Rodolfo Margaria and the First Walk on the Moon

Gabriele S. Grasso; Egidio P. Beretta; Giuseppe A. Miserocchi; Michele A. Riva

INTRODUCTION: During the Cold War years, the Space Race was largely supported by the efforts of many engineers and scientists, in particular human physiologists. Rodolfo Margaria (1901–1983), director of the Institute of Human Physiology at the University of Milan, was one of the most eminent and focused his studies on the mechanics of human locomotion in subgravity, in particular on the Moon's surface. Long before the real Moon landing, Margaria was able to correctly theorize how astronauts would walk on lunar soil, what would be the optimal pattern of progression, as well as determine the optimum and maximum speed at one-sixth of the Earth's gravity. On 21st July 1969 at 02:56 UTC, great excitement was aroused by the television images of Neil Armstrong's first steps on the Moon. Instead of walking, he moved around making small leaps, as expected from Margaria and colleagues.

KEYWORDS: physiology, aerospace medicine, subgravity locomotion.

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The year 2019 marks the 50th anniversary of the Apollo 11 launch, the spaceflight that landed the first two people on the Moon. This commemoration may represent a timely occasion to remember the contribution provided by the Italian physiologist Rodolfo Margaria (**Fig. 1**) in the comprehension of the mechanisms of human locomotion in subgravity.

Rodolfo Margaria (1901–1983) was one of the most prominent figures in the field of physiology, both in Italy and worldwide. He was born in Chatillion (Aosta) in 1901 and received a degree in medicine from the University of Turin in 1924. Subsequently, he became a research fellow at the University of Turin, where he started to lecture in biochemistry. During that period, he frequently traveled around the world to collaborate with the most eminent physiologists, primarily in London, Plymouth, Cambridge, Boston, New York, and Philadelphia. At the age of 32, he became Full Professor of Physiology, initially in Ferrara and, then, in 1948, at the University of Milan, where he held the position until his retirement in 1977. During his career, he became chief of the Center for Studies and Research on Aeronautical Medicine at the Department of Aeronautics in Guidonia (1938–1943), dean of the Higher Institute of Physical Education of Lombardy (1965–1977), and director of the Study Center of Physiology of Muscular Work of the Italian National Research Council (1969–1974). His remarkable cultural heritage was transferred to a considerable numbers of pupils, who became professors of physiology in Italy and Northern America. His scientific contribution essentially covered three main domains: 1) the capacity and power of the energy processes in muscular activity; 2) respiratory function; and 3) the biomechanics and energetics of locomotion. Here is an outline of his contribution in these domains.

The Capacity and Power of the Energy Processes in Muscular Activity

In 1933, Margaria, together with David Bruce Dill (1891–1986) and Harold T. Edwards (1897–1937) from Harvard's Fatigue Laboratory, postulated the concept of oxygen debt being related to the production of lactic acid during muscular contraction.[15] This hypothesis was confirmed by studying the kinetics of oxygen consumption at the onset and at the end of muscular exercise.[13,16] Further studies allowed the mechanical efficiency of splitting of high energy compounds to be estimated.[5,6,14] In fact, Margaria provided the first ever measurement of muscular power that is related to the production of lactic acid. This was based on an original experimental and analytical approach that monitored the accumulation of lactic acid in the bloodstream during an increasing workload.[10] It should be mentioned that, in parallel with a human model, an experimental approach in animal models was developed by

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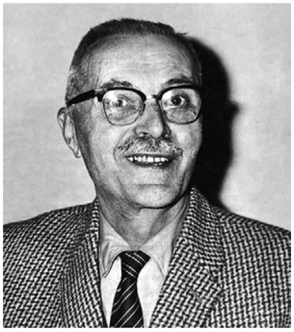

Fig. 1. Rodolfo Margaria (1901–1983).

Margaria's collaborators in order to relate oxygen debt with the availability of high-energy phosphates in the gastrocnemius muscle of an exercising dog.[18]

Respiratory Function

Margaria provided an outstanding contribution that led to the discovery of carbonic anhydrase, a ubiquitous key enzyme that is involved in different processes and, consequently, became a well-known multidrug target.[1] Furthermore, he went on to estimate the mechanical work of breathing as well as the efficiency of breathing patterns.[17] Knowing the energy cost of locomotion, Margaria and his collaborators proposed an index of respiratory efficiency which was represented by the ratio between the mechanical cost of breathing and the energy cost of locomotion. These studies represent the basis for the perturbation in respiratory mechanics caused by chronic diseases such as fibrosis and emphysema.

Biomechanics and Energetics of Locomotion

Starting from the pioneering research of Wallace O. Fenn (1893–1971) in the 1930s,[7] Margaria and his collaborators, relying on a force plate that allowed mechanical work to be related with the oxygen energy consumption, carried out a complete and accurate analysis of the mechanics of marching and running of humans under normal gravity conditions.[3,4] Moreover, Margaria studied and characterized the efficiency and the energy cost of human locomotion.[9,12] Further developing a study published in 1957 by Fenn[8] concerning elastic energy stored in the human body, Margaria proceeded to estimate the utilization of muscle elasticity during exercise.[2,19]

Margaria and Locomotion in Subgravity

While Margaria developed his studies on human locomotion, research in the field of aerospace exploration was evolving quickly. The new challenge of the conquest of space pushed Margaria to face the problem of human locomotion under subgravity conditions. In 1964, Margaria reported his first theoretical results regarding subgravity in a publication that appeared in the *Aerospace Medicine* journal.[11]

To better explain movement on the Moon's surface, Margaria started considering the mechanics of marching and running in 1-G conditions. **Fig. 2** shows the analysis of gaits which were used to perform a study on locomotion in subgravity, highlighting that, at 1 g, the potential and kinetic energy alternate with sine wave oscillations during each step. During walking, the two different energetic components are in the opposite phase, thus the overall work is less than the one deriving from the single component, and at each step there is a transformation of potential energy into kinetic energy and vice versa. On the other hand, during running at 1 g (**Fig. 3**), oscillations of the two forms of energy are in phase, resulting in an overall work

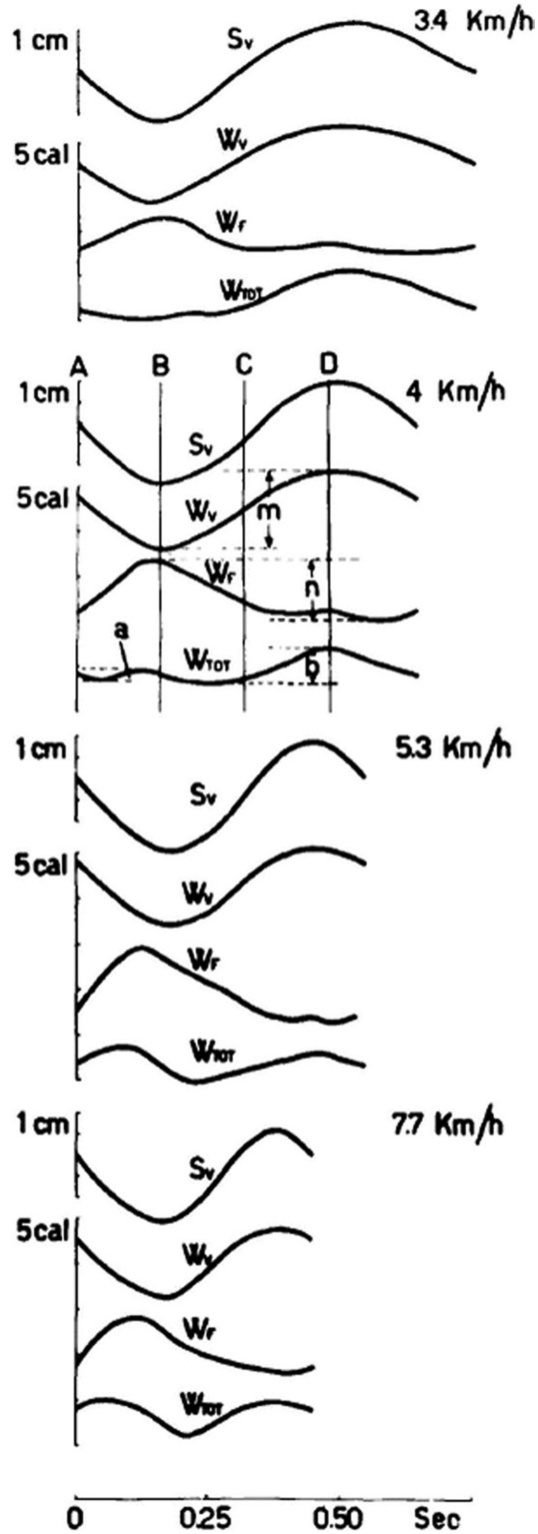

Fig. 2. Analysis of the potential (W_v) and kinetic (W_f) energy at different speeds of walking at 1 g. W_v is calculated from the vertical displacement of the center of gravity S_v, W_f from the speed changes in forward direction. W_{tot} is the sum of the two curves W_v and W_f.[11]

that is equal to the sum of the two components and, therefore, the energy cost is much greater with respect to the one used in the march. Moreover, the mechanical efficiency associated with

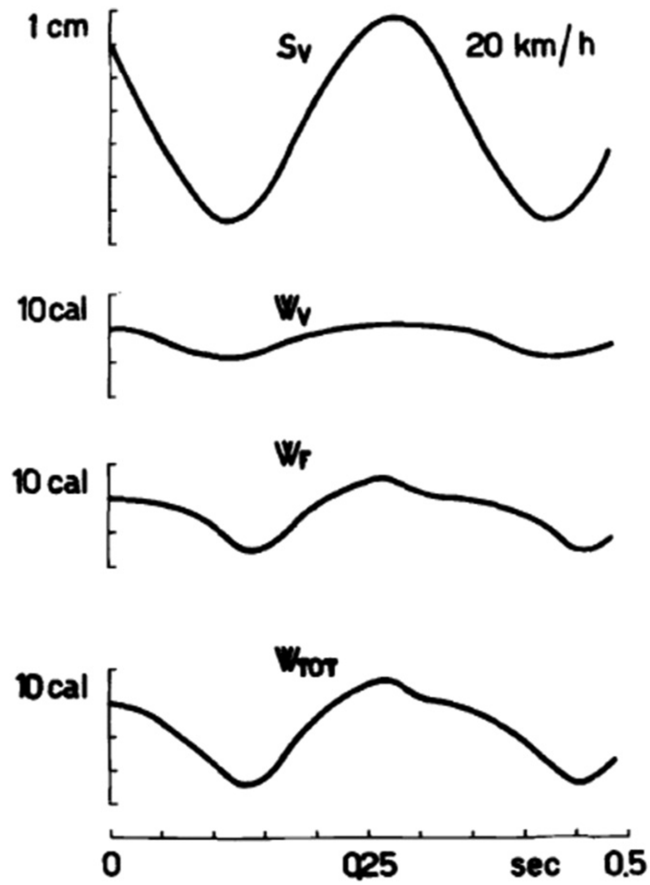

Fig. 3. Analysis of the potential (W_v) and kinetic (W_f) energy of running at 20 km/h at 1 g. W_v is calculated from the vertical displacement of the center of gravity S_v, W_f from the speed changes in forward direction. W_{tot} is the sum of the two curves W_v and W_f.[11]

each step, in terms of a ratio between the mechanical work and the corresponding energy consumption, is extremely high. However, the elastic energy leading to muscle contraction can accumulate in one phase and be released in the following one. Indeed, during the motion of the body, part of the energy is dissipated into heat which is required for the stretching of the muscle fibers during the impact of the foot with the ground; nevertheless, the remnants are accumulated as elastic energy in the muscles. This bundle of energy is thus transformed into work since the muscles shorten as a consequence of the foot pushing on the ground. This generates an acceleration both in an upwards and forward direction.

After this introduction, Margaria theorized what locomotion would be best advised on the Moon's surface, where the acceleration of gravity would be reduced to one-sixth (0.16 g) of that on Earth. Concerning walking on the Moon's surface, it was theorized that the gain in potential energy, as well as its transformation into a kinetic component, decreases during each step for the forward progression. Consequently, the maximum speed reachable in a Moon march would have been very low, less than 1.5–2 km/h. Margaria estimated that if a natural step rate on the Earth were 100–120 steps per minute, on the Moon it would have been no more than 40–50 steps per minute (**Fig. 4**, right). "It is very likely that on the Moon's surface walking will be unpractical, and locomotion will be possible only through a mechanism similar to that of running, in which the two energy components, potential and kinetic, will increase at the same time, as an effect of the muscular push."[11] When Margaria considered the mechanics of running on the Moon's surface, he hypothesized that, given the assumption that the muscular force on the Moon is the same as on the Earth, the vertical component of the push would have been appreciably greater, precisely as a result of the reduction of bodyweight to one-sixth. "The main peculiarities of the mechanics of running on the Moon […] are: a) a greater forward incline of the body during the push, b) a very sensible reduction of the force applied at each step because of the decreased vertical component […] c) a much lower maximum speed of running than at g = 1."[11] Therefore, in subgravity, the more suitable method of locomotion was expected to be by loping, hopping, or skipping (Fig. 4, left).

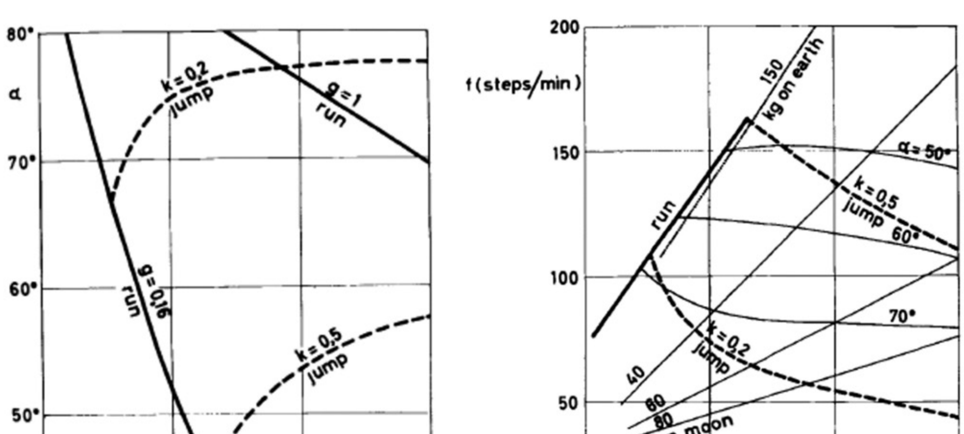

Fig. 4. Model proposed by Rodolfo Margaria on subgravity locomotion. Left: the angle α formed by the direction of the push of the foot with the horizontal at each step plotted vs. the mean speed of progression, V_f. In lunar gravity (g = 0.16) conditions, at increasing speed of progression, α progressively decreases (solid line) so running is no longer possible and progression takes place by jumping (broken lines). The two broken lines have been calculated by assuming two different friction coefficients (k) of the lunar soil. Right: the frequency of steps in running on Earth as a function of the speed of progression (solid line): the intersection between the "run" line and the broken ones determines the maximal running step rate reachable before jumping occurs for speed progression.[11]

In conclusion, Margaria and Cavagna had theorized that astronauts in lunar gravity would adapt their gaits to minimize energy expenditure. They predicted that traction would be low, the natural transition from walk to run would occur at a much lower speed, and that jumping or hopping would often be used.

On July 21, 1969, Neil Armstrong (1930–2012), commander of the Apollo XI mission, stepped off Eagle's footpad and his first step onto the lunar surface was broadcast on live TV to a worldwide audience. Edwin E. Aldrin, lunar module pilot, joined him on the surface and tested methods for moving around, including two-footed kangaroo hops. Loping became the preferred method of movement, as brilliantly expected by Margaria 5 years before, in 1964.

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