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Evaluation of acute cardiorespiratory responses to hydraulic resistance exercise

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ABSTRACT

F.I. KATCH, P.S. FREEDSON, and C.A. JONES. Evaluation of acute cardiorespiratory responses to hydraulic resistance exercise. *Med. Sci. Sports Exerc.*, Vol. 17, No. 1, pp. 168–173, 1985. Accurate evaluation of the acute responses to resistance exercise training depends on the stability of the criterion measures. This is particularly true for maximal effort exercise where continuous "all-out" effort for each repetition is encouraged. The present study evaluated reliability of repetition number (repN), respiratory gas parameters ($\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}_E$), and heart rate (HR) for shoulder (SE), chest (CE), and leg (LE) exercise performed maximally on a single-unit, 3-station hydraulic resistance exercise machine (Hydra-Fitness, Belton, TX). On 2 separate days, 20 college men completed three 20-s bouts of SE, CE, and LE with a 20-s rest between bouts and 5 min between exercise modes. There were no significant differences between bouts or test days for repN, gas measures, or HR. Subjects performed 17, 19, and 21 reps during SE, LE, and CE. $\dot{V}O_2$ was 1.7 $l \cdot min^{-1}$ (24.3 $ml \cdot kg^{-1} \cdot min^{-1}$) for SE, 1.87 $l \cdot min^{-1}$ (25.5 $ml \cdot kg^{-1} \cdot min^{-1}$) for CE, and 2.1 $l \cdot min^{-1}$ (28.6 $ml \cdot kg^{-1} \cdot min^{-1}$) for LE. These values, averaged, represented 52.8% of the max $\dot{V}O_2$ determined on a continuous cycle ergometer test. The corresponding HR's during hydraulic exercise averaged 84.6% of HR max. Test-retest reliability coefficients ranged from r = .67 to .87 for repN, r = .41 to .83 for gas measures, and r = .72 to .89 for HR. The MET level averaged 7.5 (heavy), and caloric expenditure per minute averaged 35% higher compared with literature values for free weights and 29.4 and 11.5% greater than circuit exercise on Nautilus or Universal Gym equipment, respectively. It is concluded that there are reliable individual differences in repN, respiratory gas parameters, and HR during maximal effort exercise of relatively short duration performed on a multiple-station hydraulic resistance exercise apparatus.

HYDRAULIC RESISTANCE EXERCISE, RESPIRATION, GAS EXCHANGE, HEART RATE, CARDIOVASCULAR RESPONSE, CALORIC EXPENDITURE, EXERCISE INTENSITY, RELIABILITY, OXYGEN CONSUMPTION

Circuit weight training improves muscular strength and cardiovascular fitness (4–7,18). The duration of a single circuit usually varies between 7 and 12 min for a 10-station routine, depending on the rest interval between exercises (15–60 s) and the number of repetitions performed per exercise (6–15 reps). Research with circuit weight training includes conventional free weights and barbells (8,10,17), stacks of weight plates that permit variable resistance exercise (4,6,7,16), and cam and pulley devices that emphasize multiple repetitions consisting of both concentric and eccentric muscle contractions performed to "momentary muscular failure" (9,11).

Recently, exercise machines have been developed that incorporate hydraulic cylinders to provide both variable speed and variable resistance (Hydra-Fitness Industries, Belton, TX). An important design feature of this equipment permits concentric-only maximal-effort exercise for the agonist and antagonist muscle groups during each repetition of a particular movement. When the machines are placed in typical circuit fashion, this type of resistance training is similar in function to traditional circuit weight training (3,6). In conventional circuit training, the weight overload is usually set at 40–70% of maximum lift capability. For hydraulic resistance exercise, the individual attempts to exert maximum muscular force against a level arm throughout the complete range of motion in both directions of the movement. The nature of such "all-out" repetitive contractions during a given bout of exercise should significantly augment heart rate and metabolic response.

The present study is the first to evaluate individual differences in acute heart rate responses and measures of gas exchange for a 3-station, hydraulic resistive exercise machine. Because the magnitude of the heart rate and metabolic response depends to a large extent on exercise intensity, the reproducibility of maximum repetition number was determined during multiple bouts of chest, shoulder, and leg exercise. In addition, we have compared the absolute and relative energy expenditure of the hydraulic exercises with published data on other forms of resistance exercise.

METHODS

Subjects. Table 1 presents the descriptive characteristics for the 20 male subjects. They were college students at the University of Massachusetts, Amherst, with no prior experience in a supervised program of weight training or weight lifting. Subjects received medical clearance from the University Health Services and

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TABLE 1. Physical characteristics of subjects ($N = 20$).

Variable	Mean	SD
Age (yr)	23.7	4.37
Weight (kg)	73.3	8.12
Height (cm)	176.0	8.11
Percent body fat†	12.7	4.64
Lean body weight (kg)	63.3	6.72
Max $\dot{V}O_2$ ($l \cdot min^{-1}$)	3.7	0.46
Max $\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	50.1	5.17
Max $\dot{V}O_2$ [$ml \cdot kg\ (LBW)^{-1} \cdot min^{-1}$]	57.9	5.11
Heart rate$_{max}$ ($beats \cdot min^{-1}$)	193.4	8.71
Ventilation$_{max}$ ($l \cdot min^{-1}$)	109.1	17.35
R_{max}	1.11	0.05

† Underwater weighing (13) with correction for residual air volume (15) and conversion to body fat (14).

Figure 1—Subject performing chest exercise on the single-unit, 3-station hydraulic exercise apparatus.

signed an informed consent document in accord with University Human Subjects Review Guidelines.

Test apparatus. Figure 1 illustrates the exercise apparatus. On this device, there are three hydraulic cylinders; each is attached to its own layer system that provides concentric reciprocal movement primarily for the arms (chest press-chest row), arms and shoulders (shoulder press-lat pull), and legs (quadriceps extension-hamstring flexion).

Description of exercises. One of the experimenters demonstrated proper form and technique for each exercise according to guidelines specified by the manufacturer. The seat belt attachment on the machine was fastened around the waist to minimize extraneous movements. Resistance to movement can be regulated by selecting one of six speed settings from a dial on the machine. These settings correspond to six orifice sizes through which hydraulic fluid passes. The diameters of the orifices vary from 0.076 mm (setting 1) to 0.031 mm (setting 6). The dial setting for each exercise in the present study was 3 (0.076 mm orifice for CE and SE and 0.062 mm for LE). The exercises were performed as follows:

Chest exercise (CE). At the start of CE, the handles of the lever arm are held as close as possible to the axillary region just in front of the chest. The back and head remain in contact with the machine's upper body support. The handles are then moved forward as rapidly and forcefully as possible until a full extension position is achieved; the arms are then moved back to the starting position in similar fashion during the flexion phase of the movement.

Shoulder exercise (SE). At the start of SE, the handles of the lever arm are held at shoulder height. The arms are then thrust forcibly upward to full extension and then pulled down with maximal force to the starting position. The head and back are kept in contact with the upper body support.

Leg exercise (LE). At the start of LE, the arms hang vertically and grasp the underside of the bench to help secure the body to the machine. The head and back remain in contact with the upper body support. The ankles of both legs fit between ankle pads, with care taken to position the middle of the knee in line with the pivot of the lever arm. To initiate movement, both legs are fully extended with maximum effort from an initial angular position at the knee of approximately 90° and then flexed with maximum effort back to the starting position.

Each subject performed the maximum number of repetitions possible within a 20-s time interval. To count as one complete repetition, the exercise had to be performed as specified in the instructions. Repetitions were determined by visual observation for all exercises. During SE, a microswitch attached to the lever arm verified the visual count. There were never any discrepancies between the visual and microswitch counts.

Sequence of testing. Subjects were tested on four different days; days 1 and 2 were for assessment of body composition and max $\dot{V}O_2$, respectively. On the remaining two days, subjects performed three bouts of CE, SE, or LE, with the sequence of performing exercises on the first day balanced across subjects. Body weight was measured on each day prior to testing. During the final 2 min of a 12-min rest period on the exercise apparatus, heart rate (HR) and gas exchange measurements ($\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}_E$) were obtained. Subjects then performed a given bout of exercise for 20 s followed by a 20-s rest interval. This sequence of 20 s exercise, 20 s rest was repeated three times for each of the exercise stations. There was a 5-min rest (no exercise) until the next series of three exercise bouts was performed. Subjects were instructed to perform maximally ("all out") for each repetition on all exercises. Strong verbal encouragement was given to exhort subjects to exert maximum muscular effort on each repetition.

Max $\dot{V}O_2$ test. Max $\dot{V}O_2$ was assessed on a Monark cycle ergometer. Pedalling rate was 60 rpm paced by a calibrated auditory-visual metronome; pedal rpms were counted electronically from a microswitch mounted on the pedal crank. Initial resistance was 1 kp for the first 2 min and 2 kp for the next 2 min. Thereafter, it was increased by 0.5 kp for each succeeding 3-min interval until subjects would no longer continue. This protocol is essentially the same as that described in a prior report (13). To compute max $\dot{V}O_2$, a plot was made of $\dot{V}O_2$ in relation to the actual work performed. The highest of two successive pairs of $\dot{V}O_2$ scores were averaged and designated max $\dot{V}O_2$. For all subjects, this occurred within the last 3 min of the test, even though pedal rpm and, thus, work rate usually declined during the last minute or two of performance.

Gas-exchange measurements. Metabolic measurements were determined by open circuit spirometry with an aliquot bag system for collection of expired air. Subjects breathed through a Rudolph high-velocity, low-resistance valve. Gas samples were collected for 40 s during each exercise/rest bout and expressed on a per-min basis. Expired air was also sampled during minute 5 of the 5-min rest interval between bouts. Expired gas volume was measured electronically as it passed through a turbine transducer into a mixing chamber. The flow transducer generated electronic pulses that were counted and displayed on a digital readout. The transducer was calibrated manually by forcing successive 3-l aliquots through it from a calibrated 3-l syringe at both steady (slow) and pulsatile (fast) flow rates that ranged from 3 to 70 l for 30-s intervals. A 120-l Tissot gasometer was used as the criterion measure to calibrate the transducer by having expired air pass in series from the Tissot through the transducer while a subject ran on a treadmill for 1-h periods at 0° grade and at different incline levels.

For gas analysis, the fractional concentration of the expired air samples were analyzed for O_2 and CO_2 by use of Applied Electrochemistry O_2 and CO_2 analyzers. Both analyzers were calibrated before and following each test with commercially prepared gas mixtures verified by the micro-Scholander technique. Energy expenditure was calculated for each interval as $\text{kcal} \cdot \text{min}^{-1} = \dot{V}O_2\ (\text{l} \cdot \text{min}^{-1}) \times$ caloric equivalent per 1 O_2 at the given R (14). For R-values that exceeded 1.0, the caloric equivalent per l oxygen at an R of 1.0 was used.

Heart rate (HR; beats · min^{-1}). A standard three-lead ECG and strip chart recorder were used to monitor HR continuously during all bouts of hydraulic exercise and the max $\dot{V}O_2$ test. For the analysis, HR was calculated from the last 6 beats of each 20-s bout of hydraulic exercise and the last 5 s of each minute during the max $\dot{V}O_2$ test.

RESULTS

Reliability of repetition number (repN)

To examine the metabolic and cardiovascular response of the three resistive exercises where work time during the performance was held constant, the stability of individual differences was determined for the number of repetitions performed for each exercise. Table 2 shows that the between-day reliability for repN, averaged across bouts for each exercise, was $r = 0.76$ for LE, $r = 0.87$ for CE, and $r = 0.89$ for SE. There were no significant differences between days for corresponding bouts of each exercise ($P > 0.05$). However, repN performed for each exercise (using the average of test and retest), declined slightly across bouts 1 to 3; 1.1 reps (5.7%) during LE, 2.4 reps (11%) during CE, and 2.5 reps (13.9%) during SE.

Reliability of gas exchange measures and heart rate

Oxygen uptake ($\dot{V}O_2$, $l \cdot min^{-1}$). The results in Table 3 illustrate that reliability for $\dot{V}O_2$ ranged from $r = 0.41$ to 0.69 for individual bouts across exercises. For each exercise, the average reliability across bouts was $r = 0.52$ for LE and $r = 0.58$ for CE and SE.

A repeated measures ANOVA (days × bouts × exercise) revealed that for each exercise, there were significant increases in $\dot{V}O_2$ between successive bouts of each exercise ($F = 216.9$; $P < 0.05$). For the exercise × bout interaction ($F = 5.49$; $P < 0.05$), a Tukey post-hoc multiple range test showed that $\dot{V}O_2$ LE and CE (bout 1) were not significantly different. All other between exercise comparisons of $\dot{V}O_2$ for all bouts and exercises were significantly different at $P < 0.05$. In most cases, LE elicited the highest VO_2 response followed by CE and SE.

TABLE 2. Reliability of number of repetitions performed for three bouts of leg, chest, and shoulder exercise.

	Bout 1			Bout 2			Bout 3		
Exercise	Mean	r*	SD	Mean	r	SD	Mean	r	SD
Legs	19.4	.676	5.39	18.8	.827	5.10	18.3	.769	4.80
Chest	21.9	.892	6.50	20.8	.883	5.98	19.5	.834	5.55
Shoulders	18.0	.867	5.59	16.4	.927	5.15	15.5	.863	5.19

* r = reliability coefficient between Day 1 and Day 2 test scores; $r = 0.433$ is significant at $P < 0.05$. Values for mean and SD are averages of Day 1 and Day 2 scores.

TABLE 3. Reliability of respiratory gas exchange and heart rate during three bouts of leg, chest, and shoulder exercise.

Variable	Leg			Chest			Shoulder		
	Mean	r*	SD	Mean	r	SD	Mean	r	SD
Oxygen uptake ($l \cdot min^{-1}$)									
Bout 1	1.17	.414	0.270	1.14	.691	0.263	1.02	.488	0.274
Bout 2	1.96	.595	0.424	1.78	.411	0.375	1.66	.585	0.355
Bout 3	2.10	.560	0.428	1.87	.638	0.323	1.78	.676	0.366
Carbon dioxide ($l \cdot min^{-1}$)									
Bout 1	1.25	.650	0.340	1.25	.812	0.366	1.14	.757	0.363
Bout 2	2.10	.690	0.501	2.05	.495	0.413	1.74	.701	0.428
Bout 3	2.44	.735	0.549	2.35	.783	0.369	2.04	.748	0.474
Ventilation ($l \cdot min^{-1}$)									
Bout 1	42.9	.542	13.84	44.0	.780	16.42	41.1	.717	15.85
Bout 2	60.4	.562	14.20	61.8	.582	16.30	54.3	.830	16.65
Bout 3	68.5	.681	14.62	68.4	.722	14.04	58.3	.810	15.48
Heart rate ($beats \cdot min^{-1}$)									
Bout 1	143.7	.738	11.72	145.5	.798	10.48	139.3	.717	11.43
Bout 2	150.4	.809	12.63	152.5	.886	9.16	147.0	.771	12.81
Bout 3	156.6	.854	12.62	156.2	.698	8.43	152.5	.882	11.87

* r = reliability coefficient between Day 1 and Day 2 test scores; $r = 0.433$ is significant at $P < 0.05$. Values for mean and SD are averages of Day 1 and Day 2 scores. $\dot{V}O_2$, expressed in $ml \cdot kg^{-1}$, is 28.6 (legs), 25.5 (chest), and 24.3 (shoulders). In METs, it is 8.2 (legs), 7.3 (chest), and 6.9 (shoulders).

Heart rate (beats/min). The reliability coefficients for HR averaged across bouts was $r = 0.80$ for legs and $r = 0.79$ for chest and shoulders. With the exception of chest exercise, reliability and, hence, individual differences increased from bout 1 to bout 3 as a function of increasing heart rate. The results of the repeated measures ANOVA showed that the differences in HR between successive exercise bouts were significant for all exercises ($P < 0.05$). The magnitude of the increase in HR from bout 1 to 3 was fairly similar; 12.9 bpm (9.0%) for legs, 10.7 bpm (7.4%) for chest, and 13.2 bpm (9.5%) for shoulders. There were no significant differences in HR between corresponding bouts of the three exercises (exercise × bout interaction: $F = 0.34$). Reliability was higher for HR on each exercise (averaged across bouts) compared to the measures of gas exchange.

DISCUSSION

In this experiment, individuals were asked to perform maximally at one of 6 pre-set resistance settings throughout the range of movement for each repetition. However, there was no way to quantify the total amount of work or power accomplished. The external gauges mounted at eye level did provide immediate visual feedback of force exerted, but these gauges were not useful for quantitative assessment. Thus, any inconsistency in repN or exercise effort could produce low reliability for heart rate and metabolic response, as well as significant differences in the aboslute scores for these variables. In the present study, it was encouraging that reliability for repN ranged from $r = 0.68$ to $r = 0.93$, since fluctuation in maximal effort exercise could have markedly affected concomitant measures of heart rate and gas exchange. For $\dot{V}O_2$, reliability coefficients ranged from $r = 0.41$ to $r = 0.69$; for heart rate, reliability ranged from $r = 0.72$ to $r = 0.89$. These results show that the acute $\dot{V}O_2$ and heart rate responses were consistently stable across days. These findings for $\dot{V}O_2$ are in contrast to data of Wilmore et al. (19), who reported that reliability for $\dot{V}O_2$ and kcal ranged from $r = 0.20$ to r=0.70. The low coefficients were ascribed to decreased interindividual differences in $\dot{V}O_2$ expressed relative to body weight, rather than unstable measurements during circuit exercise.

The peak $\dot{V}O_2$ measured during the three hydraulic exercises were 2.10, 1.87, and 1.78 $l \cdot min^{-1}$ for LE, CE, and SE, respectively. For comparison purposes with the data of others, oxygen consumption and heart rate were expressed relative to maximal values on the cycle ergometer test. For LE, $\dot{V}O_2$ was 57.4%; for CE, it was 51.9%; and $\dot{V}O_2$ for SE was 49.2%. Heart rate was highest during LE (85.4%), followed by heart rate during CE (85.2%) and SE (83.2%). Thus, it can be stated that subjects performed exercise at an average heart rate of 84.6% of HR max, at a corresponding average $\dot{V}O_2$ of 52.8% of the max $\dot{V}O_2$. McArdle and Foglia (12) reported that $\dot{V}O_2$ ranged from 0.43 $l \cdot min^{-1}$ to 0.59 $l \cdot min^{-1}$ during one set of 8 reps for the 2-arm curl, arm and back press, and squat free weight and isometric exercises. Post-exercise $\dot{V}O_2$ was higher during the first minute of recovery (0.84 to 1.27 $l \cdot min^{-1}$) compared to exercise. In terms of energy cost, the peak metabolic intensity was approximately 6 $kcal \cdot min^{-1}$. The highest heart rate occurred during the 2-arm press (134 beats/min or approximately 69% of maximum heart rate using an age-predicted maximum heart rate of 195). Byrd and Barton (2) reported that novice weight lifters had heart rates that averaged 145 beats/min after a 1-h workout, while the heart rate of experienced lifters averaged 152 beats/min.

Wilmore et al. (18) reported that 30 s of circuit exercise performed by men and women on Universal

Gym equipment for three circuits of 10 exercises (performed at 40% of 1 RM) required 70% of max HR and 45% or less of max $\dot{V}O_2$. For circuit exercise performed by five men at 7 stations using Cybex isokinetic equipment at slow speed (60°/s) and fast speed (120°/s) for 3 circuits, 12 reps/set and 30-s interval between sets, heart rate averaged 69% of max HR, and $\dot{V}O_2$, averaged throughout exercise, was 49% of max $\dot{V}O_2$ (3). Energy expenditure, computed in the same manner as in this study, averaged 9.6 and 9.9 $kcal \cdot min^{-1}$ for slow and fast speed circuits, respectively.

A recent study by Hempel and Wells (9) evaluated the energy expenditure of circuit exercise using Nautilus equipment. For the 16 male subjects, $\dot{V}O_2$ corresponded to 35.9% of max $\dot{V}O_2$, and heart rate averaged 71.7% of max heart rate.

Table 4 compares the pertinent data of the present study with results from the literature that have evaluated various forms of resistance exercise relative to heart rate and metabolic response. These comparisons show that the three exercises performed on the hydraulic equipment produce greater metabolic and heart rate responses than exercise performed isometrically and with free weights (12) or typical circuit exercise workouts on Universal Gym (19) or Nautilus equipment (9, 11). This is true even when the average response based on the three exercises is used as the frame of comparison.

The caloric expenditure for the three hydraulic exercises averaged 37.7 kJ (9.0 $kcal \cdot min^{-1}$); this is approxmately 35% higher than exercise with free weights (12), 29.4% greater than the average kJ based on two studies using Nautilus (9, 11), and 11.5% higher kcal than circuit exercise with Universal equipment (19). The energy expenditure values in the present study averaged 8.9% less than slow and fast speed isokinetic circuit exercise (3). It seems reasonable that differences in kcal (and associated physiological measurements) between the present results and other studies of circuit exercise are due in part to methodological differences. We have reported values associated with each bout of exercise (and the average) in contrast to an average value determined throughout circuit exercise.

TABLE 4. Comparison of maximal physiological response to resistive exercise.†

Study	Mode	Sex	% Max$\dot{V}O_2$†	% Max HR	kJ	kcal
Hempel (9)	Nautilus, Circuit	M	35.9	71.7	29.7	7.1
		F	38.3	76.1	24.3	5.8
Liverman (11)	Nautilus, Circuit	M	—	—	22.6	5.4
Wilmore (18)	Universal, Circuit	M	41.4	78.2	33.1	7.9
		F	46.8	87.6	28.5	6.8
Gettman (3)	Isokinetic, slow	M	49.0	69.0	40.2	9.6
	Isokinetic, fast				41.4	9.9
McArdle (13)	Isometric, free weights	M	—	69.0‡	25.1	6.0
Present Study	Hydraulic	M	52.8	84.6	37.7	9.0

† Based on a body weight of 68.03 kg (150 pounds).
‡ Estimated from age-predicted max HR of 195 beats.

Although the reliability of individual differences in work performance (reps) was only moderate, it was high enough to provide for consistency across days in the physiological response to maximal effort exercise. The use of on-line analog to digital devices interfaced with a microcomputer would provide two important advances with this type of equipment: (1) feedback to the user regarding effort (e.g., time to peak effort, average work and power, total work and power, and work and power expressed relative to range of motion), and (2) quantification for precise evaluation and comparison with other modalities of resistance exercise.

The results of the present study demonstrate that exercise performed on a 3-station hydraulic resistance apparatus produces reliable individual differences in repN, heart rate, and associated respiratory gas measurements. The magnitude of the average heart rate and metabolic response patterns with maximal effort hydraulic exercise is in the range recommended by the American College of Sports Medicine to promote improvements in cardiorespiratory fitness (1). When energy expenditure is expressed in the MET classification scheme for defining exercise intensity, the MET level averages approximatly 7.5, which would be considered heavy intensity exercise.

A description of the Total Power apparatus is available from the manufacturers: Hydra-Fitness Industries, 2121 Industrial Park Road, Belton, TX 76513. This study was supported by a grant from Hydra-Fitness Industries to the Department of Exercise Science, University of Massachusetts, Amherst, MA.

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Frank I. Katch and Patty S. Freedson are Fellows of the American College of Sports Medicine.

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REFERENCES

1. American College of Sports Medicine. Position statement on the recommended quantity and quality of exercise for developing and maintaining fitness in healthy adults. *Med. Sci. Sports* 103:1978.
2. Byrd, B. and D. Barton. Heart rate response to normal weight lifting workouts of novices and experienced lifters. *J. Phys. Educ.* 7:24–26, 1973.
3. Gettman, L. The aerobic cost of isokinetic slow and fast speed circuit training programs. *Abstracts of Research Papers.* Washington, DC: American Association, Health, Physical Education, Recreation, and Dance, 1978, p. 31.
4. Gettman, L. R., J. J. Ayres, M. L. Pollock, L. Pollock, and A. Jackson. The effect of circuit weight training on strength, cardiorespiratory function, and body composition of adult men. *Med. Sci. Sports* 10: 171–176, 1978.
5. Gettman, L. R., J. J. Ayres, M. L. Pollock, L. Durstine, and W. Grantham. Physiologic effects on adult men of circuit strength training and jogging. *Arch. Phys. Med. Rehab.* 60:115–120, 1979.
6. Gettman, L. R., L. A. Culter, and T. A. Strathman. Physio-

logic changes after 20 weeks of isotonic vs isokinetic circuit training. *J. Med. Phys. Fitness.* 20:265–274, 1980.
7. GETTMAN, L. R., P. WARD, and R. D. HAGAN. A comparison of combined running and weight training with circuit weight training. *Med. Sci. Sports Exerc.* 14:229–234, 1982.
8. GIRANDOLA, R. N. and V. L. KATCH. Effects of nine weeks of physical training on aerobic capacity and body composition in college men. *Arch. Phys. Med. Rehab.* 54:521–524, 1973.
9. HEMPEL, L. S. and C. L. WELLS. Oxygen utilization during performance of the 20-minute nautilus express circuit. *Med. Sci. Sports Exerc.* 15: 169, 1983.
10. LARSSON, L. Physical training effects on muscle morphology in sedentary males at different ages. *Med. Sci. Sports Exerc.* 14:203–206, 1982.
11. LIVERMAN, R. D. and C. GRODEN. Metabolic analysis of high intensity weight training. *Med. Sci. Sports Exerc.* 14:169, 1982.
12. MCARDLE, W. D. and G. F. FOGLIA. Energy cost and cardiorespiratory stress of isometric and weight training exercises. *J. Sports Med. Phys. Fitness* 9:23–29, 1969
13. MCARDLE, W. D., F. I. KATCH, and G. S. PECHAR. Comparison of continuous and discontinuous treadmill and bicycle tests for max $\dot{V}O_2$. *Med. Sci. Sports* 5:156–160, 1973.
14. MCARDLE, W. D., F. I. KATCH, and V. L. KATCH. *Exercise Physiology. Energy, Nutrition and Human Performance.* Philadelphia: Lea and Febiger, 1981, pp. 374–376, 101, 485.
15. SIRI, W. E. Body composition from fluid spaces and density. In: *Techniques for Measuring Body Composition.* Washington, DC: National Academy of Sciences-National Research Council, 1961, pp. 223–244.
16. WILMORE, J. H. A simplified method for determining residual lung volume. *J. Appl. Physiol.* 27:96–100, 1969.
17. WILMORE, J. H. Alterations in strength, body composition and anthropometric measurements consequent to a 10-week training program. *Med. Sci. Sports* 6:133–138, 1974.
18. WILMORE, J. H., R. B. PARR, and R. N. GIRANDOLA. Physiological alterations consequent to circuit weight training. *Med. Sci. Sports* 10:79–84, 1978.
19. WILMORE, J. H., R. PARR, and P. WARD. Energy cost of circuit weight training. *Med. Sci. Sports* 10:75–78, 1978.