Resistance Exercise Energy Expenditure is Greater with Fatigue as Compared to Non-Fatigue

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ABSTRACT

Scott CB, Earnest CP. Resistance Exercise Energy Expenditure is Greater with Fatigue as Compared to Non-Fatigue. JEPonline 2011;14(1):1-10. We retrospectively investigated data from two separate studies to estimate and compare aerobic and anaerobic exercise energy expenditure (EE) along with the aerobic recovery EE component for 1-set of resistance exercise. One study was completed using non-fatiguing lifts where the exercise was stopped before muscular failure. In another study muscular failure (fatigue) was the end point of all lifts. Work (weight lifted × upward vertical displacement) and all EE components were examined. Non-fatiguing lifts were carried out at 50% of a 1-RM for 7, 14 and 21 repetitions. Lifts to failure were carried out at ~37%, ~46%, ~56%, 70%, 80% and 90% of a 1-RM. Individual regression lines were created for fatigue and non-fatigue conditions for each male subject between work and all estimates of EE. The results of our analyses showed that the averaged slopes between fatigue and non-fatigue were proportional for: total EE/work (p = 0.87), anaerobic exercise EE/work, (p = 0.73) and recovery EE/work (p = 0.19). However, the Y-intercepts of the two studies were significantly greater for fatiguing as compared to non-fatiguing lifting for: total EE/work (p = 0.007), anaerobic exercise EE/work (p = 0.001) and recovery EE/work (p = 0.01), but not aerobic exercise EE/work (p = 0.17). For aerobic exercise EE/work, lifting to fatigue had a greater O₂ uptake/work slope as compared to lifts that were not completed to fatigue (p = 0.04). We conclude that lifting a weight to muscular failure can entail significantly greater aerobic, anaerobic and recovery EE components as compared to non-fatiguing lifting.

Keywords: Anaerobic Energy Expenditure, Oxygen Uptake, EPOC, Lactate, Resistance Training
INTRODUCTION

Resistance training is considered an intense form of exercise when sets are performed to or close to muscle failure, regardless of the percentage of a one repetition maximum (1-RM) selected. To the contrary, when a completed set of lifted weights does not approach fatigue the exercise can be considered light-to-moderately heavy. Though this may be intuitively obvious, the distinction between each form of exercise may be critical for exercise programming depending on the goals of the participants. For example, recent studies have shown that self-selected resistance training intensities are lower then what is recommended (3,4,8) and a better understanding of the energetic demands associated with various resistance training intensities will ultimately help resistance training programming efforts.

Two contemporary studies using disparate energy expenditure methodologies – steady state and non-steady state - each report energy expenditure relationships with resistance training-type work that appear much higher than past estimates (9,10). We reason that the energy expenditure characteristics of steady rate aerobic-type exercise should not be used to model the energy expenditure of non-steady rate anaerobic-type exercise because the physiological and metabolic characteristics for each are different. When lifting a moderately-heavy to heavy weight for example, we rationalize that: 1) intense muscle contractions create enough force to effectively limit blood flow to and from working skeletal muscle, impeding exercise O₂ uptake (14), 2) anaerobic glycolytic ATP production can account for a significant amount of overall energy expenditure (10-13), 3) a single bout of resistance training results in a greater O₂ uptake in the recovery from exercise than during the actual exercise itself (10,11), and 4) heavy to severe exercise can induce “extra” increases in aerobic and anaerobic energy expenditure, likely related to changing metabolism-work efficiency and/or the increased recruitment of muscle needed to prolong fatigue (1,15).

The primary aim of this retrospective investigation was to compare two previous studies that utilized non-steady state methods of energy expenditure estimation: one where a single set of lifting was completed before muscle fatigue took place (10), the other where muscular failure was the end point of the set (11). We asked the question: Are the energy expenditure-to-work relationships different between single sets of fatiguing and non-fatiguing resistance training protocols?

METHODS

Data collected from two previous studies were examined (10,11). Both studies used 1-set of bench press exercise to determine the energy expenditure characteristics accompanying non-muscular and total muscular fatigue (these were not training studies). Comparisons were made of the aerobic, anaerobic and recovery energy expenditures of each study.

Subjects

Each protocol had received previous approval by the University of Southern Maine’s Institutional Review Board (IRB). In addition, the current retrospective study underwent further review and approval by the IRB. For the present investigation only data from male subjects were compared as men and women can have different aerobic and anaerobic responses to resistance training (see Table 1).
Table 1. Subject characteristics: all males (mean ± SD)

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>data pts</th>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>1-RM (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatigue study</td>
<td>13</td>
<td>78</td>
<td>23.8 ± 2.1</td>
<td>178.7 ± 6.6</td>
<td>85.9 ± 11.3</td>
<td>102.5 ± 20.8</td>
</tr>
<tr>
<td>Non-Fatigue study</td>
<td>4</td>
<td>36</td>
<td>32.8 ± 10.4</td>
<td>177.5 ± 9.5</td>
<td>76.8 ± 13.1</td>
<td>108.0 ± 15.0</td>
</tr>
</tbody>
</table>

Table 1 legend: N = subject number; data pts = number of lifts measured for each study.

Procedures
In the non-fatigue study (10), exercise was performed at 50% of 1-RM for 7, 14 and 21 repetitions (exhaustion was not the end point of any of these lifts); each workload was performed 3 times for a total of 9 lifts (36 total data points). In the fatigue study (11), a single set of the bench press was performed until muscular failure at the following percentage of 1-RM (repetition number at exhaustion), ~37% (~37 reps), ~46% (~26 reps), ~56% (~20 reps), 70% (~12 reps), 80% (~8 reps) and 90% (~5 reps); each lift was performed once (78 total data points). Work was recorded as the product of force (kilograms of weight lifted) × vertical (upward) displacement of lifting a bar using a standard Smith Machine; the distance the bar travelled was recorded electronically. To determine energy expenditure for both studies we performed separate measurements of aerobic exercise O\textsubscript{2} uptake, blood lactate concentrations and a modified excess post-exercise oxygen consumption (EPOC) measurement; the summation of all three measures provide an estimate of total energy expenditure.

Oxygen uptake was measured via a Parvomedics MMS-2400 metabolic cart (Sandy, UT) in 15-second sampling intervals. Before lifting a 5-minute supine resting energy expenditure (REE) measurement was taken with the subject lying on the bench with both feet on the ground. The average O\textsubscript{2} uptake (l min\textsuperscript{-1}) of this rest period was subtracted from all exercise O\textsubscript{2} uptake and EPOC measurements. Exercise O\textsubscript{2} uptake underwent conversion as 1 liter of O\textsubscript{2} = 21.1 kJ. EPOC was recorded with the subjects feet elevated horizontal to the bench so that the subject was completely supine. EPOC was measured until falling below 5.0 ml·kg\textsuperscript{-1}·min\textsuperscript{-1} (a typical standing resting measure) or below the averaged measured REE and underwent conversion as 1 liter of O\textsubscript{2} = 19.6 kJ. Blood lactates were collect via a minimum of two Lactate Pro analyzers (FaCT Canada Consulting) at rest and from a peak lactate measurement taken at 2-minutes or 4-minutes post-exercise (whichever was highest). Anaerobic exercise energy expenditure was calculated as the difference between resting and peak lactate values multiplied by body weight (kg), then by 3.0 ml of O\textsubscript{2} (2). This O\textsubscript{2} equivalent estimate was converted to Joules as 1 L O\textsubscript{2} = 21.1 kJ. Total energy expenditure was recorded as the sum of aerobic and anaerobic exercise energy expenditures and EPOC.

Statistical Analysis
Energy expenditure measures and work regression lines were computed for each subject, and then averaged with the slope and Y-intercept data presented in Table 2. Comparisons were made using a standard t-test (with alpha level set at p < 0.05).
Table 2. Averaged individual slopes and Y-intercepts of fatigue (F) and non-fatigue (NF) studies (mean ± SD)

<table>
<thead>
<tr>
<th>Study</th>
<th>Anaerobic /work</th>
<th>Exercise O2 /work</th>
<th>EPOC /work</th>
<th>Total EE /work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope F</td>
<td>0.049 ± 0.01</td>
<td>0.029 ± 0.01</td>
<td>0.018 ± 0.02</td>
<td>0.084 ± 0.03</td>
</tr>
<tr>
<td>Slope NF</td>
<td>0.046 ± 0.02</td>
<td>0.017 ± 0.004</td>
<td>0.024 ± 0.004</td>
<td>0.086 ± 0.02</td>
</tr>
<tr>
<td>P value</td>
<td>0.73</td>
<td>0.04</td>
<td>0.19</td>
<td>0.87</td>
</tr>
<tr>
<td>Y-int F</td>
<td>8.12 ± 3.9</td>
<td>-3.27 ± 3.9</td>
<td>17.4 ± 7.7</td>
<td>21.2 ± 10.4</td>
</tr>
<tr>
<td>Y-int NF</td>
<td>-1.4 ± 2.9</td>
<td>-0.31 ± 1.9</td>
<td>6.08 ± 1.8</td>
<td>4.4 ± 2.8</td>
</tr>
<tr>
<td>P value</td>
<td>0.007</td>
<td>0.001</td>
<td>0.17</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 2 legend. Slope and Y-intercept represent individual subject relationships between energy expenditure and work that were subsequently averaged (F, n = 13 men, 6 workloads each performed once, reference 11; NF, n = 4 men, 3 workloads each performed 3 times, reference 10); TEE = total energy expenditure; work = force × vertical distance; Anaerobic = anaerobic exercise energy expenditure; Exercise O2 = aerobic exercise energy expenditure; EPOC = excess post-exercise oxygen consumption energy expenditure; significant differences between F and NF are shown in bold print.

RESULTS

Data reflecting differences in energy expenditure characteristics are presented in Table 2. Regarding the amount of work performed, the slopes of the fatigue and non-fatigue regression lines were not significantly different for total energy expenditure (p = 0.87; Figure 2), anaerobic exercise energy expenditure (p = 0.73) and recovery energy expenditure (p = 0.19). The two slopes were different for aerobic exercise energy expenditure (p = 0.04), being greater for the fatigue study. The Y-intercept data were significantly greater for the fatigue as compared to non-fatigue study for total energy expenditure (p = 0.007; Figure 2), anaerobic exercise energy expenditure (p = 0.001) and recovery energy expenditure (p = 0.01); the Y-intercepts were not different for aerobic exercise energy expenditure.

DISCUSSION

Our intent was to examine the energy costs including the aerobic and anaerobic contributions of lifting a weight, along with the recovery from that lift. These were not training studies. Indeed, rather than examine a complete workout, we choose to quantifying resistance training energy expenditure one exercise at a time (future studies will add sets and exercises to investigate how this subsequently effects aerobic, anaerobic and recovery energy costs). Our approach allows us to witness unique differences between steady state and non-steady state exercise. As an example, with 1-set of non-steady state resistance exercise, exercise O2 uptake always represents the lowest measured energy expenditure as compared to anaerobic and EPOC energy expenditures (10,11). To the contrary
under steady state conditions energy expenditure is defined in terms of exercise O$_2$ uptake. Also, after a single set of lifting to fatigue, EPOC energy expenditure appears as a relatively constant quantity unrelated to the volume of work completed (11); with aerobic exercise, EPOC “size” is related to duration and intensity (6,7).

For a single set of resistance training comparing a series of repetitions carried out to fatigue with a series of repetitions not performed to fatigue, our data indicate total energy expenditure, including anaerobic energy expenditure and recovery energy expenditure, are larger for fatiguing as compared to non-fatiguing exercise as indicated by the Y-intercept data (Table 2). It is further apparent that the ratio of aerobic energy expenditure to work significantly increased with exercise to fatigue (Table 2). From these data we suggest that the energy expenditure of fatiguing resistance exercise must be modeled differently as compared to non-fatiguing resistance exercise.

**Exercise O$_2$ uptake**
The gold standard modeling of exercise energy expenditure with work applies specifically to easy to moderately intense aerobic exercise when steady rate power outputs, steady state O$_2$ supply and steady state O$_2$ uptakes are achieved. Because muscular endurance and strength resistance exercise do not fulfill these criteria, we describe non-steady state energy expenditure for a given work bout [in kJoules (kJ)] and not steady state energy expenditure over a per minute time period of power output (kJ min$^{-1}$).

As compared to lighter workloads, heavy to severe steady state aerobic exercise reveals an “extra” energy expenditure component - a slow O$_2$ component - that is thought to be caused by a decrease in efficiency and/or the increased recruitment of muscle fibers in an attempt to resist fatigue and prolong work (1,15). The increasing aerobic exercise energy expenditure - work relationship (slope) for fatiguing as compared to non-fatiguing lifting may likewise, but not necessarily, be related to increased muscle recruitment as non-steady state work is prolonged (lasting minutes). At the Y-intercept, a significant change in aerobic energy expenditure was not found between fatiguing and non-fatiguing exercise (each lasting seconds). As lifting continues and fatigue approaches those muscles involved with body positioning and placement would likely contribute to the disproportionate rise in exercise O$_2$ uptake with work output, more intense contractions by the muscles doing the actual lifting would have impeded blood flow (14). The non-proportional rise in O$_2$ uptake with fatiguing as compared to non-fatiguing resistance exercise indicates that the aerobic energy expenditure of the exercise is not consistent as repetitions continue.

**Anaerobic Energy Expenditure**
Our method of determining anaerobic energy expenditure is based on the difference between peak and resting blood lactate measurements in the estimation of (glycolytic) anaerobic exercise energy expenditure (2). As with non-steady state exercise O$_2$ uptake, our anaerobic data provide information regarding a given work bout (kJ) and not work rate or power output over time (kJ min$^{-1}$). Correlation between anaerobic energy expenditure and work was good for both fatigue ($r = 0.79$, p < 0.0001) and non-fatigue ($r = 0.95$, p < 0.05) studies. The slope data indicate that the increase (change) in anaerobic energy expenditure with work when lifting to muscular failure is proportional to non-fatiguing lifts. However, the greater Y-intercept data for fatiguing as compared to non-fatiguing lifts reveals a significantly larger anaerobic contribution to energy expenditure for the single set lifts to fatigue. It appears that a single set of lifting to fatigue results in an “extra” anaerobic energy expenditure component as compared to non-fatiguing conditions.
Excess Post-exercise Oxygen Uptake (EPOC)
After a single bout of resistance training EPOC exceeds exercise $O_2$ uptake, whether fatigue is involved or not (10,11). In this regard both the exercise and recovery energy expenditures are required to better portray the energy demands associated with lifting (our $O_2$ uptake to energy expenditure conversion for EPOC dismisses anaerobic glycolytic ATP re-synthesis; 13,14).

Figure 1.

Figure 1 legend. Excess post-exercise oxygen consumption data is shown for the fatigue study (11). Note that while the regression line indicates EPOC energy expenditure rises with work and the correlation is statistically significant ($p < 0.05$), it also is a poor correlation ($r = 0.35$). ANOVA analysis indicated no significant differences in the EPOC energy expenditure among lifts to fatigue at percentages of a 1-RM that ranged from 37% to 90% (nor were differences detected in EPOC among non-fatigue lifts at 50% of 1-RM for 7, 14 and 21 reps; however, EPOC did differ between fatigue and non-fatigue protocols; see ref. 10).

It has been mentioned that the larger the metabolic disturbance of exercise the greater the EPOC will be, but this consideration is often reserved for aerobic-type exercise where exercise duration (time) and intensity (% of $VO_2$max) have a significant impact on EPOC (7). Anaerobic-type exercise also has duration (time) and intensity (% of 1-RM) components. Yet %$VO_2$max and %1-RM do not appear to be compatible descriptions of intensity in relationship to EPOC. Indeed, aerobic exercise duration increases EPOC in a linear fashion while aerobic exercise intensity is thought to exponentially increase EPOC volume (6). With fatiguing anaerobic-type exercise, ANOVA testing indicated that EPOC’s were in fact similar among all lifts to fatigue (lasting seconds to minutes) as no statistical differences were seen among lifting intensities that ranged from ~37 to 90% of 1-RM consisting of 4 to 37 reps (11). For the non-fatigue lifts ANOVA again indicated no difference among EPOC’s (50% of 1-RM lifting consisting of 7, 14 and 21 reps (10). Haddock and Wilkin likewise saw no increases in
EPOC-related energy expenditure between 1-set of lifting and 3-sets of lifting to fatigue even though the volume of work was tripled for the latter (5).

EPOC data for both studies was purposely collected in the short term, until a standing resting O\textsubscript{2} uptake was achieved. The lifting to fatigue data reveal poor but significant correlation between EPOC energy expenditure and weight lifting work (r = 0.35, p = 0.002; Figure 1), as well as between EPOC and aerobic (r = 0.27, p = 0.02) but not EPOC and anaerobic (r = 0.22, p = 0.06) exercise energy expenditures. The non-fatigue lifting study on the other hand reveals good correlation between EPOC and anaerobic energy expenditure (r = 0.75, p < 0.0001) along with EPOC and work (r = 0.83, p < 0.0001), but not with EPOC and aerobic exercise energy expenditure (r = 0.17, p = 0.42). Meirelles and Gomes (6) indicate a paucity of data and subsequent knowledge regarding EPOC and resistance training related energy expenditure, we concur. Within groups the question arises, “which is more important for interpretation purposes: ANOVA comparisons that reveal statistical similarity and therefore no differences among EPOC’s after various lifting bouts or, statistically significant correlation between EPOC and lifting that indicate an increase in EPOC with work?” While we cannot

**Figure 2.**

![Figure 2 legend. Total energy expenditure and work. All data are for 1-set of the bench press exercise. The data for the bottom line (open circles) were obtained from lifts that did not result in fatigue. The top line (closed circles) was obtained from lifts completed to fatigue. The slopes of the two lines above are not significantly different (p = 0.87). However, the Y-intercepts of each line are significantly different (p = 0.007). We conclude that non-fatiguing lifts cannot be utilized to estimate the total energy expenditure (TEE) of lifting to fatigue (TEE = anaerobic and aerobic exercise energy expenditure + recovery energy expenditure). Non-fatigue, TEE = 4.4 + (0.086 × work); fatigue, TEE = 21.2 + (0.084 × work).](image-url)
answer this question specifically, between group analyses of the Y-intercept between fatigue and non-fatigue studies lead us to the conclusion that the short-term recovery (EPOC) energy expenditure contributions after a single set of fatiguing and non-fatiguing resistance training are different.

**Total energy Expenditure**
The total energy expenditure of non-steady state lifting consists of aerobic and anaerobic exercise energy expenditure components along with a modified aerobic recovery energy expenditure (EPOC). Figure 2 reveals that a composite of the three energy expenditure components is not only different between 1-set of lifting among fatigue and non-fatigue protocols, but also that the difference is somewhat proportional throughout a wide range of lifting intensities and work (respectively, different Y-intercept, similar slope; Table 2). In fact, at a work output of 100 J, there is an estimated 56% difference in total energy expenditure between non-fatigue (13 kJ) and fatigue lifts (29.6 kJ); at a work output of 500 J, non-fatigue total energy expenditure (47.4 kJ) is 25% less than lifting to fatigue (63.7 kJ). We conclude that with equivalent single sets of resistance training work, fatiguing exercise results in greater total energy expenditure as compared to non-fatiguing exercise.

The Y-intercept data of EPOC energy expenditure and work was significantly greater but the slope of EPOC and work was similar for fatigue and non-fatigue weight lifting protocols. The same was true for anaerobic energy expenditure and work as well as total energy expenditure and work. Why is this? We speculate that the anaerobic, aerobic recovery (EPOC) and total energy expenditure’s for 1-set of resistance exercise to fatigue may be related to a capacity or limit of muscle recruitment along with an equivalent utilization of ATP, creatine phosphate (CP) and oxygen stores, regardless of work output or the aerobic and anaerobic (glycolytic) energy expenditure contributions that differ, often dramatically, both within and between lifting protocols. As an example, because anaerobic energy expenditure (based on blood lactate) and EPOC are not well related, 37 reps at 37% of a 1-RM at fatigue recruits a similar amount of muscle mass and uses a similar amount of stored ATP, CP, and oxygen as does 8 reps at 80% of 1-RM at fatigue, resulting in a similar short-term EPOC. It is of further interest to determine if or how additional sets and exercises affect EPOC.

**CONCLUSIONS**

These retrospective data reveal that with 1-set of non-steady state resistance exercise, O$_2$ uptake increases disproportionately with fatiguing as compared to non-fatiguing exercise. Moreover, anaerobic, aerobic recovery (EPOC), and total energy expenditures are significantly greater with resistance work involving fatigue as compared to non-fatigue. It is concluded that energy expenditure modeling for fatiguing resistance exercise cannot be based on non-fatiguing measurements. For anaerobic-type exercise to fatigue we continue to propose that a valid estimate of energy expenditure cannot be based on steady-state O$_2$ uptake measurements and must include the sum of aerobic and anaerobic exercise and aerobic recovery energy expenditures.
REFERENCES


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