

# Inclusion of Eccentric Actions on Net Caloric Cost Resulting From Isoinertial Resistance Exercise

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## ABSTRACT

Net O<sub>2</sub> uptake was measured from maximal-effort 3-set, 8-repetition seated leg press protocols on an isoinertial ergometer. Subjects (25 women, 9 men) did 2 workouts each exerting concentric-eccentric (CE) and concentric-only (CO) knee extensor forces to measure work and net caloric cost. Significant ( $p < 0.05$ ) relationships between work and net caloric cost resulted from CE and CO workouts for the male, female, and total subject sample. Two-way repeated-measures analyses of variance showed CE workouts resulted in significantly higher work but not net caloric cost and values. CE workouts likely relied on the knee extensors series elastic element to perform an additional ~3,600 J of eccentric work at no additional net caloric cost. Unlike other exercise modes, maximal-effort eccentric actions on the isoinertial ergometer, as done in the current study, provide no additional net caloric cost and is thus safe to administer to populations in whom metabolic cost is a concern.

**Key Words:** strength training, seated leg presses, metabolism, energy

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## Introduction

Resistance exercise, performed with standard isoload strength training equipment (barbells, dumbbells, machines with a selectorized weight stack), elicits numerous physiological responses. A common acute response include a greater net caloric cost associated with concentric (muscle shortening) vs. eccentric (muscle lengthening) contractions (14). Because potential force output at a given contractile velocity is greater with muscle lengthening, eccentric actions performed during standard isoload strength training are submaximal, to in part explain the lower net caloric

costs (30). Yet the inclusion of eccentric actions are important for adaptations commonly associated with resistance exercise.

In contrast to the manner standard isoload equipment operates, an isoload inertial (isoinertial) strength training ergometer (YoYo Inertial Technologies, Stockholm, Sweden) that uses a pair of flywheels to exercise the knee extensors during seated leg press repetitions (6) has been developed. Kinetic energy transfer, provided by the spinning flywheels, causes a cord connecting the flywheels to the ergometer's footplate to rewrap around the axle at a rate comparable with its unwrapping. As the cord rewraps, the footplate begins to return to the original starting position to begin the next repetition. At that time, the knee extensors resist the footplate's returning motion to incur eccentric loading. When maximal efforts are exerted during knee extensor shortening, the ergometer offers more eccentric loading than conventional isoload strength training equipment (6). Because the ergometer does not require gravity to operate and provides the knee extensors with concentric and eccentric isoinertial resistance, it has been suggested for use during space flight to attenuate in-flight muscle mass and strength losses (6). However, before the ergometer can be used in flight, physiological responses resulting from exercise, including relative contributions to net caloric cost during concentric and eccentric actions, must be understood. Though the isoinertial ergometer was designed for use during space travel (6), this form of strength training is increasingly used in healthy (3) and paraplegic populations (19, 20, 27). Because the ergometer provides immediate use for people of different strength levels without adding external resistance, such as isoload equipment requires, its use is becoming increasingly more common. For instance, isoinertial exercise equipment has recently been used in the training programs of disuse atrophy models, in which the metabolic cost of such exercise may be an issue (19).

**Table 1.** Subject characteristics (mean  $\pm$  SEM) for men ( $n = 9$ ), women ( $n = 25$ ), and total ( $n = 34$ ) subjects.

Characteristic (units)	Men	Women	Total
Age (y)	23.56 $\pm$ 1.85	22.51 $\pm$ 1.13	22.84 $\pm$ 0.63
Height (m)	1.78 $\pm$ 0.16	1.60 $\pm$ 0.14	1.70 $\pm$ 0.02
Weight (kg)	78.58 $\pm$ 7.52	61.25 $\pm$ 4.76	68.97 $\pm$ 2.37
Body surface area (m <sup>2</sup> )	1.95 $\pm$ 0.61	1.66 $\pm$ 0.26	1.79 $\pm$ 0.04

The specific aim of the current study was to compare the net caloric cost of the leg press exercise on an isoinertial ergometer both with and without maximal-effort eccentric actions. Work and net caloric cost data was compared from seated leg press workouts using concentric-eccentric (CE) or concentric-only (CO) knee extensor muscle actions. The current study also established the relationship between work and net caloric cost resulting from CE and CO knee extensor exercise protocols on the ergometer. Because it does not operate like standard strength training equipment, we hypothesized inclusion of maximal-effort knee extensor lengthening actions on the ergometer may result in different levels of net caloric cost than earlier studies examining metabolic expenditures of eccentric work with isoload or isokinetic devices (5, 9, 15, 24). Current study results will be discussed in the context of prior investigations examining the metabolic cost of eccentric actions.

## Methods

### *Experimental Approach to the Problem*

To assess test-retest reliabilities for work and net caloric cost data from each CE and CO workout, intraclass correlation coefficients were first determined. To compare the metabolic expenditure of leg presses with and without maximal-effort eccentric actions, work and net caloric cost data were examined using a 2-way repeated-measures analysis of variance (ANOVA). Exercise protocol (CE, CO) and gender served as the 2 factors used in the ANOVA. Finally, to assess the strength of association between work and net caloric cost, separate CE and CO Pearson product moment correlation coefficients were determined. An alpha of 0.05 was used to establish statistical significance for all tests.

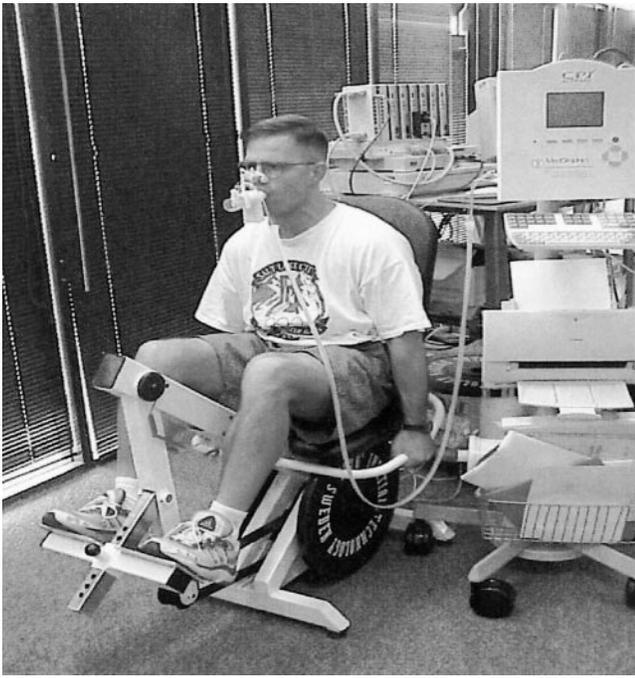
### *Subjects*

Healthy subjects (25 women, 9 men) provided written consent to participate in this project, which was approved by the local human subjects committee. Subjects came to the laboratory 5 times as part of the project. The first meeting was a familiarization session to acquaint subjects with exercise on the isoinertial ergometer. The final 4 meetings, separated by 5–7 days of rest, involved 2 bilateral leg press CE and CO workouts each. The sequence of the final 4 workouts was

randomized and balanced to prevent an order effect. Subjects were instructed to exert maximal effort during all workouts. Because flywheel velocity dictates the magnitude of loading on the isoinertial ergometer, all subjects extended their knees as quickly as possible against to incur the maximal concentric isoinertial resistance with each repetition for all 4 workouts. With the subject's knees fully extended, the spinning flywheels use kinetic energy to cause the cord to rewrap around the axle at rate comparable to its unwrapping. CO workouts involved exerting no force as the cord rewraps around the axle to return to the exercise's starting position, whereas CE workouts required subjects to resist the footplate's return to the starting position as their knee extensors lengthened to incur eccentric loading. Exerting maximal voluntary resistive effort as the cord rewrapped around the axle (CE workouts), the footplate's returning motion could not be stopped by the lengthening knee extensors. Subject characteristics, collected from the 4 workouts, appear in Table 1.

### *Experimental Procedures*

At the start of workouts, subjects were weighed and then sat upright on the ergometer to determine their baseline O<sub>2</sub> uptake. Wearing a nose clip and breathing into a mouthpiece, O<sub>2</sub> uptake was recorded using a metabolic cart (CPX Express System, Medgraphics Corp., St. Paul, MN) and gases that were calibrated according to manufacturer's recommendations prior to each workout. Step-by-step gas volume and concentration calibration instructions provided by the manufacturer were followed, enabling the metabolic cart to measure and record accurate O<sub>2</sub> uptake values. The metabolic cart provided breath-by-breath analysis of values averaged over 15-second intervals as subjects sat quietly on the ergometer for 10 minutes. Because O<sub>2</sub> consumption declined during the first 5 minutes of quiet sitting, baseline O<sub>2</sub> uptake was obtained from average values from the second 5-minute period. Fifteen-second O<sub>2</sub> uptake values, during the second 5-minute period, deviated  $\pm$ 2% from the eventual resting value. After subjects were disconnected from the metabolic cart, they next performed a 5-minute stationary bicycle (model 818E, Monark Ergomedic, Stockholm, Sweden) warm-up against 1 kilopond of resistance at 70 rpm. After the warm-up, subjects re-



**Figure 1.** Subject performs isoinertial ergometer leg presses as  $O_2$  uptake is measured. As the footplate returns to the starting position, the knee extensors: (a) decelerate the returning footplate to incur eccentric knee extensor loading (concentric-eccentric workouts) or (b) completely relax the knee extensors (concentric-only workouts) with each repetition.

turned to the ergometer and were reattached to the metabolic cart. Once their  $O_2$  uptakes returned to baseline values, subjects began their leg press workout.

Using maximal effort and starting each repetition with hips and knees flexed  $130^\circ$  and  $100^\circ$ , respectively, subjects exerted force as their knee extensors shortened against inertial resistance (concentric loading). At the start of each repetition, inertial resistance is overcome and each flywheel (mass 4.2 kg, radius 23 cm) joined together by an axle, starts spinning. A cord, connecting the ergometer's footplate to an axle, unwraps and rewraps during concentric and eccentric

phases per repetition, respectively. Depending on the randomization assignment per workout, subjects exerted maximal effort to decelerate the ergometer's footplate as the cord rewraps around the axle to incur eccentric knee extensor loading (CE workouts), or they provided no eccentric forces, allowing the footplate to return to the original starting position unimpeded (CO workouts). Figure 1 depicts the measurement of  $O_2$  uptake during seated leg presses on the inertial resistance ergometer.

Each workout involved a 3-set, 8-repetition protocol with 60 seconds rest between sets. The current study set-repetition scheme was chosen to mimic what is typically performed in conventional strength training protocols and in prior isoload and isokinetic study protocols examining the metabolic cost of eccentric exercise (9, 14, 24, 26, 28).

At the completion of each workout, subjects remained attached to the metabolic cart while seated upright on the ergometer until  $O_2$  uptake returned to their baseline value. During workouts flywheel velocity was concurrently recorded with a light sensor attached to on-line data collection software (MP100, Biopac Systems Incorporated, Santa Barbara, CA) at a sampling rate of 10 Hz. Work expressed in joules, the sum of concentric and eccentric (CE workouts) or concentric-only (CO workouts) work per set was calculated from flywheel velocity data with the following equation (6):

$$E_{kin} = (1/2)(J)(\omega^2)$$

where  $J$  = rotation inertia and  $\omega$  = angular velocity.

Net  $O_2$  uptake was determined by summing the difference between exercising and baseline  $O_2$  values resulting from workouts. Net  $O_2$  uptake, measured in liters, was converted to net caloric cost by multiplying net  $O_2$  uptake by 5, the non-steady-state equivalent of kilocalories expended per liter of  $O_2$  consumed (14).

## Results

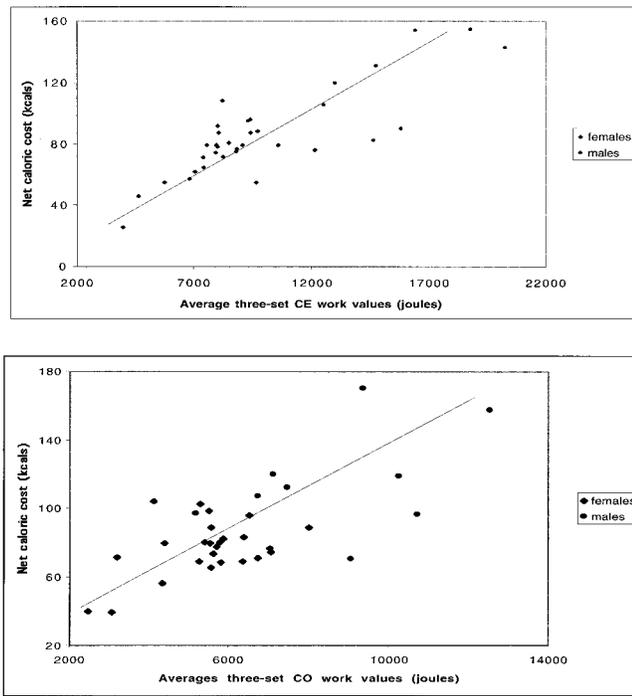
No subjects were injured from the maximal-effort seated leg press workouts on the isoinertial ergometer. Assuming  $\alpha$  and  $\beta$  values of 0.05 and 0.80, respectively,

**Table 2.** Intraclass and Pearson product-moment correlation coefficients for men ( $n = 9$ ), women ( $n = 25$ ), and total ( $n = 34$ ) subjects.

Measurement	Men	Women	Total
Intraclass correlation coefficient for CE† work data	0.86	0.55	0.89
Intraclass correlation coefficient for CO† work data	0.60	0.86	0.81
Intraclass correlation coefficient for CE net caloric cost data	0.67	0.49	0.79
Intraclass correlation coefficient for CO net caloric cost data	0.76	0.63	0.81
CE work and net caloric cost Pearson product-moment correlation coefficient	0.64*	0.64*	0.84*
CO work and net caloric cost Pearson product-moment correlation coefficient	0.40*	0.35	0.68*

† CE = concentric-eccentric; CO = concentric only.

\* Significant ( $p < 0.05$ ) Pearson product-moment correlation coefficients.



**Figure 2.** Concentric-eccentric (top) and concentric-only (bottom) data relationships between work and net caloric cost.

and a large effect size of typical strength training investigations (11, 18) the current study's sample size exceeded the estimated sample size required (21). Table 2 shows intraclass and Pearson product-moment correlation coefficients. Intraclass correlation coefficients suggest work and net caloric cost data from CE and CO workouts on the isoinertial ergometer were reproducible over the period examined.

The correlation between work and net caloric cost data, averaged from the 2 CE workouts, was significant ( $r = 0.84$ ) and yielded the following equation: predicted net caloric cost =  $23.29 + (0.006309597)(\text{work})$ . From the CE workouts, women showed a significant relationship between work and net caloric cost ( $r = 0.64$ ) and yielded the following equation: predicted net caloric cost =  $22.5594 + (0.006)(\text{work})$ . Men also showed a significant relationship between work and net caloric cost ( $r = 0.64$ ), which yielded the following equation: predicted net caloric cost =  $39.3871 + (0.005)(\text{work})$ .

The correlation between work and net caloric cost data, averaged from the 2 CO workouts, was also significant ( $r = 0.68$ ) and yielded the following equation: predicted net caloric cost =  $32.49 + (0.00866109)(\text{work})$ . From the CO workouts, women showed a significant relationship between work and net caloric cost ( $r = 0.35$ ) and yielded the following equation: predicted net caloric cost =  $58.596 + (0.003)(\text{work})$ . In contrast, male data collected from CO workouts was not significant ( $r = 0.40$ ,  $p = 0.14$ ). Graphs illustrating

**Table 3.** CE and CO work and net caloric cost data (mean  $\pm$  SEM), averaged across 2 workouts, for men ( $n = 9$ ), women ( $n = 25$ ), and total ( $n = 34$ ) subjects.

Measurement (units)	CE†	CO†
Work (J)		
Men	15,055.51 $\pm$ 1,102.1**	8,710.88 $\pm$ 763.98**
Women	8,119.41 $\pm$ 346.0*	5,456.76 $\pm$ 259.72
Total	9,955.23 $\pm$ 643.10*‡	6,318.15 $\pm$ 363.45
Net caloric cost (kcal)		
Men	119.62 $\pm$ 9.21**	116.64 $\pm$ 10.27**
Women	74.04 $\pm$ 3.44	76.62 $\pm$ 3.23
Total	86.10 $\pm$ 4.83	87.21 $\pm$ 4.60

† CE = concentric-eccentric; CO = concentric only.

‡ Value is comprised of  $6,105.81 \pm 432.00$  J of concentric work.

\* Significantly ( $p < 0.05$ ) greater than between-workout CO value.

\*\* Significantly ( $p < 0.05$ ) greater than within-workout female value.

correlations between work and net caloric cost data for CE and CO workouts appear in Figure 2.

Table 3 depicts mean gender differences between CE and CO work and net caloric cost data. Men observed significantly greater work and net caloric cost values for CE and CO workouts vs. female data. Comparing CE and CO work values with pooled gender data show CE workouts resulted in significantly greater values. Concentric work data, averaged from the 2 CE workouts was  $6,105.81 \pm 432.00$  J, comparable with Table 3 CO work values. Comparing CE and CO net caloric cost values with pooled gender data show both types of workouts were statistically equal. Study results suggest CE workouts on the isoinertial ergometer provide an additional  $\sim 3,600$  J of eccentric work vs. CO workouts with no additional net caloric cost.

## Discussion

Prior studies have examined the relative contributions of concentric and eccentric muscle actions toward net caloric cost (1, 2, 4, 9, 14, 23–28). Cycle ergometry employing similar loads and pedaling rates during concentric and eccentric actions noted oxygen uptake was 2.4–5.2 times less during muscle lengthening (2, 23). During eccentric actions on a cycle ergometer, oxygen uptake was greater with increasing work rates, though the relative cost of negative work decreased with higher pedal speeds (2, 4). Greater oxygen uptake resulting from eccentric work on a cycle ergometer occurs through increases in force output rather than pedaling rate (1). Comparing 6 weeks of concentric or eccentric cycle ergometry examined changes in isometric knee

extensor strength and oxygen uptake as a function of work rate (25). After 6 weeks, training adaptations with cycle ergometry showed oxygen uptake for eccentric exercise was less than or equal to muscle shortening actions despite a 7-fold increase in work rates (25). After 5 weeks of eccentric cycle ergometry training, oxygen uptake and respiratory exchange ratios both declined significantly, suggesting the trained knee extensors became utilized fewer muscle fibers and relied on changes to viscoelastic properties involved in the exercise protocol (7).

Isoload resistance exercise results in eccentric actions requiring 14–20% the energy cost of corresponding concentric movements (14, 24, 26). Using  $^{31}\text{P}$  magnetic resonance spectroscopy in 8 healthy subjects, the metabolic cost of concentric exercise was proportional to the mechanical power generated, yet intensity increased during eccentric exercise resulted in little added energy expenditure (26). Using an isoload seated leg press apparatus and a set-repetition protocol similar to the current investigation, a group performing concentric and eccentric knee extensor actions observed a doubling of resistance with only a 14% increase in energy cost vs. subjects performing concentric-only training (14). Performing seated isoload leg presses on an inclined sled apparatus yielded the net energy cost from eccentric muscle actions of only 20% of that for concentric exercise despite similar work values (24).

Unlike isoload contractions, which involve applying force against a constant external load, isokinetic exercise imposes a resistance relative to a muscle's mechanical advantage through a range of motion at a constant velocity. Comparing maximal-effort concentric and eccentric muscle actions done at the same velocity, smaller net caloric cost differences exist (9, 28). Examining maximal-effort elbow flexor actions, concentric and eccentric work and net energy expenditure, resulting from a 4-set, 12-repetition isokinetic ( $1.08 \text{ rad}\cdot\text{s}^{-1}$ ) protocol, were statistically equal (9). Concentric and eccentric squatting actions performed at a constant angular velocity (8.5 m per second) resulted in a comparable metabolic cost, although greater force was exerted during knee extensor lengthening through the angles (70–160°) examined (28).

Although prior studies (1, 2, 4, 14, 25, 26) showed small increases in net caloric cost with the inclusion of lengthening actions, the current study's CE workouts caused no additional net caloric cost (Table 3) despite an additional  $\sim 3,600 \text{ J}$  of eccentric work vs. CO data. Several factors, including the resistance inherent with this form of exercise, adenosine 5'triphosphatase (ATPase) activity, and the knee extensors' series elastic element (SEE), may account for the current study results. The isoinertial ergometer provides more eccentric resistance than standard isoload strength training equipment but less than maximal isokinetic lengthening

actions, which note higher net caloric costs from eccentric work than isoload or current study results (6, 9, 14, 24, 26, 28). Yet current study isoinertial ergometer data show greater eccentric work at a reduced net caloric cost vs. isoload knee extensor exercise (14, 24, 26). Thus, it does not appear the relationship between eccentric work and its resultant metabolic cost is linear across different modes (isokinetic, isoload, isoinertial) of strength training.

ATPase activity differs during concentric and eccentric muscle actions (26, 32). As sarcomeres shorten against an external resistance, ATPase activity is proportional to the mechanical power generated (26). During concentric actions sarcomeres may continue to shorten by breaking down additional ATP. However during eccentric muscle actions, intact cross-bridges work against an external resistance to resist sarcomere lengthening (26, 32). In vitro work suggests stretching cross-bridges can form bonds and develop tension without ATP breakdown (13). Greater rates of sarcomere lengthening, such as maximal-effort eccentric actions on the isoinertial ergometer, likely increase muscle stiffness to maintain cross-bridges and keep force output high (5). Although ATPase activity reduces energy expenditure for lengthening actions, it does not explain differences in net caloric cost for eccentric work in the current and prior (9, 14, 24–26) studies using different strength training modes.

SEE describes the combined utilization of stored elastic energy and increased reflex potentiation of involved muscles (8). Greater SEE knee extensor involvement during different jumping protocols resulted in higher vertical displacements and power outputs (8). To store elastic energy, muscles must be activated as they stretch, and, if the lengthening duration is great enough, increased muscle potentiation occurs through the stretch reflex (8, 10). During maximal-effort CE ergometer workouts, knee extensor lengthening likely both stored elastic energy and increased muscle potentiation for the following repetition. In contrast, leg press studies using isoload equipment paused during repetitions to negate the effects of the SEE (14, 24). Stored elastic energy utilization resulting from the SEE during isoinertial knee extensor lengthening spared ATP breakdown, in contrast to the net caloric cost of eccentric work done in isoload investigations (14, 24). Kinetic energy transfer on the isoinertial ergometer, causing the cord to rewrap around the axle for eccentric loading, is fundamental to its operation and likely led to greater knee extensor SEE involvement. Resulting from CE leg press repetitions on the isoinertial ergometer, both an increased muscle potentiation and stored elastic energy utilization led to no additional net caloric cost with the inclusion of  $\sim 3,600 \text{ J}$  of eccentric work.

## Practical Applications

Eccentric actions improve muscle performance and function and are therefore important to a variety of clinical and athletic applications (11, 14, 15, 26, 32). Maximal-effort eccentric actions on the isoinertial ergometer result in less net caloric cost than other forms of resistance exercise. This finding has relevance to both space flight and paraplegia, 2 populations for whom the metabolic cost of exercise is a concern. During space flight the knee extensors lose mass and strength, which result from reduced energy intake, decreased rates of protein synthesis, and mechanical loading of postural muscle groups (6, 14, 16, 29). Optimizing in-flight factors (mode, intensity, and duration) may lead to net caloric cost reductions of as much as 50%, thereby making long-term manned space missions more tenable (12). In-flight endurance exercise led to net caloric costs of 600 kcal per hour yet does not address mass and strength losses to postural muscle groups (14–16, 31). In contrast, an in-flight isoinertial leg press countermeasure could likely attenuate decreases in protein synthesis rates and knee extensor mass and strength loss, at a minimal net caloric cost because increased eccentric loading during non-weight-bearing was an effective countermeasure to sarcopenia (22). However, the knee extensors SEE, an important feature in explaining current study results, is normally compromised during space flight (33). Titin, a cytoskeletal filament located in the I band of sarcomeres, also contributes greatly to active muscular tension during eccentric actions (33). During non-weight-bearing conditions titin's role is diminished, which leads to myofibrillogenesis and sarcopenia (33). Prior work suggests a reparative effect on skeletal muscle exposed to chronic eccentric exercise (17). Thus, preflight ergometer training should impose greater eccentric loads to maintain more normal SEE and titin function in microgravity, thereby helping to preserve knee extensor performance and function at a net caloric cost far less than endurance activity (31).

Isoinertial exercise has recently been examined as an exercise modality for paraplegics (19, 20, 27). Like space flight, paraplegics exhibit sarcopenia, which could best be attenuated with exercise imposing a minimal net caloric cost. Upper extremity isoinertial ergometers were shown to improve cardiorespiratory and strength outcomes in paraplegics following 12 weeks of training (20). Acute effects with this form of exercise included  $\dot{V}O_2$  and heart rate measurements of 49 and 76.8% of their peak responses, respectively (19). In comparing isoinertial exercise with another rehabilitative modality (Thera-band training) common to paraplegics,  $\dot{V}O_2$  and heart rate responses were similar between protocols, yet Thera-band training resulted in higher ratings of perceived exertion (27). Applying current study results to this population suggests

maximal-effort eccentric actions on upper extremity isoinertial ergometers may be advantageous in training paraplegics because they provide no additional net caloric cost.

## References

1. ABBOTT, B.C., AND B. BIGLAND. The effects of force and speed changes on the rate of oxygen consumption during negative work. *J. Physiol.* 120:319–325. 1953.
2. ABBOTT, B.C., B. BIGLAND, AND J.M. RITCHIE. The physiological cost of negative work. *J. Physiol.* 117:380–390. 1952.
3. ABERNETHY, P.J., AND J. JURIMAE. Cross-sectional and longitudinal uses of isoinertial, isometric, and isokinetic dynamometry. *Med. Sci. Sports Exerc.* 28:1180–1187. 1996.
4. ASMUSSEN, E. Positive and negative muscular work. *Acta Physiol. Scand.* 28:366–382. 1952.
5. AURA, O., AND P.V. KOMI. Mechanical efficiency of pure positive and negative work with special reference to the work intensity. *Int. J. Sports Med.* 7:44–49. 1986.
6. BERG, H.E., AND P.A. TESCH. A gravity-independent ergometer to be used for resistance training in space. *Aviat. Space Environ. Med.* 65:752–756. 1994.
7. BONDE-PETERSEN, F., J. HENRIKSSON, AND H.G. KNUTTGEN. Effect of training with eccentric muscle contractions on skeletal muscle metabolites. *Acta Physiol. Scand.* 88:564–570. 1973.
8. BOSCO, C., AND P.V. KOMI. Potentiation of mechanical behavior of the human skeletal muscle through prestretching. *Acta Physiol. Scand.* 106:467–472. 1979.
9. CARUSO, J.F., W.A. SKELLY, T.D. COOK, G.J. GIBB, D.R. MERCADO, AND M.L. MEIER. An isokinetic investigation of contractile mode's effect on the elbow flexors. *J. Strength Cond. Res.* 15:69–74. 2001.
10. CAVAGNA, G.A., B. DUSMAN, AND R. MARGARIA. Positive work done by the previously stretched muscle. *J. Appl. Physiol.* 20: 157–158. 1968.
11. COLLIANDER, E.B., AND P.A. TESCH. Effects of eccentric and concentric muscle actions in resistance training. *Acta Physiol. Scand.* 140:31–39. 1990.
12. CONVERTINO, V.A. Physiological adaptations to weightlessness: Effects on exercise and work performance. In: *Exercise and Sports Sciences Reviews*. K.B. Pandolf and J.O. Holloszy, eds. Baltimore, MD: Williams and Wilkins, 1990. pp. 119–166.
13. CURTIN, N.A., AND R.E. DAVIES. Very high tension with very little ATP breakdown by active skeletal muscle. *J. Mechanochem. Cell Motility* 3:147–154. 1975.
14. DUDLEY, G.A., P.A. TESCH, R.T. HARRIS, C.L. GOLDEN, AND P. BUCHANAN. Influence of eccentric actions on the metabolic cost of resistance exercise. *Aviat. Space Environ. Med.* 62:678–682. 1991.
15. DUDLEY, G.A., P.A. TESCH, B.J. MILLER, AND P. BUCHANAN. Importance of eccentric actions in performance adaptations to resistance training. *Aviat. Space Environ. Med.* 62:543–550. 1991.
16. FITTS, R.H., D.R. RILEY, AND J.J. WIDDRICK. Physiology of a microgravity environment invited review: Microgravity and skeletal muscle. *J. Appl. Physiol.* 89:823–839. 2000.
17. FRIDEN, J., J. SEGER, M. SJOSTROM, AND B. EKBLUM. Adaptive response in human skeletal muscle subjected to prolonged eccentric training. *Int. J. Sports Med.* 4:177–183. 1983.
18. HATHER, B.M., P.A. TESCH, P. BUCHANAN, AND G.A. DUDLEY. Influence of eccentric actions on skeletal muscle adaptations to resistance training. *Acta Physiol. Scand.* 143:177–185. 1991.
19. JACOBS, P.L., E.T. MAHONEY, M.S. NASH, AND B.A. GREEN. Circuit resistance training in persons with complete paraplegia. *J. Rehabil. Res. Dev.* 39:21–28. 2002.
20. JACOBS, P.L., M.S. NASH, AND J.W. RUSINOWSKI. Circuit training

- provides cardiorespiratory and strength benefits in persons with paraplegia. *Med. Sci. Sports Exerc.* 33:711–717. 2001.
21. KEPPEL, G., W.H. SAUFLEY, AND H. TOKUNAGA. *Introduction to Design and Analysis*. New York, NY: W.H. Freeman and Company, 1992.
  22. KIRBY, C.R., M.J. RYAN, AND F.W. BOOTH. Eccentric exercise training as a countermeasure to non-weight bearing soleus muscle atrophy. *J. Appl. Physiol.* 73:1894–1899. 1992.
  23. KNUTTGEN, H.G., J.F. PATTON, AND J.A. VOGEL. An ergometer for concentric and eccentric muscular exercise. *J. Appl. Physiol.* 53:784–488. 1982.
  24. KOMI, P.V., M. KANEKO, AND O. AURA. EMG activity of the leg extensor muscles with special reference to mechanical efficiency in concentric and eccentric exercise. *Int. J. Sports Med.* 8:22–29. 1987.
  25. LASTAYO, P.C., T.E. REICH, M. URQUHART, H. HOPPELER, AND S.L. LINDSTEDT. Chronic eccentric exercise: Improvements in muscle strength can occur with little demand for oxygen. *Am. J. Physiol.* 276:R611–R615. 1999.
  26. MENARD, M.R., A.M. PENN, J.W.K. LEE, L.A. DUSIK, AND L.D. HALL. Relative metabolic efficiency of concentric and eccentric exercise determined by <sup>31</sup>P magnetic resonance spectroscopy. *Arch. Phys. Med. Rehabil.* 72:976–983. 1991.
  27. NASH, M.S., P.L. JACOBS, J.M. WOODS, J.E. CALRK, T.A. PRAY, AND A.E. PUMAREJO. A comparison of 2 circuit exercise training techniques for eliciting matched metabolic responses in persons with paraplegia. *Arch. Phys. Med. Rehabil.* 83:201–209. 2002.
  28. SELIGER, V., L. DOLEJS, AND V. KARAS. A dynamometric comparison of maximum eccentric, concentric, and isometric contractions using EMG and energy expenditure measurements. *Eur. J. Appl. Physiol.* 45:235–244. 1980.
  29. STEIN, T.P., M.J. LESKIW, M.D. SCHULTER, R.W. HOYT, H.W. LANE, R.E. GRETEBECK, AND A.D. LE BLANC. Energy expenditure and balance during space flight on the space shuttle. *Am. J. Physiol.* 276:R1739–R1748. 1999.
  30. TESCH, P.A., P. BUCHANAN, AND G.A. DUDLEY. An approach to counteracting long-term microgravity-induced muscle atrophy. *Physiologist* 33:S77–S79. 1990.
  31. VOROBYOV, E.I., O.G. GAZENKO, A.M. GENIN, AND A.D. EGOV. Medical results of Salyut-6 manned space flights. *Aviat. Space Environ. Med.* 54:S31–S40. 1983.
  32. WALKER, P.M., F. BRUNOITTE, I. ROUHIER-MARCER, Y. COTTIN, J.-M. CASILLAS, P. GRAS, AND J.-P. DIDIER. Nuclear magnetic resonance evidence of different muscular adaptations after resistance training. *Arch. Phys. Med. Rehabil.* 79:1391–1398. 1998.
  33. WEICKER, H. Stretch-shortening-cycle in microgravity, spinal proprioceptive and tendomuscular elastic energy release. *Int. J. Sports Med.* 18(Suppl 4):S326–S329. 1997.

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