The effect of time-under-tension and weight lifting cadence on aerobic, anaerobic, and recovery energy expenditures: 3 submaximal sets

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Abstract: We examined the aerobic and anaerobic energy expenditures of weight lifting (bench press); submaximal work was kept constant among protocols. Ten male subjects (age, 23.2 ± 3.1 years; height, 177.3 ± 5.3 cm; weight, 82.1 ± 11.5 kg) were randomly assigned to 3 lifting sessions of 3 sets of 5 repetitions at 70% 1 repetition maximum (1RM) using 3 lifting cadences: 1.5 s down and 1.5 s up (15 s per set), 4 s down and 1 s up (25 s per set), and 1 s down and 4 s up (25 s per set). No differences were found among the aerobic exercise energy expenditures for each lifting cadence. However, anaerobic energy expenditure was significantly different among protocols: 1.5 down–1.5 up, 16.5 ± 8.1 kJ; 4 down–1 up, 21.6 ± 8.1 kJ; and 1 down–4 up, 26.7 ± 7.2 kJ ($p = 0.001$). Excess postexercise oxygen consumption (EPOC; after each set) was lower for 1.5 down–1.5 up, 38.6 ± 17.8 kJ; versus 4 down–1 up, 50.2 ± 23.5 kJ; and 1 down–4 up, 50.0 ± 22.6 kJ ($p = 0.002$). Total energy expenditure also was significantly less for 1.5 up–1.5 down, 60.2 ± 23.8 kJ; versus 4 down–1 up, 80.0 ± 27.7 kJ; and 1 down–4 up, 84.2 ± 28.3 kJ ($p = 0.001$). Differences in EPOC and total energy expenditure with submaximal lifting were based not on the amount of work performed or with a particular eccentric–concentric cadence, but on the time to completion of the weight lifting exercise – time-under-tension; longer submaximal lifting times had greater energy expenditure.

Key words: resistance exercise, energy cost, eccentric, concentric.

Résumé : On analyse la dépense d’énergie aérobie et anaérobie au développé-couché en haltérophilie; on maintient constante la quantité sous-maximale de travail accompli dans chacun des protocoles. On assigne aléatoirement dix sujets masculins (âgé, 23,2 ± 3,1 ans; taille, 177,3 ± 5,3 cm; poids, 82,1 ± 11,5 kg) à trois séances d’haltérophilie comprenant 3 séries de 5 répétitions réalisées à 70 % 1RM selon trois cadences de mouvement : abaisser en 1,5 s et lever en 1,5 s (15 par série), abaisser en 4 s et lever en 1 s (25 par série) et 3) abaisser en 1 s et lever en 4 s (25 par série). On n’observe aucune différence de dépense d’énergie aérobie d’une cadence de mouvement à l’autre. En revanche, la dépense d’énergie anaérobie varie significativement d’une cadence de mouvement à l’autre : 16,5 ± 8,1 kJ, 21,6 ± 8,1 kJ et 26,7 ± 7,2 kJ ($p = 0{,}001$). Le surplus d’oxygène consommé au cours de la récupération postexercice (EPOC; après chaque série) est plus faible dans le protocole 1 que dans les protocoles 2 et 3 : 38,6 ± 17,8 kJ comparativement à 50,2 ± 23,5 kJ et 50,0 ± 22,6 kJ respectivement ($p = 0{,}002$). La dépense totale d’énergie (TEE) est aussi significativement plus faible en 1 qu’en 2 et 3 : 60,2 ± 23,8 kJ comparativement à 80,0 ± 27,7 kJ et 84,2 ± 28,3 kJ respectivement ($p = 0{,}001$). Les différences au niveau de l’E-POC et de la TEE au cours d’une séance sous-maximale d’haltérophilie ne sont pas dues à la quantité de travail accompli ou à la cadence pliométrique–miométrique dictée par le protocole mais au temps requis pour exécuter le mouvement – le temps pendant lequel les muscles sont en tension : plus l’exécution prend du temps, plus la dépense d’énergie est élevée.

Mots-clés : exercice contre résistance, coût énergétique, pliométrique, miométrique.

[Traduit par la Rédaction]

Introduction

Resistance training continues to undergo analysis concerning the optimum program design to achieve a desired outcome. As an example, strength development requires explicit combinations of lifting intensity, frequency, and number of sets performed (Rhea et al. 2003). Skeletal muscle hypertrophy appears to likewise be promoted by specific program designs (Burd et al. 2010; Shepstone et al. 2005). To examine these differences further, Toigo and Boutellier (2006) have suggested that “…the design and description of all future resistance exercise” include “fractional and temporal distribution of the contraction modes per repetition and duration[s] of one repetition” (pg. 648). We hypothesized that a format of resistance training in terms of repetition *timing* — eccentric and concentric time under tension — would affect the energy costs associated with the lifts.

Previous studies have shown that the concentric phase contributes most to the O_2 uptake of lifting and recovery, with the eccentric phase adding less to O_2 uptake measurements (Dudley et al. 1991; Seliger et al. 1968). The intent of the

Received 31 July 2011. Accepted 20 November 2011. Published at www.nrcresearchpress.com/apnm on 8 March 2012.

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present investigation was to determine both the aerobic and anaerobic energy expenditure characteristics of 3 different lifting cadences. We measured exercise and recovery oxygen uptake in addition to blood lactate levels for 3 sets of the bench press, using *equivalent* submaximal work bouts, lifting intensity, and recovery periods because modifying these variables affects energy costs (Abdessemed et al. 1999; Scott and Earnest 2011). Repetition times for this study were modified to include equivalent as well as brief and elongated eccentric and concentric lifting periods.

Materials and methods

Subjects

This investigation was approved by the human subject Institutional Review Board at the University of Southern Maine. Ten male volunteers were informed of the experimental risks and signed an informed consent document before data were collected (age, 23.2 ± 3.1 years; height, 177.3 ± 5.3 cm; body weight, 82.1 ± 11.5 kg; 70% of 1 repetition maximum (1RM), 74.9 ± 11.2 kg. All subjects had a history of weight training (i.e., weight training 3 times per week for at least 3 months).

Procedures

Subjects reported to the lab for 4 separate visits. Subjects were asked to not exercise on the day of testing and to have fasted for at least 4 h prior to testing (most tests were completed in the morning). On the first visit, a1RM for the bench press was recorded on a Smith machine, consisting of a horizontal bar that slides on vertical tracks where weight can only be lifted in the vertical plane (York Barbell Company Inc., York, Pa., USA). Weight was gradually increased until a single repetition could not be completed. Subjects warmed up with a light weight of their choice before attempting the 1RM. During each attempt good form was stressed and 5-point contact was maintained with the bench and floor. The tester chose the weight increase for each lift and adequate rest (3–5 min) between attempts was given. Each 1RM was attained within 3–4 lifts. To minimize fluctuations in power output, subjects also practiced lifting and lowering the bar at a cadence set by a metronome at 1.5 s down and 1.5 s up, 4 s down and 1 s up, and 1 s down and 4 s up. A small fly wheel attached to a microprocessor was connected to a moving cable on the Smith machine that recorded the distance the bar traveled. Work (J) was recorded as the product of weight lifted and vertical (upward) distance the bar traveled. During the following 3 visits to the lab, subjects were randomly assigned to bench pressing 3 sets at 70% of their 1RM (74.9 ± 11.2 kg). Each set consisted of 5 repetitions (this number was selected from a pilot study to ensure that subjects could perform the work required without fatigue (lifting to fatigue influences energy expenditure; Scott and Earnest 2011). Three lifting cadences were created: 1.5 s down and 1.5 s up (15 s of lifting per set, 45 s overall), 4 s down and 1 s up (25 s of lifting per set, 75 s overall), and 1 s down and 4 s up (25 s of lifting per set, 75 s overall). Each lifting session consisted of the following measures: 5 min of resting, supine energy expenditure (liters of O_2 uptake per minute); resting blood lactate (mmol); exercise O_2 uptake (kJ); recovery blood lactate (mmol); rest and recovery O_2 uptake (kJ); and work (J).

Oxygen uptake was measured using a standard metabolic cart (MMS-2400, PavoMedics, Sandy, Utah, USA). The metabolic cart was calibrated a minimum of 2 times immediately before all testing, using room air and calibration gas (16% O_2, 4% CO_2); ventilation was calibrated using a 3-L syringe. Oxygen uptake was measured in 5- and 15-s sampling periods. Before each lift, resting O_2 uptake was averaged over a 5-min period with each subject lying supine with their back on the bench (feet on floor). At the end of the 5-min rest, each subject began lifting at the required cadence while O_2 uptake continued to be measured throughout the exercise period. Aerobic exercise energy expenditure was estimated at 1 L O_2 = 21.1 kJ.

The rest period after the 1st and 2nd set was selected as 4 min. After the 3rd set was completed and the weight was racked, each subject had their feet elevated on a chair parallel to the height of the bench; excess postexercise oxygen consumption (EPOC) was recorded until measurements fell below 5.0 $mL \cdot kg^{-1} \cdot min^{-1}$ (a typical standing–resting O_2 uptake). Rest and recovery oxygen uptake (EPOC) were converted to energy expenditure as 1 L of O_2 = 19.6 kJ to dismiss any glycolytic component from the O_2 uptake measurement (Scott et al. 2009). Each subject's resting O_2 uptake was subtracted from exercise, rest, and recovery.

Blood lactate measurements were recorded in duplicate using 2 handheld lactate analyzers (Lactate Pro, Arkray Inc., B.C., Canada). For data analysis, the 2 measures were averaged. Resting blood lactate was collected with subjects lying supine before the resting O_2 uptake measurement. Blood lactate was collected in the supine position. After the 1st and 2nd set blood lactate was taken at the 3-min mark and after the 3rd and last set, peak lactate was determined as the highest blood lactate concentration recorded at 3, 4, or 5 min postexercise. Anaerobic exercise energy expenditure for each set was converted into an O_2 equivalent measure (in milliliters) as the difference between subsequent lactate values, multiplied by body weight (kg), then multiplied by 3.0 mL of O_2 (di Prampero and Ferretti 1999). These conversions to O_2 equivalents were subsequently converted to Joules as 1 L O_2 = 21.1 kJ. Total energy expenditure was recorded as the sum of aerobic and anaerobic exercise energy expenditures and EPOC.

Statistical analyses

Data were examined among sets and lifting groups using repeated measures ANOVA with the appropriate post hoc test (SigmaPlot 12; Point Richmond, Calif., USA). Pearson correlation also was performed between work and aerobic, and anaerobic and recovery energy expenditures. α level was set at $p \leq 0.05$ (only significant p values are reported).

Results

Comparisons among groups are provided in Table 1. The within-group comparisons are listed below.

1.5 s down–1.5 s up

Work completed was not different among the 3 sets: 1, 154.9 ± 24.2 J; 2, 155 ± 23 J; 3, 155.1 ± 25.6 J (p =

Table 1. Total work and energy expenditure for 3 sets of 5 repetitions at 70% 1RM (bench press; 15 total repetitions).

Lifting cadence (s)	Total work (J)	Anaer EE (kJ)	Aer EE (kJ)	EPOC (kJ)	TEE (kJ)
1.5 down–1.5 up	464.9±71.5	16.5±8.1*	5.1±3.9	38.6±17.8*	60.2±23.8*
4 down–1 up	451.2±71.5	21.6±8.1*	8.2±5.3	50.2±23.5	80.0±27.7
1 down–4 up	463.1±74.8	26.7±7.2*	7.4±6.3	50.0±22.6	84.2±28.3

Note: Values are means ± SD; Lifting cadence, eccentric (down)–concentric (up) lifting times; Total work, the sum of 3 sets (weight lifted × distance the bar traveled upward); Anaer EE, combined anaerobic energy expenditure of the 3 sets; Aer EE, combined exercise aerobic energy expenditures of the 3 sets; EPOC, the combined recovery energy expenditures after each of the 3 sets.

*Significantly different from data within the same column, $p < 0.005$.

0.67). Aerobic exercise energy expenditure was not different among sets: 1, 1.8 ± 1.3 kJ; 2, 1.7 ± 1.6 kJ; 3, 1.5 ± 1.5 kJ ($p = 0.76$). Anaerobic energy expenditure was different for the 1st set (9.5 ± 5.2 kJ) as compared with the 2nd (4.6 ± 3.1 kJ) ($p = 0.004$) and 3rd sets (2.4 ± 1.8 kJ) ($p = 0.001$) but not the 2nd vs. 3rd sets ($p = 0.13$). EPOC differed between the 1st (11.4 ± 5.9 kJ) and 3rd sets (14.2 ± 6.5 kJ) ($p = 0.04$) but not the 2nd set (12.9 ± 6.3 kJ) ($p = 0.30$); the 2nd and 3rd sets were not different ($p = 0.20$). Total energy expenditure was not different among sets: 1, 22.7 ± 10.3 kJ; 2, 19.2 ± 8.8 kJ; 3, 18.2 ± 7.1 kJ ($p = 0.10$). The method of determining anaerobic energy expenditure, subtracting rest and each set's previous lactate levels from the subsequent set's peak lactate (summed, 16.5 ± 8.1 kJ) versus subtracting resting lactate levels from set 3 only (16.5 ± 8.0 kJ) was not significantly different ($p = 1.00$). Blood lactate levels peaked 3.0 ± 0.0 min after set 3.

4 s down–1 s up

Work completed was not different among the 3 sets: 1, 151.4 ± 25 J; 2, 149.6 ± 23.7 J; 3, 150.1 ± 23.2 J ($p = 0.37$). Aerobic exercise energy expenditure was not different among sets: 1, 2.4 ± 2.1 kJ; 2, 2.8 ± 2.3 kJ; 3, 3.1 ± 2 kJ ($p = 0.57$). Anaerobic energy expenditure was different for the 1st set (10.5 ± 6.8 kJ) as compared with the 3rd (3.8 ± 3.2 kJ) ($p = 0.03$) but not the 2nd set (7.3 ± 3.9 kJ) ($p = 0.16$); the 2nd and 3rd sets did not differ ($p = 0.27$). EPOC differed between the 1st (15.6 ± 8.1 kJ) and 2nd sets (16.0 ± 8.2 kJ) versus the 3rd set (18.5 ± 7.5 kJ) (respectively, $p = 0.001$ and $p = 0.002$) but not the 1st and 2nd sets ($p = 0.54$). Total energy expenditure was not different among sets: 1, 28.5 ± 12.4 kJ; 2, 26.1 ± 9.2 kJ; 3, 25.4 ± 7.7 kJ ($p = 0.31$). The method of determining anaerobic energy expenditure, subtracting rest and each set's previous lactate levels from the subsequent set's peak lactate (summed, 21.6 ± 8.1 kJ) versus subtracting resting lactate levels from set 3 only (21.0 ± 7.2 kJ) was not significantly different ($p = 0.87$). Blood lactate levels peaked 3.3 ± 0.7 min after set 3.

1 s up–4 s down

Work completed was different among the 2nd (151.9 ± 25.2 J) and 3rd sets (155.5 ± 26.3 J) ($p = 0.007$) but not with set 1 (155.6 ± 24.4 J) ($p = 0.06$). Aerobic exercise energy expenditure was not different among sets: 1, 2.0 ± 2.5 kJ; 2, 2.9 ± 2.2 kJ; 3, 2.5 ± 1.9 kJ ($p = 0.13$). Anaerobic energy expenditure was different for the 1st set (13.5 ± 4.6 kJ) as compared with the 2nd (6.9 ± 3.6 kJ) and 3rd sets (6.4 ± 4.1 kJ) ($p = 0.002$) but not the 2nd set versus the 3rd set ($p = 0.78$). EPOC differed between the 3rd set (19.5 ± 9.4 kJ) versus the 1st (14.2 ± 5.8 kJ) ($p = 0.001$) and 2nd sets (16.4 ± 7.9 kJ) ($p = 0.04$) but not for the 1st and 2nd sets ($p = 0.09$). Total energy expenditure was not different among sets: 1, 29.7 ± 9.8 kJ; 2, 26.1 ± 8.4 kJ; 3, 28.4 ± 12.0 kJ ($p = 0.25$). The method of determining anaerobic energy expenditure, subtracting rest and each set's previous lactate levels from the subsequent set's peak lactate (summed, 26.7 ± 7.2 kJ) versus subtracting resting lactate levels from set 3 only (27.0 ± 7.3 kJ) was not significantly different ($p = 0.97$). Blood lactate levels peaked 3.1 ± 0.3 min after set 3.

Discussion

When designing resistance training programs, time-under-tension requires consideration (Toigo and Boutellier 2006). This study appears to be the first to consider the impact of eccentric and concentric contraction times on the subsequent energy costs of resistance training where work and rest periods were held constant. Fatigue also played no role as submaximal lifting took place. We hypothesized that different exercise cadences would influence the energy expenditures associated with lifting and lowering a weight. This was partially true. Differences in anaerobic energy expenditure were found for all lifting cadences both among (Table 1) and within groups (see Results section). Within group differences also were found with EPOC (between and after all sets); this was expected in part because of the last set (3rd) having an extended recovery as compared with the assigned 4-min rest period for the 1st and 2nd sets. To the contrary, the aerobic energy expenditure of each lifting period was similar both within and among protocols. When total energy expenditures were accounted for (aerobic and anaerobic exercise + aerobic rest–recovery) differences among the 3 sets were not found within any protocol.

Among protocols EPOC (i.e., summed rest–recovery energy expenditures) and total energy expenditure were significantly larger for the 4 down–1 up and 1 down–4 up protocols as compared with the 1.5 down–1.5 up protocol. Because lifting time-under-tension was 30 s less for the briefest of the 3 protocols and work (weight lifted × distance the bar traveled) among protocols was similar, the significantly longer lifting times for 4 down–1 up (75 s) and 1 down–4 up (75 s) as compared with 1.5 down–1.5 up (45 s) appear responsible for the larger EPOC and total energy expenditure differences. A t test between the total energy expenditures of 4 down–1 up and 1 down–4 up revealed no difference ($p = 0.85$).

Work load along with the length of the rest periods between sets affects lactate levels (Abdessemed et al. 1999) so the present investigation was designed to equate these variables among protocols. We measured work as the product of weight lifted and displacement of the bar because it is the most appropriate method of determining resistance exercise volume (McBride et al. 2009). We did not want muscular failure to take place among protocols because lifting to fatigue increases the energy costs of equivalent nonfatiguing workloads (Scott and Earnest 2011). Rating of perceived exertion among protocols was not measured; however, subject comments suggested that the 4 s down–1 s up lifts was the most difficult. Interestingly, work for this protocol was almost statistically lower ($p = 0.07$) than the other protocols, suggesting that eccentric–concentric contraction times have the potential to influence bar movement and subsequent work output (Table 1).

Correlation analyses (Table 2) revealed no relationship between work and exercise O_2 uptake. For 3 sets of resistance exercise, anaerobic and total energy expenditures are best associated with work. Moreover, the largest component to energy costs was the rest and recovery O_2 uptakes that peaked *after* each set and were summed to provide an estimate of EPOC energy expenditure. Previous studies have shown that the amount of work (volume) may or may not correlate with EPOC. For the current study, overall EPOC for both 1.5 s down–1.5 s up and 1 s down–4 s up did correlate with overall work while it did not correlate for 4 s down–1 s up. Why is this? Lifting to (or close to) fatigue may providean explanation. In this and a previous study where lifts were not completed to fatigue, overall work output was related to overall EPOC (Scott et al. 2009). However, when fatigue was the ending point of lifts, work and EPOC were not correlated (Scott et al. 2011*a*, 2011*b*). Perhaps the noncorrelation for work and EPOC was associated with the difficulty of the 4 s down–1 s up protocol.

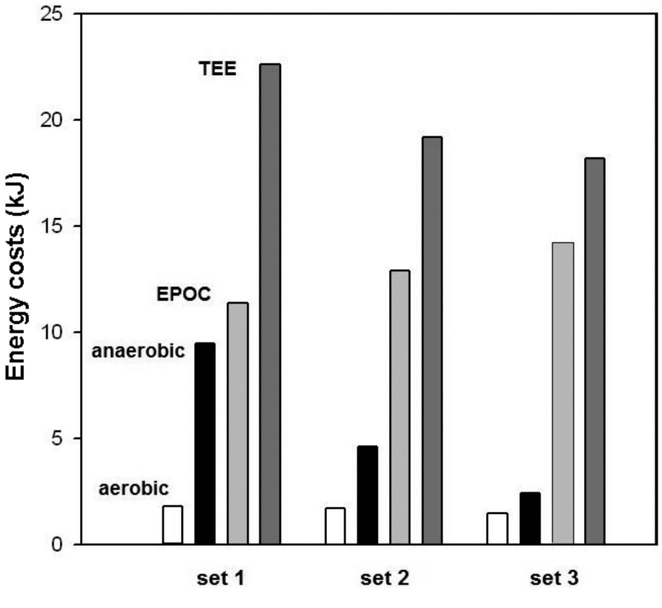
There was no preliminary warm-up before lifting started, possibly causing the highest lactate levels after the 1st set for each protocol. Anaerobic (glycolytic) energy expenditure contributions were significantly lower by the 3rd (final) sets. Moreover, rest–recovery O_2 uptake within protocols increased to become significantly larger by the 3rd sets, caused in part from an extended final EPOC collection period and the likelihood of an increased use of ATP–PC and oxygen stores (that our data collection methods account for within rest–recovery periods) (see Results section, Fig. 1). These energy exchange trends — decreased lactate production, increased ATP, PC utilization — have been reported elsewhere for high intensity intermittent exercise (Gaitanos et al. 1993). We also found that whether lactate-associated anaerobic energy expenditure was summed as the difference between each set or from peak lactate after set 3, estimates were virtually identical within lifts (see Results section). Thus, an estimate of anaerobic energy expenditure for 3 sets of submaximal lifting only requires a resting lactate and peak lactate measure after set 3. Decreasing blood lactate levels with intermittent exercise progression may be the result of the subsequent exercise and (or) rest period consuming (oxidizing) lactate (Rieu et al. 1988). However, muscle biopsy analysis suggests that lactate levels decrease after intermittent, brief, intense exercise because of a decrease in production, not an increase in removal (Gaitanos et al. 1993).

Table 2. Overall correlation with work: 3 sets of the bench press; 70% 1RM (15 total repetitions).

Work	TEE	Aer EE	Anaer EE	EPOC
1.5 s down–	0.79	–0.09	0.64	0.78
1.5 s up	(**0.009**)	(0.81)	(**0.05**)	(**0.008**)
4 s down–	0.66	–0.05	0.74	0.54
1 s up	(**0.04**)	(0.90)	(**0.01**)	(0.11)
1 s down–	0.69	0.13	0.82	0.65
4 s up	(**0.03**)	(0.73)	(**0.003**)	(**0.04**)

Note: Work, lifting cadence seconds, eccentric–concentric; TEE, total energy expenditure; Aer EE, aerobic exercise energy expenditure; Anaer EE, anaerobic energy expenditure; EPOC, rest and recovery energy expenditures after each set. Significance is shown in bold (*p* value in parenthesis).

Fig. 1. Energy costs for 5 repetitions and 3 intermittent sets of 1.5 s eccentric–1.5 s concentric contractions. Gas exchange data were collected in 15-s periods. Anaerobic energy expenditure is based on the difference of blood lactate levels after each set (see Materials and methods section). The acronym EPOC is used to express the summed rest–recovery periods of each set. Total energy expenditure (TEE) is the sum of all exercise and recovery estimates within sets. Note that anaerobic (glycolytic) energy costs decrease as EPOC increases with set progression, suggesting greater ATP–PC and stored oxygen contributions to subsequent exercise periods (sets). Bangsbo (1996) has shown efficiency improvement with subsequent bouts of intermittent exercise. However, the apparent decrease in TEE with progressive sets was not significantly different for any lifting cadence.



From this viewpoint, "anaerobic exercise" cannot be modeled after "aerobic exercise".

The effect of contraction-types and speed has been previously studied with resistance training; our study differs from others in that we use matched and unmatched eccentric and concentric lifting periods with equivalent work, rest periods, and lifting intensities. Mazzetti et al. (2007) have shown that explosive concentric contractions (squats) at 60% 1RM with standardized eccentric lifting times have the greatest potential to increase energy expenditure rates (kcal·min^{-1}), both aerobically and anaerobically. However, when data were expressed as a capacity (kcal), the explosive concentric protocol with heavier weight (80% 1RM, equal work) had slightly but significantly larger energy expenditures. Hunter et al. (2003) found that traditional lifting (65% 1RM; 0.9 s concentric, 0.8 s eccentric) had greater energy expenditure than super slow lifts (25% 1RM; 10 s concentric, 5 s eccentric) with exercise intensity and work being several times greater for traditional lifts. With a constant work output, Barreto et al. (2010) found similar EPOCs after circuit-type training at slow (2 s concentric, 2 s eccentric) and faster (1 s concentric, 1 s eccentric) lifting velocities, with lifting time doubled between groups. Because this study used female and ours male subjects, a gender difference may explain the disparate results between studies.

With brief measurement and exercise times (e.g., 5 s), the variability of any estimate of energy expenditure (aerobic or anaerobic) is extensive and therefore a study limitation (see Scott et al. 2009). Moreover, software analysis and subject breathing characteristics often do not allow gas exchange measurements to be within a precise period of time. As an example we had 2 subjects whose 5-s measurement periods were instead collected anywhere from 3 to 18 s, a problem that was corrected by converting O_2 uptake in liters per minute to liters per second, then multiplying by the length of the actual measurement period in seconds.

In conclusion, anaerobic (glycolytic) energy expenditure based on blood lactate levels appears affected by submaximal lifting cadence, time-under-tension, as well as by subsequent sets. Total energy expenditure is related to the amount of work performed for nonfatigue lifting. However, with equivalent work and rest periods, a particular eccentric–concentric cadence appears to best effect total energy expenditure because of the time-under-tension of the weight lifting set(s), with longer lifting times having greater energy expenditure.

Acknowledgements

The dedication, talents and teamwork of Mike Leary, Andrew Tenbraak, Caroline Breton, and John Letendre enabled the collection of data for this investigation.

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