MAN-ENVIRONMENT HEAT EXCHANGE
A METHOD FOR THE BIOMECHANICAL ASSESSMENT OF THE ENERGY COST IN REAL COMPETITION

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HISTORICAL BACKGROUND

The Neapolitan Alfonso Borelli was one of the first scientists who conceptually associated oxygen consumption with the muscular activity. Indeed, in the chapter entitled "De usu respirationis" of his book "De Motu Animalium" (1680), he describes his own individual experience made some years before on the Etna. The following titles of paragraphs show that such a mechanism was already clear in his mind: "Through breathing, air particles mix with blood", "The mixture of air introduced in blood through the breathing produce preserves animal life", "This is the reason why breathing is more difficult and rapid during pressing motion and muscular activity", "That is why muscular activity in rarefied air causes difficulty in breathing".

However, the first scientists who developed laboratory experiments in the field of thermophysiology were Lavoisier, Laplace and Sequin between 1775 and 1785. They detected on Guinea pigs at first and then on men that - under comfortable temperature conditions - the oxygen consumption was at its lowest before eating; slightly increased when the environment temperature decreased; sharply increased after food intake and ever more when working.

In mid-XIX century the chemical-physical studies by Regnault and Reiset were developed. They sought to demonstrate that oxydation was the main source of animal heat by using the oxygen consumption as the simple measure of heat production.

Hoping to relate life processes to the well-known physics laws, Reubner, Helmholtz and others verified the principle of energy conservation both for biosystems and inanimated systems, defined the basal metabolic temperature and discovered that the hot blood biosystems were basically homoiothermic.

Mayer was the first physician to develop the idea of equating an animal with a sort of thermal machine where the breathing heat is partially turned into muscular activity.

M. Hirn sought to experimentally demonstrate this hypothesis for man by locking an individual in a thermal chamber and placing two rubber pipes in his mouth - the former for air intake and the latter for emission gases - which were then measured in terms of oxygen consumed and carbon dioxide produced. The breathing chemical and thermal effects were thus evaluated both under basal and working conditions - that is by lifting his own weight on the circumference of a mobile wheel.

Indeed the temperature increase in the chamber was measured until when - becoming constant - the radiation emission of the walls was equivalent to the heat produced by the body within it. Afterwards, the individual was replaced by a burner (Bunsen jet) regulated in such a way to keep air in the chamber at the same constant temperature. From the volume of the gas burnt it was then possible to infer the heat produced by the combustion and, by way of analogy, the quantity of heat produced by the human body in that given time.

This interesting experience led to the result that every 30 grams of oxygen consumed corresponded to 150 calories. Considering the time element, it is appropriate to think over the remarkable accuracy of the results obtained, since this value of the oxygen mechanical equivalent is still used to make rapid calculations in the field of Industrial Medicine.

THERMOPHYSIOLOGY PRINCIPLES

As is well-known, man is a homoiothermic animal. This means that his ideal life conditions are possible only within a very limited temperature range, without the use of clothing.

Both an "internal temperature" and a "surface external" temperature of the body can be identified since, in the case of the man-environment heat exchange, homoiothermy is guaranteed by the existence of a temperature gradient from inside to outside.

Internal temperature can usually vary from 36.3°C and 37.7°C. If it reaches 39-39.5°C the individual is on the verge of a heat collapse; a 40.5°C value entails the risk of a complete paralysis of the thermo-regulating mechanisms; whereas values higher that 42°C cause irreversible brain damage alongside with enzymic blocks and lethal consequences.

Test on animals showed that the pre-optical hypothalamus is the main seat of thermic regulation control processes. This area is assisted by extra-hypothalamic sensors located in the bone marrow, sensitive to the local temperature variations. In order not to alter the internal heat exchange, the heat produced by the oxydation and fission processes at muscular level is removed by the body through the skin.

In the case of muscular activity the heat energy produced by the fission processes builds up in the muscular mass and causes the related increase in the local temperature which, by thermally levelling off in the microcapillaries, warms the blood flow. Hence the blood, after entering the muscle at the internal body temperature, reaches the skin surface at the muscle temperature, thereby dispersing the heat surplus through well-known physical and physiological mechanisms.

After all the heat energy produced by the physical and metabolic activity is removed from the production area by means of the blood flow and dispersed in the external environment at the skin level.

Hence the changes in the skin blood flow play a key role in heat dispersion. The increase in the skin blood flow entails a further drain on the cardio-circulatory load (the heart capacity can reach values 5-6 times higher than the basal ones for maximum loads), even though it is partially made up for by the increase in the plasmatic volume to the detriment of the interstitial liquid.

The changes stemming from the correspondent vasomotorial changes practically confine themselves to change the features of the "skin radiator". Indeed, since the blood flow can range from 0.16 to 2.6 litres/m/m the temperature, conductivity and skin heat dispersion ability are substantially altered.

The process of heat dispersion in the external environment has a merely "physical" character and depends on the temperature, humidity and radiant power of the integuments in relation to temperature humidity and speed of the environment air.

The man-environment heat exchange can occur by convection, radiation, conduction and evaporation.

Convection is the process transferring heat from the skin to the environment by direct radiation associated to the status of thermal excitation of the air film molecules in contact with the body.

Radiation is the process transferring heat from the skin to the environment by direct irradiation linked to the release of electromagnetic radiation emission in the infrared band by the body.

Conduction is the process transferring heat from a higher temperature area to a lower temperature one.

Evaporation is the process transferring heat from the skin to the environment, linked to the change in the status of a vaporizing liquid.

At the level of the skin two different processes occur: the former which is generally below 30°C, known as "Perspiratio insensibilis", caused by the natural diffusion of steam through the skin; the latter over 30°C, known as "vaporization", which is subject to the thermo-regulating control causing perspiration. A further vaporization occurs at the level of the mucosa of the breathing segment. Therefore respiration is made through a heat cession to the environment which can be relevant, during physical efforts, due to the increase in the ventilation frequency. Thus physical activity and the related heat production trigger a series of physiological mechanisms designed to keep homoiothermy such as: variation in the oxygen consumption, lung ventilation, heart beating frequency, peripheral circulation and finally the activation of sweat-glandes.

THE EVOLUTION OF THE MICROSCOPIC VISION

The Weinbaun and Jiji biothermal equation.

In thermophysiology the key instrument for dissipating the internal heat surplus is given by the increase of the peripheral blood flow which, by changing the conductivity of muscular tissues, consequently alters the emission-dispersion characteristics of the "skin radiant".

Even though the process for dissipating heat appears to be well-defined and understandable in its entirety, indeed the "local" microscopic vision of the heat exchange mechanism and the definition of the tissue temperature has so far been devoted no satisfactory analytical description. From 1985 to 1989, on the Journal of Biomechanical Engineering, a group of researchers from the New York University seemed to provide a remarkable contribution to the evolution of the microthermophysiology by defining a new biothermal equation.

Weinbaum, Jiji, Zhu and Lemons thus proposed and then generalized an equation where the microscopic average tissue temperature was for the first time connected with blood flow and the local microvascular geometry.

A model was made of the basic mechanism which allows the heat transfer from the tissue to the blood. This transfer is not - as believed so far - the result of the heat exchange of arteriovenous counter-flow of those capillaries having a diameter higher that 100 .m, which are considered to be more important from the thermal viewpoint.

This was made on the basis of a theoretical forecast proposed by Chen and Holmes in 1980 who - as to the microcapillary blood flow - made a clear-cut distinction between the heat exchange and the mass (oxygen) exchange. This means that, in the first case, blood vessels under 50 .m are already thermally balanced with the local tissue and do not participate in the heat removal which is exchanged and removed only at the level of those arterioles and venules having a diameter higher than 50 .m.

The first equation proposed was valid only for blood vessels of the same diameter, but is interesting to note that the last generalization of the equation to include different diameter blood vessels and the expression of the effective conductivity tensor have the merit of keeping the same analytical form also in the most general case.

In this last instance, we have the advantage that the mathematical device of the analytical extension of the temperature function enables us to describe - with a good degree of approximation - the temperature range of the close tissue, thereby allowing for the first time to assess the theoretical results by means of the experimental data of the tissue temperature.

THE EVOLUTION OF THE MACROSCOPIC VISION

The assessment of the energy cost in real competition.

Scientific knowledge remains partial in every field, even though it records a steady increase thanks to the efforts of the theoretical and experimental researchers.

Thus, if the advanced (microscopic) technologies and the brilliant theoretical intuition enabled us to perfect knowledge in the field of microthermophysiology, the same instruments are contributing to extend knowledge in the field of macrothermophysiology.

Due to sport evolution, the need to extend knowledge calls for an in-depth analysis of the equations regulating man-environment heat exchanges under "free" (real) conditions - with all the difficulties we can imagine. Even though these equations are all well-known - with a certain degree of approximation - (apart from the model of the evaporation process) they were confirmed by extrapolating them from laboratory controlled conditions.

In this respect a joint research by CONI - ENEA - FILPJ was started at the beginning of 1989 designed to assess the athlete's energy cost in real competition.

Considering the high complexity of the issue, the need was recognized to tackle it through an integrated multi-discipline approach, by resorting to knowledge in the field of physiological biomechanics and the specific equipment provided by CONI, to the sophisticated methods and instruments by ENEA and finally to athletes and to the technical and specialized knowledge in the field of physical biomechanics by FILPJ.

The "simple" idea is that of viewing athletes as complex thermal machines. Therefore the joint application of both principles of Thermodynamics must allow us to statistically assess the average work carried out by athletes during competitions. Obviously, from a theoretical point of view, the problem could be rapidly solved if it was possible to make the athletes' direct calorimetry during their performance. Since this is technically impossible, it is common practice in sport to assess the athlete's work by means of the "simpler" indirect calorimetry.

This means that through an appropriate oxygen mechanical equivalent we can trace back - through the fuel kinetics - the work carried out in laboratory which, for many sports, is made day by day more similar to the real competitive load.

In the case of fighting sports pertaining to FILPJ (wrestling and judo) the few experimental data are indeed limited and it is virtually impossible to extrapolate reliable data from these laboratory results which can allow an adequate training, based on scientific principles.

The idea is therefore that of retracing direct calorimetry by means of the well-known energy equation of the man-environment heat exchange. The athlete's body superficial average temperature can be thus directly reckoned.

In doing so, on the basis of the athlete's heat-energy emission recorded by "remote sensing" techniques, more reliable quantitative data can be obtained on the competition performance without affecting his real performance.

The necessary preliminary step relied on the theoretical forecast which enabled us to outline the first physical-mathematical theory thoroughly describing wrestling competitions.

The model and characterization of the generic motion of the "couple of athletes" system - developed thanks to the specific techniques of statistical mechanics - allowed to demonstrate that it belongs to the class of bidimensional Brownian motion. By applying Einstein methods - adequately modified through the second principle of thermodynamics - it is recorded that the average kinetic energy is directly proportional to one fifth of the athlete's overall oxygen consumption. On the other hand, the use of variational analysis - applied to the aspect of interaction between athletes in static conditions and extendable to competition on the basis of the principle of Galileo's relativity - enabled us to identify the physical principles on which this interaction (throwing techniques) relies and to infer and define the lower energy consumption trajectories.

From a historical point of view, the theory of the variation calculation was born thanks to the study of the brachistocrone or "lower transit time" trajectory. This problem was studied by Galileo, Jacobi, Bernoulli and Lagrange who are generally considered to be the founders of the variational theory.

It was applied to the problem of identifying the lower transit time trajectory that a body can cover between two points when only the gravitational force acts on it.

In our case, since by first approximation, we deem correct the assumption according to which the initial thrust exerted by the attacking athlete on the attacked one acts for a negligible lapse of time, we are once again faced with a formally similar case.

The field of forces external to the "couple of athletes" system is conservative and not depending on time (gravitational field). Therefore the principle of minimal action will hold true and the body thrown will cover the lower transit time trajectory. Moreover, if we use the Jacobi form of the minimal action principle - thereby operating an appropriate functional exchange and recalling that, in our case, time is a constant of motion - we can demonstrate either that the body covers a minimum lenght curve in the space of configurations or that its trajectory coincides with the geodesic of a specific symmetry.

These important results achived make it possible to experimentally study real competition by means of thermovision tv cameras which record the athlete's heat emission in the infrared band on a magnetic tape.

We can thus obtain quantitative data related to the athletes' thermo-energy dispersion which accounts for 75-80% of the overall consumption of the metabolic energy produced.

Considering the bio-chemical origin of the athlete's metabolic energy - for the aerobic "steady state" conditions - it was possible for the first time to associate - with a good degree of approximation - the oxygen input and the heat output by means of a simple relation; whereas the relation connecting the anaerobic-lactacid energy input with the heat output is more complex and still unknown. In this respect, the first functional links are being attempted during experiments.

The data on heat emission - recorded by the TV camera through 4 photograms a minute - are soon analyzed by a highly specialized system for Image Processing, the EDI system, (ENEA Digital Imagery), capable of providing - through sophisticated data processing - factors such as:

- the statistical survey on the "grey tones" (maximum, minimum, average and standard deviation);
- the construction of appropriate histograms;
- the cumulative integral of the image in terms of energy;
- the kinetic trend of the phenomenon.

In order to obtain more reliable data, images are subjected to the "electronic" cleaning system, thereby eliminating all the interferences of the environment background which distorts and downgrades the results obtained.

A further step was providing the same images through the pseudo-colour technique, thus allowing to obtain heat maps of the athletes' bodies on a high definition screen. These maps enable us to identity the most used muscles, that is to say "the most warmed up" ones.

The initial stage of the study allowed the gauging of the heat energy emitted as a function of the oxygen intake detected by telemetrics by means of an athlete placed on an engine conveyor belt running at constant speed for a given period of time. This was done through the application of the thermodynamic principle of energy conservation, that is under conditions of no or virtually negligible "physical" work and of aerobic "steady state".

Alledgedly, the technologies used allowed for the first time to follow the evolution kinetics of both phenomena (oxygen input and radiation output), thereby enabling us to try and find the functional relation linking them.

The present stage of research is hinged on the assessment of the screening effect caused by the clothing used in some forms of wrestling; whereas the subsequent stages envisage the differential assessment of the "physical work" both in the "concentric" and in the "eccentric" stages; the execution of "throwing techniques" in laboratory and finally gymnasium competition trials and analyses of real competitions.

The quality of the information gathered and the favourable outcome of some direct and indirect verifications are source of hope for the amount of original information to be found in the future and for the profitable use of this new method both in the field of physical-technical training and shock prevention.

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