Acción, Vol. 20/ s/n publicación continua 2024, E-ISSN: 1812-5808,
https://accion.uccfd.cu

Review Article

Considerations for work, power and energy expenditure during physical exercise

Consideraciones sobre el trabajo, la potencia y el gasto energético durante el ejercicio físico

Considerações sobre trabalho, potência e gasto energético durante o exercício físico

Islay Pérez Martínez
Bindura University of Science Education, Zimbabwe.
I D: https://orcid.org/0000-0002-9011-6474
Email: islaycuba2015@gmail.com

Lysias Tapiwa Charumbira
Bindura University of Science Education, Zimbabwe.
ID : https://orcid.org/0000-0002-8129-5327
Email: lysiastapiwacharumbira1968@gmail.com

Hugo Faustino Molina Montalvo
University of Matanzas, Cuba
I D: https://orcid.org/0009-0003-5011-1323
Email: hugo.molina@umcc.cu

Autor para correspondencia: Islay Pérez Martínez

E-mail: islaycuba2015@gmail.com

Abstract

The main objective of this work is to guide researchers and sports professionals interested in estimating work, power and energy expenditure during physical exercise, using step benches, treadmills and cycle ergometers. The importance of adequate planning and control of training loads is emphasized, as well as the need to have adequate equipment and precise measurements to perform stress tests. Examples of

Acción, Vol. 20/ s/n publicación continua 2024, E-ISSN: 1812-5808,
https://accion.uccfd.cu

estimating the O_2 requirement when walking, running on a treadmill, and using bicycles are provided. It analyses how to calculate energy efficiency during exercise and the factors that determine it, offering examples of how to do it.

Keywords: Physical exercise, Work, Power, Energy Expenditure.

Resumen

Este trabajo tiene como objetivo principal proporcionar orientación para investigadores y profesionales del deporte interesados en estimar el trabajo, la potencia y el gasto energético durante el ejercicio físico, utilizando banco de pasos, cintas de correr y cicloergómetros. Se enfatiza la importancia de una adecuada planificación y control de las cargas de entrenamiento, así como la necesidad de disponer de un equipamiento adecuado y mediciones precisas para la realización de pruebas de esfuerzo. Se ofrecen ejemplos de estimación del requerimiento de O_2 al caminar correr en cinta rodante y usando bicicletas. Se analiza cómo calcular la eficiencia energética durante el ejercicio y los factores que la condicionan, ofreciendo ejemplos de cómo hacerlo.

Palabras clave: Ejercicio físico, Trabajo, Potencia, Gasto de Energía.

Resumo

O principal objetivo deste trabalho é orientar os investigadores e profissionais do desporto interessados em estimar o trabalho, a potência e o gasto energético durante o exercício físico, utilizando bancos com step, passadeiras e cicloergómetros. Salienta-se a importância do planeamento e controlo adequado das cargas de treino, bem como a necessidade de dispor de equipamento adequado e medidas precisas para a realização de testes de esforço. São fornecidos exemplos de estimativa da necessidade de O2 ao caminhar, correr numa passadeira e utilizar bicicletas. Analisa como calcular a eficiência energética durante o exercício e os fatores que a determinam, oferecendo exemplos de como o fazer.

Palavras-chave: Exercício físico, Trabalho, Potência, Gasto Energético.

Recibido :19.09.24 **Aprobado**: 14.12.24

Introduction

Adequate planning and strict control of training loads are critical in high-performance sports. The sports coach has to be able to know what to measure and how to measure it. You have to know how to evaluate the information you obtain from the different measurements to be able to use it effectively in decision-making, both during training and during competition.

The systematic practice of a sporting discipline is distinguished by the fact that it causes a change in the individual's environment. A physical activity regimen is introduced to which the body was not previously adapted. Faced with this new stimulus, the body tries to adapt to the entire complex of systems. The interaction between the various responses of these systems will determine the effectiveness of the body's response as a whole (Pérez et al., 2021).

Knowledge about the energy demands coming from physical activities is essential when planning sports training. How will the load influence the athlete's body? Which energy system has the greatest role during the activity carried out? How do we know the amount of energy spent? How to estimate energy efficiency during exercise? What is the total work done? What is the power exerted? These are questions that the coach must ask himself if he wants to implement a training program that adjusts to the particularities of the athlete.

This article has the aim of offering explanations of how to calculate the values of work, power and energy expenditure using benches, treadmills and cycle ergometers. These variants, although they are not the only ones, are widely used by doctors, physiologists, and physical trainers and are an important reference to estimate the work capacity of the individual's body during physical exercise.

Development

Acción, Vol. 20/ s/n publicación continua 2024, E-ISSN: 1812-5808,
https://accion.uccfd.cu

Measurement Units

Intending to standardize the terms for the measurement of energy, force, work and power, the world of science has adopted a common system of terminology called International System (SI) Units. This system is also used by the different sciences whose object of study is related to sports. It allows the expression of the results to be standardized, facilitating their understanding and dissemination.(Table 1).

Table 1. SI Units of Importance in the Measurement of Human Exercise Performance

Units for Quantifying Human Exercise	SI Units
Mass	Kilogram (kg)
Distance	Meter (m)
Time	Second (s)
Force	Newton (N)
Work	Joule (J)
Energy	Joule (J)
Power	Watt (W)
Velocity	Meters per second ($m \cdot s^{-1}$)
Torque	Newton-meter ($N \cdot m$)

Work and Power

The work done during physical activity and the power exerted are two important factors when estimating training load. The feedback that this information offers facilitates the prescription of physical exercise appropriate to the individual characteristics of the athlete.

When we talk about the work done during a physical activity we can define it as the product of the force and the distance through which that force acts.

Work = force x distance

The unit used to express force is Newton (N), while the unit for distance is meters (m). The following example shows how to calculate the work done during a weight-lifting exercise. If a 15-kilogram weight is lifted upward a distance of 70 centimeters (0.7 m), the work done can be calculated as follows:

Convert kg to N, where 1 kg = 9.81 N

so 15 kg = 147.2 N

Work = 147.2 N x 0.7 m

= 103 Newton-meters (N · m) or 103 joules (J)

The work done was calculated by multiplying the force expressed in N by the distance travelled expressed in m and the resulting work was expressed in Joule, which is the SI unit for work (where 1 joule = 1 N · m).

Although SI units are the preferred units for quantifying exercise performance and energy expenditure, other traditional units can also be used to express both work and energy. Using the same values as the previous example, work can be expressed in kilogram-meters (kgm) or kilopond-meters (kpm). The 15 kg weight is considered 15 kg force (or 15 kiloponds), which was displaced at a distance of 0.7 meters, resulting in a work of 10.5 kgm or 10.5 kpm. Since 1 kgm is equivalent to 9.81 J, the work done was 103 J (10.5 kgm x 9.81 j/kgm.) (Table 2)

Table 2. Common Units Used to Express the Amount of Work Performed or Energy Expended

Term	**Abbreviation**	**Conversion Table**
Kilogram-meter	kgm	1 kgm = 9.81 joules (J)
Kilopond-meter	kpm	1 kpm = 1 kgm
kilocalorie	kcal	1 kcal = 4186 J or 4.186 kJ 1 kcal = 426.8 kgm
Joule	J	1 J = 1 Newton-meter (N · m) 1 J = 2.39 x 10^{-4} kcal 1 J = 0.102 kgm

The term power is used to detail how much work is done per unit of time. The SI unit for power is the Watt (W), which translates to 1 Joule per second. We can determine the power in the following way:

Power = Work / Time

The concept of power is important because it describes the rate at which work is done. The work rate and power output describe the intensity of the exercise. To calculate power, let's take the following example of an athlete who did work equivalent to 20,000 Joules in one minute.

Power = 20 000 joules / 60 seconds

= 333.3 watts (W)

The unit of measurement used in the SI for power is the watt. However, there are a group of other units traditionally used to express power. It is important to be able to convert energy, work, and power values from one unit to another.

Table 3. Common Terms and Units Used to Express Power

Term	Abbreviation	Conversion Table
Watt	W	$1 W = 1 J \cdot s^{-1}$ $1 W = 6.12 kgm \cdot min^{-1}$
Horsepower	hp	$1 hp = 745.7 W$ or $J \cdot s^{-1}$ $1 hp = 10.69 kcal \cdot min^{-1}$
Kilogram-meter $\cdot min^{-1}$	$Kgm \cdot min^{-1}$	$1 kgm \cdot min^{-1} = 0.163 W$

Work and Power Measurements

a) Bench Step

The term ergometry refers to the measurement of work performance. The word ergometer refers to the apparatus or device used to measure a specific type of work (Powers S. K. & Howley, 2012). Many types of ergometers are used in exercise physiology laboratories today. One of the first ergometers used to measure work capacity in humans was the bench. This ergometer is still used today and simply involves the subject getting on and off a bench at a specific pace. The calculation of the work done during the climb and descent to the bench (stepping) is. Let's analyze as an example an 80 kg man who goes up and down on a 30-centimeter (0.3 meter) bench for 5 minutes, at a pace of thirty steps per minute. The amount of work performed during this 5-minute exercise can be calculated as follows:

Force = 784.8 N = (80 kg x 9.81)

Distance = 0.3 m · step^{-1} x 30 steps · min^{-1} x 5 min

= 45 m

Therefore, the total work performed is:

784.8 N x 45 m = 35316 Joules (J) or 35.3 Kilojoules (kJ)

The power output during this 5 minutes (300 seconds) of exercise can be calculated as:

Power = 35316 J / 300 s

= 117.7 J · s^{-1} or 117.7 watts (W) (table 3)

Using a more traditional unit of work, the kilogram-meter (kgm), power can be calculated as follows:

Work = 80 kg x 0.3m x 30 steps · min^{-1} x 5

= 3600 kgm

Power = 3600 kgm / 5 min

= 720 kgm · min^{-1} or 117.4 watts (table 3)

b) Cycle Ergometer

The cycle ergometer is very popular equipment in gyms and sports physiology laboratories. It was used for the first time more than 100 years ago and is still a widely used ergometer today both in the medical and sports areas, for carrying out stress tests and for training. This type of ergometer is a stationary bicycle that allows you to estimate the total work done in a certain time interval. A common type of cycle ergometer is the friction brake bicycle, which has a belt wrapped around the wheel called a flywheel. The strap can be loosened or tightened to provide a change in resistance. The distance travelled by the wheel is determined by calculating the distance travelled per revolution of the pedals (6 meters per revolution on a standard bicycle) multiplied by the number of revolutions of the pedal. These tests have been used to assess the cardiac response to effort and the determination of $VO_{2\ max}$ both in heart patients and in trained athletes. Direct or indirect methods are used in it that can be applied continuously or intermittently, apparently with the same results.

Cardiopulmonary exercise testing on a cycle ergometer is widely applied in endurance sports as well as in clinical settings. It provides a comprehensive insight into integrated cardiopulmonary function within a single laboratory session (Wenzel et al., 2024).

The physiological foundations of testing with this type of ergometer are based on the experiments of Von Dobeln, Astrand, Margaria and Saltin (the late 1950s, and early 1960s). The criteria of these researchers remain valid to this day (Delgado & Martínez, 2010).

Most bicycle ergometer protocols consider workloads in submaximal conditions. The duration of stress tests on the cycle ergometer is variable. They range from single-stage tests (2-6 min.) with a single load, to multi-stage tests (1-2-3 min.) in steps with progressive loads.

Consider the following example for calculating work and power using the cycle ergometer.

Duration of exercise = 5 min

Resistance against flywheel = 1.5 kg or 14.7 N

Distance travelled per pedal revolution = 6 m

Pedaling speed = 60 rev $\cdot$ min^{-1}

Therefore, the total revolutions in 5 min = 5 min x 60 rev $\cdot$ min^{-1} = 300 rev

Hence, total work = 14.7 N x (6m $\cdot$ rev^{-1} x 300 rev)

= 26460 J or 26,5 kJ

To calculate power, divide the total work done by the time.

Power = 26460 J / 300 s

= 88 W

Below is how to perform work and power calculations using other units of measurement.

Work = 1.5 kg x 6 m · rev^{-1} x 60 rev · min^{-1} x 5 min

= 2700 kgm or kpm

Power = 2700 kgm / 5 min = 540 kgm · min^{-1}

= 88 W

c) Treadmill

These tests have been designed to evaluate physical performance capacity through direct measurement and analysis of exhaled gas samples. They are fundamentally direct methods for determining VO_{2max}, although currently, through statistical inference, some protocols have been modified and are used for direct calculation. The physiological bases of these tests are found in the discoveries of Bruce and Margaria, who at the beginning of the 60s directly related performance, load, heart rate, and $VO_{2\ max}$. (Delgado & Martínez, 2010).

Calculating the work done while a subject runs or walks on a treadmill in a horizontal position is difficult to measure. Although running horizontally on a treadmill requires energy, the vertical displacement of the body's centre of gravity is not easily measured. Which makes it difficult to measure the work done during horizontal walking or running. However, it is easier to calculate the amount of work when walking or running uphill (Powers S. K. & Howley, 2012).

The incline of the treadmill is expressed in units called percentage slope. Percentage slope is defined as the amount of vertical rise per 100 units of belt travel. For example, a subject walking on a treadmill with a slope of 10% travels 10 meters vertically for every 100 meters of treadmill travel. The percentage slope is calculated by multiplying the sine of the tape angle by 100. The tape angle (expressed in degrees) can be determined by simple trigonometric calculations or by using a measuring device.

Currently, treadmills allow you to program the degree of inclination with which you want to work.

To calculate work performance during treadmill exercise, it is necessary to know the subject's body weight and the distance travelled vertically. The vertical run is calculated by multiplying the distance the belt travels by the percentage of the slope. This can be written as:

Vertical displacement = % slope x distance

The percentage slope is expressed as a fraction and the total distance travelled is calculated by multiplying the treadmill speed ($m \cdot min^{-1}$) by the total minutes of exercise. The following example shows how to calculate the work done during exercise on a treadmill.

Subject's body weight = 70 kg (force = 686.7 N)

Treadmill speed = 200 $m \cdot min^{-1}$

Treadmill angle = 7.5% grade (7.5% / 100) = 0.075 as fractional grade)

Exercise time = 15 min

Total vertical distance traveled = 200 $m \cdot min^{-1}$ x 0.075 x 15 min = 225 m

Therefore, total work performed = 686.7 N x 225 m

= 154507.5 J or 154.5 kJ

Power = 154507.5 J / 900 s

= 171.6 W

Using more traditional units, the following calculations can be made:

Work = 70 kg x 0.075 x 200 $m \cdot min^{-1}$ x 15 min

= 15750 kgm or 154507.5 J or 154.5 kJ (table 3)

Power = 15750 kgm / 15 min

= 1050 $kgm \cdot min^{-1}$

During exercise training, it can be beneficial to vary exercise intensity between two or more levels for varying durations: this so-called "interval training" has advantages compared to continuous training (Westonet al., 2014), (Yue et al., 2022). Because heart rate is a variable that is commonly used to set exercise intensity (Garber et al., 2011), this has inspired the development of accurate and robust heart rate control systems.

Compared to other exercise modalities, e.g. cycle ergometry, treadmill exercise has a relatively high energy expenditure at a given heart rate (Lafortuna et al., 2008), especially at low to moderate intensities, cf. (Abrantes et al., 2012).

Research comparing cycle and treadmill modalities indicates that treadmill testing produces peak oxygen consumption (VO2) values that exceed cycle ergometry testing by 10-20% in most populations (Muscat et al., 2015). This discrepancy can be partially explained by local fatigue experienced within the leg musculature resulting in test termination before one reaches maximal cardiovascular limits (Keeney et al., 2015).

Measurement of Energy Expenditure

Measuring an individual's energy expenditure at rest or during physical exercise has many practical applications. One of them is its use in body weight reduction programs with the use of exercises. Knowledge of the energy cost of walking, running or swimming at different speeds is useful for people who use these ways to lose weight. In general, two techniques are used to measure human energy expenditure: direct calorimetry and indirect calorimetry.

Direct Calorimetry

When the body uses energy to do work, heat is released. This heat production by cells occurs both through cellular respiration (bioenergetics) and cellular work. The general process can be drawn schematically as (Brooks et al., 2005) (Spence & Mason, 1992) (Stegeman, 1981):

Foodstuff + O_2 ⟶ ATP + heat

↓ cell work

Heat

The rate of heat production in an individual is directly proportional to the metabolic rate. Therefore, measuring a person's heat production (calorimetry) provides a measure of metabolic rate.

The SI unit for measuring thermal energy is the joule. However, a common unit used to measure thermal energy is the calorie. A calorie is defined as the amount of heat necessary to raise the temperature of one gram of water by one degree Celsius. Because the calorie is very small, the term kilocalorie (kcal) is commonly used to express the energy expenditure and energy value of foods. One kcal is equivalent to 1000 calories. When converting kcal to SI units, 1 kcal is equivalent to 4186 joules or 4.186 kilojoules.

The process of measuring a person's metabolic rate by measuring heat production is called direct calorimetry. This technique involves placing a person in an airtight chamber called a calorimeter, which is isolated from the environment, usually by a jacket of water surrounding the chamber, and space is left for the free exchange of O_2 and CO_2 from the chamber. The person's body heat raises the temperature of the water circulating through the chamber. Therefore, by measuring the change in temperature per unit of time, the amount of heat produced can be calculated. Additionally, the person loses heat through the evaporation of water from the skin and respiratory tract. This heat loss is measured and added to the total heat captured by the water to obtain an estimate of the person's rate of energy utilization. (Brooks et al., 2005) (Consolazio et al., 1963).

Indirect Calorimetry

Although direct calorimetry is considered an accurate technique for measuring metabolic rate, building a chamber that is large enough to conduct exercise physiology research in humans is expensive. Additionally, using direct calorimetry to measure metabolic rate during exercise is complicated because the ergometer itself can produce heat. Fortunately, another procedure can be used to measure metabolic rate. This technique is called indirect calorimetry because it does not involve direct measurement of heat production. The principle of indirect calorimetry can be explained by the following relationship:

$$\text{Foodstuffs} + O_2 \longrightarrow \text{Heat} + CO_2 + H_2O$$

(Indirect calorimetry) (Direct calorimetry)

Because there is a direct relationship between O_2 consumed and the amount of heat produced in the body, measuring O_2 consumption provides an estimate of metabolic rate (Astrand, 2003) (Brooks et al., 2005) (Fox et al., 1998). To convert the amount of O2 consumed into heat equivalents, it is necessary to know the type of nutrient (carbohydrates, fats or proteins) that was metabolized. The energy released when fat is the only metabolized food is 4.7 kcal (or 19.7 kJ) L O_2^{-1}, while the energy released when only carbohydrates are used is 5.05 kcal (or 21. 13 kJ) · L O_2^{-1}. Although not exact, the caloric expenditure of exercise is often estimated to be approximately 5 kcal (or 21 kJ) per litre of O_2 consumed (Hopkins & Powers, 1982). Therefore, a person exercising with an oxygen consumption of 2.0 · min^{-1} would expend approximately 10 kcal (or 42 kJ) of energy per minute (Powers S. K. & Howley, 2012).

The most common technique used to measure oxygen consumption today is called open-circuit spirometry. In the classic technique, the subject wore a nose clip (to prevent nasal breathing) and a respiratory valve that allowed ambient air to be breathed while the exhaled gas was directed to a collection bag that was then analyzed to determine the volume of gas and the percentage of O_2 and CO_2. The gas volume is measured in a gasometer and the O_2 and CO_2 are analysed chemically or with the help of calibrated gas analysers. Modern open-circuit spirometry employs computer technology that measures the volume of exhaled gas breath-by-breath, which is then directed to a mixing chamber where samples are taken for continuous gas analysis. Calculations of O_2 consumption and CO_2 production are then performed automatically. Although the computer system certainly facilitates the process of measuring oxygen consumption, the traditional method is used as a “gold standard” to ensure that the automated system is working correctly. (Bassett et al., 2001).

Spirometry is used, for example, in the evaluation of dyspnea, which is the main symptom of many cardiac, pulmonary and neuromuscular diseases, which manifest with exercise intolerance. (Zagolin et al., 2020).

Common Expressions of Energy Expenditure

Acción, Vol. 20/ s/n publicación continua 2024, E-ISSN: 1812-5808,
https://accion.uccfd.cu

Oxygen consumption can be used to express energy expenditure in different ways (Howley & Franks, 2007).

VO_2 ($L \cdot min^{-1}$)

Oxygen consumption (VO2) can be calculated in litres of oxygen used per minute (L/min). Powers & Howley (2012) use as an example a woman trained with 60 kg during a submaximal treadmill run:

Ventilation (STPD) = 60 $L \cdot min^{-1}$

Inspired O_2 = 20.93 %

Expired O_2 = 16.93 %

VO_2 ($L \cdot min^{-1}$) = 60 $L \cdot min^{-1}$ x (20.83% O_2 – 16.93% O_2) = 2.4 $L \cdot min^{-1}$

$kcal \cdot min^{-1}$

Oxygen consumption can also be expressed in kilocalories used per minute. The caloric equivalent of 1 L of O_2 varies from 4.7 $kcal \cdot L^{-1}$ for fats to 5.05 $kcal \cdot L^{-1}$ for carbohydrates. However, for practical reasons, and with little error, 5 kcal per litre of O_2 is used to convert VO_2 to kilocalories per minute.

Total energy expenditure is calculated by multiplying the kilocalories expended per minute ($kcal \cdot min^{-1}$) for the duration of the activity in minutes. For example, if a 60 kg woman runs on the treadmill for 30 minutes at VO_2 = 2,4 $L \cdot min^{-1}$, the total energy expenditure can be calculated as follows:

2.4 $L \cdot min^{-1}$ x 5 $kcal \cdot L^{-1}$ O_2 = 12 $kcal \cdot min^{-1}$

12 $kcal \cdot min^{-1}$ x 30 min = 360 $kcal \cdot min^{-1}$

VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$)

When the measured oxygen consumption, expressed in litres per minute, is multiplied by 1000 to obtain millilitres per minute and then divided by the subject's body weight in kilograms, the value is expressed in millilitres of O_2 per kilogram of body weight per minute, or ml. $\cdot kg^{-1} \cdot min^{-1}$. This allows comparisons to be made between people of different body sizes. For example, for a 60 kg woman with a VO2 = 2.4 L min^{-1}:

$2.4 \text{ L} \cdot \text{min}^{-1} \times 1000 \text{ ml} \cdot \text{L}^{-1} / 60 \text{ kg}$

$= 40 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$

METs

The resting metabolic rate is usually measured with an individual at quiet supine rest, after a period of fasting and not participating in exercise. The resting metabolic rate varies with age and gender, being less in females than males, and decreases with age (Knoebel, 1984). The MET (metabolic equivalent) is a term used to represent resting metabolism and is taken, by convention, to be $3.5 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$. This is called 1 MET (Costa et al., 2021).

The metabolic unit (MET) is used to measure effort and express functional capacity. It is the unit that has been most widely used and is equivalent to a resting O_2 consumption (245ml / min for a 70kg subject and 350ml / min for a 100kg subject) (Delgado & Martínez, 2010).

In essence, the energy cost of activities can be expressed in terms of multiplies of the MET unit. Using the preceding information:

$40 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1} / 3.5 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1} = 11.4 \text{ METs}$

$kcal \cdot kg^{-1} \cdot hr^{-1}$

The expression MET can also be used to express the number of calories the subject consumes per kilogram of body weight per hour. In the example mentioned above, the subject is working at 11.4 MET or $40 \text{ ml kg}^{-1} \text{ min}^{-1}$. When this value is multiplied by $60 \text{ min} \cdot \text{hr}^{-1}$, it is equivalent to $2400 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{hr}^{-1}$, or $2.4 \text{ L} \cdot \text{kg}^{-1} \cdot \text{hr}^{-1}$. If the person uses a mixture of carbohydrates and fats as fuel, VO_2 is multiplied by 4.85 kcal per litre of O_2 (average between 4.7 and 5.05 kcal/L O_2) to give $11.6 \text{ kcal} \cdot \text{kg}^{-1} \cdot \text{hr}^{-1}$. The following steps show the details.

$11.4 \text{ METs} \times 3.5 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1} = 40 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$

$40 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1} \times 60 \text{ min} \cdot \text{hr}^{-1} = 2400 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{hr}^{-1}$

$= 2.4 \text{ L} \cdot \text{kg}^{-1} \cdot \text{hr}^{-1}$

Acción, Vol. 20/ s/n publicación continua 2024, E-ISSN: 1812-5808,
https://accion.uccfd.cu

$$2.4\ L \cdot kg^{-1} \cdot hr^{-1} \times 4.85\ kcal \cdot L^{-1}\ O_2 = 11.6\ kcal \cdot kg^{-1} \cdot hr^{-1}$$

Estimation of Energy Expenditure

The long history of maximal exercise testing has allowed for the development of numerous protocols for general and specific applications, with treadmills and cycle ergometers representing the most common modalities. (Banerjee et al., 2012; Beltz et al., 2016).

Researchers studying the oxygen cost (O_2 cost = VO_2 at steady state) of exercise have shown that it is possible to estimate the energy expended during physical activity with reasonable accuracy (Hopkins & Powers, 1982) (Powers et al., 1984) (Coast & Welch, 1985) (Daniels & Daniels, 1992) (Daniels, 1985).

Walking, running, and cycling are activities that have been studied in detail. The relationships between the relative O_2 requirement ($ml \cdot kg^{-1} \cdot min^{-1}$) and walking/running speed are straight lines (Hopkins & Powers, 1982) (American College of Sports Medicine, 2010).

There is a similar relationship for cycling, up to a power of about 200W. The fact that this relationship is linear over a wide range of speeds and power outputs is convenient and calculates O_2 cost (or energy cost) very simply. Estimating the energy expenditure of other types of activities is more complex. For example, the estimation of energy expenditure during tennis depends on whether the match is singles or doubles and is also influenced by the skill level of the participants. However, it is possible to estimate the energy expended during a tennis match.

The VO_{2max} assessment is a measure that reflects the capacity of the circulatory, cardiac, muscular and metabolic systems to capture, transport and use oxygen during physical activity. Several studies, such as those by McCarthy et al., (2020) and Kelley et al., (2018), have shown that VO_{2max} is an important indicator of health and physical performance (Tauda & Bravo, 2023).

Maximal oxygen consumption (VO_{2max}) is an integral indicator of the state of the cardiovascular system, respiration, the capacity of blood to transport oxygen, and the ability of muscles to use oxygen to generate energy for muscle contraction. Another important indicator of the body's adaptation to exercise is exercise economy. The exercise economy is considered an important indicator of sports physique, which is of particular importance in endurance sports. The exercise economy is easily determined, but behind the value of this index is a complex combination of various metabolic, cardiorespiratory, biomechanical and neuromuscular characteristics that are unique to everyone (Popov et al., 2024).

Comparative studies between gradual exercise tests using the treadmill or the bicycle ergometer have shown a higher VO_2 when running on the mat, however, if we consider that the maximum body capacity (VO_{2max}) does not depend exclusively on cardiac activity, it is reasonable to think that the differences between the two ergometers do not represent different myocardial performance. (Delgado & Martínez, 2010).

In research carried out with different sports, a higher $VO_{2\ max}$ is observed on the mat than on the bicycle. The results show that after a cycle ergometer load and after a race, $VO_{2\ max}$ is similar in both cases. It is concluded that the test induces non-significant alterations in lung function that may be associated with muscle alterations and hypoxemia induced by exercise in non-elite athletes. (Basset & Boulay, 2000) (Ferguson, 2002)

Example of estimation of the O_2 requirement of treadmill walking

Stress tests, whether using the bench test, the treadmill, the cycle ergometer or isometric exercises, are procedures that allow evaluating the adequate degree of coronary circulation for the increased O_2 requirements of the myocardial fibre during physical exercise.

When a man begins to walk or run on a treadmill, he immediately begins to expend energy at a value that is proportional to the intensity of the movement. However, your VO_2 does not immediately increase to the level required to provide, through oxidation, all the energy expended in even light work, nor does it instantly return to the resting level when work stops. VO_2 rises rapidly from resting level in the first two minutes and then a stabilization is observed. When work continues at a constant intensity, VO_2

remains constant. A man's $VO_{2\ max}$ refers to his maximum intensity of aerobic energy released for a given job (oxidative energy release).

$VO_{2\ max}$ will increase with adequate training. But with age, it decreases from 50 ml/kg, at 18 years of age, to 26 ml/kg, at 75 years of age. (Delgado & Martínez, 2010).

The O_2 requirement of horizontal treadmill walking can be estimated with reasonable accuracy for speeds between 50 and 100 m · min^{-1} using the following formula:

VO_2 (ml · kg^{-1} · min^{-1}) = 0.1 ml · kg^{-1} · min^{-1} / (m · min^{-1}) x speed (m · min^{-1}) + 3.5 ml · kg^{-1} · min^{-1} (resting VO_2)

This equation tells us that the O_2 requirement of walking increases as a linear function of walking speed. The slope of the line is 0.1 and the Y-intercept is 3.5 ml · kg^{-1} · min^{-1} (resting VO_2). The O_2 cost of grade walking is:

VO_2 (ml · kg^{-1} · min^{-1}) = 1.8 ml · kg^{-1} · min^{-1} x speed (m · min^{-1}) x %grade (expressed as a fraction)

The total O_2 requirement of grade treadmill walking is the sum of the horizontal O_2 cost and the vertical O_2 cost. For example, the O_2 cost of walking at 80 m · min^{-1} at 5% grade would be:

Horizontal O_2 cost = 0.1 ml · kg^{-1} · min^{-1} x 80 m · min^{-1} + 3.5 ml · kg^{-1} · min^{-1}

= 11.5 ml · kg^{-1} · min^{-1}

Vertical O_2 cost = 1.8 ml · kg^{-1} · min^{-1} x (0.05 x 80) = 7.2 ml · kg^{-1} · min^{-1}

Hence, the total O_2 requirement of walking would amount to:

11.5 ml · kg^{-1} · min^{-1} + 7.2 ml · kg^{-1} · min^{-1} = 18.7 ml · kg^{-1} · min^{-1}

This O_2 requirement can be expressed in METs by dividing the measured (or estimated) VO_2 (ml · kg^{-1} · min^{-1}) by 3.5 ml · kg^{-1} · min^{-1} per MET:

18.7 ml · kg^{-1} · min^{-1} / 3.5 ml · kg^{-1} · min^{-1} per METs

The Formulas are taken from: (Powers & Howley, 2012), (American College of Sports Medicine, 2010)

Example of estimation of the O_2 Requirement of Treadmill Running

The O_2 requirement of horizontal treadmill running for speeds greater than 134 $m \cdot min^{-1}$ can be estimated like the procedure used to estimate the O_2 requirement for treadmill walking. The O_2 cost of the horizontal component is calculated using the following formula:

$$VO_2\ (ml \cdot kg^{-1} \cdot min^{-1}) = 0.2\ ml \cdot kg^{-1} \cdot min^{-1} / m \cdot min^{-1} \times speed\ (m \cdot min^{-1}) + 3.5\ ml \cdot kg^{-1} \cdot min^{-1}\ (resting\ VO_2)$$

What is the oxygen cost of a person running at 6 mph (161 m/min or 9.7 km/hr)?

$$VO_2\ (ml \cdot kg^{-1} \cdot min^{-1}) = 0.2\ ml \cdot kg^{-1} \cdot min^{-1} / m \cdot min^{-1} \times 161\ m \cdot min^{-1} + 3.5\ ml \cdot kg^{-1} \cdot min^{-1} = 35.7\ ml \cdot kg^{-1} \cdot min^{-1}\ or\ 10.2\ METs\ (35.7 / 3.5)$$

The Formulas are taken from: (Powers & Howley, 2012), (American College of Sports Medicine, 2010)

Example of the O_2 requirement of cycling

The O_2 requirement for cycling can be easily estimated for power outputs between 50 and 200 watts. The total O_2 cost of cycling on a cycle ergometer is comprised of three components. These include the resting O_2 consumption, the O_2 demand associated with unloaded cycling (energy cost of moving the legs), and the O_2 requirement that is directly proportional to the external load on the cycle.

First, the resting O_2 consumption is estimated at 3.5 $ml \cdot kg^{-1} \cdot min^{-1}$. Second, at a cranking speed of 50-60 rpm, the oxygen cost of unloaded cycling is also approximately 3.5 $ml \cdot kg^{-1} \cdot min^{-1}$. Finally, the relative O_2 cost of cycling against an external load is 1.8 $ml \cdot kgm^{-1} \cdot work\ rate \cdot body\ mass^{-1}$. Putting these three components together, the collective formula to compute the O_2 of cycling is:

$$VO_2\ (ml \cdot kg^{-1} \cdot min^{-1}) = 1.8\ ml \cdot kgm^{-1}\ (work\ rate) \times M^{-1} + 7\ ml \cdot kg^{-1} \cdot min^{-1}$$

The work rate on the cycle ergometer is expressed in $kgm \cdot min^{-1}$

M is body mass in kilograms

7 $ml \cdot kg^{-1} \cdot min^{-1}$ is the sum of resting O_2 consumption (3.5) and the O_2 cost of unloaded cycling (3.5).

For example, the O_2 cost of cycling at 600 kgm/min (100 W) for a 70 kg man is:

1.8 ml · kgm^{-1} (600 kgm · min^{-1}) x 70 kg^{-1} + 7 ml · kg^{-1} · min^{-1} = 22.4 ml · kg^{-1} · min^{-1}

The Formulas are taken from: (Powers & Howley, 2012), (American College of Sports Medicine, 2010).

Calculation of Exercise Efficiency

Efficiency describes the ability to convert energy expenditure into work; it is expressed as the relationship between the work done and the energy invested to do the work. A more efficient individual uses less energy to do the same amount of work. Exercise physiologists have long sought ways to mathematically describe the efficiency of human movement. Although gross, net, delta and instantaneous efficiency measurements have been used to describe exercise efficiency, one of the most common and simplest expressions is net efficiency. (Whipp & Wasserman, 1969) (Gaesser & Brooks, 1975) (Donovan & Brooks, 1977) (Stuart et al., 1981) (Powers et al., 1984) (Cavanagh & Kram, 1985) (Daniels & Daniels, 1992) (Moseley & Jeukendrup, 2001).

Net efficiency is defined as the mathematical ratio of work output divided by the energy expended above the rest (Powers & Howley, 2012):

% net efficiency = (work output / energy expended) x 100

No machine is 100% efficient, because some energy is lost due to the friction of the moving parts. Likewise, the human machine is not 100% efficient because energy is lost as heat. It is estimated that a gasoline car engine operates at approximately 20% to 25% efficiency. Similarly, the net efficiency for humans exercising on a bicycle ergometer ranges from 15% to 27%, depending on work pace. (Whipp & Wassermant, 1969) (Gaesser & Brooks, 1975) (Donovan & Brooks, 1977) (Shephard, 1982) (Powers et al., 1984)

Calculating net efficiency during bicycle ergometer or treadmill exercise requires measuring the subject's work output and energy expenditure during exercise and at rest. It should be noted that VO_2 measurements must be performed under steady-state conditions. The work rate on the bicycle ergometer or treadmill is calculated as explained above and is usually expressed in kgm min^{-1}. Expenditure during this type of exercise is usually estimated by first measuring VO_2 ($L \cdot min^{-1}$) using open-circuit spirometry and then converting it to kcal or kJ using exact conversion based on the types of foods used for fuel. In the following example, we will use 5 $kcal \cdot L^{-1}$ O_2 to show how to do this calculation. To perform the calculation using the net efficiency formula, both the numerator and denominator must be expressed in similar terms. Because the numerator (work rate) is expressed in kgm min-1 and energy expenditure is expressed in $kcal \cdot min^{-1}$, we have to convert one unit to match the other. Consider the following example of calculating net efficiency during submaximal exercise on a steady-state cycle ergometer.

Resistance against the cycle flywheel = 2 kg

Cranking speed = 50 rpm

Steady-state resting VO_2 = 0.25 $L \cdot min^{-1}$

Steady-state exercise VO_2 = 1.5 $L \cdot min^{-1}$

Distance travelled per revolution = 6 $m \cdot rev^{-1}$

Therefore:

Work rate = 2 kg x (50 $m \cdot rev^{-1}$ x 6 $m \cdot rev^{-1}$)

= 600 $kgm \cdot min^{-1}$

Net energy expenditure = (1.5 $L \cdot min^{-1}$ – 0.25 $L \cdot min^{-1}$) x 5 $kcal \cdot L^{-1}$

= 6.25 $kcal \cdot min^{-1}$

To convert kgm to kcal: 600 $kgm \cdot min^{-1}$ / 426.8 $kgm \cdot kcal^{-1}$ = 1.41 $kcal \cdot min^{-1}$

Net efficiency = (1.41 $kcal \cdot min^{-1}$ / 6.25 $kcal \cdot min^{-1}$) x 100

= 22.6%

Factors that Influence Exercise Efficiency

Exercise efficiency is influenced by three main factors: the work rate of the exercise, the speed of movement, and the fibre composition of the muscles performing the exercise.

Work rate and exercise efficiency represent changes in net efficiency during cycle ergometry exercise as a function of work rate. That efficiency decreases as the work pace increases (Donovan & Brooks, 1977) (Powers et al., 1984). This is because the

Acción, Vol. 20/ s/n publicación continua 2024, E-ISSN: 1812-5808,
https://accion.uccfd.cu

relationship between energy expenditure and work rate is curvilinear rather than linear over a wide range of energy outputs (Gaesser & Brooks, 1975) (Powers et al., 1984).

Research has shown that there is an optimal movement speed for any given work pace. Evidence suggests that optimal movement speed increases as power output increases (Coast & Welch, 1985). In other words, at higher powers, a higher movement speed is required for optimal efficiency. At low to moderate work rates, a pedalling speed of 40 to 60 rpm is generally considered optimal during arm or bicycle ergometry (Gaesser & Brooks, 1975) (Michielli & Stricevic, 1977) (Shephard, 1982) (Powers et al., 1984) (Deschenes et al., 2000) (Ferguson et al., 2001).

People differ in their net efficiency during cycle ergometer exercise. Because? Evidence suggests that subjects with a high percentage of slow muscle fibres show greater exercise efficiency compared to subjects with a high percentage of fast muscle fibres. The physiological explanation for this observation is that slow muscle fibres are more efficient than fast fibres. That is, slow fibres require less ATP per unit of work performed compared to fast fibres (Powers & Howley, 2012).

Higher efficiency can improve exercise performance. For example, compared to subjects with relatively low efficiency, subjects with high efficiency can generate greater energy output with any energy expenditure. Therefore, it is not surprising that studies have shown that endurance performance improves with high exercise efficiency (Horowitz et al., 1994).

Conclusions

This study underscored the significance of accurate measurement, careful load management, and understanding energy dynamics for enhancing training efficacy and optimizing performance in athletic and exercise contexts.

Direct or indirect calorimetry can measure energy expenditure at rest or during exercise. Direct calorimetry uses measurement of heat production as an indication of metabolic rate. Indirect calorimetry estimates metabolic rate by measuring oxygen consumption.

Net efficiency is the mathematical relationship between the work done divided by the energy expenditure during rest, which is expressed as a percentage.

Exercise efficiency decreases as work pace increases. This happens because the relationship between work rate and energy expenditure is curvilinear.

There is an optimal movement speed to achieve maximum efficiency at any work pace. Subjects who have a high percentage of slow muscle fibres have greater efficiency during exercise compared to subjects with a high percentage of fast fibres. This occurs because slow muscle fibers are more efficient than fast fibres.

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Declaración de conflicto de intereses: Los autores declaran no tener conflictos de intereses sobre el artículo.

Contribución de autoría: *Conceptualización*: I. Pérez .*Curación de datos*: I. Pérez, L. T. Charumbira *Análisis formal*: I. Pérez, L. T. Charumbira, H. F. Molina *Investigación:* I. Pérez, L. T. Charumbira, H. F. Molina Metodología: I. Pérez .*Administración del proyecto:* I. Pérez, *Supervisión:* I. Pérez. *Validación*: I. Pérez, L. T. Charumbira, H. F. Molina.*Redacción-borrador original*: I. Pérez, L. T. Charumbira, H. F. Molina Redacción. *Revisión y edició*n: I. Pérez.