2. THE ENERGY HOUSEHOLD OF THE BODY
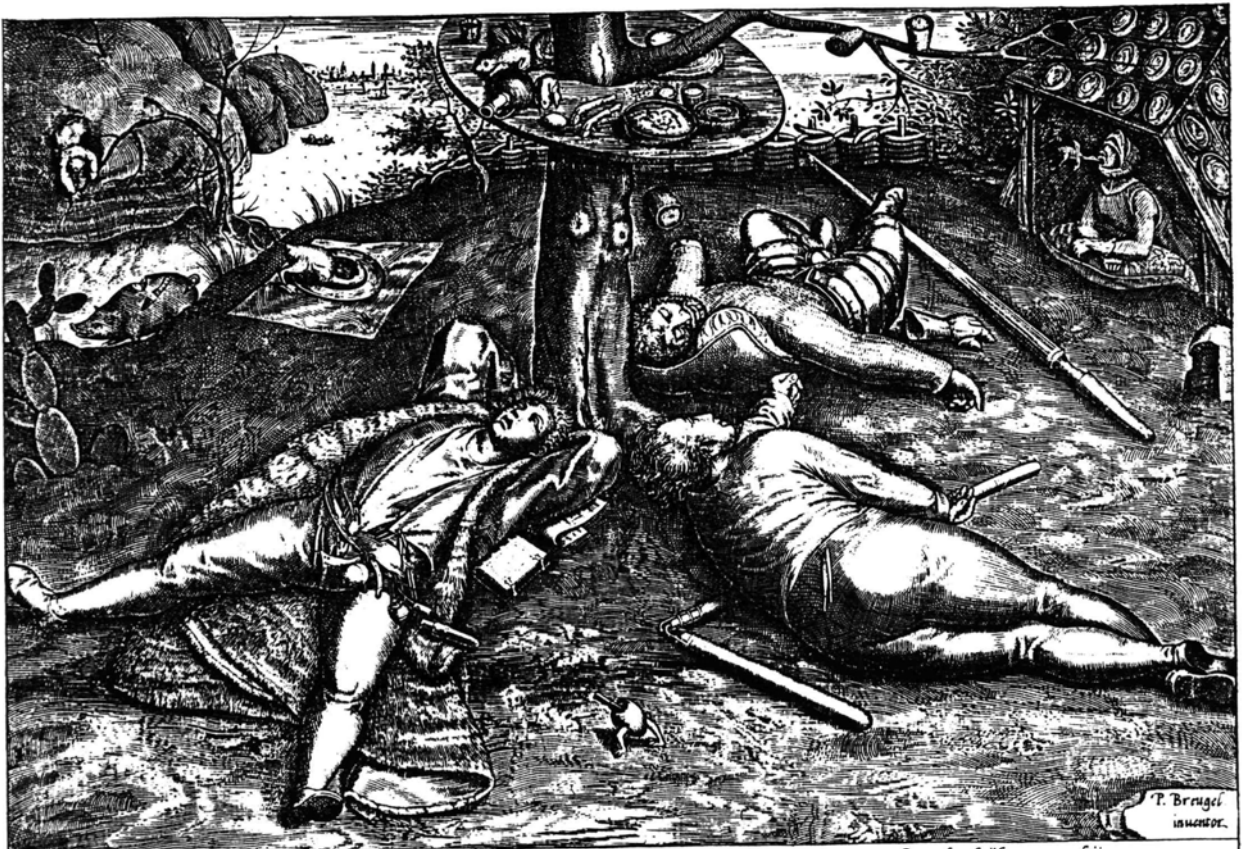
2.2. *ENERGY CONSUMPTION OF THE BODY*

Die dâr luy en lacker fyt bôr crijfman oft clercken
die gheraeckt daer en fmaeckt cluk van als fonder werken

Die tuijnen fijn worsten die huijfen met vlayen
cappuijnen en kieckens tvluechter al ghebrayen

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inuentor.

When no external work is done the lowest oxygen consumption rate is obtained, the internal energy diminishes at its lowest rate, BMR; the **basal metabolic rate,**

$$\frac{\Delta W}{\Delta t} = 0; \quad \text{BMR} = \frac{\Delta U}{\Delta t} \approx 70 kcal/h = 81W;$$

The BMR is the rate at which the internal energy of the organism decreases while fasting and being completely at rest!
Basal metabolic rate for all mammals correlates with the body mass M (in the above example M≈65kg):

$$\text{BMR} = \frac{\Delta U}{\Delta t} = C \cdot M^{3/4};$$

with C≈ 90 kcal/kg$^{3/4}$; **Kleiber's Law**
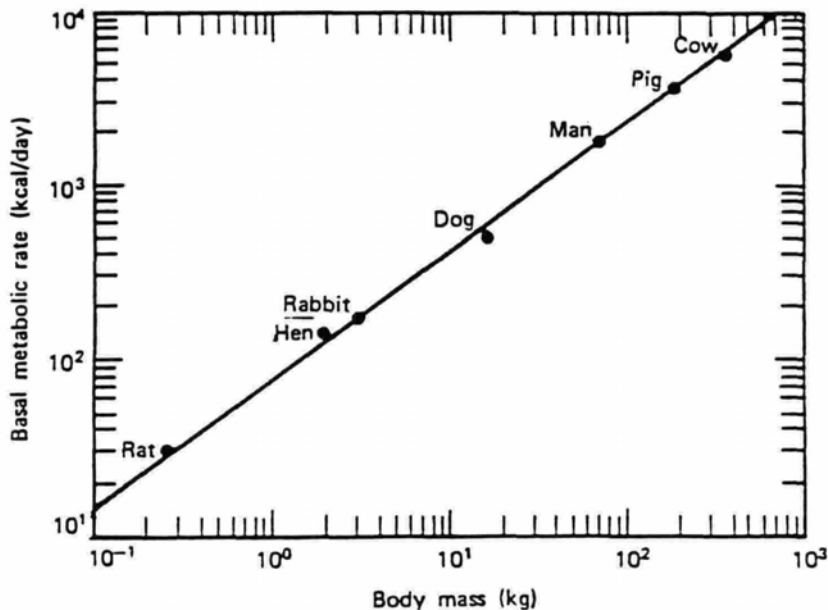
Kleiber's law represents a biological scaling law which is physiologically justified by the argument that the basal metabolic rate is corresponds directly to the cross sectional area of the muscle mass in the mammal. This area varies with $M^{3/4}$.

The basal metabolic rate reflects the rate at which each organ and part of the body does internal work! For example work done by

- heart (*pumping blood through the blood vessels*)
- lung (*breathing*)
- liver (*chemical processes*)
- kidney (*separating waste products*)
- brain (*thinking*)

$$BMR = \frac{\Delta U}{\Delta t} = \frac{\Delta Q_{heart}}{\Delta t} + \frac{\Delta Q_{lung}}{\Delta t} + \frac{\Delta Q_{liver}}{\Delta t} + \frac{\Delta Q_{kidney}}{\Delta t} + \frac{\Delta Q_{brain}}{\Delta t} + \frac{\Delta Q_{etc}}{\Delta t}$$

The following table lists the contributions of the various body organs to the BMR and the necessary rate of oxygen consumption

Organ	Rate of Energy Consumption (Expt.) $\left(\frac{dO_2}{dt}\right)$		Percent of Basal Metabolic Rate	Rate of Energy Consumption (Theoretical)
	(ml/min)	(kcal/day)		(kcal/day)
Heart	17	117	~7%	140
Lung				35
Kidney	26	180	~10%	$(.74/e) \approx 180$
Liver & Spleen	67	470	~27%	
Brain	47	325	~19%	
Skeletal Muscle	45	310	~18%	
(Remainder by difference)	48	328	~19%	
Total	~250	1730	100%	

The brain constitutes only 2.5% of body weight, but is responsible for ≈ 20% of the BMR (dreams). *It requires a fair amount of oxygen consumption.*

All activities, from slow walking to race bicycling require the body to do external work:

$$\frac{\Delta W}{\Delta t} > 0$$

It also requires a higher rate of oxygen consumption and an increase in the metabolic (catabolic) rate $\Delta U/\Delta t$. The released internal energy ΔU is partly used to do the external work but converts partly into heat which is irridiated into the outer environment.
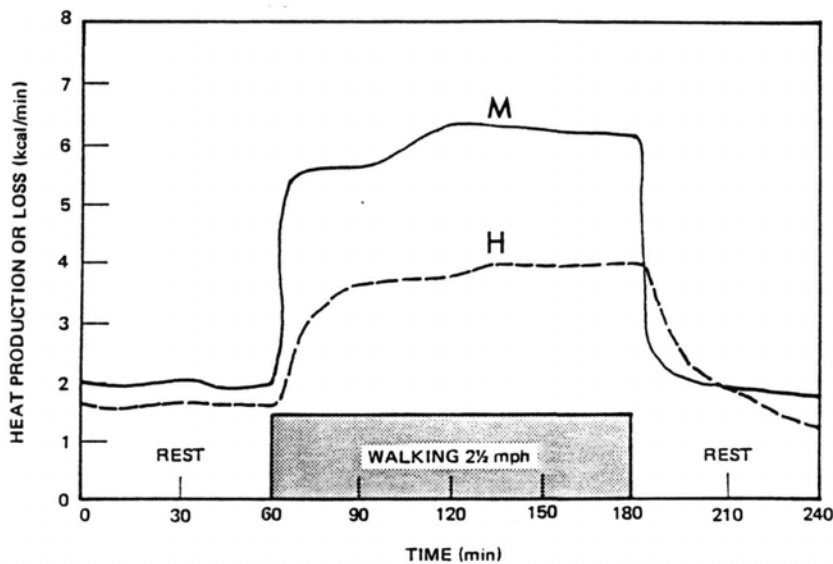
example: lecturing originates heat flow of 100 - 300 W/person
figure shows an average heat production **M** by change of internal energy of 390 $kcal/hr$ = 453 W and an average heat loss **H** of 260 $kcal/hr$ = 300 W (assuming constant walking)

To compensate losses of internal energy associated with basal metabolism and daily activities daily food intake is necessary. People with limited body activities require (faculty members):

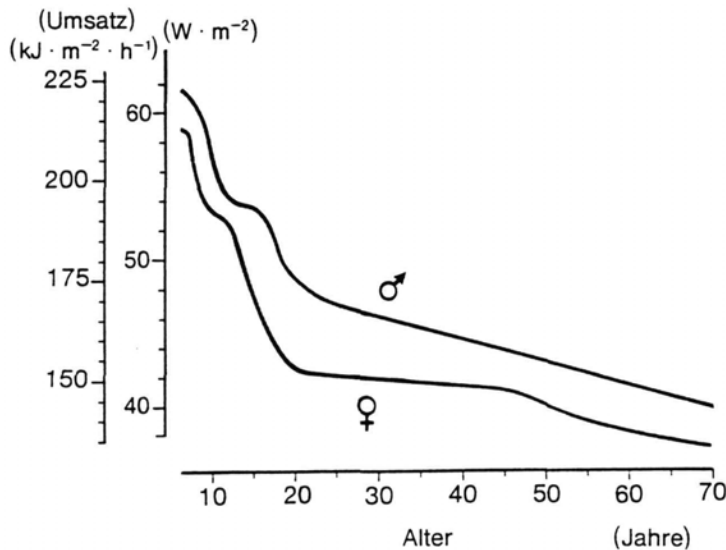$$\approx 150 kcal/hr \cdot 12hr + 70\text{kcal}/\text{hr} \cdot 12hr = 2640 kcal/day$$

A construction worker with a heavy work load requires:

$$\approx 450 kcal/hr \cdot 12hr + 70\text{kcal}/\text{hr} \cdot 12hr = 6240 kcal/day$$

The losses of internal energy are also directly correlated with age! Figure shows losses normalized to body surface area A in units m^2
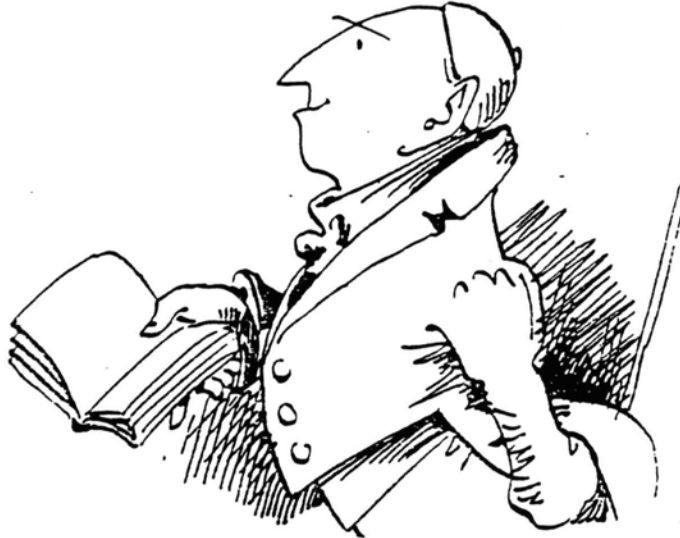
$$A \approx 0.202 \cdot H^{0.425} \cdot M^{0.725}$$

with $H \equiv$ height of body in [m]; $M \equiv$ mass of body in [kg]

$$1W/m^2 \equiv 0.86 \ kcal/(hr \cdot m^2)$$

52

EXAMPLE   AVERAGE DAILY INTERNAL ENERGY CONSUMPTION OF A MIDDLE AGED FACULTY MEMBER

Activity	time period [hr]	Catabolic Rate [kcal/min]	energy consumption
Sleep	10	1.2	720
Thinking	2	3.0	360
Bicycling	1	5.7	342
Walking	2	3.8	456
Lecturing etc	6	4.0	1440
Domestic work	3	2.0	360

These activities and non-activities require a consumption of internal energy of $\Delta U \approx 3678$ kcal

To compensate these losses by food intake requires a daily ration of ≈ 740 g (based on an average energy content of 5 kcal/g food)

However, choosing a Double Huddle Cheese Burger with fries takes nearly care of the daily energy needs (≈ 2200 kcal) after subtraction of breakfast!
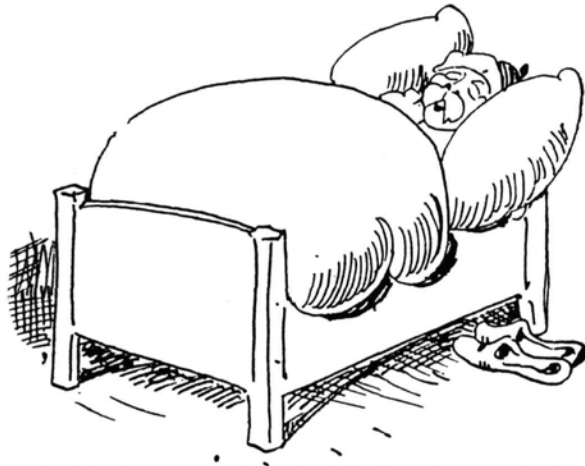**Dinner goes into fat storage!**

Food intake in excess of the internal energy loss increases the weight of the body!

reduced food intake (diet) and/or hard work decreases the weight of the body!

EXAMPLE   FOOD CONSUMPTION

The basal metabolic rate determines the energy consumption ΔU of the body (m$\approx$ 75 kg) during a 10 hour night sleep!

MBR = 80 kcal/hr ΔU = 800 kcal

To recover the losses on internal energy, you have the choice of cereal ($\approx$300 kcal/bowl) plus milk ($\approx$90 kcal/bowl), or the 'healthy' version with two eggs ($\approx$80 kcal/egg), three slices of bacon ($\approx$ 300 kcal/slice) and hashbrowns ($\approx$ 500 kcal).

With the first choice you replace the consumed energy from the fat reservoir of the body. Fat contains ≈ 9.3 kcal/g, to replace 410 kcal you need to convert ≈ 44 g of your fat storage. Your loss in body mass is $\Delta m \approx 44$ g.

With the second choice you overcompensate your losses by 760 kcal and add to the fat storage reservoir of your body. Your gain in body mass is $\Delta m \approx 82$ g.

NOTE: Because of the high energy content of fat, 9.3 kcal/g (the average energy content of food is ≈ 5 kcal/g), the increase in fat is a very efficient way of storing energy.

DIET

means reduced food intake to convert body fat into internal energy U.

Taking the previous estimate of a daily consumption $\Delta U \approx 3700$ kcal, how long does a middle aged person have to be on a diet of 2000 kcal/day to reduce his body mass by 10 kg?

This translates into a daily conversion of 1700 kcal; fat contains 9.3 kcal/g

$$\Rightarrow \quad 10 \text{ kg} \equiv 93{,}000 \text{ kcal}$$
$$\Rightarrow \quad 93000/1700 \approx 54 \text{ days}$$

Two months of fasting are required

Alternative way of loosing weight is an increase in external body activity, **work ΔW**

Most efficient way of "working" is cycling (see next section)
How many hours of cycling are required to reduce the body mass by 10 kg?

Catabolic rate for cycling is $\Delta W/\Delta t \approx 600$ kcal/hr

$$\Rightarrow \quad 10 \text{ kg} \equiv 93{,}000 \text{ kcal}$$
$$\Rightarrow \quad 93000/600 \approx 155 \text{ hours}$$

With 10 hrs of cycling per day a two week bike vacation is required.

Good fitness and reasonably reduced food intake are necessary!

Der Kaspar, der war kerngesund,
ein dicker Bub und kugelrund.
Er hatte Backen rot und frisch;
die Suppe aß er hübsch bei Tisch.
Doch einmal fing er an zu schrein:
„Ich esse keine Suppe! Nein!
Ich esse meine Suppe nicht!
Nein, meine Suppe eß ich nicht!"

Am nächsten Tag – ja sieh nur her!
da war er schon viel magerer.
Da fing er wieder an zu schrein:
„Ich esse keine Suppe! Nein!
Ich esse meine Suppe nicht!
Nein, meine Suppe eß ich nicht!"
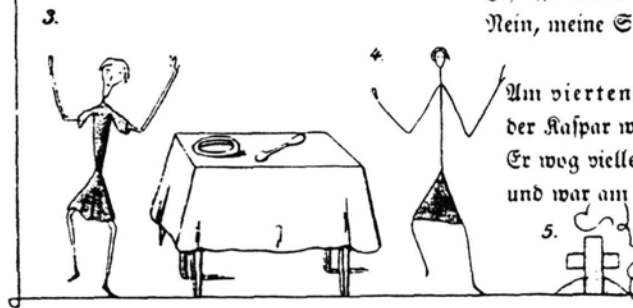
Am dritten Tag, o weh und ach,
wie ist der Kaspar dünn und schwach!
Doch als die Suppe kam herein,
gleich fing er wieder an zu schrein:
„Ich esse keine Suppe! Nein!
Ich esse meine Suppe nicht!
Nein, meine Suppe eß ich nicht!"

Am vierten Tage endlich gar
der Kaspar wie ein Fädchen war.
Er wog vielleicht ein halbes Lot –
und war am fünften Tage tot.
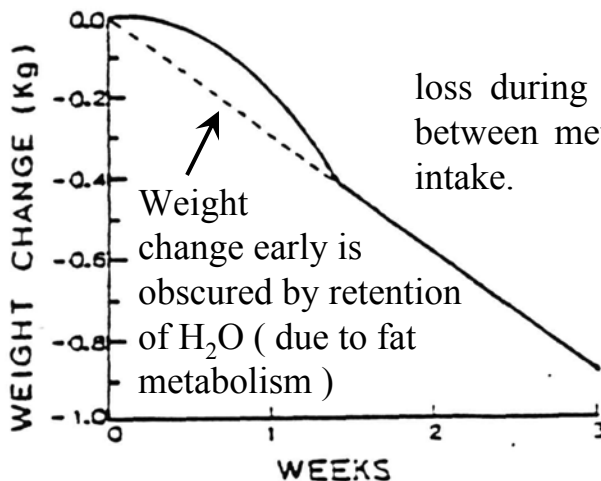
Typical time course of weight loss during a period of constant difference between metabolic expenditure and caloric intake.

(388 kcal/day deficit)

388/9.3 = 42g of fat per day

~1/10 lb loss per day after equilibrium is reached

Weight change early is obscured by retention of H_2O (due to fat metabolism)

Energy consumption by work

$$\frac{\Delta W}{\Delta t}$$

$\equiv$ work rate done by external body activity

$\Delta W = F \cdot \Delta x$; work $\equiv$ force F over distance Δx

EXAMPLE   Mountain climber

lifting body against
gravitational forces F=m·g

average climber mass m=70 kg
height Δh=150 m

ΔW = m·g·Δh = 70 kg 9.81 m/s^2 150 m = 1.03·10^5 J

Person walking along a horizontal street for a distance $\Delta x = 150$ m requires less external work;

average force supplied by foot to the street $F_w \approx 0.15$ W.

$$\Delta W = F_w \cdot \Delta x = 0.15 \; 70 \text{ kg} \; 9.81 \text{ m/s}^2 \; 150 \text{ m} = 1.55 \cdot 10^4 \text{ J}$$

However a lot of internal force F_L is necessary to lift the legs against gravitational forces (internal work)

$$\Delta W_L = F_L \cdot \Delta x_L \approx m/7 \text{ kg} \; 9.81 \text{ m/s}^2 \; 0.1 \text{ m}$$

for a m=80 kg person:

$$\Delta W_L = 11.2 \text{ J}$$

net energy is not increased because dropping the leg releases potential energy

However, internal work appears as muscle heat ΔQ (not as external work ΔW) and the internal work W_L reduces the internal energy U.

The internal muscle work the body performs creates heat inside the body.

The body can be considered as a machine doing external work. This requires a conversion of $\Delta U \to \Delta W$. However, like in any other machine, no conversion is possible without any heat loss.

see $\Rightarrow$ **Second law of Thermodynamics**

The efficiency of the machine is determined by the amount of heat loss, or by the efficiency ϵ of the conversion.

$$\epsilon = \frac{\Delta W}{\Delta U} \equiv \frac{work\ done}{energy\ consumed}$$

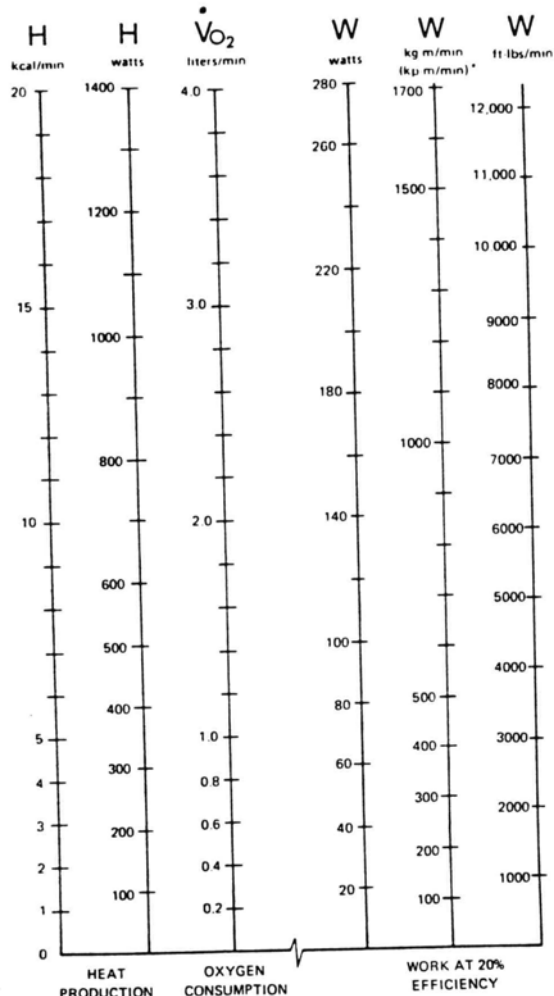The heat loss increases internal body heat or internal energy!

The efficiency for the various kind of external work depends on the detail of the muscle and body movement.

The efficiency for external work varies between 2 % and 20 %!

Mechanical Efficiency of Man and Machines

Task or Machine	Efficiency (%)
Cycling	~20
Swimming (on surface)	<2
Swimming (underwater)	~4
Shoveling	~3
Steam engine	17
Gasoline engine	38

most efficient external activity is cycling: $\epsilon \approx 20\%$

H	H	$\dot{V}_{O_2}$	W	W	W
kcal/min	watts	liters/min	watts	kg m/min (kp m/min)*	ft-lbs/min

HEAT PRODUCTION OXYGEN CONSUMPTION WORK AT 20% EFFICIENCY

*SOME ERGOMETERS ARE CALIBRATED IN, AND SCANDINAVIAN LITERATURE EXPRESSES MECHANICAL WORK IN KILOPOND METERS PER MINUTE (kp-m/min), WHICH IS EXACTLY EQUAL TO kg-m/min IN A STANDARD EARTH GRAVITY OF 1n

The maximum power deliverance depends on its time period. For short periods of time the maximum power deliverance can be very large, e.g. bicycling and rowing $\Delta W \approx 1500$ W for ≈ 6 s.

Power		Time
h.p.	watts	
~2	~1500	6 sec
~1	~750	1 min
~0.35	~260	35 min
~0.2	~150	5 hr
~0.1	~75	laborer's daily work

For short periods the delivered power exceeds the persons maximum rate of oxygen consumption: **anaerobic phase**,

for long periods the delivered power is proportional to the rate of oxygen consumption: **aerobic phase**.