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AEROBIC AND ANAEROBIC CONTRIBUTIONS TO NON-STEADY STATE ENERGY EXPENDITURE DURING STEADY STATE POWER OUTPUT

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ABSTRACT

Scott CB, Shaw B, Leonard C. Aerobic and Anaerobic Contributions to Non-Steady State Energy Expenditure during Steady State Power Output. *JEPonline* 2008;11(2):56-63. We estimated aerobic and anaerobic energy expenditure during and after a 6-min intense steady-state workload that is typically modeled using oxygen-only measurements; gender comparisons were made. Maximal testing revealed peak oxygen uptake was not different between men (N = 8) ($46.5 \pm 8.0 \text{ ml kg}^{-1} \text{ min}^{-1}$) and women (N = 8) ($42.6 \pm 7.5 \text{ ml kg}^{-1} \text{ min}^{-1}$) ($p = 0.34$). Subjects later cycled for 6-min at a similar physiological intensity based on the maximal test results. Perceived exertion for the 6-min ride was similar between men, 18.1 ± 1.7 and women, 18.1 ± 2.4 ($p = 0.80$). However, power output for the 6-min ride was greater in men (203 ± 23 Watts) as compared to women (145 ± 34 Watts) ($p = 0.001$). Pooled data (men and women) revealed exercise energy expenditure was significantly greater when containing an anaerobic component ($271.2 \pm 66.1 \text{ kJ}$ vs $328.0 \pm 74.5 \text{ kJ}$; $p < 0.03$); this also was true for men- but not women-only data. Relative energy expenditure contributions for exercise and recovery were similar for men and women: anaerobic exercise, 13-14%; aerobic exercise, 65%; aerobic recovery, 21-22%. We conclude that gender comparisons regarding the extent of aerobic and anaerobic contributions to energy expenditure can be confounded by the method of interpretation (absolute and relative data analyses). Estimates of anaerobic energy expenditure throughout 6-min of intense exercise exceeds that of the slow O₂ component that occurs for the last 3-min of exercise.

Key Words: Oxygen Deficit, Blood Lactate, Slow Oxygen Component, Gender Comparisons.

INTRODUCTION

During low to moderate intensity steady-state power output, oxygen uptake measurements plateau and achieve steady-state, providing a valid estimate of energy expenditure (1). At higher exercise intensities however, oxygen uptake appears to momentarily plateau but then begins to gradually rise, departing from a steady-state. This phenomenon – the slow O₂ component – has been said to represent “extra” exercise energy expenditure because power output remains unchanged as oxygen uptake increases (1). However, at higher exercise intensities working skeletal muscle becomes more dependent on rapid carbohydrate breakdown as a fuel source (2) and lactate production can exceed lactate removal. Thus, during heavy to severe exercise it is apparent that there is an anaerobic energy component to so-called “extra” energy expenditure (3, 4). Unfortunately the anaerobic potential of “extra” energy expenditure often goes unrecognized because excess energy expenditure is routinely modeled solely as an oxygen uptake measurement.

In this descriptive investigation our objective was to estimate aerobic and anaerobic energy expenditure during and after a 6-minute intense steady-state bike ride that is designed to elicit a slow O₂ component. We asked the question, does anaerobic energy expenditure make a significant contribution to exercise during an exercise test that is known primarily for its ability to increase oxygen uptake? We also compared aerobic and anaerobic energy expenditure contributions between men and women.

METHODS

Subjects

This study was approved by the University of Southern Maine’s Institutional Review Board. Informed consent was obtained from sixteen physically active men (24.1 ± 2.4 years; $n = 8$) and women (24.3 ± 4.5 years; $n = 8$) (total $n = 16$; Table 1).

Procedures

Subjects refrained from eating and drinking at least 3 hours prior to testing. Subjects completed two exercise tests on separate days (at least 1 week apart), a maximal exercise test to exhaustion and a 6-min submaximal exercise test. Gas exchange was collected in 15 second sampling periods throughout both exercise tests. The metabolic cart was calibrated at least twice prior to all testing (Parvomedics metabolic cart, Sandy, UT). Tests were completed using a Diamondback road bicycle mounted on a Velodyne cycle ergometer (Velodyne Sports, Laguna Hills, CA). For maximal testing, subjects started with a workload of 30 Watts with the load being increased 10 Watts every 30 seconds until voluntary exhaustion. VO₂ peak was taken as the highest recorded oxygen uptake during the maximal test.

The results from the maximal test were used to calculate the workload for the submaximal test. The workload for the submaximal test was determined as that work rate (Watts) located midway between the anaerobic threshold and VO₂ max. The anaerobic threshold was calculated as a ventilatory threshold where an abrupt and steady increase in the ratio of Ve/VO₂ occurred after an initial plateau (5).

Gas exchange for the 6-min submaximal test was collected at rest, during exercise and into recovery. Resting oxygen uptake was recorded for 5 minutes prior to the 6 minute test as the subject sat quietly on the bike. Upon completion of the intense 6-minute steady state ride, the subject immediately dismounted from the bike and sat quietly until oxygen uptake fell below the previously recorded 5-minute seated resting value. During exercise, aerobic energy expenditure was converted as 1 liter O₂

= 21.1 kJ. During recovery, energy expenditure was recorded as 1 liter O₂ = 19.6 kJ (6). Seated resting oxygen uptake was subtracted from all exercise and recovery data.

The slow O₂ component and O₂ deficits were measured using the apparent plateau in oxygen uptake occurring 3 minutes into the intense steady-state bike ride (4). The slow O₂ component was quantified as oxygen uptake above the plateau recorded at the 3-minute mark until the end of exercise at 6 minutes. Two O₂ deficits were calculated. The first O₂ deficit was measured as the difference in the oxygen uptake plateau recorded at the 3-minute mark and the actual oxygen uptake measured from the start of exercise (black area, figure 1). The second O₂ deficit was recorded as the difference between the first O₂ deficit and the peak of the slow O₂ component (4). Anaerobic energy expenditure was recorded as the total O₂ deficit (tO₂ deficit): the sum of O₂ deficit 1 and O₂ deficit 2. The O₂ deficits were converted to kJ as 1 liter O₂ = 21.1 kJ.

Resting blood lactate levels were recorded in duplicate prior to submaximal testing (Lactate Pro, Arkay Inc., Kyoto, Japan). Blood lactate levels also were recorded in duplicate and averaged at 4, 6 and 8 minutes into the seated recovery. Peak blood lactate was taken as the highest averaged lactate reading during the recovery period. Anaerobic energy expenditure was estimated as the difference between resting and peak blood lactate concentrations, calculated as Δ blood lactate, and converted to oxygen uptake equivalents as 3 ml O₂ kg⁻¹ mM⁻¹ (then as, 1 liter O₂ = 21.1 kJ) (7).

Statistical Analyses

Descriptive data are presented as means \pm standard deviation (SD). Data comparisons for differences utilized a standard independent samples t-test. Relationships were tested using Pearson correlation. Alpha levels were set at 0.05.

RESULTS

Data taken from maximal testing are portrayed in table 1 where men and women had similar peak VO₂ (men, 46.5 \pm 8.0 ml kg⁻¹ min⁻¹; women, 42.6 \pm 7.5 ml kg⁻¹ min⁻¹; p = 0.34) and ventilatory threshold measurements (men, 34.3 \pm 6.7 ml kg⁻¹ min⁻¹; women, 32.8 \pm 6.5 ml kg⁻¹ min⁻¹; p = 0.67) indicating similar fitness levels for both groups. Men however, had a greater peak power output as compared to the women at exhaustion (238.8 \pm 27.5 versus 166.6 \pm 37 Watts, respectively; p = 0.001).

Table 1. Subject characteristics and fitness parameters from maximal testing.

| | Men (n = 8) | Women (n = 8) | p |
|--|--------------------|----------------------|----------|
| Age | 24.1 \pm 2.4 | 24.3 \pm 4.5 | 0.89 |
| Height (cm) | 182.0 \pm 5.5 | 163.3 \pm 6.7 | 0.001 |
| Weight (kg) | 80.6 \pm 8.7 | 61.0 \pm 5.9 | 0.001 |
| VO₂ peak ml kg⁻¹ min⁻¹ | 46.5 \pm 8.0 | 42.6 \pm 7.5 | 0.34 |
| Peak Watts | 238.8 \pm 27.5 | 166.6 \pm 37 | 0.001 |
| VT ml kg⁻¹ min⁻¹ | 34.3 \pm 6.7 | 32.8 \pm 6.5 | 0.67 |
| VT % of VO₂peak | 72.0 \pm 8.1 | 70.3 \pm 13.2 | 0.80 |

Mean \pm SD, VO₂peak = maximal oxygen uptake achieved during test to exhaustion;
VT = ventilatory threshold

The intense 6-min steady-state workload was based on the data of the maximal test to exhaustion in an attempt to standardize exercise intensity between genders, at a workload located half-way between the ventilatory threshold and peak VO_2 . During the intense 6-min ride work rates for men (203.1 ± 23 Watts) were greater than that of women (145.0 ± 33.6 Watts) ($p = 0.001$). Consequently both aerobic and anaerobic energy expenditure was larger for men as compared to women (table 2). When the data of both men and women were pooled energy expenditure for the 6-min ride was larger when it contained an anaerobic (blood lactate, 328 ± 74.5 kJ; O_2 deficit, 328.3 ± 77.8 kJ) as opposed to an aerobic-only (271.2 ± 66.1 kJ) estimate ($p = 0.03$).

Table 2. Absolute data for an intense 6-minute submaximal workload (mean \pm SD).

| | Men (n = 8) | Women (n = 8) | p | Men & Women |
|---|--------------------|----------------------|----------|------------------------|
| Watts | 203.1 \pm 23 | 145.0 \pm 33.6 | 0.001 | 174.1 \pm 40.9 |
| Δblood lactate (kJ) | 66.4 \pm 13.4 | 47.2 \pm 6.6 | 0.003 | 56.8 \pm 14.2 |
| 1O_2 deficit (kJ) | 42.2 \pm 5.0 | 32.3 \pm 10.3 | 0.03 | 37.2 \pm 9.3 |
| 2O_2 deficit (kJ) | 27.4 \pm 10.4 | 12.3 \pm 5.1 | 0.002 | 19.8 \pm 11.1 |
| tO_2 deficit (kJ) | 69.5 \pm 7.7 | 44.6 \pm 10.0 | 0.001 | 57.1 \pm 15.5 |
| Exer. O_2 (kJ) | 319.7 \pm 26.3 | 222.7 \pm 57.2 | 0.001 | 271.2 \pm 66.1 |
| slow O_2 (kJ) | 18.6 \pm 7.8 | 11.1 \pm 5.3 | 0.04 | 14.8 \pm 7.5 |
| recovery O_2 (kJ) | 107.6 \pm 20.6 | 72.8 \pm 22.4 | 0.008 | 91.3 \pm 27.3 |
| recovery O_2 (sec) | 986 \pm 206 | 1108 \pm 276 | 0.37 | 1047 \pm 242 |
| EEE (kJ) (lac + exer O_2) | 386.1 \pm 27.6 | 269.9 \pm 58.4 | 0.001 | 328.0 \pm 74.5 |
| EEE (kJ) (tO_2 deficit + exer O_2) | 389.3 \pm 22.2 | 267.2 \pm 63 | 0.001 | 328.3 \pm 77.8 |
| TEE (kJ) (lac + exer O_2 + recovery O_2) | 493.7 \pm 40.5 | 346.6 \pm 82.8 | 0.001 | 425.0 \pm 97.6 |

Energy expenditure data are reported in kJ; 1 O_2 deficit = oxygen deficit one; 2 O_2 deficit = oxygen deficit two; t O_2 deficit = total oxygen deficit (O_2 deficit 1 + O_2 deficit 2; see figure 1); Exer. O_2 = exercise oxygen uptake; slow O_2 = slow oxygen component; recovery O_2 = recovery oxygen uptake; EEE = exercise energy expenditure; TEE = total energy expenditure; lac = Δ blood lactate (kJ); p = alpha level for standard t-test between men and women.

Within gender, absolute aerobic energy expenditure estimates for men (319.7 ± 26.3 kJ) were significantly less as compared to exercise energy expenditure that was supplemented with anaerobic estimates using either blood lactate (386.1 ± 27.6 kJ; $p = 0.001$) or total O_2 deficit (389.3 ± 22.2 kJ; $p = 0.001$) (table 2). This trend was not evident in women: aerobic energy expenditure, 222.7 ± 57.2 kJ; aerobic + lactate, 269.9 ± 58.4 kJ ($p = 0.12$); aerobic + O_2 deficit, 267.2 ± 63 kJ ($p = 0.16$) (table 2).

Relative comparisons (table 3) between gender indicated that men (85.2 ± 4.1) and women (87.0 ± 5.2) rode at similar intensity (% of maximal power output) ($p = 0.46$) during the 6-min ride. Rating of perceived exertion was identical between men (18.1 ± 1.7) and women (18.1 ± 2.4) ($p = 0.80$). Whether expressed as blood lactate or O_2 deficit measurement, anaerobic energy expenditure during exercise contributed similarly between men and women: lactate men, $17.2\% \pm 3.3$; lactate women, $17.5\% \pm 3.9$ ($p = 0.89$); O_2 deficit men, $18.0\% \pm 2.6$; O_2 deficit women, $17.0\% \pm 2.9$ ($p = 0.48$). When recovery energy expenditure is included, lactate measurements reveal a $13.5\% (\pm 2.6)$ anaerobic

energy expenditure contribution for men and 13.8% (± 3.1) for women, a non-significant difference ($p = 0.82$).

Table 3. Relative (%) data for the 6-minute submaximal workload (mean \pm SD).

| | <i>Men (n = 8)</i> | <i>Women (n = 8)</i> | <i>p</i> | <i>Men & Women</i> |
|---|--------------------|----------------------|----------|------------------------|
| Watts (% max) | 85.2 \pm 4.1 | 87.0 \pm 5.2 | 0.46 | 86.1 \pm 4.6 |
| Watts kg⁻¹ | 2.6 \pm 0.44 | 2.4 \pm 0.44 | 0.42 | 2.5 \pm 0.43 |
| RPE | 18.1 \pm 1.7 | 18.1 \pm 2.4 | 0.80 | 18.1 \pm 2.0 |
| Δ Lactate (%EEE) (EEE = lac + exer O ₂) | 17.2 \pm 3.3 | 17.5 \pm 3.9 | 0.89 | 17.3 \pm 3.4 |
| tO₂ deficit (%EEE) (EEE = tO ₂ deficit + exer O ₂) | 18.0 \pm 2.6 | 17.0 \pm 2.9 | 0.48 | 17.5 \pm 2.7 |
| Exer O₂ (%EEE) (EEE = lac + exer O ₂) | 82.8 \pm 3.3 | 82.5 \pm 3.9 | 0.89 | 82.7 \pm 3.4 |
| Exer O₂ (%EEE) (EEE = tO ₂ deficit + exer O ₂) | 82.0 \pm 2.6 | 83.0 \pm 2.9 | 0.89 | 82.5 \pm 2.7 |
| Slow O₂ (% of Exer O ₂) | 5.9 \pm 2.7 | 5.3 \pm 2.6 | 0.66 | 5.6 \pm 2.6 |
| Slow O₂ (% of lac + exer O ₂) | 4.3 \pm 1.7 | 4.3 \pm 2.0 | 0.99 | 4.3 \pm 1.8 |
| Slow O₂ (% of tO ₂ deficit + exer O ₂) | 4.8 \pm 2.1 | 4.3 \pm 2.0 | 0.63 | 4.6 \pm 2.0 |
| Δ Lactate (% of TEE) (TEE = lac + exer O ₂ + recovery O ₂) | 13.5 \pm 2.6 | 13.8 \pm 3.1 | 0.82 | 13.6 \pm 2.7 |
| Exer O₂ (% of TEE) (TEE = lac + exer O ₂ + recovery O ₂) | 64.9 \pm 3.8 | 65.4 \pm 3.7 | 0.80 | 65.1 \pm 3.6 |
| Recovery O₂ (% of TEE) (TEE = lac + exer O ₂ + recovery O ₂) | 21.7 \pm 3.2 | 20.8 \pm 2.6 | 0.58 | 21.3 \pm 2.8 |

Mean \pm SD; RPE = rating of perceived exertion; Δ Lactate and lac = Δ blood lactate; tO₂ deficit = total oxygen deficit (O₂ deficit 1 + O₂ deficit 2; see figure 1); Exer O₂ = exercise oxygen uptake; recovery O₂ = recovery oxygen uptake; EEE = exercise energy expenditure; TEE = total energy expenditure; p = alpha level for standard t-test between men and women.

DISCUSSION

Anaerobic Energy Expenditure

Our energy expenditure data were analyzed as a capacity (kJ) estimate for exercise and recovery as opposed to a rate-function estimate (e.g., kJ min⁻¹). Intense steady-state workloads can produce an “extra” non-steady state increase in energy expenditure that is often explained solely in the context of a slow O₂ component (i.e., as aerobic energy expenditure). Yet at work rates that take place above the ventilatory threshold – where lactate production exceeds lactate removal - an anaerobic energy expenditure component is evident that compliments aerobic energy expenditure. Compared to aerobic estimates our pooled data reveal significantly larger exercise energy expenditure when supplemented with anaerobic estimates using either blood lactate or O₂ deficit measurements (see

table 2). These findings are of interest because many models of “extra” energy expenditure do not consider the anaerobic component.

Δ Blood lactate measurements estimate anaerobic energy expenditure over the entire 6-minute test and were larger than the anaerobic energy expenditure accounted for by the O_2 deficit measured during the first 3-minutes of exercise. We also estimated a second O_2 deficit in an attempt to identify an anaerobic component to the “extra” energy expenditure (4). When totaled, the two O_2 deficits were virtually identical to the blood lactate estimation of energy expenditure ($r = 0.70$; $p = 0.003$). This suggests that anaerobic glycolysis contributed to energy expenditure both before and after the start of the slow O_2 component. While speculative, no difference was found between the second O_2 deficit and the slow O_2 component suggesting similar anaerobic and aerobic contributions to the “extra” increase in energy expenditure for this 6-min test. The O_2 deficit and recovery oxygen uptake can not concurrently be used to estimate total energy expenditure (6). However, relative energy expenditure contributions can be estimated using Δ blood lactate measurements: anaerobic exercise contributions were ~13-14%, aerobic exercise contributions were ~ 65% and recovery contributions were ~21-22 % (table 3).

Slow O_2 Component

The slow O_2 component contributed less than 6% to exercise oxygen uptake, less than 5% to exercise energy expenditure that contains an aerobic and anaerobic component and less than 4% of total energy expenditure (test length will affect this contribution) (table 3). Based on all absolute and relative estimates, anaerobic energy expenditure throughout 6-minutes of exercise exceeds the energy expenditure of the slow O_2 component occurring over the last 3-minutes of exercise.

Limitations

Our study certainly has limitations. Blood lactate concentrations represent a questionable marker of anaerobic energy expenditure with the possibility of production and removal rates differing between subject and gender. Yet under the strict conditions of brief and intense exercise, when blood lactate peaks after the exercise has ended (i.e., when lactate production exceeds lactate removal), Δ blood lactate has in fact been shown to provide a reasonable estimate of anaerobic energy expenditure (7, 8). Oxygen deficit estimations of anaerobic energy expenditure also are controversial in that the peak rate of energy expenditure is estimated and not directly measured. While strikingly similar, the Δ blood lactate and O_2 deficit estimates of anaerobic energy expenditure should have been different in that blood lactate portrays anaerobic glycolytic ATP re-synthesis but not the use of ATP and creatine phosphate (CP) stores. Converting the O_2 deficit into oxygen equivalent units portrays anaerobic energy expenditure not only as having an anaerobic glycolytic component, but also the muscles use of stored “high energy” phosphates ATP and CP as well. It is understood that all estimates of anaerobic energy expenditure are questionable yet the pooled anaerobic data sets each point to the same conclusion; anaerobic metabolism contributes to overall energy expenditure.

Gender Comparisons

Both blood lactate and O_2 deficit estimates of anaerobic energy expenditure reveal a larger anaerobic component to exercise energy expenditure in men as compared to women (table 2). The oxygen uptake data for exercise and recovery also indicates the same for aerobic energy expenditure (9, 10). A straight forward explanation for the larger aerobic and anaerobic energy expenditure for men as compared to women is that men were taller and heavier, recruit more muscle and worked at a greater power output during the 6-minute intense ride. The absolute data appear to justify the increased glycogen utilization (2, 11), blood lactate concentrations (12, 13) oxygen deficit (14, 15) and anaerobic metabolism (16) during intense exercise that suggests greater anaerobic energy expenditure in men as compared to women. However, absolute differences in aerobic and anaerobic

energy expenditure are to be expected when pedaling at work rates that differ by 60 Watts (whether within or between subjects, male or female).

For men, estimates of aerobic exercise energy expenditure (319.7 ± 26.3 kJ) were significantly less as compared to exercise energy expenditure that was supplemented with anaerobic estimates using either blood lactate (386.1 ± 27.6 kJ) or total O₂ deficit (389.3 ± 22.2 kJ) ($p = 0.001$) (table 2). This trend was not evident in women: aerobic energy expenditure, 222.7 ± 57.2 kJ; aerobic + lactate, 269.9 ± 58.4 kJ ($p = 0.12$); aerobic + O₂ deficit, 267.2 ± 63 kJ ($p = 0.16$). At a statistical power of 0.80, 23 women would be required to reveal statistical significance. Within gender comparisons suggest men had significant anaerobic contributions to exercise energy expenditure while women did not (note that the standard deviations of the women's data in the present study were double that of the men for these measures revealing large variability). But the comparisons just mentioned are within, not between groups.

Unlike the absolute comparisons, relative comparisons of energy expenditure between women and men revealed striking similarity (table 3). No percentage of aerobic or anaerobic energy expenditure as part of exercise, recovery or total energy expenditure was different between women and men. These findings indicate that aerobic and anaerobic energy expenditure contributions are not different between-gender. Subjects rode the bike for 6-minutes at an equivalent physiological intensity, resulting in cycling at a similar percentage of peak Watts for both genders (table 3). Similarity in the rating of perceived exertion (RPE) and Watts kg⁻¹ between gender also suggests that the work rate we chose - located halfway between the ventilatory threshold and VO₂max - seems to have adequately represented a standardized physiological marker. When using a relative marker of physiological intensity for test standardization, data analyses should perhaps focus on relative differences for a between gender comparison.

CONCLUSIONS

We conclude that gender comparisons of the extent of aerobic and anaerobic metabolic contributions to energy expenditure are confounded by the method of interpretation (absolute versus relative data analyses). However, when the data were pooled anaerobic energy expenditure during an intense 6-minute bout of steady-state power output makes a significant contribution to exercise energy expenditure. The slow O₂ component arising halfway through the ride was a rather meager contributor to over-all energy expenditure and did not exceed anaerobic contributions throughout exercise.

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