

INTERMITTENT RESISTANCE EXERCISE: EVOLUTION FROM THE STEADY STATE

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Abstract. Oxygen uptake measurements are without question useful and a staple measurement for the estimation of exercise energy costs. However, steady state models cannot be used to successfully model intermittent resistance exercise energy costs. Our laboratory has taken steps to avoid such comparisons between these discrepant exercises. We have separated out exercise and recovery periods during resistance training and utilize capacity (kJ) estimates as opposed to rate measures (kJ min^{-1}). Moreover, we avoid anaerobic threshold concepts as applied to resistance exercise. When viewed accordingly, resistance exercise energy costs are opposite those of the steady state model: exercise oxygen uptake is highest for steady state exercise and lowest for resistance exercise, recovery oxygen uptake can be the highest energy cost for resistance exercise whereas for steady state exercise it may or may not be meaningful, and anaerobic energy costs represent a significant component of resistance exercise that plays little to no role with steady state exercise.

Key words: anaerobic energy, blood lactate, excess post-exercise oxygen consumption (EPOC)

Introduction

Nutritional and heat measurements once dominated the study of life's energy exchanges. That all changed when the results of 22 experiments completed over a period of 12 years (involving 5 human subjects total!) had been published in their entirety (Atwater and Benedict 1902; Benedict and Carpenter 1909). Oxygen uptake, quite literally, now dictates the study of human energy exchange. Indeed, contemporary exercise scientists are trained to recognize oxygen uptake as the only valid means to estimate energy expenditure. As stated by McLean and Tobin (1987), "the Atwater and Benedict respiration chamber [from 1892–1904]... was a landmark in human calorimetry... it would be surprising to find anyone who would now challenge the view that oxygen consumption provides an accurate measure of energy expenditure" (pp. 68).

Perhaps the most important concept behind any gold standard measure of biological energy exchange is that of a steady state. Max Rubner's calorimeter held its canine inhabitant for 45 days; Atwater and Benedict achieved highest accuracy only after several days of measurement with a human subject. The greatly improved

cost and ease of data collection certainly helped promote gas exchange measurements over those of heat. More importantly however it became apparent that the demands of physical exertion, in all its formats, actually required experimentation outside of a confined chamber. Inside or outside of a calorimeter the steady state model is now applied to most every form of movement called 'exercise', steady state or not.

The central tenet of this manuscript is not to refute the unquestioned usefulness of oxygen uptake measurements within exercise science laboratories worldwide. A majority concern however is with the false concept that steady state exercise can be used to successfully model intermittent resistance exercise energy costs. Using capacity (kJ) as opposed to rate (kJ min^{-1}) measurements, our laboratory separates intermittent resistance exercise sets from their recovery periods, just as is done for continuous steady state exercise (having only one exercise and recovery period, respectively), and we have found rather profound differences. We adopt the terminology of Reis et al (2011) with energy expenditure referring specifically to oxygen uptake, and with the term energy costs referring to an estimate using both gas exchange conversions along with anaerobic costs.

Oxygen uptake (LO_2) as Energy Expenditure (kJ)

Over 150 years ago it was shown that the ratio of carbon dioxide produced to oxygen consumed was related to the type of food eaten (McLean and Tobin 1987; Frankenfield 2010). The respiratory exchange ratio (RER) provides energy expenditure (i.e., oxygen uptake) conversions for glucose and fat consumption (and combinations thereof):

<u>Substrate</u>	<u>Conversion</u>
Fat	1 liter of O_2 = 19.6 kJ
Glucose	1 liter of O_2 = 21.1 kJ

Reviews of indirect calorimetry describe these conversions best in the context of a steady state where gases exchanged are not precipitously rising and falling (Ferrannini 1988; Simonson and DeFronzo 1990). Perhaps because resistance exercise exemplifies non-steady state conditions, energy expenditure associated gas exchange conversions resulting from substrate utilization are typically ignored altogether, having been replaced with oxygen-only measurements. We have addressed this problem by separating the actual resistance exercise periods (each lasting seconds) from the recovery periods (each lasting minutes) and assigning glycogen oxidation during the lift, and fat and lactate oxidation in the recovery periods between exercise sets (Scott 2011). We assess the 1.5 kJ energy conversion difference between glucose and fat oxidation to the anaerobic metabolic component of ATP re-synthesis, being the result of glycolytic contributions to energy exchange when data are expressed as liters of oxygen consumed (Scott 2012a). This component is dismissed from recovery oxygen uptake when fat and lactate are proposed as the dominant oxidized substrates.

The steady state dominates the modeling of most all forms of exercise. Indeed, oxygen uptake throughout multiple resistance exercise and recovery periods is typically averaged to report a single $\text{ml O}_2 \text{ min}^{-1}$ measurement – the very model of steady state exercise (Figure 1). The steady state model suggests that exercise oxygen uptake by far represents the largest overall contribution to energy expenditure. In fact, the single excess post-exercise oxygen consumption (EPOC) measurement that follows steady state exercise is not included as part of the overall average. How does this compare when resistance exercise sets also are separated from their recovery periods? We have found that with resistance training, exercise oxygen uptake periods (sets) when summed always have the lowest contribution to overall energy expenditure. Moreover, when recovery oxygen uptake after a single set or in between

multiple sets is summed, it represented the largest component to overall oxygen uptake (Scott 2009, 2012b, 2012c). Intermittent resistance exercise and recovery oxygen uptake can be mirror opposite the steady state model.

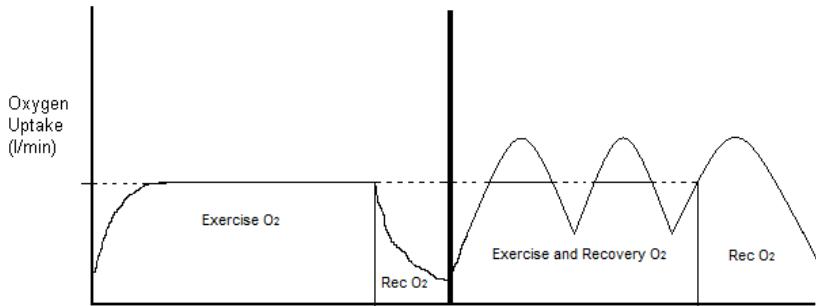


Figure 1. The steady state model is shown on left; to the right 3 hypothetical sets of resistance exercise. The horizontal dotted line reveals the steady state interpretation of energy expenditure ($l \text{ min}^{-1}$) as applied to both steady state and intermittent resistance exercise (Rec O_2 = recovery oxygen uptake). Steady state exercise has one recovery component that is not included as part of overall energy costs. As dictated by the steady state model however, exercise and recovery oxygen uptake are typically averaged as a single measure with resistance exercise, until the last recovery period. Note that oxygen uptake peaks (and plateaus) during steady state exercise and, to the contrary, peaks in the recovery from resistance exercise. Anaerobic energy costs are absent from the steady state model

Validity is assumed when changes to steady state power or work rates result in proportional changes to steady state oxygen uptake rates. In fact, oxygen uptake rates are not proportionate throughout a range of steady rate work rates (Steudel-Numbers and Wall-Scheffler 2009). This discrepancy along with the unaccountability of substrate related energy expenditure conversions, serve as a reminder that the best we can do with the indirect measures we have is obtain a reasonable estimate of energy expenditure and energy costs.

Blood Lactate as an Anaerobic Energy Cost

Exercise science would have its first and only Nobel Laureate in 1922. A.V. Hill perfected a device called a thermogalvanometer and when investigating contracting frog skeletal muscle within a small nitrogen-filled chamber, concluded that the disappearance of glycogen, the appearance of lactic acid and the amount of heat loss (i.e., energy exchange) were all related. Important as once considered, it is not far-fetched to now concede that Hill's thermal measurements are not only gone, but forgotten as well. Clearly, the study of lactic acid (lactate) has evolved exponentially since and so has our knowledge about this engaging metabolite. Indeed, blood lactate signifies important physiological 'threshold' concepts (e.g., % $\text{VO}_{2\text{max}}$) of working skeletal muscle under steady state conditions, but lactate and its associated thermal significance is considered invalid to energy cost applications.

Compromised oxygen delivery used to be the de facto definition of the anaerobic threshold with many now doubting the hypoxia argument. With resistance exercise however the hypoxic scenario is real (Edwards et al. 1972; Tamaki et al. 1994). Resistance exercise is defined in terms of a load, typically set at a percent of a one repetition maximum (% 1RM); steady state exercise and its associated anaerobic threshold are depicted as intensity at a percentage of $\text{VO}_{2\text{max}}$ (Steele et al. 2012). Unfortunately as many as 25 thresholds have been determined as part of the steady state model and this is a problem (Faude et al. 2009). Yet a threshold phenomenon for resistance

training is completely unsubstantiated. Indeed, at 20% of a maximal voluntary isometric contraction – a load well below that of strength training – blood flow to working skeletal muscle was found to be completely arrested (Edwards et al. 1972). Under hypoxic/anoxic conditions an argument can be made that oxygen uptake provides an invalid estimate of energy expenditure; ironically, these conditions instead appear to invalidate lactate production as an estimate of anaerobic energy costs.

Central to validity arguments for any metabolic marker, especially within the blood stream, is the knowledge of that metabolites rate of production and rate of removal (a steady state threshold appears to meet these criteria). This is, without question, true. It is also idealistic. Reasonable estimates taken from blood borne markers have for years provided physiological understanding, without acknowledgement of production or removal rates. Blood norepinephrine levels for example, can provide indirect evidence of sympathetic nervous extent. Blood levels of glycerol are used to indirectly assess fat metabolism. A “snapshot” blood glucose measurement literally defines how much insulin needs to be administered to a diabetic. Blood lactate levels as measured in recovery are far from a perfect estimate of anaerobic energy costs, but they certainly provide a reasonable estimate especially when the activity itself – resistance exercise – is considered anaerobic.

Decreasing lactate levels during exercise invalidate their potential in the quantification of anaerobic energy costs. For example Rieu et al. (1988) cite declining blood lactate levels during four consecutive supramaximal 45-sec treadmill sprints as proof. This interpretation however fails to acknowledge the possibility of an increasing efficiency as exercise progresses and likewise fails to properly account for recovery oxygen uptake as part of overall costs. The finding of decreasing blood lactate with repeated intermittent exercise is by no means new (Christensen et al. 1960). With resistance exercise we also found declining blood lactate levels with additional sets of lifting that were somewhat matched by an increase in recovery oxygen uptake following each set; overall energy costs declined but not significantly so (Scott 2012c). Moreover, lactate levels were similar whether measured at the start and end of multiple sets or summed after individual sets – the conclusion is not that lactate levels fail to estimate anaerobic costs. Our interpretation is that with the progression of intermittent exercise, metabolic adjustments are made to conserve glycogen and improve efficiency as stored oxygen and ATP-PC levels with re-synthesis in recovery begin to dominate “anaerobic” metabolism (Scott 2014). It is of interest that elite cyclists reveal an oxygen uptake overshoot at the beginning of exercise that settles down to a lower (more efficient) oxygen uptake as the exercise progresses (Koppo et al. 2004; Hoozeveer and Keizer 2003).

As has been well documented, blood lactate levels are useful in the reasonable estimation of energy costs when ascending and not descending (di Prampero and Ferretti 1999). Margaria and colleagues (1963, 1964) matched increases of oxygen uptake with increases in treadmill speed and grade. His great insight was to match on the same scale the rise in blood lactate levels with the rise in oxygen uptake. Based on Margaria’s concept we created an energy cost vector whose direction rises in proportion to increasing work and with increasing magnitude consisting of three metabolic components: oxygen uptake, glycolysis, and ATP-PC utilization (Scott and Fontaine 2013). None of these metabolic systems can be ignored for resistance exercise.

Imagine blood lactate levels peaking after a resistance exercise set of 10 or 15 mmol (above rest). When considered an invalid estimate, the anaerobic energy cost default is set at zero kilojoules. To the contrary, blood lactate levels this high suggest to us that this anaerobic component can be the greatest overall energy cost contributor to resistance exercise. The large recovery oxygen uptake component to resistance training further suggests a significant anaerobic energy contribution made by the high energy phosphate (ATP, CP) and oxygen

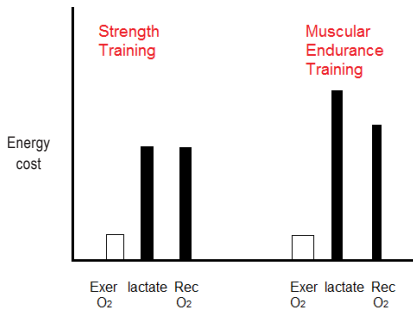


Figure 2. Aerobic and anaerobic cost estimates are shown for two types of resistance exercise (Exer O₂ = exercise oxygen uptake; Rec O₂ = recovery oxygen uptake; lactate = the energy cost contributed by a measure of blood lactate (Scott 2006))

stores within working muscle, with replenishment of these stores largely occurring in the first minutes of each recovery period (Figure 2).

Metabolic Variability: Between and Within Subjects

The concept of fast and slow twitch muscle types is well known. Demanding resistance exercise loads not only are likely to recruit a significant percentage of both fiber types, but the underlying anaerobic and aerobic metabolic systems as well. If so, oxygen and lactate measurements of brief work performed by a 60/40 fast to slow twitch ratio of skeletal muscle would likely differ from that of a 40/60 ratio. When considered separately, we found coefficients of variation approaching 50% for triplicate measures of aerobic and anaerobic energy costs during resistance exercise (Scott et al. 2009). CV's this high should invalidate both estimates. However, when aerobic and anaerobic costs are added together to provide a single overall energy cost, the CV dropped to 15%. Muscle fiber and metabolic typing indicate that oxygen-only models cannot properly portray the metabolic responses to resistance exercise and reveals the importance of reasonable estimates of both aerobic and anaerobic energy exchanges.

Because metabolic variability appears inherent to strength, speed and power related exercise, we adopted the practice of averaging data from two identical laboratory visits for each subject: 2 averaged work bouts (J) on separate days, 8 blood lactate measurements (mmol) (an average of 2 at rest and 2 at peak, for each of two visits), the average of 2 exercise oxygen uptake measurements (LO₂) (summed for each set) and the average of 2 recovery oxygen uptake measurements (LO₂) (lasting from immediately post-exercise until a standing resting oxygen uptake measure is met). Resting lactate and oxygen uptake values are subtracted from all exercise related lactate and oxygen uptake increases.

Continuous vs. Intermittent Exercise Formats

Overwhelming evidence indicates steady state exercise models do not properly estimate resistance exercise energy costs: 1) Break continuous steady state exercise into comparable intermittent components and overall oxygen uptake can increase (Christensen et al. 1960; Edwards et al. 1973; Scott 2014), 2) Anaerobic energy contributions suggest a further cost above that of oxygen uptake (Scott 1997), 3) Reviews of continuous vs. intermittent exercise

formats indicate the latter as a better means to lose body fat, again suggesting increased energy costs for intermittent exercise (Hunter et al. 1988; Boutcher 2011), 4) Momentarily arrest blood flow to working muscle – as occurs with resistance training – and oxygen uptake becomes disproportional to steady state work (Loeppsky et al. 2008), 5) The concept of an anaerobic threshold to describe resistance training is unsubstantiated, and 6) Oxygen uptake peaks in the recovery from resistance exercise as opposed to during exercise, the latter being a principal assumption of the steady state model (Scott 2012b).

Conclusions

Using capacity (kJ) as opposed to rate (kJ min⁻¹) measurements, aerobic and anaerobic energy costs for resistance exercise rise with work, as is assumed with oxygen uptake for steady state exercise. However, by separating resistance exercise (sets) from each subsequent recovery period, we have found that intermittent resistance exercise and recovery energy costs are mirror opposite: 1) intermittent exercise oxygen uptake periods when summed always had the lowest contribution to overall energy cost, 2) when recovery oxygen uptake after a single set or in between multiple sets is summed, it typically represented the largest energy cost component, and 3) Anaerobic energy costs can be likewise significantly larger than exercise oxygen uptake. Steady state models provide an invalid energy cost representation of resistance exercise.

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