Physiology of Work and Performance

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The human being is able to render great physical performances. For doing this kind of work, increased muscle activity is necessary and in order to support the long-term capability of those muscles, several organ systems have to adjust themselves to the increased strain. A medical student should be able to recognize those important physiological changes and spot the difference between trained and untrained bodies.

Physical Basics

Work and power

What are work and power in terms of physics? **Work** is the product of force and distance (F * s) and describes the energy that is used for a certain action. The unit of work is joule (J = N * m).

Power, on the other hand, includes the temporal dimension and is defined as work/time; the unit is watt (W = J/s).

Gross and net energy output

The resting metabolic rate of the human being is inevitably increased when muscles are working, and this elevated level, i.e. resting metabolic rate plus work-related additional energy turnover, is referred to as **work turnover.**

The outer work performed by the body in relation to the work turnover results in the **gross energy output** which is always below 20%. If one takes the rendered work only in relation to the increase in energy turnover (work turnover – resting metabolic rate), the **net energy output that is** yielded can reach up to 25%.

Work Physiology of Metabolism

Body delivering performance relies on a constant supply of energy, which is most of all needed in the muscles. Due to this, the human metabolism undergoes some distinct changes under physical strain.

Hormonal adjustments

Hormonally, the differences between the rest state and physical strain mainly emerge from an increased need for glucose and triglycerides. Therefore, increased levels of **cortisol, glucagon**, and **catecholamines** can be measured, while the **insulin level** is significantly lower.

Energy carriers and their provision

For the reliable contraction of muscles, the muscle cell relies on a constant provision of adenosine triphosphate (**ATP)**, the energy carrier in the cell. However, the **intracellular ATP** in an active muscle is exhausted within a few seconds and has to be resynthesized.

Within the 1st 30 seconds, the muscle obtains its energy from **creatine phosphate**. The phosphate is transferred out of this complex onto adenosine diphosphate (ADP) in order to produce new ATP. If the strain continues, **glucose** is used as the next energy carrier. It primarily originates from the muscular glycogen, the storehouse of glucose. Initially, **anaerobic** glycolysis occurs, i.e. without the supply of oxygen and with the release of **lactic acid** (lactate).

After a few minutes, **aerobic glycolysis** begins with the use of oxygen. This process is significantly more efficient and can regenerate 36 molecules of ATP out of 1 molecule of glucose. If the circulatory system cannot supply the muscle sufficiently with oxygen, **anaerobic glycolysis** still occurs simultaneously. When the stored glycogen in the muscles and liver begins to run out, the body starts to utilize **fats** since they represent by far the greatest energy reservoir in the body.

Note: The sequence of used energy carriers is: ATP, creatine phosphate, glycogen, and fat burning.

Endurance limit

In sports science, the **endurance limit** describes the maximum strain under which the body can perform an action without increased exhaustion of the muscles and while maintaining a stable equilibrium (steady state) of the respiratory and the cardiovascular system.

It is often defined as the physical strain that can be maintained over 8 hours without exhaustion. Above the endurance limit, the oxygen demand of the musculature exceeds its supply. Thus, energy production occurs in an anaerobic fashion and both heart rate and respiratory minute volume do not reach the stable plateau value referred to as

‘steady state’.

Lactate and anaerobic threshold

Lactate is produced as a metabolic product during anaerobic glycolysis and accumulates in the body in situations of very heavy strain without sufficient oxygen supply. At a blood concentration of roughly **4 mmol/L**, the **anaerobic threshold** is reached. The endurance limit is probably exceeded at this concentration and the activity has to be stopped soon.

Lactate leads to a decreased pH value, and can in an extreme case when compensation mechanisms are exhausted, resulting in **metabolic acidosis** with **hyperkalemia**. After the activity has been terminated, the accumulated lactate can be transported to the liver, where it is used under oxygen supply as the base substance for **gluconeogenesis**. However, the anaerobic threshold is different in each human being since it depends on the fitness level.

Note: In contrast to what is frequently assumed, sore muscles are not the result of high concentrations of lactate in the muscle but of painful microtraumas of the muscle fibers.

Changes in the Respiratory System

Increased oxygen intake

At target turnover, the human body uses about 250 mL of oxygen per minute. Under physical strain, this need for oxygen obviously increases and the body responds to this sometimes 10-fold increase with **increased respiratory minute volume**. On one hand, this is reached by increased breathing rate, and on the other, by increased tidal volume. Additionally, the sympathetic nervous system mediates bronchodilation and improved diffusion capacity via increased circulation.

This adjustment occurs with a delay of roughly 2 minutes during which the energy demand is covered anaerobically, and it reaches a ‘steady state’ when strain is kept below the endurance limit. In situations of very heavy strain above the endurance limit, the oxygen demand cannot be covered sufficiently and no ‘**steady state**’ is reached, even if the accumulating lactate represents an additional respiratory drive due to the consequential decrease in pH.

In the long term, strain always has to be terminated at some point. Also, the body accumulates greater **excess post-exercise oxygen consumption**.

Excess post-exercise oxygen consumption

As mentioned before, the body covers a part of its increased need for energy in an anaerobic fashion at the beginning of strain until the oxygen intake is sufficiently increased. Thus, the increased level only subsides with a certain delay since the body has to compensate for the earlier **oxygen deficit**. This deficit is referred to as **excess post-exercise oxygen consumption** which can have different magnitudes depending on the degree of the strain.

This explains why athletes have an increased respiratory frequency even some time after the strain. This can be observed especially in athletes with heavy strains above the endurance limit, e.g. sprinters. Without the ability to breath in the ‘steady state’, the body accumulates greater and greater excess post-exercise oxygen consumption as not only the energy reserves have to be refilled but also accumulated lactate is metabolized which requires oxygen as well. Comparatively lower levels of ‘excess post-exercise oxygen consumption’ are seen in continuous aerobic activity performed below the endurance limit e.g., long-distance runners.

Changes in the Cardiovascular System

The oxygen intake in the lungs is of little use for the body if it is not reliably transported to the working muscles. Thus, the cardiovascular system has to react to the demands and increase circulation appropriately. The crucial changes are mediated via the activation of the **sympathetic** nervous system with the release of **catecholamines** from the adrenal medulla.

Adjustments in the vascular system

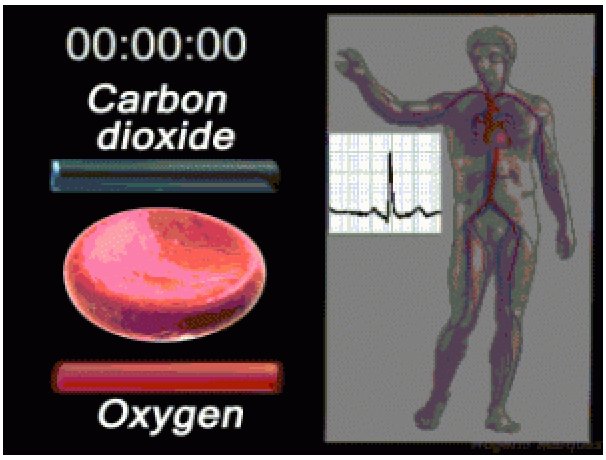


Image: ‘Aninmation of a typical human red blood cell cycle in the circulatory system’ by Rogeriopfm. License: CC BY-SA 3.0

In order to increase circulation in the muscles up to 40 times compared to the resting state, heavy local **vasodilation** is needed.

This is done by using the byproducts of the active muscles in order to increase circulation in primarily this exact location. These byproducts are potassium, lactate, carbon dioxide, and low oxygen partial pressure. The **total peripheral resistance (TPR)** drops.

On the other side, **α1-adrenoreceptor**-mediated vasoconstriction occurs in the periphery, especially in the intestinal tract. Also, the venous vessels contract and transport the blood that is stored in the veins into the arterial circulation as additional preload.

Via these effects and increased cardiac output, the **arterial blood pressure** rises. The **systolic blood pressure** increases by up to 20 mm Hg, the **diastolic blood pressure**, however, changes only a little. This can be explained by the decreased total peripheral resistance.

The consequence is an increased **blood pressure amplitude**, i.e. the difference between the systolic and the diastolic value rises.

Note: Under strain, Psyst is increased, Pdiast is slightly increased or remains the same, and the difference between the 2 increases.

Increased heart ejection

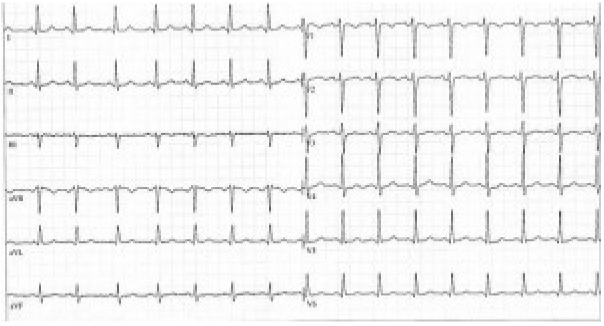
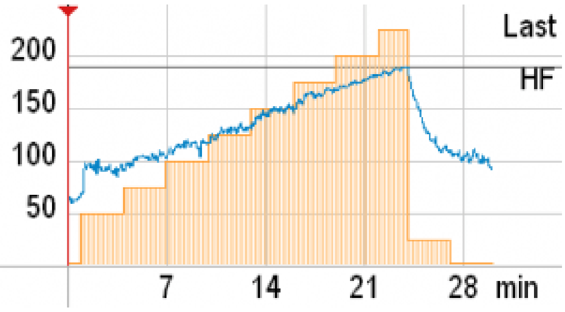


Image: ‘An unobtrusive 12-lead ECG’ by Bionerd. License: CC BY 3.0

Analogous to the increased respiratory minute volume of the lung, the heart has to increase the output blood volume in order to ensure sufficient oxygenated blood supply for the muscles. Under strain, the heart has an increased **stroke volume** and increased **cardiac output**.

The **cardiac output** is the product of stroke volume and heart rate. The sympathetic nervous system causes this via **positive inotropic** (increased contractility) and **positive chronotropic** (increased heart rate) stimulation.

In contrast to the up to a 10-fold increase of the respiratory minute volume, the heart volume can only be increased 2–3 times the resting level in an untrained person. Here, the so-called **C-fibers** play an important role. They are afferent fibers of the muscles that cause an increase in the heart rate via the central circulatory center.



After the beginning of the strain, the heart rate rises with delay and reaches a ‘**steady state’** that is dependent on the intensity of the action.

Hereby, there is a close relation between the strain load and heart rate since the stroke volume is only increased in the beginning and further adjustment is made via the factor of frequency.

If the body is above its endurance limit, the heart rate is not in a steady state but in a continuous increase.

Note: Under heavy physical strain, cardiac output (CO) is the limiting factor, not the respiratory minute volume (RMV).

Sum of recovery pulses

Like the respiratory minute volume, the heart rate decreases with a certain delay after the strain has been terminated. Here, the body continues to need a high level of circulation in order to refill the used energy storage. The **sum of recovery pulses**, i.e. the number of pulse beats until the original resting heart rate is reached, was established as a feasible measure.

During activities below the endurance limit, the sum of recovery pulses is mostly below 100 and correlates with the load of the rendered performance.

Training

Training summarizes all the processes of adaptation in the human body at repeated strain that lead to increased performance. A distinction is made between **endurance training** for long-term strains and **strength training** which aims for a short-term maximum power of musculature.

Endurance training requires frequently repeated and constant moderate strain. As mentioned before, the limiting factor for a physical strain is the cardiac output which means that the oxygen need of the muscle cannot be covered. Since the human heart rate cannot exceed a certain individual maximum value of 180–200/min, the body has to resort to the modification of the **stroke volume of the left ventricle** as a long-term adjustment.

Thus, endurance athletes have an enlarged heart and an **increased stroke volume** compared to untrained people. The **resting pulse** in trained athletes reaches very low values of 40/min at a similar cardiac output due to the increased stroke volume. Also, the trained body allows a higher maximum **respiratory minute volume** and an increased oxygen intake. Endurance training also enhances fat oxidation and decreases lactic acid accumulation in skeletal muscle which improves performance at given oxygen levels.

Note: The maximum heart rate does not change in trained people either; the increase in performance is due to an increased stroke volume.

Performance Diagnostics

A central part of sports medicine is performance diagnostics, which quantify and track the fitness level of the subject. Several methods are available.

Spiroergometry

Spiroergometry is a frequently used diagnostic procedure to determine performance with the help of determining breathing gases (spirometry) under strain (ergometry). This method provides insights about the respiratory and cardiovascular system and their adaptability.

Image: ‘Treadmill for functional diagnostics for competitive athletes’ by RIANbot. License: CC BY-SA 3.0

To simulate strain, the subject is placed on a bicycle- or treadmill-ergometer. During performance diagnostics, all vital parameters like heart rate and blood pressure are constantly monitored.

In the exercise stress test, the bicycle allows for a more reliable analysis since it is more stable. Additionally, spirometric diagnostics for the determination of respiratory volumes and the oxygen usage are done.

Then, the strain is gradually increased until reaching exhaustion while the responses of the body are observed. This way, one can determine, e.g., the individual endurance limit or the maximum heart rate in order to create a customized training plan.

Spiroergometry can help to localize the exact reason for fatigue or dyspnea that restricts the exercise capacity, to the functional problems of heart, lungs, or muscle.

Lactate measurement

The mentioned spiroergometry is often supplemented by **lactate measurements**. This involves the determination of lactate blood concentrations between the different levels of a strain of the ergometry. The blood is taken mostly from the earlobe.

Concentrations below 2 mmol/L suggest sufficient oxygen supply for the muscles. The area between 2 and 4 mmol/L is referred to as the aerobic-anaerobic transition zone. At concentrations **> 4mmol/L**, the **anaerobic threshold** is exceeded and the strain has to be terminated soon.

Knowing the strain intensity at which the anaerobic threshold is reached allows an athlete to coordinate his training and to pace himself in competitions. After longer endurance training, the anaerobic threshold is shifted to heavier strains.

Notes