approach in boys and men that lower limb muscle mass is a better predictor of VO₂max than body mass or FFM. Nevertheless, a significant positive linear correlation has been detected for the relationship between VO₂max or VO₂ at anaerobic threshold and FFM in study groups including both lean and obese young women (Lafortuna et al. 2006) or adolescent obese girls (Lafortuna et al. 2009). As a consequence, among obese adults and adolescents, a higher aerobic capacity in absolute terms, although remarkably reduced when considered per unit body mass, is often reported (Lafortuna et al. 2006, 2009; Hulens et al. 2001a). Goran et al. (2000) investigated a sample of subjects composed of a group of children in a spectrum of different body compositions and a group of overweight and normal women, and found that the amount of body fat has no direct influence on maximal aerobic capacity, which in turn depends mainly on FFM, absolute VO₂max resulting significantly higher in obese than in lean subjects, without any significant difference when expressing VO₂max by unit FFM.

Nevertheless, as remarked for anaerobic performance, also during tasks with an aerobic profile, the exercise capacity is remarkably reduced in obesity (Hulens et al. 2001a). In fact, the execution of most modalities of exercise require more mechanical work and demand more energy for obese than for lean individuals, in proportions dictated by the mass of the body parts involved and the biomechanical paradigm employed for the specific movements. Hence, while the greater VO₂ attained by obese subjects at maximal exercise may be considered as the consequence of a larger FFM and muscle mass (as discussed above), the greater values displayed during submaximal work are related to higher energy requirements of the specific motor activity.

2.3.2 Bicycle Exercise

During exercise on bicycle ergometers, the same mechanical external work is performed by obese and normal-weight individuals, since the subjects use mainly their legs to generate a rotary motion and overcome an imposed load acting at the level of the crank resistance. Notwithstanding this mechanical setting, the

energy cost of bicycle ergometer exercise has been found to be increased by about 15–20 % for effect of body mass in the two genders at different ages by several investigators (Anton-Kuchly et al. 1984; Berry et al. 1993; Hulens et al. 2001a; Salvadori et al. 1999; Lafortuna et al. 2006, 2008, 2009).

Anton-Kuchly et al. (1984) estimated that about 60–70 % of such a difference could be attributed to the extra work of moving heavier legs, while the remaining 20–30 % could be explained by the postural activity required to stabilize the larger mass of trunk while pedaling on the ergometer. In fact, Lafortuna et al. (2008) assessed that the net energy required to move the legs was dependent on the degree of body adiposity, and that, when this amount of energy is accounted for, the energy cost of exercise is independent of BMI at all workloads and no difference is detectable between obese and lean individuals. Also, using a model based on pedal frequency, leg mass and workload devised by Francescato et al. (1995) to predict the energy expended for cycling, Lafortuna et al. (2006) obtained evidence that the obesity-related higher energy cost of cycling is largely due to the effect of the higher mass of legs.

In principle, also other factors such as higher oxygen cost of breathing (Kress et al. 1999) and increased proportion of glycolytic IIb type muscle fibers (Kriketos et al. 1997), which have been demonstrated to be substantially less efficient than type I fibers during cycling (Coyle et al. 1992), may contribute to the increased cost of exercise. Nonetheless, the intrinsic muscle efficiency during cycling, as represented by *work efficiency* calculated by the changes of work performed and the energy expended above the condition of free pedaling without load (Berry et al. 1993), has been reported to be similar among obese and lean people (Lafortuna et al. 2008), confirming that the main determinant of higher energy cost of cycling may be better due to the higher energy entailed in limb movements and body stabilization than to intrinsic differences in muscle performance. In Fig. 2.4 is summarized the key findings concerning the energetics of bicycle ergometer exercise in obese and lean individuals. The figure shows the net metabolic energy required for pedaling at different workloads in the two groups (panel a), the energy required for the movements of the legs without any mechanical load (panel b), and the mechanical efficiency of cycling after accounting for the energy of leg movements (panel c).

2.3.3 Walking

Different from the setting of bicycle exercise, during walking, mechanical work is performed involving a large number of body segments to cyclically raise and accelerate the body center of mass at each step, so that the subject's own weight results to be an important load. Therefore, obese people expend much more metabolic energy during walking than non-obese individuals (Melanson et al. 2003; Browning and Kram 2005; Browning et al. 2006; Lafortuna et al. 2008), with values of energy expenditure 1.8 to 2.3-fold higher than those required for

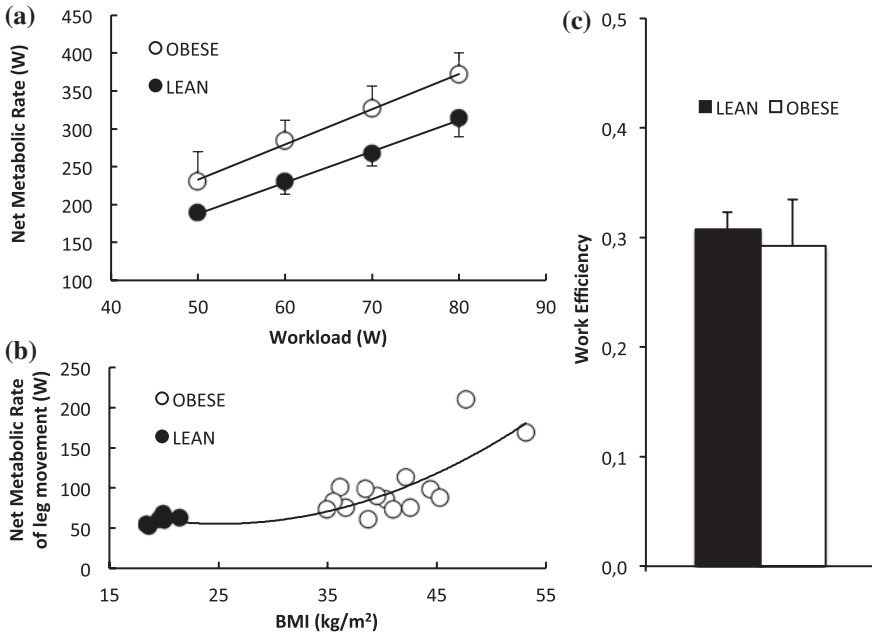
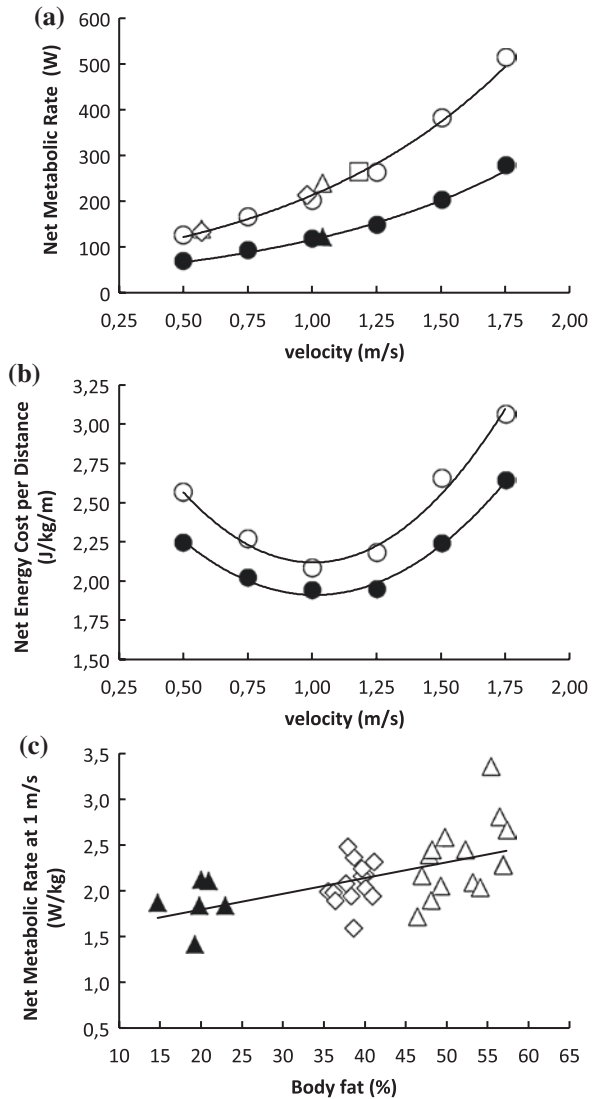


Fig. 2.4 The energetics of bicycle ergometer exercise in obese and lean women. The net metabolic rate required for cycling is plotted against the mechanical workload in panel *a* for the two groups, while the net metabolic rate pertaining to the leg movements without mechanical load is plotted against BMI for each individual subject in panel *b*. The average pedaling *work efficiency*, which accounts for leg movements without load, is shown in panel *c* for obese and lean subjects. *Closed symbols* lean subjects; *open symbols* obese subjects. Vertical bars denote 1 SD. Regression lines through the data are shown as continuous lines. (Data from Lafortuna et al. 2008)

lean individuals, depending on body mass difference, walking speed, and ground incline during locomotion. When the net metabolic rate (gross metabolic cost of standing) is expressed per unit body mass, the difference is considerably reduced but not suppressed. The same trend is also detectable in the energy cost per distance during walking (i.e., the metabolic energy per kilogram body mass to walk a given distance) which has been found to be 5–15 % higher for effect of obesity, as observed by different investigators in obese adults and adolescents (Browning and Kram 2005; Browning et al. 2006; Lafortuna et al. 2008; Peyrot et al. 2009). Interestingly, Browning et al. (2006) found that mass specific metabolic rate and energy cost per distance are related to body composition (body fat %) but not to body mass distribution (thigh mass to body mass ratio).

Figure 2.5 illustrates in panel *a* the large difference in net metabolic energy expended by obese and lean subjects for walking at different velocities, showing in (panel *b*) also the energy per unit body mass and distance, while (panel *c*) presents the relationship between mass-specific metabolic rate expended for walking at 1 m/s and body composition for single individuals with a different degree of body adiposity.

Fig. 2.5 The energetics of walking in obese and lean women and girls. Net metabolic rate in absolute terms and expressed per body mass and per distance (cost per distance) are plotted against walking velocity (panels *a* and *b*). Mass-specific net metabolic rate at the velocity of 1 m/s is plotted as a function of body composition (body fat %) in single individuals ranging from normal weight to obesity classes II and III (panel *c*). Note that mass-specific net metabolic rate at 1 m/s in W/kg numerically corresponds to the net cost per distance in J/kg/m, at the same velocity. Closed symbols: lean subjects; open symbols: obese subjects. Regression lines through the data are also shown in panel *c*. [Circles adult women from Browning and Kram 2005; triangles adult women from Lafortuna et al. (2008); squares adult women from Mattsson et al. (1997); diamonds adolescent girls from Lafortuna et al. (2010)]



Thus, due to the higher metabolic energy expended by obese individuals, walking may be an exhausting task, requiring a considerable fraction of the individual's aerobic maximal capacity. Young obese women walking at 1.3 m/s on 4 % incline have been reported to exercise at about 75 % of their maximal capacity, while the lean counterpart did at about 50 % (Lafortuna et al. 2008). It is conceivable that such a task may be scarcely sustained by older and less fit individuals, as confirmed by the findings of Mattsson et al. (1997).

Overall, these findings evidence that total body mass is a primary determinant of metabolic energy required for walking, but obesity plays an unfavorable role also due to other factors, besides weight excess.

As will be addressed in greater detail in [Chap. 3](#), several biomechanical factors may affect the metabolic cost of walking and could explain the lower economy of obese locomotion. Step width and hip abduction have been observed to be amplified in obese individuals (Spyropoulos et al. 1991), which require a larger metabolic cost of walking (Donelan et al. 2001). Moreover, obese subjects walk with a greater magnitude of ankle dorsiflexion and lesser magnitude of ankle plantar flexion (Spyropoulos et al. 1991) and this may substantially alter the interplay between stretch and recoil of tendon/muscle tissue (Fukunaga et al. 2001a) and contrast an efficient recovery of elastic energy at the end of the contact phase (Ishikawa et al. 2005). In the foot of the obese individual, a significantly reduced plantar arch height and large alterations in pressure distribution (Hills et al. 2001), may also adversely affect foot mechanics during walking gait (Messier et al. 1994), reducing the plantar aponeurosis deformation during foot contact and interfering with the kinetics of elastic energy storage (Ker et al. 1987). Furthermore, it has been argued that body distribution of adiposity rather than body weight per se, might be an important determinant of the metabolic cost of obese locomotion, the greater cost of walking being associated to the extra mechanical work deriving from a larger momentum of inertia due to disproportionately heavier limbs (Myers and Steudel 1985; Saibene and Minetti 2003; Browning et al. 2007), but experimental evidence about the contribution of thigh mass to body mass ratio in obese subjects is still inconclusive (Browning et al. 2006).

Nevertheless, based on the results obtained from experiments with additional weights to the legs of lean subjects, it is debated (Browning and Kram 2009) that one expects that the energy cost of walking for obese people would be fairly higher than actually observed (i.e. around 10 % over that of non-obese individuals), and some optimizing strategy in movements might be involved enabling obese subjects to consume less energy for walking than expected. In spite of its attractiveness, unfortunately such a hypothesis appears substantially speculative at present.

2.4 Functional Limitations During Exercise and Impact for the Prescription of Physical Activity

While the execution of short and brisk movements of chiefly anaerobic character is principally limited in obese people by the imbalance between the size of skeletal muscle and the disproportionate accumulation of fat tissue, the aerobic performance is mainly reduced due to the greater metabolic energy required to move the heavier body, or single body segments.

Thus, a major priority of exercise prescription is to focus on activities which contribute to muscular fitness and preserve muscle mass. This goal seems important also in view of the effects of caloric restriction (a powerful tool against weight excess concomitantly used with physical activity) which result in reductions in both fat and fat-free mass. A net loss of muscle tissue would have negative

outcomes on both anaerobic and aerobic functions, especially in women who are inherently endowed with a lower amount of skeletal muscle relative to body mass.

During aerobic activity such as ergometer cycling or walking, the relative aerobic effort at a given exercise intensity (cycling workload or walking velocity) is higher for obese individuals compared with the lean counterpart and during relatively severe exercise the energy requirements may approach or even exceed the limits of the individual's aerobic capacity (Salvadori et al. 1999; Browning and Kram 2005; Lafortuna et al. 2006; Lafortuna et al. 2008). Therefore, also in view of a considerable degree of sedentariness and poor aerobic conditioning frequently observed in obese individuals, the employment of protocols aiming at improving the cardiovascular endurance should be encouraged with a scheme appropriate for obese people.

Finally, the comparison of the physiological responses to cycling and walking is very interesting for the formulation of exercise protocols suitable for obese individuals.

Based on the fact that a smaller muscle mass is used in cycling exercise to attain the same metabolic energy expenditure of walking (Hermansen and Saltin 1969), with a greater metabolic stress and energy requirement per unit of contracting muscle (Koyal et al. 1976), it has been evidenced in obese adults and adolescents (Lafortuna et al. 2008, 2010) that walking is a convenient mode of exercise, compared to cycling. Walking permits in fact to attain any given energy expenditure at a comparatively lower average heart rate (or in a shorter time), with lower lactic acid blood concentration and higher fat oxidation.

In practice, by some reckoning from these data comparing the metabolic responses of the two modalities, to obtain the energy expenditure of 250 kcal with a bout of 25 min activity, cycling should be performed at an intensity requiring an average heart rate of about 160 b/min with 3 g of lipids oxidation, whereas it will be sufficient to walk at intensity requiring an average heart rate of about 130 b/min, with over 11 g of lipid oxidation.

Under this perspective, for obese individuals, inherently limited in their work capacity, it is very attractive to devise forms of physical activity enabling the attainment of a considerable energy expenditure by preference promoting substantial fat oxidation with the lower subjective perception of effort and exercise intensity, which could ultimately allow a better tolerance and adherence to physical activity protocols.

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