TOTAL ENERGY COSTS – AEROBIC AND ANAEROBIC, EXERCISE AND RECOVERY – OF FIVE RESISTANCE EXERCISES

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Abstract. We utilized a non-steady state method (kJ per set, not kJ min^{-1}) to estimate the total energy costs (aerobic and anaerobic, exercise and recovery) of five different resistance exercises: incline bench press, squat, deadlift, shoulder shrug and calf raise. Using a Smith machine, work was precisely measured as the product of the vertical distance the lifting bar traveled and the amount of weight lifted. The average of two lifts performed on separate days was completed by 16 women (165 cm; 61.1 kg; 21.8 years) and 22 men (180.5 cm; 83 kg; 23.7 years). Overall 40 data points (the averages of 80 lifts) were plotted and correlations completed within each exercise for work and total energy costs: deadlift $r = 0.997$, squat $r = 0.977$, incline press $r = 0.947$, shoulder shrug $r = 0.921$ and calf raise $r = 0.941$ ($p < 0.05$). The amount of oxygen consumed during exercise for each lift represented the lowest energy cost contribution (18%), followed by anaerobic (31%) and excess post-exercise oxygen consumption (EPOC, 51%) ($p < 0.05$). The identification of work (J) along with an estimate of the total energy costs (kJ) revealed remarkably consistent relationships within any given resistance exercise, leading to a predictable increase in the cost of lifting for each exercise. However, due to the muscle/joint and movement characteristics of each exercise, the work to cost relationship differed for all lifts.

Key words: work, anaerobic energy expenditure, intermittent exercise

Introduction

Estimates of the energy costs of lower intensity steady state exercise are well documented. Steady state procedures however, have not been validated when applied to brief intense intermittent activity, with resistance training serving as a primary example (Scott 2014a, 2104b). Even so, descriptions of energy exchange to describe most all forms of exercise are typically reported as a steady state cost of movement as liters of oxygen per minute (or kJ min^{-1}). The costs of completing a specific task also has been reported (Steudel-Numbers and Wall-Scheffler 2009) and can be applied to resistance exercise in terms of a total energy cost per set (Scott 2006).

Our intent for this descriptive investigation was to examine and compare the total energy costs (kJ) – aerobic and anaerobic, exercise and brief recovery – for one set of five different types of resistance exercises: incline bench press, squat, deadlift, shoulder shrug and calf raise (comparisons also were made with a previous investigation of the horizontal bench press). Modifications to a Smith machine allowed us to precisely determine the distance the lifting bar moved (work was recorded as the product of weight lifted and the vertical distance the bar traveled) in an attempt to determine the relationship between the work and total energy costs for and among five different resistance exercises.

Methods

Subjects

This investigation was approved by a human subjects institutional review board at the University of Southern Maine. Sixteen women (165 cm; 61.1 kg; 21.8 years) and twenty-two men (180.5 cm; 83 kg; 23.7 years) were informed of the experimental risks and procedures of the study and voluntarily signed an approved subject consent form before any testing began. Subjects had to be in the "maintenance phase" of a resistance training program, defined by ACSM's criteria as a history of training 3 or more times per week, for at least 3 months.

Procedures

Subjects reported to the lab a total of 3 times for each lift. On the first visit informed consent was obtained, height and weight were recorded, a lifting weight was selected and a 1.5 s up and 1.5 s down lifting cadence were practiced. Lifting loads were not based on percent VO_2 max or percent of a one repetition maximum because the former describes aerobic intensity and the latter represents a load (Steele et al. 2012) that is not standardized among different lifts (Hoeger et al. 1987; Kerksick et al. 2014). Subjects selected a weight and repetition number under the criteria of the Borg Scale of perceived exertion as "somewhat hard" to lift. Subjects were requested to rack the weight well before muscular failure, because fatigue increases overall energy costs (Scott and Earnest 2011). Resistance exercises, weight lifted (kg), repetitions, work (J) and total energy costs (kJ) for males and females are provided in Tables 1 and 2, respectively. The exercises performed were deadlift (men only), squat, incline bench press, shoulder shrug and calf raise.

Table 1. Individual data for male subjects (n = 22), exercise performed, weight lifted, repetitions completed, work and total energy cost

Exercise	Weight (kg)	Reps	Work (J)	Total cost (kJ)
1	2	3	4	5
Deadlift	22.7	22	302.3	84.0
Deadlift	22.7	26	342.4	95.2
Deadlift	63.5	30	1138.6	172.7
Squat	81.6	10	365.8	41.8
Squat	104.3	15	826.2	95.1
Incline press	40.8	10	208.6	18.8
Incline press	54.5	10	209.7	22.5
Incline press	31.8	14	206.0	28.2
Incline press	49.9	7	208.6	17.3

1	2	3	4	5
Incline press	63.5	10	342.1	35.7
Incline press	27.3	10	109.8	12.8
Shrug	72.5	11	91.8	19.5
Shrug	90.6	11	143.3	44.8
Shrug	63.4	12	110.5	23.0
Shrug	40.8	34	120.8	25.3
Shrug	22.7	22	61.6	12.6
Shrug	40.8	10	49.9	13.7
Calf raise	81.6	10	95.6	26.2
Calf raise	54.4	20	107.9	40.3
Calf raise	63.6	10	67.5	21.1
Calf raise	63.6	13	96.3	33.6
Calf raise	59.0	10	68.9	20.3
Calf raise	49.9	20	106.9	34.7
Calf raise	49.9	20	144.4	40.7

Table 2. Individual data for female subjects (n = 16), exercise performed, weight lifted, repetitions completed, work and total energy cost

Exercise	Weight (kg)	Reps	Work (J)	Total cost (J)
Squat	31.7	14	152.2	31.3
Squat	31.7	17	191.0	39.6
Squat	59.1	10	236.5	31.6
Squat	22.7	10	82.4	28.4
Squat	22.7	10	67.5	16.2
Incline press	11.4	10	41.6	6.8
Incline press	27.3	10	109.7	12.8
Incline press	18.2	7	57.4	6.9
Incline press	18.2	10	71.7	9.4
Incline press	13.6	10	47.6	10.9
Incline press	18.2	10	88.5	11.2
Shrug	18.2	10	13.4	7.8
Shrug	31.7	10	27.6	5.9
Calf raise	31.7	18	57.0	22.3
Calf raise	31.7	15	50.4	15.9
Calf raise	31.7	10	38.7	11.4

The Smith machine (York; York, PA) was modified so that one of the cables attached to the lifting bar was connected to a small flywheel attached to an electronic processor. Moving the bar a distance of 106.6 cm resulted in a coefficient of variation (CV) of 0.25% per repetition and a CV of 0.75% among sets. Work is reported as the product of the vertical distance the bar travels and the amount of weight lifted in Joules (McBride et al. 2009).

Each resistance exercise was completed twice (on separate days) with the data set for each subject being the average of the two visits. Two blood lactate measures were taken (and averaged) from the subjects index finger using a micro-lancet both before lifting began and two minutes after the set was completed (Lactate Pro, Arkray

Inc, Kyoto, Japan). Subjects were then hooked up to the metabolic cart and 5 minutes of resting data were collected before each lift in the position the exercise was completed (i.e., standing for shoulder shrug, calf raise, squat and deadlift; lying at an incline for the incline press) (ParvoMedics TrueOn, 2400; Sandy, Utah). The metabolic cart was calibrated twice before each test.

On command subjects began lifting at a cadence of 1.5 s up and 1.5 s down for each complete repetition. All weights were racked before fatigue took place. Oxygen uptake was recorded throughout exercise and recovery. Immediately post-exercise subjects were seated and recovery took place until 2 consecutive 15 s measurements of oxygen uptake at or below 5.0 ml kg min^{-1} (a typical standing resting oxygen uptake measurement).

Resting oxygen uptake was subtracted from all exercise and recovery oxygen uptake measurements. Exercise oxygen uptake values were converted to an energy cost estimate as 1 liter of O_2 uptake = 21.1 kJ (representing glucose oxidation); excess post-exercise oxygen consumption (EPOC) was converted as 1 liter of O_2 uptake = 19.6 kJ (representing fat and lactate oxidation) (Scott 2006; Scott et al. 2009). Resting blood lactate measures were subtracted from peak recovery blood lactate values (Δ) then converted to an energy cost estimate: Δlactate × 3.0 ml O_2 × body weight (kg) × 21.1 kJ per liter of O_2.

Statistical Analysis

Pearson correlations were calculated separately between work and total energy cost for each exercise; linear regressions were calculated for each lift. Aerobic and anaerobic percent (%) contributions to each lift were analyzed between genders with a standard t-test and, among % exercise oxygen uptake, % anaerobic and %EPOC energy components with ANOVA and the appropriate post-hoc test. Alpha levels were set at $p < 0.05$.

Results

For each subject, the resistance exercise, amount of weight lifted, repetition number, work and the total energy costs involved are detailed in Tables 1 (men) and 2 (women). Correlation between work and total energy costs along with linear regression equations are provided in Table 3. The percent contribution of the oxygen consumed during the lifting period (exercise O_2) and EPOC along with the anaerobic glycolytic contributions for each lift are provided in Table 4. Men and women did not differ in terms of the percent contribution of each energy cost component within each exercise ($p > 0.05$). Differences were found among the percent components of the total energy cost estimate (Table 4).

Table 3. Correlation between work (J) and total energy cost (kJ) for each exercise with regression

Exercise	r	p	Regression	Power
Deadlift	0.997	0.047000	cost = 56.592 + (0.102 × work)	0.001
Squat	0.977	0.000200	cost = 14.931 + (0.0942 × work)	0.994
Inc press	0.947	0.000003	cost = 3.21+ (0.0911 × work)	0.996
Shrug	0.921	0.001000	cost = 0.0455 + (0.246 × work)	1.000
Calf raise	0.941	0.000050	cost = 1.945 + (0.296 × work)	0.946

Table 4. Percent contribution of the total energy cost components per set (mean ± SD)

Exercise	Gender	% exer O_2	% anaerobic	% EPOC
Deadlift	men	24.0 ±2.0	32.8 ±7.1	43.1 ±8.6
Squat	men	13.1 ±2.9	22.0 ±5.4	65.0 ±8.3
	women	16.8 ±6.9	21.1 ±4.6	62.1 ±8.8
Incline press	men	14.8 ±2.1	43.6 ±10.6	41.4 ±9.0
	women	11.5 ±4.4	43.5 ±14.4	45.0 ±10.8
Shrug	men	26.3 ±22.1	29.3 ±9.4	44.8 ±17.9
	women	14.0 ±8.9	32.3 ±28.8	54.4 ±19.0
Calf raise	men	20.4 ±3.4	28.6 ±5.2	51.0 ±7.8
	women	21.5 ±2.2	24.8 ±13.8	53.5 ±11.7
		* 18.0 ±5.2	* 30.9 ±8.3	* 51.1 ±8.4

exer O_2 – that volume of oxygen consumed during the lift; anaerobic data are based on blood lactate concentrations; EPOC – excess post-exercise oxygen uptake; * – all energy cost components are significantly different (p = 0.001).

Discussion

No model of the energy costs of strength, speed and power related activity has been universally agreed on. However, at least 2 formats of energy cost interpretation exist: 1) as a per minute (rate) function (e.g., kJ min^{-1}) or 2) as the cost of a particular exercise task from start to completion (kJ). Using the latter, our data demonstrate remarkably predictable relationships between a measure of the work completed and our estimation of total energy costs – aerobic and anaerobic, exercise and recovery – for a given resistance exercise (Table 3). The type of resistance exercise, the movement patterns of the lift and the muscle mass recruited all appear to influence the total energy cost outcome (Figure 1). The lowest contribution to the total energy costs of all lifts was the oxygen consumed during exercise (18%), with significantly greater costs coming from EPOC (51.1%) followed by anaerobic (glycolytic, 30.9%) components (Table 4).

Founded on heat measurements (the gold standard), the study of biological energy exchange now appears mostly as a per-minute (l min^{-1}) measurement of oxygen uptake. Though lacking validation, steady state per-minute models represent the current state of affairs as applied to non-steady state intermittent resistance exercise. It has been suggested for example that the EPOC after resistance exercise (in liters per minute format) may be utilized to better estimate energy costs (Vezina et al. 2014). Such a model may certainly be a step forward from traditional averaged exercise-plus-EPOC measures of oxygen uptake during resistance training. We argue however, that our 3 component non-steady state model (Table 4) contains all the metabolic systems associated with resistance exercise, the most important of which appear to be the EPOC (representing the use of oxygen, ATP, and phosphocreatine (PCr) stores) and anaerobic (glycolytic/lactate) components. Until direct calorimeter measurements of actual heat loss during weight lifting are recorded and compared to current methodology, all estimations of the energy costs of resistance exercise can and should be questioned.

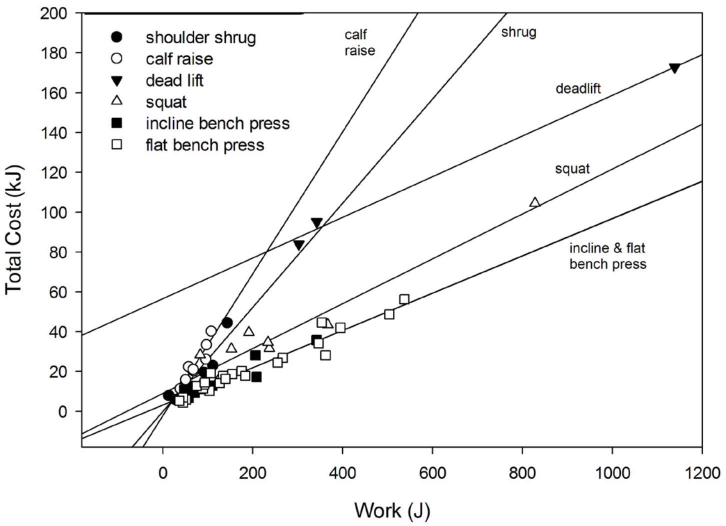

Figure 1. Linear regression characteristics are portrayed for each of the 5 lifts in the current investigation, where work was completed at a specific 1.5 s up – 1.5 s down cadence. Differences and similarities are evident. For example, the regression for the flat bench press of a previous investigation (Scott et al. 2009) is virtually identical to the incline bench press of the current study. Moreover, the bench press, squat, and dead lifts all appear to have a similar slope with a different Y-intercept, perhaps indicating the differences in recruited muscle mass but similar work to total cost ratio for each lift. The calf raise and shoulder shrug also have somewhat similar work to total cost slopes that are however much different than those lifts that require multiple muscle-joint movements (i.e., bench and incline press, squat and deadlift).

Perhaps the greatest limitation of our study was the independent variable used to estimate dependent energy costs (inertia was not measured). Weight lifters, scientists, trainers and coaches alike, typically do not interpret resistance training in the context of 'Joules'. Tables 1 and 2 provide the exercise, amount of weight lifted, work and repetitions performed for each subject. The use of blood lactate as a marker of anaerobic (glycolytic) energy costs also can be interpreted as a limitation. Steady state aerobic models promote blood lactate levels as an energy cost descriptor limitation. In contrast, with work as opposed to power output, rises in blood lactate appear to be a predictable anaerobic (glycolytic) metabolic marker (Buitago et al. 2014; Gorostiago et al. 2014; Scott et al. 2009). The Smith machine limits movement to a single plane and may not be appropriated to free weight lifting.

Conclusion

In terms of estimating the costs of resistance training, steady state models lack validity yet have universal appeal. Unfortunately, oxygen-only (l min^{-1}) measurements of exercise and recovery have the potential to underestimate the overall energy costs of brief intense intermittent exercise (Vezina et al. 2014), with resistance exercise serving as a primary example. The identification of work (J) along with an estimate of total energy costs (kJ) – aerobic and anaerobic, exercise and brief recovery – reveals remarkably consistent relationships within a given resistance exercise. We suggest that the total energy costs of intermittent resistance exercise are better described using capacity (kJ) as compared to rate-function (kJ min^{-1}) measures of oxygen uptake.

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