ENEBI 2015
ENCONTRO NACIONAL DE ENGENHARIA BIOMECÂNICA
ENGENHARIA BIOMECÂNICA PARA VIVER SEM LIMITES
05 a 08 DE MAIO UBERLÂNDIA-MG

EVALUATION OF DIFFERENT METHODS OF MECHANICAL WORK CALCULATION AND THEIR EFFECT ON THERMODYNAMIC ANALYSIS OF RUNNERS ON A TREADMILL TEST

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Abstract*. The performed power is an important physical quantity when one evaluates a person running using Thermodynamic analysis of the human body. Nevertheless, there is not yet an ultimate conclusion of its calculation. In this work four equations of performed power available in literature are used to apply the First and Second Laws of Thermodynamics to runners on a treadmill running test aiming to discuss which of these definition would lead to results of internal temperature of the body closer to the one measured after the test. Results indicate that the equation with better results may not take into account all the movements that can be considered as useful mechanical power. The energy efficiency calculated using different definitions of performed power varied from 8 to 56%.*

Keywords*: Thermodynamic analysis, performed power, treadmill running test*

1. INTRODUCTION

An overall study of human body behavior requires the use of the Second Law of Thermodynamics in order to assess the quality of the energy conversion processes that take place in its several organs and systems. Over the past decades, several authors performed experimental and numerical studies attempting to confirm the “Prigogine’s principle”. Balmer (1982), Aoki (1991), Rahman (2007), Silva and Annamalai (2008) analyzed the entropy generation over the lifespan and all their results confirmed the minimum entropy principle. Mady *et al*. (2012) obtained that not only the entropy production decreases over time, but also the exergy efficiency decreases as a function of lifespan. Albuquerque-Neto *et al*. (2010), Mady *et al*. (2013) and Henriques *et al*. (2014) applied the exergy analysis to the human body during physical activities. Several authors such as Prek (2005), Rabi *et al*. (2012) and Mady *et al*. (2014) tried to correlate the points of minimum destroyed exergy with thermal comfort and thermal sensation conditions. Furthermore, the concept of entropy production and destroyed exergy were even applied in cancerous and neurons cells as indicated in Luo (2009) and Genc (2013).

To perform the energy and exergy analysis to the human body, the performed work, or performed power, must be precisely determined, not only to fulfill energy and exergy balances, but also to evaluate how physical exercise impacts body efficiency, which was evaluated, on energy basis, by Kaneko (1990), Ito *et al*. (1983), Williams and Cavanagh (1983) and Bijker *et al*. (2001) and, on exergy basis, by Albuquerque-Neto (2010), Mady *et al*. (2013) and *Henriques et al*. (2014). The methods used to obtain the performed power in literature lead to values from 343 to 1650 W for speeds between 3.6 and 3.9 m/s, as demonstrated in Kaneko (1990), which show that the discussion on the calculation of performed work in a treadmill running test has not yet come to an ultimate conclusion.

Cavagna *et al.* (1976) determined external performed work as the variation of mechanical energy of center of mass. Moreover, they affirmed that it was composed of a parcel related to the work performed against gravity and another one associated with velocity changes. Then, by means of experimental data, performed work on a treadmill as a function of speed was determined. Right after, Cavagna and Kaneko (1977) defined total performed work as the sum of external (Cavagna *et al*., 1976) and internal work, which is the work related to limbs movement, and they also determined an expression to calculate it from values of speed. Sakurai and Miyashita (1985) highlighted the difference between mechanical energy variations calculated by two methods: limbs movement and center of mass. Kram and Taylor (1990) discussed the role played by weight and the time interval where the feet touch the ground. In addition, Arampatzis *et al*. (2000) evaluated different methods of calculating performed work and concluded that cinematic methods fail in identifying extreme accelerations.

The present work aims at discussing the thermodynamic significance of the performed work of a person running on a treadmill with a slope of 1% and compare it with literature equations, such the one proposed by Cavagna and Kaneko (1977) that take into account the internal (the work done at each step during level walking and running to lift the center of mass of the body and to increase its forward speed) and external work (maintain the motion of the center of gravity). Internal temperature values measured on running test will be confronted with those obtained by thermodynamic analysis using four different equations to calculate performed power. Moreover, a comparison will be made with the maximum available work that the body can perform from the hydrolysis of the substance ATP in the cellular metabolism.

2. METHOD

As mentioned above, for the precise thermodynamic analysis of human body it is necessary to calculate correctly the performed work. Apart from simple energy and exergy analyses, determination of performed work is also necessary to analyze metabolic behavior of human body. Figure 1(a) indicates the energy analysis applied to the cellular metabolism discussed in Mady and Oliveira Junior (2013), where the energy released of the oxidation of nutrients (M) is transformed into heat (Q_M) and work (W). Meanwhile, Fig. 1(b) displays the exergy analysis of the cellular metabolism, where B_M is the exergy variation of reactions of oxidation of nutrients (maximum work that could extract the body of nutrients consumed). Since this kind of study takes into account the quality of the energy conversion in a given process, it is possible to calculate the maximum available work from the Gibbs Free Energy of ATP hydrolysis (W_{MAX}=-ΔG_{ATP}), indicated by Eq. (1). Therefore, the Thermodynamic analysis gives an upper limit to the performed work, which is the maximum quantity that the body can transform into work (or power) from the exergy content of nutrients. Moreover, the difference between maximum available and performed work quantifies the inefficiencies among the process of ATP utilization demonstrated in the third column of Figure 1(b). From the exergy analysis, it is also possible to calculate the irreversibilites quantified by the destroyed exergy ($B_{d,ATP}$ and $B_{d,r}$).

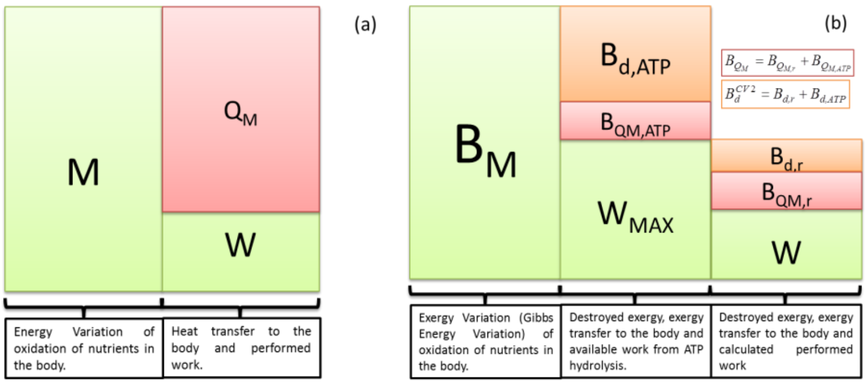

Figure 1. (a) Energy analysis of the conversion of the chemical energy of substrates into work and heat, (b) Exergy conversion process in the cellular metabolism. From nutrient oxidation, ATP formation and use of ATP

The Thermodynamic concept of performed work is: *"work is done by a system on its surroundings if the sole effect on environment external to the system could be characterized by a rising of a weight*". Based on this concept question can be made: which expression of mechanical power done by the human body would take into account all the movements of the body that are capable of being computed as a useful effect? On a stationary bicycle, this effect is more easily calculated, however for a runner this discussion is more subtle. Equation (2) is commonly used in exercise physiology according to references as Powers and Howley (2000). Nevertheless, Cavagna and Kaneko (1977) discusses that the external mechanical power (therefore the definition that satisfies the Thermodynamic concept) is calculated as indicated in Eq. (3). The total mechanical power (internal and external), can be computed by Eq. (4).

$$\dot{W}_{MAX}\,(\mathrm{W}) = -\Delta\dot{G}_{ATP} \tag{1}$$

$$\dot{W}(\mathrm{W}) = mgV\sin(\theta) \tag{2}$$

$$\dot{W}(\mathrm{W}) = m(9.42 + 4.73V)4.184/60 \tag{3}$$

$$\dot{W}(\ \mathrm{W}\ ) = m\left(9.42 + 4.73V + 0.266V^{1.993}\right)4.184/60 \tag{4}$$

In order to discuss the calculation of performed work, a comparison of these four equations will be held based on experimental data obtained by Mady *et al*. (2013) for runners in a treadmill with 1% of slope. The methods to calculate the energy transfer to environment and internal temperature are also available in the same article.

3. RESULTS

First Law Analysis was applied based on experimental data obtained by Mady *et al*. (2013) for 09 and 10 runners, indicated in the present analysis as runners 1 and 2. For subject 10 the maximum velocity was 15 m/s, and the performed power calculated by Eqs. (1) to (4) are demonstrated in Figure 2. It is evident that the value calculated by Eq. (2) led to smaller results of power. A comparison of Eq. (1) and (4) indicates that the method proposed by Cavagna

(1977) has equivalent results with the maximum performed work obtained by ATP hydrolysis. The only difference is that first equation is a function of indirect calorimetry results and the second is a function of the velocity, which resulted in different shapes of the curves. With the values of metabolism presented in Figures 3 to 5, and the values of performed power showed in Figure 2 it is possible to obtain the energy efficiency for the subject 10: 8.9%, 36.4% and 58.6%, for Eq. (2), (3) and (4), respectively. The definition of efficiency used is the ratio of performed power to the metabolism, both integrated over the entire test.

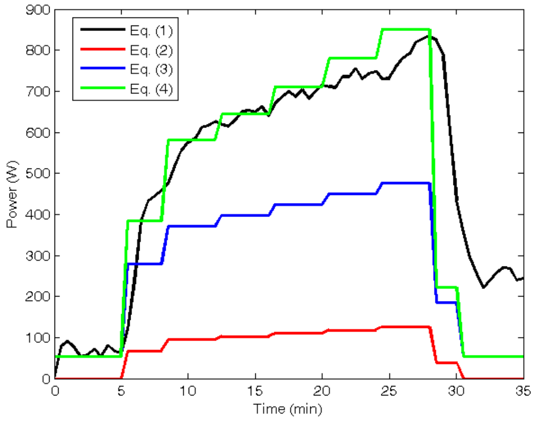

Figure 2. Performed power as a function of time calculated using Eqs (1) to (4)

In Figs. 3 to 5 (a) and (c), the calculated internal temperature (line in blue) and the measured points of tympanic temperature (dots in black) are indicated as a function of time. It is also indicated in Figs. 3 to 5 (b) and (d) the energy balance for the runner during physical activity, where the metabolism (*M*) is demonstrated in blue, the performed power (*W*) in green and energy transfer to environment (Q_{env}) in red. From these figures, it is possible to conclude that higher values of performed work resulted in lower values of energy transfer to the environment and lower values of internal temperatures. Nevertheless, the lowest performed power calculated from Eq. (2) led to results of internal temperature closer to the one measured at the end of the test. This result may lead to the conclusion that the most proper definition of performed power for a Thermodynamic analysis is the one of the Eq. (2). Moreover, the difference of the Eq. (1) and Eq. (2), in Figure 2 indicated in black and red respectively, are better interpreted using The Second Law of Thermodynamics, where there is a limitation of the maximum available work, and it is possible to compute the inefficiencies of the body and/or the heat dissipated to the environment as indicated in Mady *et al*. (2013).

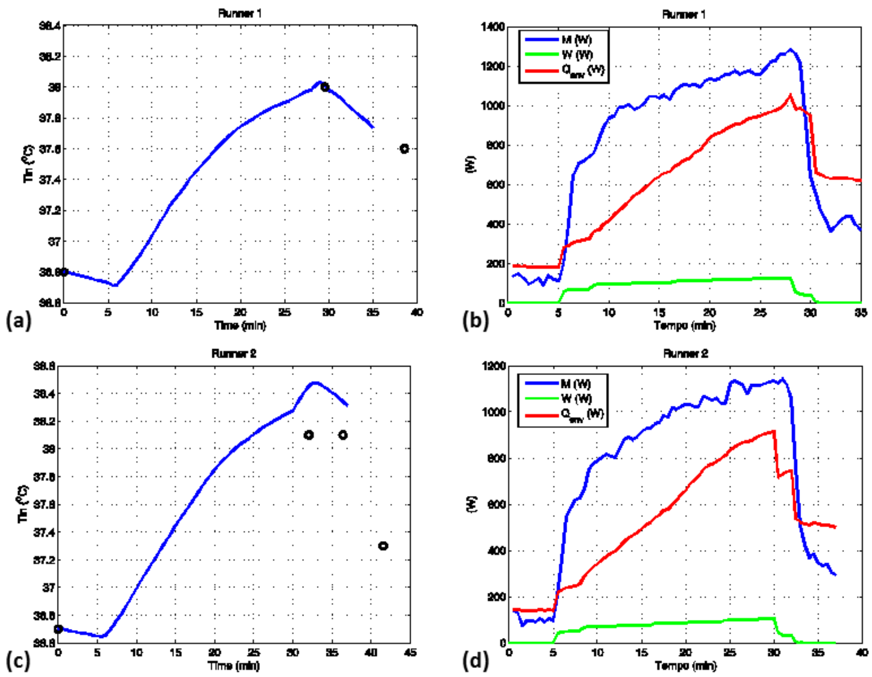

Figure 3. Results of: (a) and (c) internal temperature, (b) and (d) energy balance as a function of time for runners 9 and 10. Performed power calculated by Eq. (2)

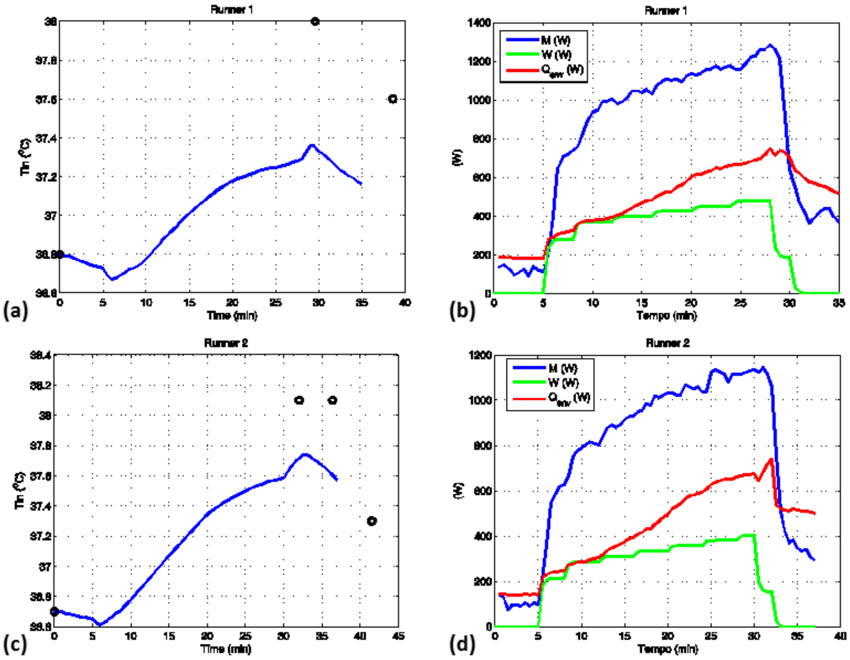

Figure 4. Results of: (a) and (c) internal temperature, (b) and (d) energy balance as a function of time for runners 9 and 10. Performed power calculated by Eq. (3)

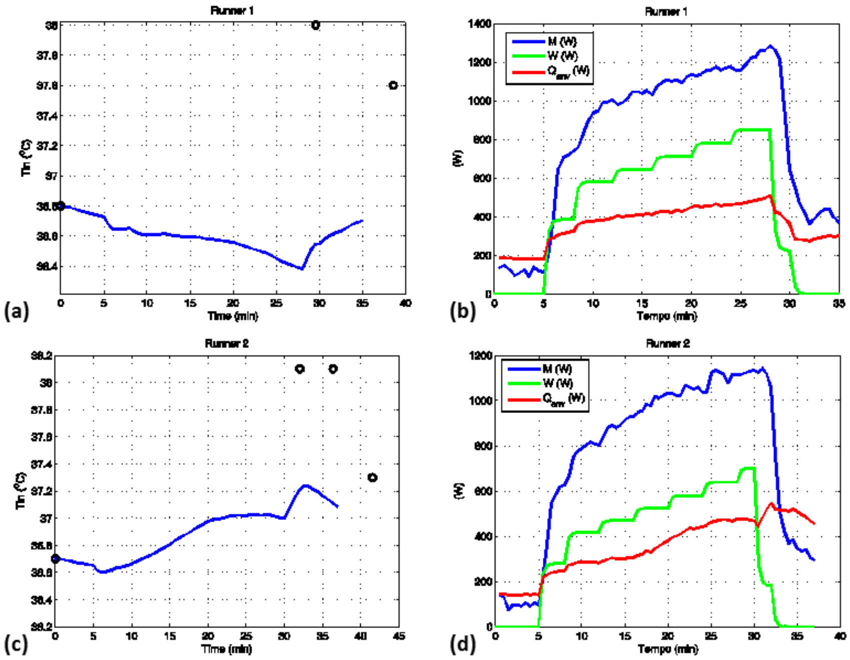

Figure 5. Results of: (a) and (c) internal temperature, (b) and (d) energy balance as a function of time for runners 9 and 10. Performed power calculated by Eq. (4)

4. CONCLUSIONS

In this work, First Law Analysis was applied to the human body during a treadmill running test using values of performed power determined by four different methods. Moreover, from the Second Law of Thermodynamics, it was possible to calculate an upper limit for the performed power. Internal temperature obtained by each method was compared with the value measured right after running test. Results indicate that the definition of performed power, expressed by Eq. (2) is the one that led to results of calculated temperature closer to the measured one. Nevertheless, this expression does not take into account several movements of the body that could be considered in the definition of work, moreover, the performed power to accelerate the body when there is a change in the speed is not computed in this definition as is computed in the definition of Cavagna and Kaneko (1977).

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