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Chronic eccentric exercise: improvements in muscle strength can occur with little demand for oxygen

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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 (*Regulatory Integrative Comp. Physiol.* 45): R611–R615, 1999.—Eccentric contractions, the lengthening of muscle while producing force, are a common part of our everyday movements. This study presents a challenge to the accepted notion that eccentric work causes obligatory muscle injury while demonstrating that an increase in muscle strength, via eccentric work, can occur with little demand for oxygen. Nine healthy subjects, ages 18–34, were randomly placed in either an eccentric or a concentric training group. Both groups trained for 6 wk while progressively increasing training frequency and duration. Significant gains in isometric leg strength were seen in the eccentrically trained subjects only. While training, the oxygen consumption required to do the eccentric work was equal to or less than that required to do the concentric work. The results demonstrate that by progressively increasing the eccentric work rate, significant isometric strength gains can be made without muscle injury and with minimal increase in metabolic demand for oxygen. The potential clinical implications of an eccentric training program that uncouples skeletal muscle strength improvements from the demand for oxygen are alluring.

concentric exercise; oxygen consumption; strength training

THE CLASSIC TEXTBOOK VIEW of skeletal muscle as shortening while contracting, thus performing concentric (Con) work, has been broadened by the observations that activated muscles frequently produce force while being lengthened, thus performing eccentric (Ecc) work. This study was designed around two unique characteristics of Ecc muscular work, *1*) high tension/force production occurs despite *2*) low demand for oxygen, to determine if strength can be increased with minimal oxygen requirement and without muscle injury.

When muscle produces force eccentrically, it can develop greater tension than when it contracts isometrically or concentrically (18–20). Indeed this increased tension or "overloading" of the muscle has been exploited to elicit increases in strength (17, 18, 20). The oxygen cost of producing such high Ecc muscular forces is much lower than equal amounts of force produced concentrically (1, 3). Specifically, Bigland-Ritchie and Woods (3) reported that the oxygen requirement of submaximal Ecc cycling is only ⅙–⅐ of that for Con cycling at the same workload.[1]

Due in part to these high Ecc tension capabilities, there remains the common perception that Ecc muscle contractions necessarily cause muscle pain and injury (9, 14). Perhaps because of this established association between Ecc contractions and muscle injury, few studies have examined prolonged exposure to Ecc training and its effect on muscle injury and strength (12, 13).

Our interest in Ecc work was stimulated by the anecdotal and experimental (12) evidence that although an initial exposure to high Ecc work rates often produces muscle soreness, damage, and injury, gradually increasing Ecc work rates results in an attenuated response or eliminates the adverse responses completely. All evidence of muscle soreness, injury, and damage disappear and the muscles seem to adapt to the Ecc stress by becoming more "resistant" to it (2, 6, 8). The unique ability of Ecc contractions to produce high muscle tensions with reduced oxygen demand could be used for improving strength and function. This may be especially important for the elderly and/or cardiovascular impaired individuals who struggle to increase muscular mass and strength.

The purpose of this study is to address two specific questions. *1*) Can a chronic Ecc training technique (cycle ergometry) improve locomotor muscle strength without causing muscle injury? *2*) Is it possible to demonstrate strength gains with Ecc training at energy intensities (measured as oxygen uptake) that have little to no functional impact on locomotor muscles trained concentrically? In an attempt to answer these questions, we compared Ecc and Con cycle ergometry in healthy individuals over a 6-wk training period. The Ecc work rates were designed to increase leg strength, yet not produce any muscle injury. As well, the Ecc

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[1] Note that because work is force × displacement, it is a product of two vectors. When distance is in the opposite direction of the force generated, work is "negative." Here we use the term work independent of the sign to designate the force generated by the muscle × the distance the muscle shortens or lengthens.

work rates were designed to elicit equal or less oxygen consumption ($\dot{V}O_2$) compared with the Con work.

METHODS

Subjects. Nine healthy subjects 18–34 (mean 21.5) years old were assigned at random to one of two exercise training groups: *1*) an Ecc cycle ergometer, two males (1 sedentary, 1 regular moderate exerciser) and two females (1 regular moderate exerciser, 1 competitive triathlete), or *2*) traditional Con ergometer, two irregularly exercising males and three light exercising females.

Ecc ergometer. An Ecc ergometer was constructed locally with the power train of a standard Monarch cycle ergometer. The Ecc ergometer has an adjustable recumbent seat. It is driven by a three-horsepower direct current (DC) motor with four idlers between the motor and the flywheel. The gear ratio from the flywheel to the pedal crank is 1:3.75. All components are mounted to a steel frame. A DC motor controller, with a 0- to 10-V output for both motor speed and load, controls the motor speed and a magnetic sensor monitors pedal rpm (which is displayed to the rider during the training session). The voltage and amperage outputs from the controller are monitored through an analog-to-digital board and dedicated computer. The ergometer was calibrated by using the original standard ergometers friction band and applying known loads (via weights) as the motor moved the flywheel in a forward direction at a fixed rpm and reading the amperage/voltage of the motor. Therefore, for a fixed load and rpm, the calibration performed in the forward direction also served to calibrate the reverse direction of the flywheel. Hence, the Ecc work rate was maintained by the subject resisting the pedal motion at a fixed rate.

Training regimen. Both the Ecc and Con groups trained for 6 wk with a progressively increasing frequency and duration of training (and a pedal rpm of 50–60). During the first week each group trained two times for 10–20 min. Both groups then exercised three times during the 2nd wk for 30 min and finally five times per week for 30 min during the 3rd–6th wk. During the first 4 wk, the Ecc group began with threefold greater work rates than the Con group. During the 5th wk, work rates were adjusted in an attempt to equalize $\dot{V}O_2$ between the groups.

Isometric strength measurements. To assess skeletal muscle strength changes, maximal voluntary isometric strength produced by the knee extensors was measured with a Cybex dynamometer before and after (2–3 days) training as well as weekly during the 6-wk training period. The subject's knee was positioned in 45° of flexion for each of three maximal voluntary isometric trials, the average of which was recorded. This test provided an assessment of both muscle strength and muscle injury (detectable as loss of muscle force production) that may have occurred (10).

$\dot{V}O_2$. $\dot{V}O_2$ was measured one time a week while training during *weeks 4–6* with the use of an open spirometric system with the subjects wearing a loose-fitting mask. Air was drawn through the mask at a flow of ~500 l/min by a shop vac. Excurrent oxygen was measured during steady-state exercising with an Ametek oxygen analyzer, and flow was measured with a Venturi flowmeter. The system was calibrated after each session by nitrogen bleed (11).

Lower extremity soreness. A visual analog scale (VAS), a valid and reliable pain measurement (4), was used to determine the perception of lower extremity muscle soreness. Each subject was queried before and after the 6-wk training period and before each training session as to their leg pain. They responded by placing a mark on a vertical 14-cm scale anchored by word descriptors (0 = no leg pain, 14 = worst possible leg pain).

Rating of perceived exertion. We asked each subject during each training session to report a rating of perceived exertion for their total body exertion as well as specific leg exertion. A Borg RPE scale (6–20 rating) (22) was used as a self-monitoring tool.

Statistical analysis. A two-way ANOVA was used to assess the strength and RPE effects of weeks of training and individuals for each group (Ecc and Con). Where significant differences were noted, a Bonferroni's pairwise multiple comparison post hoc test was performed. In all cases the α level of significance was set at 0.05.

RESULTS

Ecc cycle ergometry training started at a threefold higher work rate than the Con group, and this work rate difference increased to a sevenfold difference by the 6th wk. During this training period, however, the oxygen requirement to do this Ecc work was less than or equal to the Con training oxygen requirement (Fig. 1*C*).

During the first 2–3 wk of Ecc cycle ergometry, leg pain as noted on the 14-cm VAS (Fig. 2*A*) was minimal and there was no change in leg strength (Fig. 2*B*). During this time period the total work rate in the Ecc group was greater (~3-fold) than the Con group, but the oxygen requirements to do this Ecc work were lower (Fig. 1*C*). The perceived exertion of the legs by the Ecc group, as measured by the RPE, was significantly higher than the Con group during the 1st wk, but no differences in leg or body exertion were noted thereafter (Fig. 1, *A* and *B*).

After the 3rd wk leg discomfort was absent in all subjects (Fig. 2*A*). Coupled with this were significant isometric leg strength increases of 33% in the ECC group during the 6th wk and a 27% increase at the posttraining (2–3 days) time periods. No significant improvements in Con strength were noted at any time period (Fig. 2*B*). There were significant differences in the isometric strength results between subjects within each group, but no interaction effects of subjects × weeks.

DISCUSSION

This study was designed to examine two questions related to Ecc training. First, if both the Ecc and Con groups train at equal levels (thus the Ecc group would be working at higher work rates) could strength improvements be made at very low oxygen demand? Second, could Ecc training intensities be managed specifically to minimize muscle injury and discomfort during the early weeks of training, thereby allowing high training intensities to follow without injury? To probe these questions, we progressively ramped the work rates and set a work rate target based on a conservative estimate of the established uncoupling of Ecc work and $\dot{V}O_2$ (compared with an equal amount of Con work and the $\dot{V}O_2$).

The results of this study demonstrate that if the Ecc work rate is ramped up during the first 4 wk and then maintained for at least 2 wk, strength gains can be

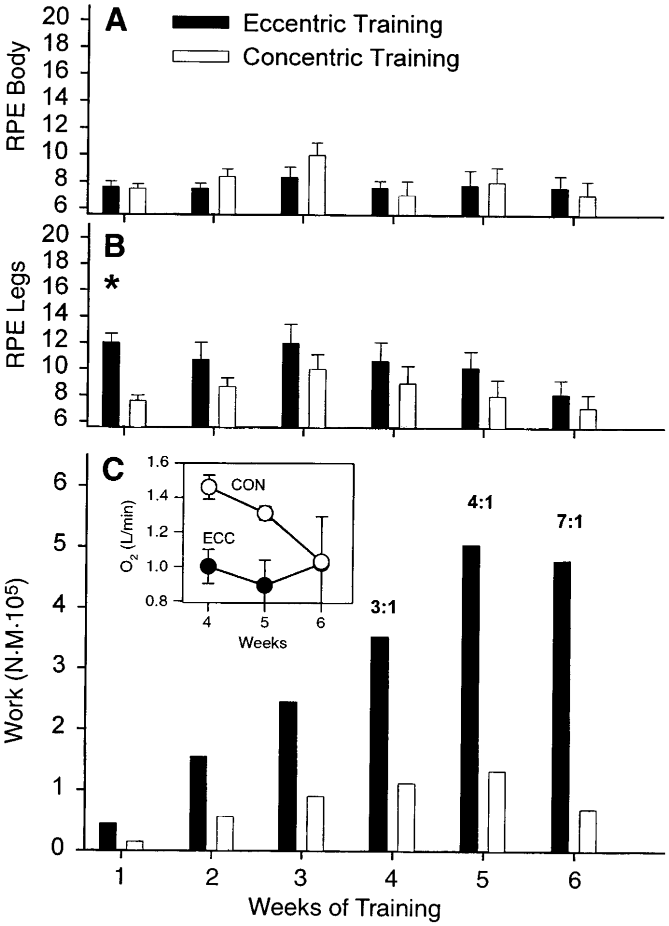

Fig. 1. Measures of perceived whole body and leg exertion as well as total work and oxygen cost were monitored during training. Mean values were calculated for all training measures, and error bars are equal to 1 SE. *$P < 0.05$, eccentric (Ecc) > concentric (Con). Body (*A*) and leg (*B*) rating of perceived exertion (RPE) was monitored with a 6–20 Borg scale. The only significant differences noted were in the RPE (legs) during *week 1* when the Ecc group had a greater perceived leg exertion. Despite large differences in workload toward the end of the study, there were no perceptable leg and/or body exertion differences. *C*: total work (positive or negative) accomplished during training for Con and Ecc groups. Workloads were progressively ramped during the first 3 wk (150, 225, 300 W for Ecc and 50, 75, 100 W for Con) and then adjusted in an attempt to equalize for *weeks 4–6* (ratios of Ecc to Con work noted above bars). *Inset* is for *weeks 4–6*, showing (no measures were taken during *weeks 1–3*) lower O_2 consumption ($\dot{V}O_2$) for the Ecc group until the 6th wk when $\dot{V}O_2$ were equalized.

made with minimal muscle soreness and without muscle injury as noted by the VAS and no loss in leg strength at any time during this study.[2] On the contrary, leg strength increased significantly in the Ecc group. Progressive ramping of the Ecc work rate prevented nearly all of the “typical” or expected muscle injury and eliminated all muscle soreness associated with the first few weeks of Ecc training. Despite efforts to equalize the exercising $\dot{V}O_2$ by altering the work rates, Ecc was less than Con throughout 5 wk of training and not equalized until the 6th week; gains in leg strength were noted with the Ecc training group, whereas no strength changes occurred in the Con group. We do not believe there was a significant learning effect with the repeated strength tests, as the Con group did not show any significant improvement in strength on the Cybex. These significant improvements in strength in the Ecc group occurred despite the significant differences in strength results between subjects in the Ecc group. We purposely recruited a heterogenous group of subjects, and we predicted the variable strength response would occur. This variability in strength improvements coupled with a significant group effect, however, suggests the effect of a strength increase in the Ecc group was quite robust. We expect that with a larger sample size and/or more homogenous groups, the variability within groups would lessen and the strength effect would be more pronounced. Variability in the Ecc measures (note

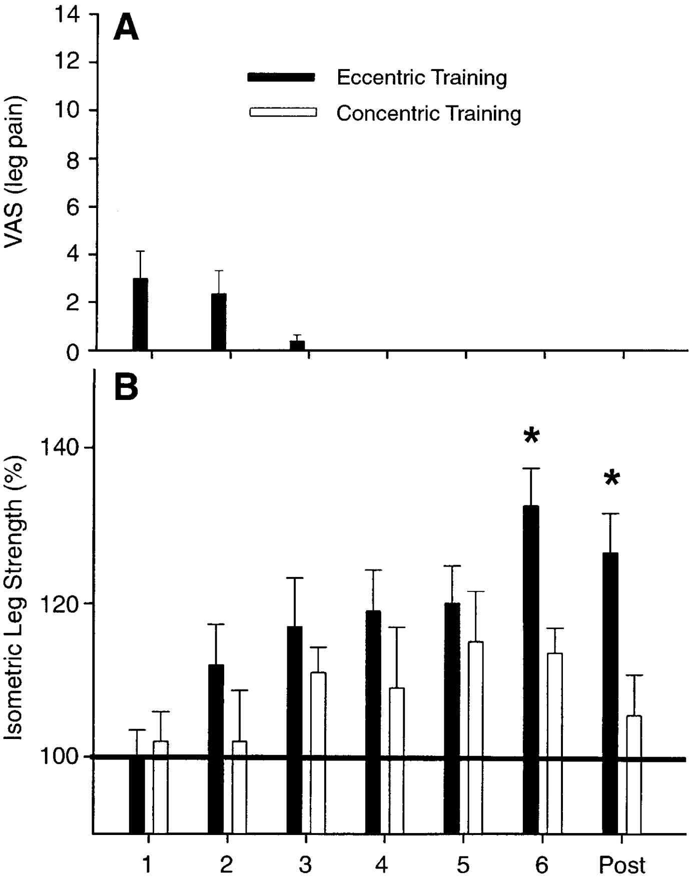

Fig. 2. Leg pain and isometric leg strength were measured weekly during training and before and after (2–3 days post) training. Mean values are shown with error bars equal to 1 SE. *Significantly different ($P < 0.05$) from initial values. *A*: leg pain was monitored with a 14-cm visual analog scale (VAS). Very little leg/muscle soreness in the Ecc group was noted during the first 3 wk and no leg pain thereafter. There was no leg pain in the Con group at any time period. *B*: isometric leg extension strength for the Ecc and Con groups is shown as a relative percent of their initial pretraining values. Overall, significant Ecc strength gains ($P < 0.05$) were noted during the 6th wk (33%) and at the 2–3 day posttraining measurement (27%). No significant increases in Con strength were noted at any time period.

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[2] Note that no direct measures of muscle damage, i.e., histological changes or creatine kinase activity, were made, because we were concerned with muscle function or lack of function (isometric strength loss), which provides the most valid measure of the totality of the injury (10).

larger error bars in the Ecc vs. Con measures) may reflect differing individual adaptations to the novel Ecc training.

There have been relatively few studies documenting the effectiveness of Ecc-specific exercises for increasing muscular strength. In 1972, Komi and Buskirk (20) reported greater tensions and increases in strength with Ecc resistance exercise compared with Con exercise. Other Ecc-only strength training studies (17, 18, 20) demonstrate that 6–13 wk of Ecc-only training can lead to improvements in Con, isometric, and Ecc strength. Likewise, training that combined Con and Ecc resulted in greater strength gains than training only in a Con fashion over an 8- to 12-wk period (5, 7). In contrast, Jones and Rutherford (19) failed to detect strength gains with resistive Ecc exercise. The studies that reported no improvements in strength did report, however, marked incidence of muscle damage and postexercise pain compared with Con or isometric resistance exercise, reinforcing the conclusion that the Ecc work leads to muscle injury.

Overall, however, chronic training programs that emphasize resistive Ecc loading have reinforced the notion that repetitive bouts of Ecc exercise do result in strength increases. This is not surprising, because the production of muscular force above the levels used in normal everyday activities (overloading) is a major stimulus for strength increases (23). What is intriguing is that these high forces and strength gains are made despite Ecc contractions having the lowest energy consumption per unit of tension exerted (3).

The mechanism by which the skeletal muscle adapts to Ecc contractions remains unclear. Repeated bouts of Ecc exercise result in an adaptation in the muscle such that it is more resistant to subsequent bouts of intense Ecc exercise (the “repeated bout effect”) (6, 8). Typically, after the first Ecc bout there is a prolonged loss in muscle strength and range of motion, a dramatic increase in muscle proteins in the blood, and the development of muscle soreness, all taken as indicators of muscle injury. However, after a repeated bout of the same exercise performed (3 days–10 wk later), the recovery of strength and range of motion occur significantly faster than that found after the first bout, soreness development is less, and muscle protein increases in the blood are blunted. Possible explanations for the apparent protective effect of repeated Ecc exercises are that weak areas of certain muscle fibers are eliminated after the initial bout (2), a more resilient structure is formed (21), or there are changes in the recruitment of motor units with subsequent exposures to Ecc contractions (15).

In response to chronic Ecc ergometry training, Friden et al. (14) noted that the muscle ultrastructure was well preserved and it underwent “regenerative activity,” making it possible for the muscle fibers to adapt to and defend against the potentially damaging tension occurring during ECC contractions. Friden reported severe muscle soreness early in the training study, which differs from our study, and he did not report the energy expenditure required to do the Ecc work, nor did he compare Ecc to Con ergometry. Although Friden’s protocol was a bit variable, profound functional changes occurred over the 8 wk of Ecc cycling, as the subjects increased their Ecc work capacity by 375% (12).

Perspectives

We feel the strength enhancements with Ecc training in our study, with very minimal cardiac demand, may have profound clinical applications. Despite improvements in strength and muscle mass with high-intensity resistance training in healthy elderly, many with cardiovascular disease cannot exercise at intensities sufficient to improve skeletal muscle mass and function (16). Exercise intensity in this population is often severely limited by the inability of the cardiovascular system to deliver adequate oxygen to fuel muscles at levels significantly above resting. For many elderly patients, the symptom-inducing metabolic limits have been estimated as low as 3 METS (16), which is equivalent to Con cycling at ~50 W on an ergometer. Such work rates may be insufficient to adequately stress muscle and prevent muscle atrophy and the concomitant functional decline. In this preliminary study we purposely tested heterogeneous groups of subjects anticipating the potential for the clinical utility of Ecc exercise with populations (patients) that tend to be very heterogeneous. Our long-term goal is to develop an Ecc skeletal muscle training paradigm that could be used in clinical settings to deliver greater stress to locomotor muscles (workloads exceeding 100 W), without severely stressing the oxygen delivery capacity of the cardiovascular system. This group of patients with, e.g., chronic heart failure and/or obstructive pulmonary disease etc., could maintain their muscle mass and potentially even experience an increase in muscle strength during their exercise rehabilitation. In this manner, one problem (cardiovascular limitation) may not have to escalate into two (cardiovascular limitation and skeletal muscle deterioration) for this population.

Ecc ergometry in normal healthy subjects produced isometric leg strength improvements while training at exercise intensities ($\dot{V}O_2$) that did not promote strength increases concentrically. The strength improvements, noted by the 6th wk of Ecc training, occurred despite the Ecc training requiring the same (or less) $\dot{V}O_2$. Likewise, the progressive Ecc training did not produce any muscle injury and only very little muscle soreness.

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REFERENCES

1. **Abbott, B. C., B. Bigland, and J. M. Ritchie.** The physiological cost of negative work. *J. Physiol. (Lond.)* 117: 380–390, 1952.
2. **Armstrong, R. B.** Muscle damage and endurance events. *Sports Med.* 3: 370–381, 1986.
3. **Bigland-Ritchie, B., and J. J. Woods.** Integrated electromyogram and oxygen uptake during positive and negative work. *J. Physiol. (Lond.)* 260: 267–277, 1976.
4. **Carlsson, A. M.** Assessment of chronic pain, part I. Aspects of the reliability and validity of the visual analogue scale. *Pain* 16: 87–101, 1983.
5. **Colliander, E. B., and P. A. Tesch.** Effects of eccentric and concentric muscle actions in resistance training. *Acta Physiol. Scand.* 140: 31–39, 1990.
6. **Clarkson, P. M., K. Nosaka, and B. Braun.** Muscle function after exercise induced muscle damage and rapid adaptation. *Med. Sci. Sports Exerc.* 24: 512–520, 1992.
7. **Dudley, G. A.** Importance of eccentric actions in performance adaptations to resistance training. *Aviat. Space Environ. Med.* 62: 543–550, 1991.
8. **Ebbeling, C. B., and P. M. Clarkson.** Muscle adaptation prior to recovery following eccentric exercise. *Eur. J. Appl. Physiol.* 60: 26–31, 1990.
9. **Evans, W. J.** Metabolic changes following eccentric exercise in trained and untrained men. *J. Appl. Physiol.* 61: 1864–1868, 1986.
10. **Faulkner, J. A., S. V. Brooks, and J. A. Opiteck.** Injury to skeletal muscle fibers during contractions: conditions of occurrence and prevention. *Phys. Ther.* 73: 911–921, 1993.
11. **Fedak, M. A., L. Rome, and H. J. Seeherman.** One-step N_2-dilution technique for calibrating open-circuit V_{O_2} measuring systems. *J. Appl. Physiol.* 51: 772–776, 1981.
12. **Friden, J.** Adaptive response in human skeletal muscle subjected to prolonged eccentric training. *Int. J. Sports Med.* 4: 177–183, 1983.
13. **Friden, J.** Changes in human skeletal muscle induced by long-term eccentric exercise. *Cell Tissue Res.* 236: 365–372, 1984.
14. **Friden, J., M. Sjostrom, and B. Ekblom.** Myofibrillar damage following intense eccentric exercise in man. *Int. J. Sports Med.* 4: 170–176, 1983.
15. **Golden, C., and G. A. Dudley.** Strength after bouts of eccentric or concentric actions. *Med. Sci. Sports Exerc.* 24: 926–933, 1992.
16. **Hanson, P.** Exercise testing and training in patients with chronic heart failure. *Med. Sci. Sports Exerc.* 26: 527–537, 1993.
17. **Johnson, B. L.** Eccentric and concentric muscle training for strength development. *Med. Sci. Sports Exerc.* 4: 111–115, 1972.
18. **Johnson, B. L., J. W. Adamaczyk, and K. O. Tennoe.** A comparison of concentric and eccentric muscle training. *Med. Sci. Sports Exerc.* 8: 35–38, 1976.
19. **Jones, D. A., and O. M. Rutherford.** Human muscle strength training: the effects of three different regimes and the nature of the resultant changes. *J. Physiol. (Lond.)* 391: 1–11, 1987.
20. **Komi, P. V., and E. R. Buskirk.** Effect of eccentric and concentric muscle conditioning on tension and electrical activity of human muscle. *Ergonomics* 15: 417–434, 1972.
21. **Newham, D. J., D. A. Jones, and P. M. Clarkson.** Repeated high force eccentric exercise: effects on muscle pain and damage. *J. Appl. Physiol.* 63: 1381–1386, 1987.
22. **Noble, B. J., G. A. Borg, and I. Jacobs.** A category ratio perceived exertion scale: relationship to blood and muscle lactates and heart rate. *Med. Sci. Sports Exerc.* 15: 523–528, 1983.
23. **Spielholz, N. I.** Scientific basis of exercise programs. In: *Therapeutic Exercise* (5th ed.), edited by J. V. Basmajian and S. L. Wolf. Baltimore, MD: Williams & Wilkins, 1990, p. 47–63.