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STEADY STATE MODELS PROVIDE AN INVALID ESTIMATE OF INTERMITTENT RESISTANCE-EXERCISE ENERGY COSTS

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ABSTRACT

The prototype modeling of biological energy exchange invokes per minute measurements of oxygen uptake (l min^{-1}), including exercise. While dedicated to steady rate power outputs, the oxygen uptake rate function model is now appropriated to intermittent exercise as well with resistance training serving as a primary example. Resistance training energy costs as described here are not properly portrayed by steady state oxygen uptake models - indeed, such application lacks validity. We instead suggest that the energy costs of brief, intense, intermittent exercise should be quantified in the context of a capacity estimate, where a bout of exercise and/or amount of work (J) completed is associated with a specific energy cost (kJoules). For resistance exercise, we propose linear models that measure work and energy *bouts* as an alternative to the steady state *rate* model.
Key Words: oxygen uptake, anaerobic energy expenditure, weight lifting

RESUMEN

El modelo biológico de intercambio de energía utiliza el consumo de oxígeno (L/min) incluido el ejercicio. Este modelo está siendo utilizado actualmente también en los modelos de ejercicio intermitente de entrenamiento con cargas. El gasto energético del entrenamiento con cargas no es el resultado directo de la utilización del coste energético derivado del oxígeno consumido, sino que debe asociarse a una relación participar entre el trabajo mecánico desarrollado y el coste en energía específica. Concretamente, para el entrenamiento con cargas, se propone una serie de modelos lineales que relacionan en base a la potencia de trabajo, una relación concreta con el coste energético, muy diferentes del modelo dinámico basado en el oxígeno.
Palabras clave: consumo de oxígeno, gasto energético anaeróbica, entrenamiento con cargas

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INTRODUCTION

The standard unit of measure for just about all descriptions of biological energy exchange consists of a per minute measurement of oxygen uptake (l min-1). Estimates of the energy costs of exercise - including those lasting seconds - likewise follow suit: a 40 m sprint, climbing a flight of stairs, resistance training, all are described in the context of the rate at which oxygen is consumed per minute. We describe why steady state oxygen models do not apply to intermittent-type exercise, with resistance training serving as the primary example. To begin, steady state exercise is typically described in the format of intensity (at a % of VO2max) with resistance training being described in the context of work (at % of a maximum load); these disparate standards do not allow an appropriate comparison (Steele et al., 2012). Briefly put, the physiologic and metabolic responses of running and cycling inadequately portray the energy costs of resistance exercise. We utilize the terms ‘energy expenditure” to denote oxygen uptake measurements and ‘energy costs’ to denote an estimate of both the aerobic and anaerobic components of energy exchange.

METHOD

The Steady State Model

Among subjects with similar body mass the energy expenditure (l min^{-1}) of steady state aerobic exercise can be interpreted to rise in linear fashion with increasing power outputs (Watts) or work rates. Margaria and colleagues (1963) put forth an energy cost model for running that favored the steady state linear approach, along with the remarked inclusion of anaerobic energetics. During steady state runs below and up to maximum oxygen uptake (VO_2 max), Margaria had steady state oxygen uptake rates dictate the estimated rate of energy expenditure (as the steady state model assumes). Above VO_2 max, a further extrapolation was made, first consisting of the glycolytic energy cost component - based on blood lactate levels - followed by contributions made from the high energy phosphate stores (ATP, PC) (Margaria et al., 1964). Each line – oxygen uptake, glycolysis, high energy phosphates - is a continuation of the former, representing a complimentary relationship between *work rates* and energy costs. In a later paper Margaria and colleagues (1964) further identified energy costs in the format of *work bouts*, specifically sprinting at 18 km hr^{-1} (11 mph) at inclines of 25% to 10% over 2 to 30 s time periods. Based on Margaria’s thesis, the relationship between work bouts and energy costs has been further described in terms of a *vector* consisting of: *magnitude*, the number of metabolic systems involved and, *direction*, the proportionate rise of increased cost to increased work (Figure 1) (Scott and Fountaine, 2013).

Margaria preceded the concept of the anaerobic threshold (with related "extra" energy expenditure). It is now understood that during heavy to severe steady rate exercise, oxygen uptake rates depart from a steady state plateau within any given subject and may continue upwards until VO_2 max or exhaustion (muscular fatigue) are reached (Figure 2). This interpretation suggests an additional non-proportional rise in energy expenditure rates at higher intensities, where the processes of fatigue often occur over minutes as opposed to seconds. While it is unclear how the concept of the anaerobic threshold should or more likely should not be used to describe the energy costs of resistance exercise, higher intensity exercise of all types are thought to change the contributions or the extent of both aerobic and anaerobic metabolism. Yet while studies have examined how the rate of power output changes the rate at which oxygen is consumed (Hansen et al., 1988; Hughson and Inman, 1986), the related recruitment of the underlying anaerobic metabolic systems has not undergone equal consideration. Limited evidence suggests that aerobic and anaerobic energy costs complement one another, as overall energy costs remain equivalent (Layec et al., 2009). That is, for a given total energy cost a low aerobic contribution can be complimented with a greater anaerobic contribution, or vice-versa.

Intermittent Exercise

Non-steady state intermittent resistance exercise also has been portrayed in the context of steady state oxygen uptake (Figure 3). Unlike continuous steady state exercise, intermittent resistance exercise typically involves brief bouts or 'sets' accompanied by a period of recovery after each set; steady state exercise contains only one recovery component. As oxygen uptake rises during resistance exercise, then rises further before falling in the recovery periods, a central tendency "steady state" (average) is typically identified representing a single energy cost rate - the costs of intermittent resistance exercise have been modeled after steady state exercise for decades (see McArdle and Foglia, 1969; Wilmore et al., 1978).

Yet there is evidence of all types indicating that the steady state model provides an invalid estimate of resistance exercise energy costs. Divide continuous "aerobic" exercise into work equivalent intermittent bouts for example and oxygen uptake typically increases, suggesting greater energy expenditure for intermittent-type exercises (Christensen et al., 1960; Edwards et al., 1973; Scott, 2014). This evidence alone serves to disprove the steady state model as a valid representation of intermittent exercise costs (Katch, 1986).

A more intriguing example is revealed for low intensity steady rate aerobic exercise where blood flow to working skeletal muscle that has been momentarily arrested likewise results in an increase in oxygen uptake rates (Loeppky et al., 2008; Roth et al., 1988). Consider especially resistance exercise where loads as low as 21% of a maximal voluntary contraction have the potential to arrest blood flow to working skeletal muscle (Edwards et al., 1972). Include an anaerobic energy component and the total energy cost difference as compared to oxygen-only measurements becomes larger still (Scott et al., 2009, 2011a; Vianna et al., 2011). Taken collectively, we strongly suggest that steady state exercise represents an invalid energy cost model for intermittent resistance exercise.

An Energy Cost model

It is not known how energy costs scale with resistance exercise as work increases: disproportionately (Figure 2), complementary (Figure 1) or additive (Figure 4). Different though they are, the steady state model and the publications of Margaria provide a starting point. Data collected by Robergs et al (2007) as a rate function of VO_2 (l min^{-1}) in steady state format, had subjects lift loads corresponding to ~4-24% of one repetition maximum testing (1-RM) (gross as opposed to net oxygen uptake was reported). Variability of oxygen uptake (always a problem) could not be accounted for in full, with the authors suggesting the possibility of an exercise-to-oxygen uptake ratio that would not be linear across all lifting intensities. Reis et al (2011) have confirmed that above 30% 1-RM of a squat resistance exercise a steady state work rate could not be attained. Increased energy costs are certainly seen as resistance training work increases but again, should these increases be depicted by a steady state/anaerobic threshold model (Figure 2)?

Intermittent exercise energy cost modeling in the realm of strength training can avoid steady state methods using volume (kJ) as opposed to rate (kJ min^{-1}) measures, where net as opposed to gross energy costs are emphasized (i.e., resting costs are subtracted from exercise costs). When resistance exercise energy costs are recorded in terms of work (as the product of weight lifted and vertical displacement of the bar), the energy costs of submaximal and maximal (to fatigue) lifts each revealed a distinct complimentary linearity (Figure 1) (Scott et al., 2009; 2011a). However, when both fatigue and non-fatigue data sets were retrospectively compared an additive scaling was observed, *with each rising in parallel* (Figure 4) (Scott and Earnest, 2011b). From the perspective of resistance work (J) and total energy cost (kJ) as opposed to intensity and oxygen uptake rates, the costs of lifting to fatigue are additive to non-fatigue conditions but in a proportional manner. Additional research is needed to examine the potential of this phenomenon throughout the almost limitless examples of resistance exercises available as it is likely each specific exercise has its own cost-to-work vector.

Lastly, as measured on separate days, both aerobic and anaerobic metabolic variance can be (unacceptably) extensive when estimated in accordance with resistance training work bouts. This represents either tremendous biological variability or a training effect, both influencing the extent of aerobic and metabolic contributions. Regardless, when aerobic and anaerobic cost estimates are together used to estimate a single total energy cost for resistance exercise work, variability decreases markedly (Scott et al., 2009; Scott and Fountaine, 2013).

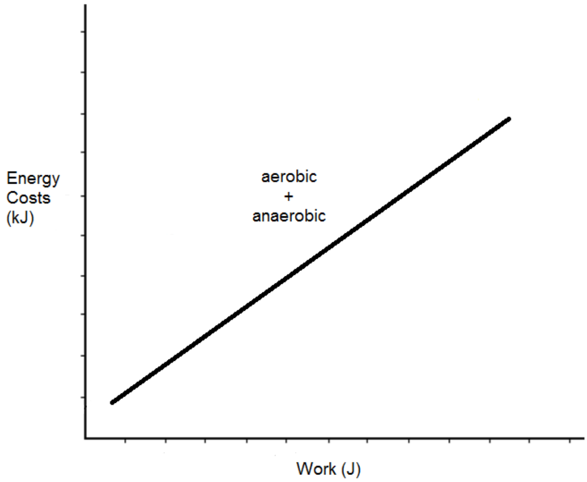

FIGURE 1: In this example aerobic and anaerobic costs are complementary, portraying a single vector-like line for bouts of work - both magnitude (the number of metabolic systems involved) and direction are depicted. Each type of resistance exercise may have its own unique vector.

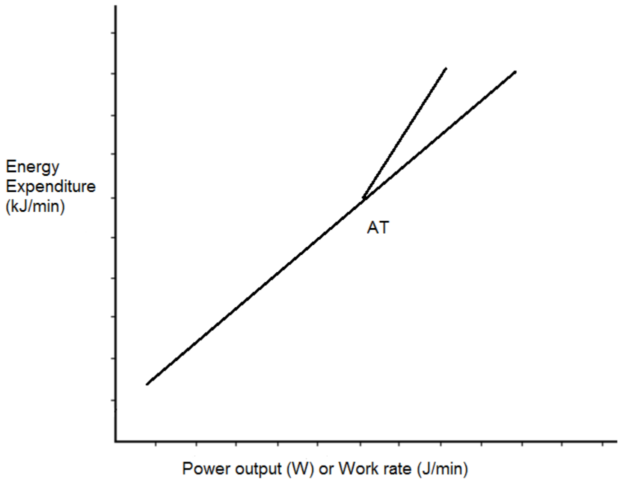

FIGURE 2: The modeling of exercise oxygen uptake (based on steady state methodology) is shown as intensity increases. Two formats are depicted: 1) linearity above and below the anaerobic threshold (AT) and 2) energy expenditure that is disproportionate (additive) to the linear steady state model after the AT is reached. It is not known how or if the concept of the anaerobic threshold with related "extra" energy expenditure occurring over minutes of running or cycling, should be applied to resistance work where fatigue often sets in within the time frame of a few repetitions (i.e., seconds).

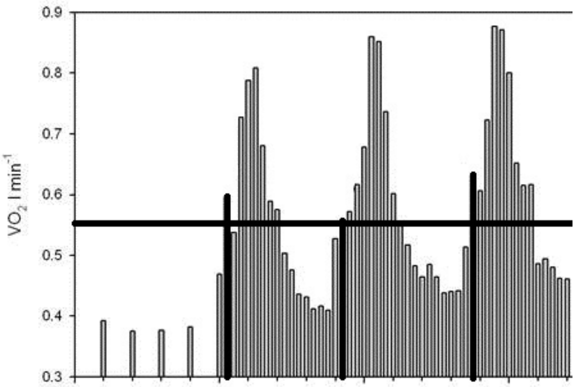

FIGURE 3: Each of three 15 s lifting periods is depicted as a black vertical bar. The recovery periods after each set are shown as grey vertical bars. The black horizontal line provides a mean (central tendency) "steady state" oxygen uptake of ~ 0.55 l min^{-1}. The steady state modeling of resistance exercise eliminates the associated oxygen cost variability of resistance exercise and recovery but makes no consideration between them, until the last recovery period. Note also that oxygen uptake rises in the recovery periods whereas with steady state exercise, recovery oxygen uptake always exponentially falls. Adapted from Scott, 2012.

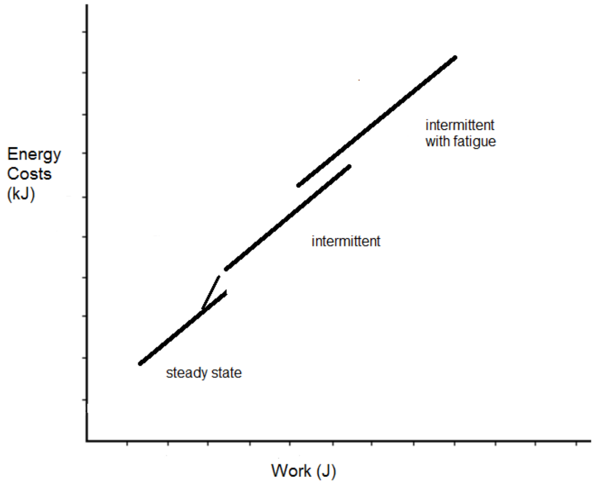

FIGURE 4: Energy costs are additive in the above depiction, but not in the manner associated with the higher intensity steady state/ anaerobic threshold model (shown here for comparison purposes only). We propose that as resistance work increases, additional metabolic systems are engaged - aerobic, glycolytic and ATP, PC stores – at an increased yet *proportional* linear cost as compared to higher intensity steady state conditions. Fatigue adds another fixed proportional cost to work bouts.

CONCLUSIONS

Intermittent conditions as well as momentary blood flow occlusion increases overall oxygen uptake during steady state exercise rates; these increased costs likely apply to resistance training. Moreover, based on volume (J) as opposed to rate (J min^{-1}) measures, lifting a weight to fatigue promotes extra aerobic and anaerobic costs that are proportional to non-fatigue conditions, adding a *fixed cost* regardless of the amount of work completed – this differs from the traditional non-proportional steady state/anaerobic threshold modeling of energy expenditure. We herein propose an additive-type linear energy cost model as an alternative to the steady state/anaerobic threshold model for intermittent resistance exercises – with each resistance exercise likely having its own energy cost to work vector.

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