Concurrent Training Enhances Athletes' Strength, Muscle Endurance, and Other Measures

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Abstract

Davis, WJ, Wood, DT, Andrews, RG, Elkind, LM, and Davis, WB. Concurrent training enhances athletes' strength, muscle endurance, and other measures. *J Strength Cond Res* 22(5): 1487–1502, 2008—We evaluated the effects of concurrent strength and aerobic endurance training on muscle strength and endurance, body composition, and flexibility in female college athletes and compared two concurrent exercise (CE) protocols. Twenty-eight women (mean age, 19.6 years) were divided into two matched groups and evaluated before and after a vigorous, 11-week, 3-days per week CE training program. One group did serial CE consisting of a warm-up, resistance exercises at low heart rate (HR), aerobics, and a range of motion cool down. The other group did integrated CE consisting of aerobics, the same resistance exercises at high HR achieved by cardioacceleration before each set, and the same range of motion cool down. The two protocols were balanced, differing only in the timing and sequence of exercises. Serial CE produced discernible ($p < 0.05$) increases in lower- (17.2%) and upper- (19.0%) body muscle strength and fat-free mass (FFM) (1.8%) and trends toward greater lower-body muscle endurance (18.2%) and reduced upper-body flexibility (−160.4%). Integrated CE produced discernible increases in lower- (23.3%) and upper- (17.8%) body muscle strength, lower-body muscle endurance (27.8%), FFM (3.3%), and lower-body flexibility (8.4%) and a decline in fat mass (−4.5%) and percent body fat (−5.7%). Integrated CE produced discernibly larger gains than serial CE for six of nine training adaptations. Effect sizes were generally moderate (44.4% of discernible differences) to large (33.3%). We conclude that serial CE produces adaptations greater than those reported in the literature for single-mode (strength) training in athletes, whereas integrated CE produces discernibly greater gains than serial CE. The results suggest synergy rather than interference between concurrent strength and aerobic endurance training, support prescription of CE under defined conditions, establish the importance of exercise timing and sequence for CE program outcomes, and document a highly effective athletic training protocol.

Key Words combined, exercise, interference, body composition, flexibility, resistance, aerobic, range of motion, integrated

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22(5)/1487–1502

Journal of Strength and Conditioning Research

Introduction

The compatibility of different exercise modes, particularly strength and aerobic endurance exercise, has been investigated for nearly 3 decades. Several investigators report that combined or concurrent exercise (CE), in which strength and aerobic endurance training are included in the same training sessions or program, interferes with the development of muscle strength or power (19,27,28,39,50,55,57). Reduction in strength adaptations from CE could result from neuromuscular fatigue induced by concurrent aerobic endurance exercise (42,59), which could limit the maximal muscle force that can be produced during resistance training (42,43). A converse reduction in aerobic capacity from concurrent strength and aerobic endurance training has seldom been reported (19,23,27,28,29,32,39 but see 21). The reduction in strength adaptations from concurrent strength and aerobic endurance training has been termed the interference effect, phenomenon, or hypothesis (27,28).

In contrast to interference, several investigators report compatibility of strength and endurance training, i.e., no reduction in strength adaptations from concurrent strength and aerobic endurance training (6,8,21,23,32,33). On the contrary, some have found a positive rather than a neutral or negative effect of CE on muscle strength (22), muscle endurance (29,38), and maximal aerobic capacity (38,47). In sports applications, concurrent training for strength and aerobic endurance has been reported to increase diverse measures of performance in basketball players (8), competitive rowers (26), endurance runners (34), soccer players (36), professional handball players (45), and competitive cyclists (53). These findings suggest that in athletes, at least, concurrent strength and aerobic endurance training has complimentary or synergic effects, rather than the contradictory or antagonistic effects implied by interference.

Clarifying the necessary and sufficient conditions for interference would have implications for medicine, science, sports, and recreational exercise. In medicine, interference or synergy of CE could slow or accelerate, respectively, the recovery of rehabilitating athletes and patients. In science, identifying the cause(s) of interference could help to elucidate the corresponding physiological mechanisms (43), whereas confirmation of synergy could promote research on converse mechanisms. In sports, interference is crucial to exercise physiologists, coaches, trainers, and athletes, who invest substantial time and resources to maximize training adaptations and competitive efficiency. Interference may be especially relevant to the high-intensity training of well-conditioned athletes, because it has been interpreted as an overtraining effect (37,47) that could impede highly trained individuals the most. Confirmation of synergy, in contrast, could lead to more efficient athletic training protocols.

Interference is also significant to recreational exercise, because the possibility has created ambiguity in exercise prescription. Some experts have de-emphasized aerobics in resistance training programs, for example, or recommended performing aerobics last to avoid "draining energy" (20). The authors of a current exercise physiology textbook concluded, "Concurrent resistance and aerobic training programs produce less muscle strength and power improvement than training for strength only." (46) Bodybuilders have portrayed aerobics as counterproductive to resistance training adaptations (58). Conversely, however, several United States national certifying, training, and medical organizations recommend CE to maximize the benefits of exercise at all levels, including the American College of Sports Medicine (ACSM) (4), the American Diabetes Association (ADA) (5), and the National Strength and Conditioning Association (NSCA) (49). These organizations have taken no position, however, on the potential compromises in program outcomes implied by the interference effect.

We therefore tested aspects of the interference hypothesis by evaluating and comparing the training adaptations induced by two forms of CE, serial and integrated. Serial CE is the sequential performance in each training session of different modes of exercise (resistance, aerobics, and range of motion [ROM]) (Figure 1A). Integrated CE is repeated alternation in each training session among different modes of exercise, in which heart rate (HR) is elevated during anaerobic resistance exercise by brief preresistance aerobics (Figure 1B). In the present study, these two protocols were balanced for exercise mode, intensity, duration, and other variables, so that the protocols differed only in the timing and sequence of exercises. Comparing their training adaptations therefore enabled evaluation of the role of exercise timing and sequence in CE training outcomes.

We tested three specific hypotheses related to concurrent training. Hypothesis 1 was that serial CE produces discernible training adaptations in strength, muscle endurance, body composition, and flexibility that are at least equivalent to comparable published adaptations for single-mode (strength) training. Hypothesis 2 was that integrated CE, a more extreme form of concurrent training, produces discernible training adaptations that are at least equivalent to comparable published adaptations for single-mode (strength) training. Hypothesis 3 was that integrated CE produces discernibly greater training adaptations than serial CE. The companion article (16) reports cardiovascular and cardiorespiratory adaptations in the same experiment and cohort.

Methods

Experimental Approach to the Problem

The rationale for Hypothesis 1 (serial CE produces discernible training adaptations at least equivalent to comparable published adaptations single-mode strength training) is the

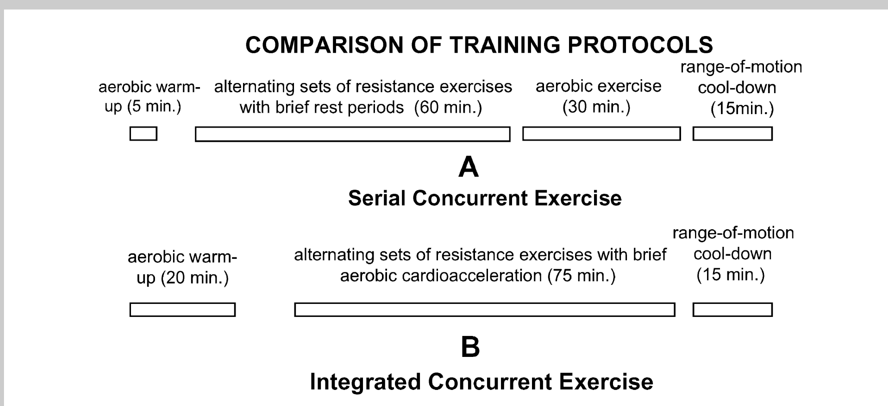

Figure 1. The two training protocols employed in this study, serial concurrent exercise (CE) (*A*) and integrated CE (*B*). The chief difference is that subjects rested before each set of resistance exercises in the serial CE protocol (conventional weight training), whereas in the integrated CE protocol, subjects increased their heart rate by brief cardioacceleration before each set of resistance exercises. The consequent additional amount of aerobic exercise during weightlifting in the integrated CE group was balanced by increasing the duration of the aerobic exercise phase of training in the serial CE group. The length of each *horizontal bar* is proportional to the duration of the corresponding component. The width of spaces between bars is not significant.

observation that well-conditioned athletes participate and develop in sports that demand high aerobic activity, strength and muscle endurance, and repeated explosive physical activity, suggesting that they can tolerate concurrent strength and aerobic endurance exercise and still exhibit positive training adaptations. The rationale for Hypothesis 2 above (integrated CE produces greater training adaptations than comparable published adaptations for single-mode training) is our earlier finding (15) that integrated CE but not serial CE rapidly reduces and eliminates delayed-onset muscle soreness (DOMS), implying faster muscle recovery after exercise (60) and therefore greater responsiveness to strength and muscle endurance training during integrated CE. The rationale for Hypothesis 3 above (integrated CE produces discernibly greater training adaptations than serial CE) is the same as for Hypothesis 2.

To test Hypothesis 1, the null hypothesis (serial CE causes interference) was rejected in favor of the alternative hypothesis (serial CE causes positive training adaptations) if mean posttraining measures after serial CE were discernibly greater than pretraining values at $p < 0.05$, effect sizes (ES) were at least moderate, and gains were at least comparable to published adaptations for strength training in athletes. To test Hypothesis 2, the null hypothesis (integrated CE causes interference) was rejected in favor of the alternative hypothesis (integrated CE causes synergistic adaptations) if mean posttraining measures after integrated CE were discernibly greater than pretraining values at $p < 0.05$, ES were at least moderate, and gains exceeded comparable gains reported for strength training in athletes. To test Hypothesis 3, the null hypothesis (integrated CE does not cause greater training adaptations than serial CE) was rejected in favor of the alternative hypothesis (integrated CE causes greater training adaptations than serial CE) if mean training adaptations in the integrated CE group were discernibly larger than those of serial CE group, and ES were at least moderate.

To test these three hypotheses, a prospective, matched-pairs, randomized, double-blind experimental design was used to compare the training adaptations of serial CE and integrated CE with each other and with published adaptations from single-mode (strength) training. Nine training variables related to strength, muscle endurance, body composition, and flexibility were measured and compared before and after an 11-week training program in serial CE and integrated CE. Well-conditioned college athletes were recruited as subjects in part because interference has been interpreted as an overtraining effect (39,47), to which highly trained individuals may be more susceptible. Using well-conditioned athletes as subjects therefore provides a potentially stronger test of the interference hypothesis. Our results are from the same experiment and cohort of college athletes described in our previous study on DOMS in men and women athletes (15). In the present report, we describe training adaptations related to muscle strength, muscle endurance, body composition, and flexibility in the much larger sample of women athletes.

A design limitation of this study was the absence of a control group for strength training alone; instead, we compared training adaptations obtained herein from CE with comparable published strength-training adaptations in athletes. As a consequence of this limitation, the present results bear more on the interference hypothesis and less on comparing concurrent training adaptations with single-mode (strength) training adaptations.

Subjects

Subjects were healthy, generally asymptomatic, well-conditioned women undergraduate college athletes aged 18–22 years (mean, 19.6 years) recruited from university sport teams (86% soccer, 14% volleyball). The university's institutional review board evaluated and approved all aspects of this research program before implementation. Each subject signed a witnessed informed consent statement describing risks, benefits, and responsibilities of participation, and the option to withdraw at any time without prejudice. All subjects undertook cardiovascular risk stratification (4) and exhibited no more than one risk factor for coronary artery disease. Of the 28 subjects, three reported an asthma condition that was controlled with Albuterol and participated in the experiment with medical clearance and without incident.

After subjects were matched in pairs and divided into serial and integrated CE groups as described below ($n = 14$ for serial CE and integrated CE), the mean demographics of the two groups were compared (mean ± *SEM*) using the two-tailed Wilcoxon matched-pairs sign-ranked test. The serial and integrated CE groups did not differ discernibly in age (19.7 ± 0.3 and 19.4 ± 0.2 years, respectively), weight (65.8 ± 2.5 and 60.9 ± 2.6 kg), height (163.7 ± 2.9 and 163.8 ± 1.1 cm), or estimated maximal aerobic capacity ($\dot{V}O_2max$) (46.6 ± 1.2 and 47.0 ± 2.4 $mL \cdot kg \cdot min^{-1}$) ($p = 0.11–0.65$) (15).

Procedures

Procedures included pretraining instruction and assessments, training, and posttraining assessments and debriefing. All subjects received uniform pretraining group instruction in the nine resistance exercises performed during testing and training, followed by individual feedback in correct form. Resistance exercises were performed in the following sequence during testing and training: seated inclined bilateral leg press, seated bilateral leg (knee) extension, seated bilateral leg (knee) flexion, front lat pull-down, flat bench press, overhead (shoulder) press, arm (biceps) curl, and triceps kickback. Weighted abdominal curl-ups (crunches) on an inclined bench were performed as the final exercise during training, but this exercise was not assessed during testing because of the difficulty and risks of measuring one-repetition maximum (1-RM) accurately. Subjects used a 4-second duty cycle during resistance exercises (2 seconds concentric, 2 seconds eccentric). All subjects were instructed uniformly in the use of Borg's Category-Ratio Rating of Perceived Pain

(RPP) and Rating of Perceived Exertion (RPE) scales (10) to regulate progression during resistance training (15), using the recommended instructional language (4,10).

Pretraining assessments included: (a) a screening test for physical fitness, in which all subjects completed 60 minutes of vigorous aerobic exercise (treadmill running or elliptical trainer) in two 30-minute blocks separated by a 5-minute rest at 60–84% of HR reserve (HRR), calculated using the Karvonen method (4), with a RPE no greater than "strong" and a RPP no greater than "weak." (b) Muscle strength, assessed as the 1-RM weight for each of the first eight resistance exercises listed above. (c) Muscle endurance, assessed as the number of repetitions to failure at 50% of 1-RM weight for the same eight resistance exercises. (d) Maximal aerobic capacity ($\dot{V}O_2max$), estimated using a graded exercise test (4) and automated with a Technogym treadmill (The Technogym Wellness Company, Gambettola, Italy). (e) Body composition (fat-free mass [FFM] and fat mass [FM]), calculated from seven-site skinfold measurements (abdominal, triceps, chest/pectoral, midaxillary, subscapular, suprailiac, and thigh) (4) using two or three measurements per site (88% and 12% of skinfold data points, respectively) and the seven-site equation for women (4). (f) Lower-body flexibility (hamstrings and trunk), assessed using the YMCA sit-and-reach test (best of two measurements) (4). and (g) Upper-body flexibility (shoulder and arms), assessed with the two-armed "back-scratch" test, using the mean of two measurements (left arm up/right arm down, left arm down/right arm up) (4). Formats, procedures, and equations recommended by the ACSM (4) were employed wherever applicable.

A matched-pairs design based on initial physical condition was implemented to avoid complications from nonlinear training adaptations that result from the well-known inverse relationship between training adaptations and physical condition (2,6,7,24,25). To create matched groups, subjects were first ranked by three criteria: muscle strength (1-RM) normalized to body weight$^{2/3}$ for all eight resistance exercises, muscle endurance (repetitions to failure at 50% of 1-RM) for all eight exercises, and estimated maximal aerobic capacity. From these three separate rank listings, a mean ranked list was prepared, and adjacent subjects on the list were defined as matched pairs. Members of each matched pair were then assigned to either the serial CE group or the integrated CE group by a random process (coin flip). This matching procedure ensured similar starting points for the serial CE group and integrated CE group, validating between-group comparisons and enabling more powerful matched-pairs statistical tests.

Both groups then participated in an 11-week training program entailing vigorous training 3 days per week consisting of concurrent aerobic, resistance, and ROM exercise. Each subject wore a Polar A-5 HR transmitter and wrist receiver during training sessions to observe instantaneous HR, adjust aerobic work rate according to the experimental design, and store mean HR data for later recording. Subjects used purpose-designed workout logs (14) to record exercise data, including mean HR during the aerobic and resistance phases of each training session, weights and repetitions for resistance exercises, water intake, and RPP and RPE data for each resistance exercise, which were used to regulate progression during resistance training following methodology detailed elsewhere (15).

The serial CE group (Figure 1A) began each training session with a 5-minute aerobic warm-up in which subjects increased their HR into the range corresponding to vigorous intensity exercise, 60–84% of HRR (4). The warm-up was abbreviated to facilitate rapid HR recovery in these well-conditioned athletes during subsequent resistance exercises and therefore enable serial CE subjects to maintain a lower HR during resistance training. Serial CE subjects then performed resistance exercises consisting of three sets each of the nine resistance exercises previously identified in the sequence listed. Immediately before every set of resistance exercises, serial CE subjects rested briefly (0.5–1 minute) in a seated position to maintain HR during resistance training in the range corresponding to light intensity exercise, 20–39% of HRR (4). The mean HR of the serial CE group during resistance training, calculated from HR data recorded during the resistance training phase of each training session, was 31.9% ± 0.4% HRR, corresponding to 107.9 ± 0.5 b·min^{-1} (15). Resistance training in the serial CE group was followed by 30 minutes of vigorous aerobic exercise and a cool down consisting of 12 basic ROM exercises (14).

The integrated CE group (Figure 1B) did the same types, volume, and intensity of exercise, but used different exercise timing and sequences designed to support an increased HR during resistance training. Integrated CE subjects began each training session with 20 minutes of vigorous aerobic exercise. The warm-up was prolonged to accelerate HR responses and limit HR recovery in these well-conditioned athletes during subsequent resistance training and therefore enable integrated CE subjects to perform resistance exercises at an increased HR. Integrated CE subjects then performed the same nine resistance exercises in the same sequence as serial CE subjects. Immediately before every set of resistance exercises, integrated CE subjects performed brief (0.5–1 minutes), vigorous aerobic exercise (generally treadmill running) at an intensity sufficient to increase HR to the upper boundary of vigorous exercise and therefore maintain HR in the vigorous range during the immediately subsequent set of resistance exercises. The mean HR of the integrated CE group during resistance training was 64.8% ± 0.3% HRR, corresponding to 151.1 ± 0.4 b·min^{-1}, discernibly larger than the corresponding mean of the serial CE group (Wilcoxon test, $n = 13$, $p = 0.0007$) (15). The realized HR of integrated CE subjects during sets of resistance exercises was approximately 10% higher than the above mean because HR was recorded continuously during 1 hour of resistance training, peaking during and immediately after preresistance cardioacceleration, and declining during and after each set of most resistance exercises. The integrated CE group concluded each training session with the same ROM cool down as the serial CE group.

Several control and monitoring procedures and tests were implemented to minimize extraneous variance in both groups and help to validate between-group comparisons. Serial and integrated protocols were equilibrated for exercise modes, i.e., both groups performed the same aerobic, resistance, and ROM exercises. Both groups also performed the same volume, intensity, and duration of each mode of exercise, and training sessions were the same duration (approximately 1.8 hours). Both groups began resistance training with the same relative weights (50% of 1-RM for each exercise) and used the same number of sets (three), initial repetitions (eight), and maximal repetitions (twelve). Both groups utilized the same method of progression during resistance training, increasing weight rapidly in the first few training sessions to reach individual capacities, then progressing based on minimizing RPP ("weak" or less) while optimizing RPE ("strong" or less) for each exercise (15). Both groups exercised on different floors of the same training facility during the same morning hours (6–10 AM) of the same days (Tuesday, Thursday, and Saturday) to eliminate diurnal and other variances. Training sessions for athletes began at 5-minute intervals, and each athlete began training at the same time to minimize variance associated with different starting times. Supervising trainers alternated between the serial CE and integrated CE groups several times per training session to preclude differential training effects or motivational influences.

To assess extraneous variance between serial CE and integrated CE groups, several variables were calculated for the two groups and compared at the end of the training period. The serial CE and integrated CE group did not differ discernibly in mean exercise compliance (percent of training sessions attended, 84.6% ± 2.6% and 81.8% ± 3.0%, respectively), mean water consumption per training session (1.0 ± 0.1 L and 1.2 ± 0.1 L), mean RPE reported for individual resistance exercises (5.1 ± 0.1 and 5.1 ± 0.1), or mean non-DOMS pain during resistance exercises (0.6 ± 0.2 and 0.6 ± 0.2) (two-tailed Wilcoxon tests, $p = 0.11–0.86$) (15). These procedures and tests helped to ensure that the only significant differences between the serial CE and integrated CE protocol were the timing and sequence of different modes of exercise and mean heart rate during resistance exercise.

After the 11-week CE program, the same measurements of muscle strength, muscle endurance, body composition, and flexibility that were made before training were repeated by the same investigators in the same sequence and following the same standardized test protocols (4). Subjects then completed a written evaluation of the training program, which contained an embedded question asking the purpose of the experiment. No subject answered this question correctly, indicating that the experimental protocol was blind. All pretraining data and more than 95% of posttraining data were collected by personnel who did not know whether the subject belonged to the serial or integrated CE group. The sole exception was the leg press, for which posttraining assessments of 1-RM and muscle endurance were made by personnel who knew the group identity of subjects. These measurements comprised less than 5% of all data, and the experimental design was therefore effectively double-blind.

Statistical Analyses

Data were entered into prepared electronic spreadsheets (Microsoft Excel®) and confirmed by trained personnel before statistical analysis and graphical display. The Wilcoxon test was generally used to compare means. The back-scratch test for upper body flexibility yielded several cases of zero hand separation in both members of matched pairs, rendering a matched-pairs sign-ranked test infeasible. Student's t-test (two-sample unequal variance) was therefore used to evaluate upper-body flexibility data. FM was analyzed using two-tailed tests because subjects consumed an ad libitum diet and we had no a priori hypothesis regarding the direction of possible changes in FM. Directional (one-tailed) tests were used to evaluate mean percent body fat and FFM because we hypothesized a priori that FFM would increase in response to concurrent training and reduce the percent body fat. Results are reported as the mean ± *SEM*. Hypotheses were accepted at $p < 0.05$ using one-tailed tests unless otherwise indicated, whereas p values between 0.05 and 0.10 are described as a trend. p values are reported to enable critical evaluations of differences. Data from some subjects and tests were missing because of absences, illness, or other contingencies, requiring post hoc rematching of subjects based on initial physical condition. Sample sizes therefore varied and are reported separately for each test conducted. ES was calculated using the standard mean difference method (56). Qualitative descriptors for quantitative ES ranges follow recommendations (56) for highly trained individuals (ES < 0.25 "trivial;" 0.25–0.50 "small;" 0.50–1.0 "moderate;" and ES > 1.0 "large").

Results

The mean pretraining values of all variables evaluated in this study were not discernibly different between serial CE and integrated CE groups (Wilcoxon test, $p > 0.10$). Therefore, serial CE and integrated CE groups began training at the same starting point, as would be expected from matching subjects initially on the basis of physical condition.

Muscle Strength

Mean lower-body muscle strength was evaluated by summing the 1-RM weights for the corresponding three exercises (leg press, leg extension, and leg flexion) and analyzed by comparing pretraining with posttraining means in each group (serial CE and integrated CE). Mean lower-body strength in the serial CE group increased by 17.2% during the 11-week training program (Figure 2 A and C).

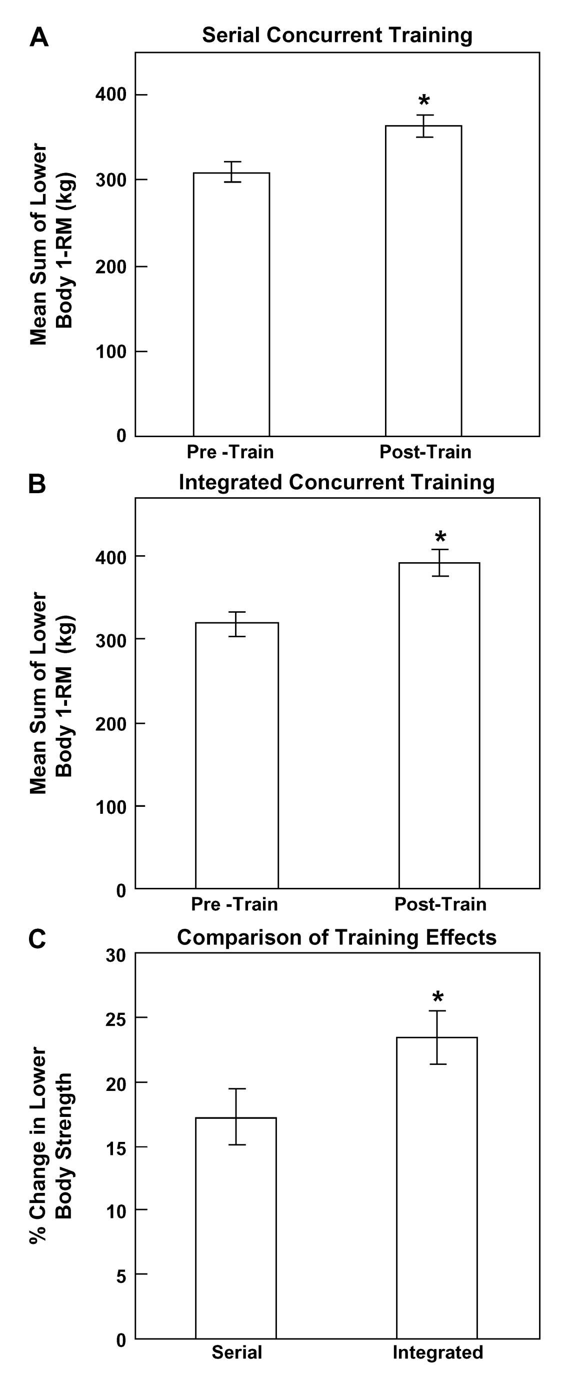

Figure 2. Mean lower-body muscle strength, assessed as the sum of one-repetition maximum weight for three lower-body exercises (leg press, leg extension, and leg curl) before (Pre-Train) and after (Post-Train) a vigorous 11-week concurrent exercise (CE) training program. *A*, serial CE group; *B*, integrated CE group; C, comparison of serial CE and integrated CE groups. *Error bars* represent 2 *SEM*. *Discernible differences between pre and post means (*A* and *B*) or between serial CE and integrated CE (*C*) at $p < 0.05$.

The posttraining mean was discernibly larger than the pretraining mean (Wilcoxon test, $n = 14$, $p = 0.0005$), and ES was large (1.16). Mean lower body strength in the integrated CE group increased by 23.3% (Figure 2 B and C). The posttraining mean was discernibly larger than the pretraining mean (Wilcoxon test, $n = 13$, $p = 0.0007$), and ES was large (1.44). Integrated CE therefore yielded a 35.4% greater mean gain in lower-body strength than serial CE (Figure 2C), discernibly larger (Wilcoxon test, $n = 13$, $p = 0.043$), and ES was moderate (0.54).

Mean upper-body strength (the sum of 1-RM weight for the lat pull-down, bench press, overhead press, arm curl, and triceps kickback) in the serial CE group increased during the 11-week training program by 19.0% (Figure 3 A and C). The posttraining mean was discernibly larger than the pretraining mean (Wilcoxon test, $n = 13$, $p = 0.0009$), and ES was large (1.38). Mean upper-body strength in the integrated CE group increased by 17.8% (Figure 3 B and C). The posttraining mean was discernibly larger than the pretraining mean (Wilcoxon test, $n = 13$, $p = 0.0007$), and ES was large (2.13). Serial CE therefore produced a 5.9% greater gain in mean upper-body strength than integrated CE (Figure 3C), which was not discernibly different (Wilcoxon test, $n = 12$, $p = 0.32$).

Muscle Endurance

Mean lower-body muscle endurance was determined by comparing the number of leg press repetitions to failure at 50% of 1-RM weight before and after training in each group. Mean leg press endurance in the serial CE group increased over the 11-week training program by 18.2% (Figure 4 A and C). There was a trend toward a greater posttraining endurance (Wilcoxon test, $n = 13$, $p = 0.098$), and ES was moderate (0.60). Mean leg press endurance in the integrated CE group increased by 27.8% (Figure 4 B and C). The posttraining mean was discernibly larger than the pretraining mean (Wilcoxon test, $n = 14$, $p = 0.011$), and ES was moderate (0.95). Integrated CE therefore produced a 52.8% greater mean gain in leg press muscle endurance than serial CE (Figure 4C), discernibly larger when the most extreme outlier pair was excluded from the analysis (Wilcoxon test, $n = 12$, $p = 0.042$), and ES was moderate (0.51). For the excluded outlier, the serial CE subject showed an anomalous 128% gain in leg press muscle endurance.

Mean upper-body muscle endurance (the sum of repetitions to failure at 50% of 1-RM weight for five exercises: lat pull-down, bench press, overhead press, arm curl, and triceps kickback) in the serial CE group increased over the 11-week training program by 9.6% (Figure 5 A and C). The posttraining mean was not discernibly larger than the pretraining mean (Wilcoxon test, $n = 13$, $p = 0.49$). Mean upper-body endurance in the integrated CE group increased over the 11-week training program by 5.2% (Figure 5 B and C). The posttraining mean was again not discernibly larger than the pretraining mean (Wilcoxon test, $n = 13$, $p = 0.39$). Integrated CE produced a 42.3% smaller mean gain in

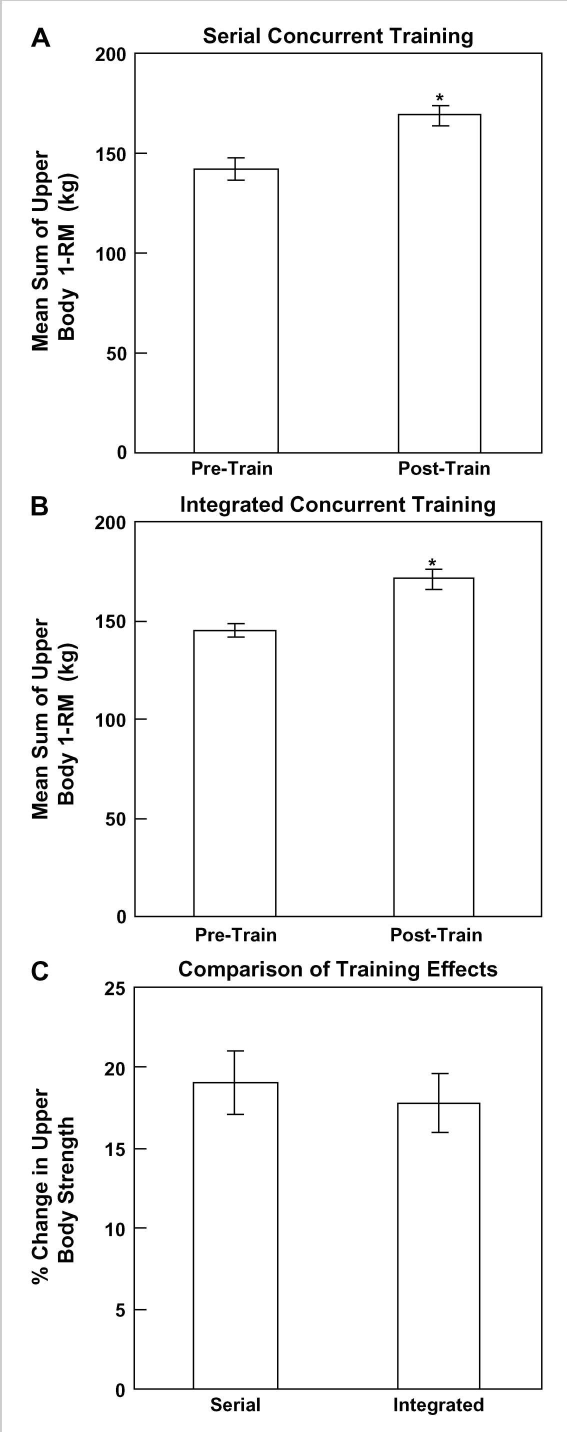

Figure 3. Mean upper-body muscle strength, assessed as the sum of one-repetition maximum weight for five upper-body exercises (lat pull-down, bench press, overhead press, arm curls, and triceps kickback) before (Pre-Train) and after (Post-Train) training. *Error bars* represent 2 *SEM*. *Discernible differences between pre and post means (*A* and *B*) or between serial CE and integrated CE (*C*) at $p < 0.05$.

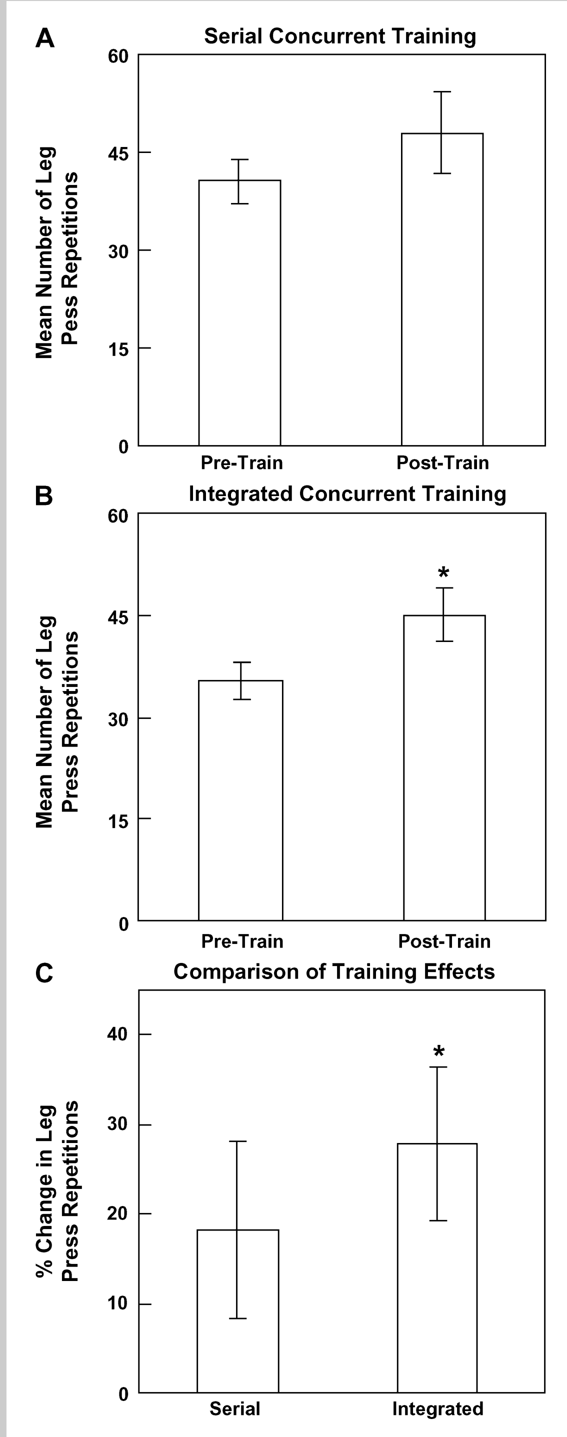

Figure 4. Mean leg press muscle endurance before (Pre-Train) and after (Post-Train) concurrent exercise training. *Error bars* represent 2 *SEM*. *Discernible differences between pre and post means (*A* and *B*) or between serial CE and integrated CE (*C*) at $p < 0.05$.

upper-body muscle endurance than serial CE (Figure 5C), but the corresponding means were not discernibly different (Wilcoxon test, $n = 13$, $p = 0.46$).

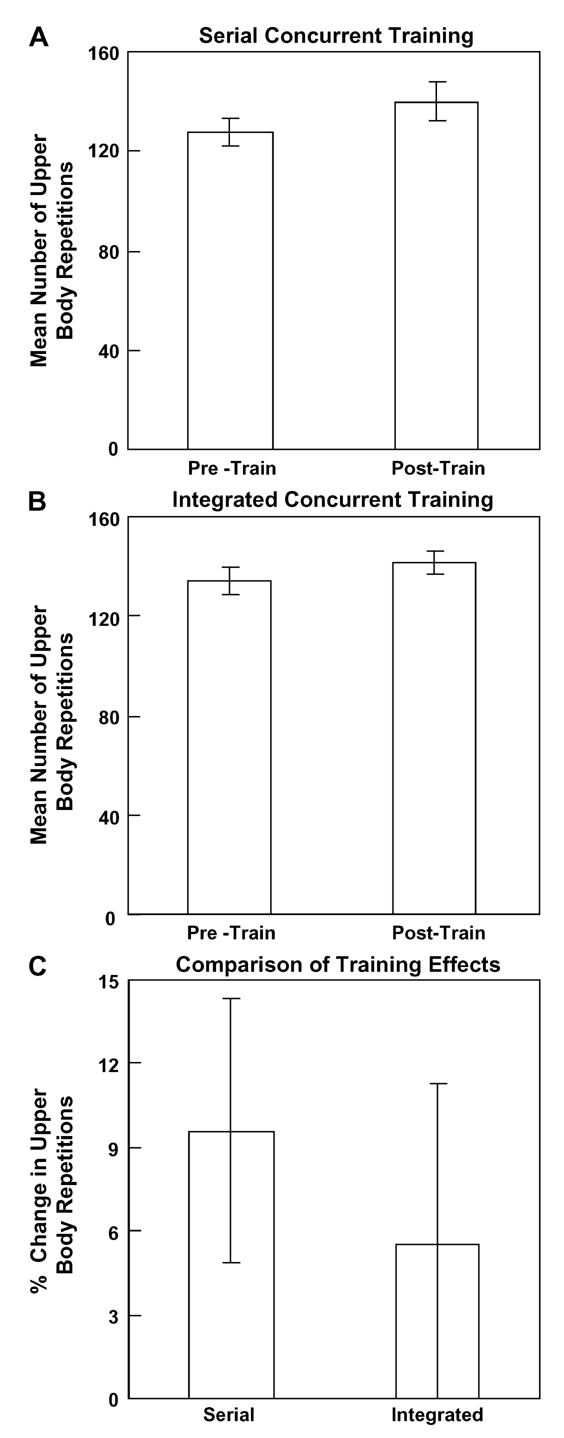

Figure 5. Mean upper-body muscle endurance before (Pre-Train) and after (Post-Train) concurrent exercise training. *Error bars* represent 2 *SEM*. *Discernible differences between pre and post means (*A* and *B*) or between serial CE and integrated CE (*C*) at $p < 0.05$.

Body Composition

Mean FFM increased in the serial CE group over the 11-week training program by 0.85 kg per athlete, or 1.8% (Figure 6 A and C). The posttraining mean was discernibly larger than the pretraining mean (Wilcoxon test, $n = 13$, $p = 0.036$), but ES was trivial (0.10). Mean FFM in the integrated CE

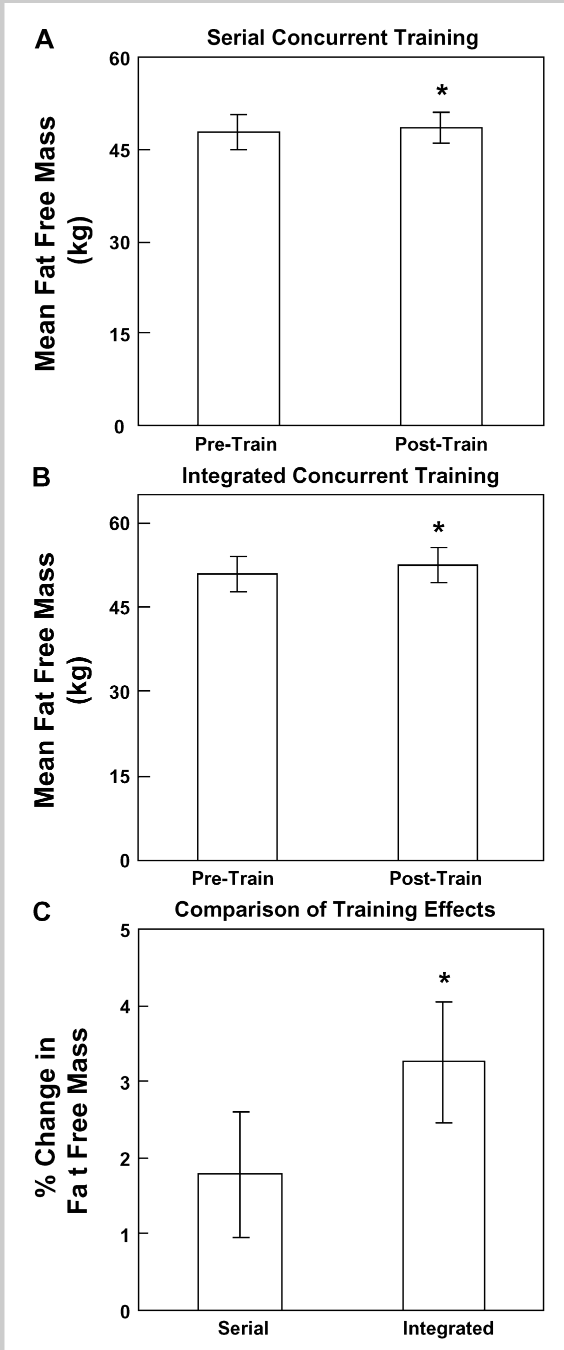

Figure 6. Mean fat-free mass (FFM) before (Pre-Train) and after (Post-Train) concurrent exercise training. *Error bars* represent 2 *SEM*. *Discernible differences between pre and post means (*A* and *B*) or between serial CE and integrated CE (*C*) at $p < 0.05$.

group increased by nearly twice the serial CE mean, 1.66 kg per athlete, or 3.3% (Figure 6 B and C). The posttraining mean was discernibly larger than the pretraining mean (two-tailed Wilcoxon test, $n = 13$, $p = 0.00007$), and ES was small (0.44). Integrated CE therefore produced a mean gain in FFM 82.2% greater than serial CE (Figure 6C), discernibly larger (Wilcoxon test, $n = 13$, $p = 0.01$), and ES was large (1.05).

Mean FM in the serial CE group over the 11-week training program increased by 0.07 kg per athlete, or 0.5% (Figure 7 A and C). The posttraining mean was not discernibly different from the pretraining mean (two-tailed Wilcoxon test, $n = 13$, $p = 0.64$). Mean FM in the integrated CE group decreased by 0.73 kg, or 4.5% (Figure 7 B and C). The posttraining mean was discernibly smaller (two-tailed Wilcoxon test, $n = 13$, $p = 0.046$), and ES was small (0.40). Integrated CE therefore produced a 991.8% greater loss of FM than serial CE (Figure 7C), discernibly larger when the most extreme outlier pair was excluded from the analysis (two-tailed test, $n = 12$, $p = 0.018$), and ES was moderate (0.75). For this most extreme outlier pair, the serial CE subject showed an anomalous 19.0% decline in FM, whereas the matched integrated CE subject showed an anomalous 17.6% increase in FM.

Mean percent body fat (%BF) decreased in the serial CE group over the 11-week training program by 1.1% (Figure 8 A and C) because of these changes in FFM and FM. The posttraining mean was not discernibly smaller than the pretraining mean (Wilcoxon test, $n = 13$, $p = 0.43$). Mean %BF in the integrated CE group decreased by 5.7% (Figure 8 B and C). The posttraining mean was discernibly smaller than the pretraining mean (Wilcoxon test, $n = 13$, $p = 0.032$), and ES was small (0.41). Integrated CE therefore yielded a 438.7% greater decrease in %BF fat than serial CE (Figure 8C), discernibly larger when the most extreme outlier pair was excluded from the analysis (Wilcoxon test, $n = 12$, $p = 0.042$), and ES was large (1.02). This most extreme outlier pair was the same pair excluded in the analysis of FM; the serial CE subject showed an anomalous 19.0% decline in %BF, whereas the matched integrated CE subject showed an anomalous 13.1% increase in %BF.

Flexibility

Lower-body flexibility was assessed using the YMCA sit-and-reach test. Mean sit-and-reach distance in the serial CE group increased over the 11-week training program by 6.5% (Figure 9 A and C). The posttraining mean was not discernibly larger than the pretraining mean (Wilcoxon test, $n = 14$, $p = 0.11$). Mean sit-and-reach distance in the integrated CE group increased by 8.4% (Figure 9 B and C). The posttraining mean was discernibly larger than the pretraining mean (Wilcoxon test, $n = 13$, $p = 0.012$), and ES was moderate (0.72). Integrated CE produced a 28.0% greater increase in mean reach distance than serial CE (Figure 9C), not discernibly larger (Wilcoxon test, $n = 13$, $p = 0.28$).

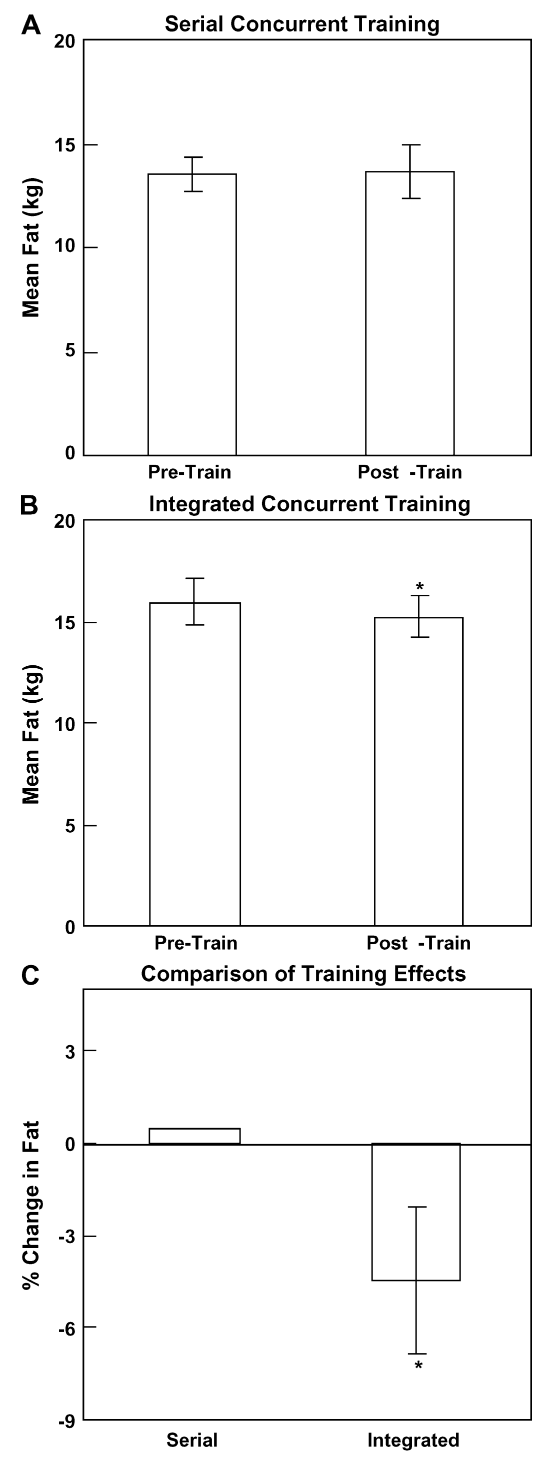

Figure 7. Mean fat mass before (Pre-Train) and after (Post-Train) concurrent exercise training. *Error bars* represent 2 *SEM*. *Discernible differences between pre and post means (*A* and *B*) or between serial CE and integrated CE (*C*) at $p < 0.05$.

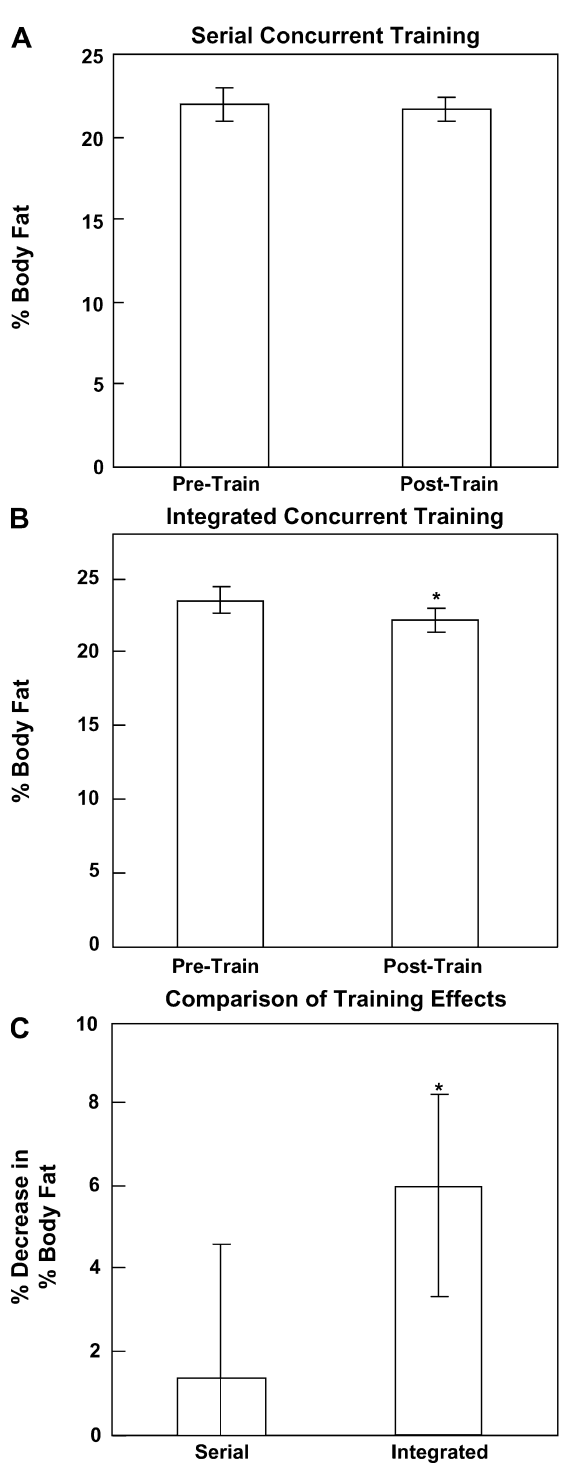

Figure 8. Mean percent body fat before (Pre-Train) and after (Post-Train) concurrent exercise training. *Error bars* represent 2 *SEM*. *Discernible differences between pre and post means (*A* and *B*) or between serial CE and integrated CE (*C*) at $p < 0.05$.

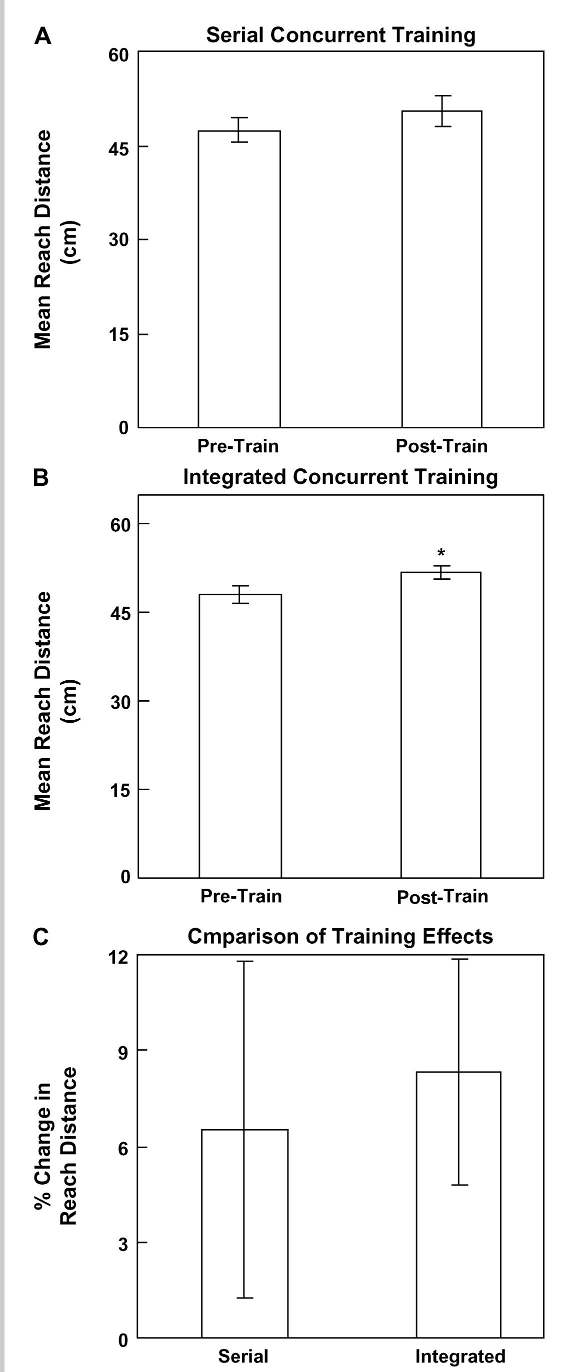

Figure 9. Mean lower-body flexibility, measured as the reach distance on the YMCA sit-and-reach test, before (Pre-Train) and after (Post-Train) concurrent exercise (CE) training. *Error bars* represent 2 *SEM*. *Discernible differences between pre and post means (*A* and *B*) or between serial CE and integrated CE (*C*) at $p < 0.05$.

Upper-body flexibility was assessed using the bilateral "back-scratch" test. Mean separation between hands in the serial CE group increased over the 11-week training program by 160.4% (Figure 10 A and C). There was a trend toward

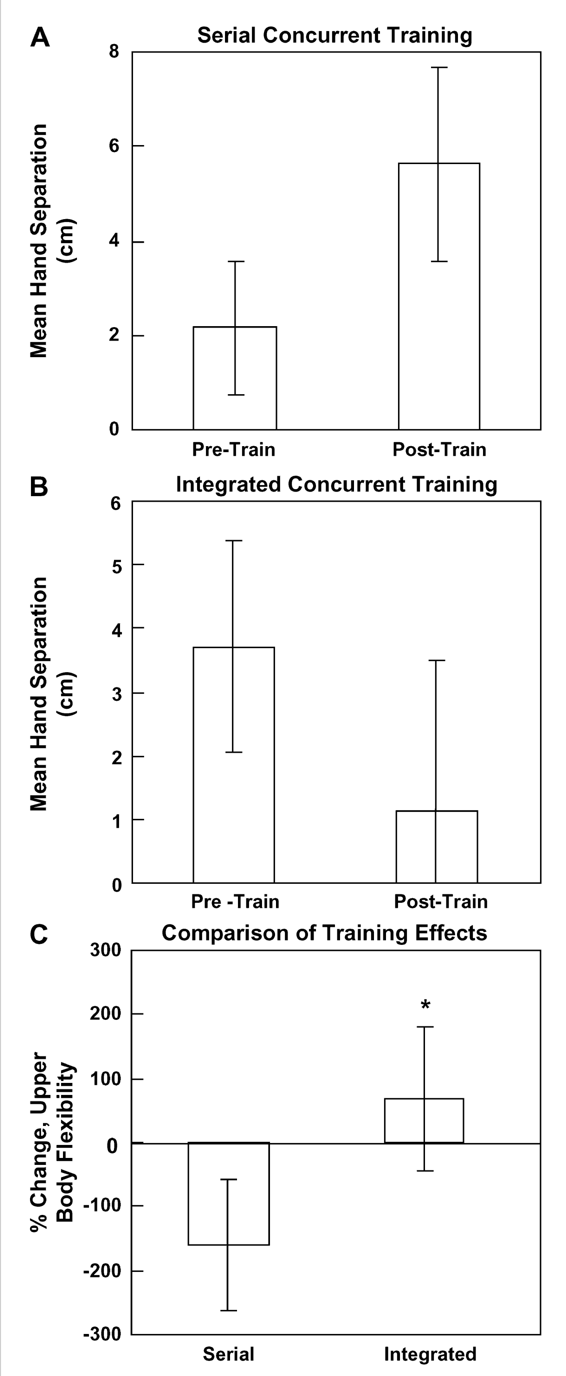

Figure 10. Mean upper-body flexibility, measured as the mean separation between hands on the "back-scratch" test, before (Pre-Train) and after (Post-Train) concurrent exercise (CE) training. Increased separation between hands signifies decreased upper-body flexibility. *Error bars* represent 2 *SEM*. *Discernible differences between pre and post means (*A* and *B*) or between serial CE and integrated CE (*C*) at $p < 0.05$.

an increase in hand separation (t-test, $n = 14$, $p = 0.054$), signifying decreased upper-body flexibility, and ES was moderate (0.65). Mean hand separation in the integrated CE group decreased by 69.7% (Figure 10 B and C). The posttraining mean was not discernibly smaller than the pretraining mean (t-test, $n = 14$, $p = 0.19$). Integrated CE yielded 143.5% less hand separation than serial CE (Figure 10C), discernibly smaller (t-test, $n = 14$, $p = 0.046$), signifying a greater increase in upper-body flexibility in the integrated CE group. Effect size was moderate (0.60).

Discussion

The results of this study (Table 1) permit acceptance of the three hypotheses tested (see INTRODUCTION) as follows. Hypothesis 1 stated that serial CE produces discernible training adaptations that are at least equivalent to comparable published adaptations for single-mode training. Serial CE induced discernible gains in muscle strength and muscle endurance, rather than interference, and ES values were generally moderate to large (Table 1). Comparable data for strength training adaptations in athletes are sparse (8), but analysis of the few studies that are available reveals that the strength gains produced here by serial CE exceed the mean published strength gains from strength training alone in athletes (Table 2) by 42.9% (upper body) to 109.8% (lower body). The strength gains produced here by serial CE are similar to mean published strength gains from concurrent training of athletes (Table 3).

Hypothesis 2 stated that integrated CE produces discernible training adaptations that are greater than comparable published adaptations for single-mode training. Integrated CE induced discernible gains in muscle strength and muscle endurance, rather than interference, and enhanced body composition and flexibility, and ES values were moderate to large (Table 1). The strength gains produced here by integrated CE exceed mean published gains from strength training alone in athletes (Table 2) by 33.8% (upper body) to 184.1% (lower body). This finding suggests that integrated CE amplifies muscle strength gains in comparison with strength training alone, i.e., that integrated CE has synergic effects on muscle strength adaptations. The strength gains produced here by integrated CE exceed mean published strength gains from concurrent training in athletes (Table 3) by 78.4% (lower body) to 30.9% (upper body).

Hypothesis 3 stated that integrated CE produces discernibly greater training adaptations than serial CE. Integrated CE induced larger training adaptations than serial CE for six of nine training adaptations assessed, and ES values were moderate to large (Table 1). The serial CE and integrated CE protocols were balanced for exercise mode, exercise intensity, and several additional program variables, and differed only in the timing and sequence of exercises. Therefore, the finding that integrated CE produces larger gains than serial CE demonstrates that exercise timing and sequence within training sessions affects the outcome of CE training protocols significantly. Specifically, aerobic increase of HR before each set of anaerobic resistance exercises amplifies strength, muscle endurance, and other adaptations.

TABLE 1. Summary and comparison of training adaptations.

Training adaptation	Serial CE	ES	Integrated CE	ES	Percent difference	ES
Lower-body muscle strength	17.2%*	L	23.3%*	L	35.4%‡	M
Upper-body muscle strength	19.0%*	L	17.8%*	L	−5.9%	–
Leg press muscle endurance	18.2%†	M	27.8%*	M	52.8%‡	M
Upper-body muscle endurance	9.6%	–	5.2%	–	−42.3%	–
Fat-free mass gain	1.8%*	T	3.3%*	S	82.2%‡	L
Fat mass	0.5%	–	−4.5%*	S	991.8%‡	M
Percent body fat	−1.1%	–	−5.7%*	S	438.7%‡	L
Lower-body flexibility	6.5%	–	8.4%*	M	28.0%	–
Upper-body flexibility	−160.4%†	M	69.7%	–	143.5%‡	M

Numbers in "Serial CE" and "Integrated CE" represent the percent differences between post-and pretraining means ([(Post − Pre)/(Pre)] × 100). Numbers in "Percent Difference" represent the percent changes in training adaptations of Integrated CE compared with Serial CE ([(Integrated − Serial)/(Serial)] × 100).

L = large; M = moderate; S = small; T = trivial; CE = concurrent exercise; ES = effect size.

*Discernible differences between pre- and post- training means at $p < 0.05$.

†Trends between pre- and post- training ($0.05 > p < 0.10$).

‡Discernibly larger training effects of integrated CE at $p < 0.05$.

The small discrepancies of values in "Percent Difference" result from a rounding error.

Most studies of CE have focused on muscle strength and aerobic endurance adaptations. A few studies have reported that indirect or compound measures of muscle endurance are enhanced by concurrent strength and aerobic endurance training (29). A study of untrained women, for example, found that serial CE increased cycle time to exhaustion by 10.5% over 12 weeks, whereas comparable volumes of aerobic training alone caused less improvement (2.4%) (50). To our knowledge, no previous study has evaluated the effect of concurrent strength and aerobic endurance training on direct measures of muscle endurance, i.e., the number of repetitions to failure at a fixed fraction of 1-RM weight. In the present study, we found substantial gains in direct measures of muscle endurance from serial and integrated CE (Table 1). Muscle endurance adaptations were greater for the lower than the upper body, and greater for integrated than serial CE (Table 1), perhaps because lower-body musculature was used for cardioacceleration between sets of resistance exercises in the integrated CE group.

Studies of body composition in untrained individuals have found that CE increases body mass and FFM significantly while reducing %BF (19). The few comparable studies on athletes (Table 3) show mixed results. Endurance athletes, whose %BF is already minimal, experienced little or no further reduction from CE (29), whereas well-conditioned competitive basketball players showed a reduction of 14.8% in %BF (8). In the present study, serial CE had small but discernible effects on body composition, whereas integrated CE was more than 5 times (438.7%) more effective than serial CE, and ES values were moderate to large (Table 1). The loss of FM in the integrated CE group occurred even though subjects consumed an ad libitum

TABLE 2. Single-mode (strength) training adaptations in athletes and individuals recreationally trained for 1 year or more, based on published studies, for comparison with the present results.

LB*	Age (yr)	Dur (wk)	Freq (d/wk)	UB*	Age (yr)	Dur (wk)	Freq (d/wk)	%BF†	Age (yr)	Dur (wk)	Freq (d/wk)
8.2%	21.3	13.8	3.1	13.3%	19.4	12.9	3.3	−7.4%	21.3	14.4	3.4

Adaptations were averaged among 14 training groups (nine male, five female) from 10 published studies (eight on athletes, two on recreationally trained individuals). Studies included in this Table are limited to those that used the same exercises and measures (1-RM, %BF) as the present study.

LB = lower-body gains (mean of data from three LB exercises: leg press, knee extension, and knee flexion); Dur = mean duration of exercise programs; Freq = mean frequency of training sessions; UB = upper-body gains (mean of data from four UB exercises: bench press, lat pull-down, overhead press, and arm curl); %BF = percent body fat change.

*Percent differences in one-repetition maximum values after training compared with before ([(Post–Pre)/ (Pre)] × 100).

†Percent difference after training compared with before.

Means were computed from the following references: LB (2,3,8,36,37,40,54), UB (8,18,30,37,40,41,54), and %BF (2,8,37,40,54).

Table 3. Concurrent (strength and endurance) training adaptations in athletes, based on published studies, for comparison with the training adaptations obtained with concurrent training in this study.

LB*	Age (yr)	Dur (wk)	Freq (d/wk)	UB*	Age (yr)	Dur (wk)	Freq (d/wk)	%BF†	Age (yr)	Dur (wk)	Freq (d/wk)
21.5%	23.1	9.4	4.1	13.6%	22.2	23.9	3.8	− 7.4%	26.9	8.5	3.5

Adaptations were averaged among 15 training groups (12 male, two female, one mixed-gender) from nine published studies.
LB = lower-body gains (mean of data from three LB exercises: leg press, knee extension, and knee flexion); Dur = mean duration of exercise programs; Freq = mean frequency of training sessions; UB = upper-body gains (mean of data from four UB exercises: bench press, lat pull-down, overhead press, and arm curl); %BF = percent body fat change.
*Percent differences in one-repetition maximum values after training compared with before ([(Post−Pre)/ (Pre)] × 100).
†Percent difference after training compared with before.
Means were computed from the following references: LB (8,22,26,29,34,36), UB (6,7,8,26,31,34,45), and %BF (8,29).

diet and caloric intake was not monitored. The greater loss of FM in the integrated CE group may be related to the greater increase in FFM (mainly muscle) in this group because CE increases FFM and basal metabolic rate proportionately (17).

Still fewer studies have incorporated ROM exercises into CE programs and examined corresponding training adaptations. A 10-week CE training program entailing resistance and ROM training on alternate days increased strength discernibly more (30%) than the same volume of weight training alone (10%) (35). In contrast, a 12-week combined ROM and resistance training program increased muscle strength by about the same (16%) as strength training alone (14%) (52). Acute stretching immediately before weight training inhibits maximal strength performance and muscle endurance performance (51). The limited data available therefore suggest that concurrent strength and ROM training are either neutral or synergic with respect to strength adaptations, as long as intensive ROM exercises do not immediately precede strength training. To our knowledge, no previous study has evaluated the effect of CE on flexibility adaptations. In the present study, serial CE had little effect on flexibility, whereas integrated CE had a greater and discernible beneficial effect. A trend toward loss of upper-body flexibility in the serial CE group (Table 1) may be related to greater levels of DOMS in the serial CE group, demonstrated earlier in this same cohort (15). Integrated CE yielded greater flexibility gains than serial CE in the upper body, perhaps also because of the absence of DOMS in the integrated but not the serial CE group (15).

Previous investigators have drawn diverse conclusions about the effects of single-mode strength training versus concurrent strength and aerobic endurance training (see Introduction). It has been suggested that the apparently conflicting findings might be reconciled based on different training frequencies (33,39,47,48). When training frequency is high (≥5 days per week), CE may interfere with strength and/or aerobic endurance adaptations (19,28,55). When training frequency is low (≤3 days per week), interference with strength and aerobic endurance adaptations is generally absent (33,47,48). Although training frequency was generally higher for the cited studies that report interference, absence of interference or synergy have nonetheless resulted from CE using training frequencies of 4 days per week (8), 7–8 days per week (23), and 8 days per week (34). Conversely, some studies report interference between concurrent strength and aerobic endurance training even in relatively low-frequency training programs (57). Evidence for the training frequency hypothesis is therefore suggestive but equivocal.

A second hypothesis holds that interference results from subjects' poor physical condition (6,7). Most studies cited here that report interference from CE used untrained or sedentary subjects, whereas most studies cited here that report absence of interference or synergy used well-trained subjects. Studies reporting absence of interference or synergy in medium- to high-frequency concurrent training protocols invariably used well-conditioned subjects (6,7,8,22,29,34). Moreover, concurrent training of well-conditioned athletes on average yields strong positive strength gains rather than interference (Table 3), and these gains equal (upper body) or exceed (lower body) average strength gains from strength training alone (Table 2). Highly trained endurance athletes who combined intensive endurance training 4–5 days per week with strength training 3 days per week, for example, experienced strength gains of 24.4% and 33.8% in the upper and lower body, respectively (34). Evidence for the hypothesis that interference is associated with poor physical condition and that synergy is associated with good physical condition is therefore strong and unequivocal.

A third hypothesis holds that interference is associated with the timing and sequence of exercises performed in a CE protocol (1). Combining strength and aerobic endurance conditioning on the same day reduced training adaptations compared with alternating modes on different days (57), particularly if aerobic endurance training preceded strength training (9). Studies of untrained men and women, however, found no difference in adaptations in a concurrent strength and endurance training program when the sequence of strength and aerobic endurance training in each training session was reversed (13,23), although in one case aerobic adaptations were compromised (23). The few studies that have evaluated exercise timing and sequence during concurrent training therefore suggest a possible effect, but its nature and prerequisites are unclear.

The present results are consistent with the "training frequency" hypothesis and the "physical condition" hypothesis of interference, and they provide conclusive evidence for the "exercise timing and sequence" hypothesis. In respect to the training frequency hypothesis, we found synergy rather than interference at a training session frequency of 3 days per week. This result does not exclude the possibility of interference from either serial CE or integrated CE at higher training frequencies, although integrated CE may support high-frequency training without interference because it reduces and eliminates physiologic DOMS and therefore speeds muscle recovery (15). In respect to the physical condition hypothesis, we found synergy, rather than interference, between strength and aerobic endurance training in well-conditioned athletes. This result does not exclude the possibility of interference from either serial CE or integrated CE in less-conditioned subjects, although integrated CE may support the training of deconditioned individuals with little or no interference because of the elimination of DOMS and acceleration of muscle recovery after resistance exercises (15).

This study supports the exercise timing and sequence hypothesis by the demonstration that training adaptations induced by CE protocols differ discernibly when only the timing and sequence of exercises are varied. Specifically, aerobic cardioacceleration before each set of resistance exercises (integrated CE) enhanced training adaptations in comparison with performing resistance training at a lower HR followed by equivalent aerobic exercise (serial CE). Longer-duration training programs may also contribute to interference, because a number of studies show no interference over the first few weeks of training but significant interference after several additional weeks of training (28,32,50). The frequency of training sessions and the duration of training programs are both components of exercise intensity. Therefore, the evidence collectively suggests that interference between strength and aerobic endurance training in CE protocols is caused by a combination of three variables: high exercise intensity, poor physical condition, and timing and sequence of exercises.

In this study, we show that concurrent training yields significant training adaptations, demonstrating the absence of interference between strength and endurance training. As noted in METHODS, it was beyond the scope of this study to conduct controls for strength training alone; hence, the present results do not permit direct comparison of concurrent training adaptations with single-mode (strength) training adaptations. Our review of the literature, however, indicates that the adaptations associated here with concurrent training are similar to or greater than comparable training adaptations reported in the literature for single-mode training in athletes (Table 2). The literature review further reveals that concurrent training in athletes (Table 3) produces greater adaptations than single-mode (strength) training (Table 2). Future investigations of serial and integrated CE could benefit from conducting internal controls for single-mode strength and endurance training.

Although this study suggests synergy between strength and aerobic endurance training under the integrated CE training protocol, the physiological mechanism(s) underlying this synergy are unknown. We noted previously (15) that the time course of DOMS reduction and elimination in both men and women trained in the integrated CE protocol is similar to the known time course of skeletal muscle angiogenesis, which may increase muscle perfusion during resistance exercise in the integrated CE group. The same mechanism could account for the apparent synergy of strength and endurance training in the integrated CE group. DOMS signifies contraction-induced muscle damage and consequent reduced capacity to generate muscular power for up to 72 hours (60), implying reduced responsiveness to strength training even in low-frequency (2 days per week) training protocols, whereas enhanced muscle perfusion increases muscle performance by up to 20% (44). The elimination of DOMS and consequent faster muscle recovery combined with enhanced muscle perfusion in the integrated CE protocol could therefore increase training adaptations compared with the serial CE protocol, as found in the present study, perhaps through the mechanism of enhanced postactivation potentiation of muscle responses to resistance exercises (11,12).

PRACTICAL APPLICATIONS

This study has two practical applications. First, the possibility of interference between muscle strength and aerobic endurance training has created ambiguity in exercise prescription (see INTRODUCTION). The present results enable rejection of the interference hypothesis for the case of well-conditioned women exercising 3 days per week in a vigorous strength/endurance regimen. This and previous studies collectively suggest that interference results from a combination of increased exercise intensity, subjects' reduced physical condition, and the timing and sequence of exercises. This conclusion helps to clarify the necessary and sufficient conditions for interference and therefore contributes to the resolution of the current ambiguity in the prescription of CE. This study validates the rationale for prescribing CE, as recommended by United States national training, certifying, and medical organizations such as the ACSM (4), ADA (5), and NSCA (49), as long as exercise intensity is matched appropriately to the physical condition of subjects and exercises are appropriately timed and sequenced.

Second, the enhanced training adaptations documented here for integrated CE demonstrate that this concurrent training protocol is a more effective exercise stimulus than serial CE for eliciting training adaptations in well-conditioned women trained in a low-frequency (3 days per week), vigorous strength and endurance program. Comparison of the present results with comparable published training adaptations during single-mode (strength) training indirectly suggests that concurrent training may produce greater training adaptations than single-mode training, although this remains to be tested by appropriate internal controls for strength training alone. The unknown physiological mechanisms responsible for synergy during vigorous integrated CE training presumably also operate during high-intensity integrated CE training for strength, power, and agility in athletes, and the same mechanisms may operate to lesser degrees during medium-intensity integrated CE training for recreational exercisers and during low-intensity integrated CE training for rehabilitating athletes or patients in a clinical setting. Enhanced training adaptations from integrated CE, combined with the potentially related elimination of DOMS (15) and consequent faster muscle recovery (21), therefore have the potential to improve training and clinical outcomes in exercise programs at all levels.

Acknowledgements

This research was funded by the Division of Physical and Biological Sciences and the Office of Physical Education, Recreation, and Sports, of the University of California at Santa Cruz. We are grateful to the 28 dedicated student-athletes who served as subjects in these studies. For their cooperation and assistance in this research, we thank Greg Harshaw, Athletic Director; Michael Runeare, women's soccer coach; and Selene Teitelbaum and Jonah Carson, women's volleyball coaches. For technical support, we thank Cindy Hodges, Danielle Lewis, and Sarah Pinneo. For administrative support, we thank Kate Aja, Dierdre Beach, Bruce Bridgeman, Caitlin Deck, Daniel Friedman, Dobie Jenkins, and Alice Yang-Murray. Additional contributors to this research include Tamara Chinn, James Cisneros, Laura Engelken, Dianne Fridlund, Jill Fusari, Kathleen Hughes, Robert Irons, Camille Jarmie, Kristin Onorato, Karen Ostermeier, Mischa Plunkett, Onelia Rodriquez, Zoe Scott, Justin Smith, and Kelly Vizcarra. After the completion of this research, the lead author became affiliated with The Miracle Workout, LLC, which developed a proprietary interest in Integrated Body Conditioning®, a health, fitness, and training system that incorporates aspects of the integrated concurrent training protocol documented in this study (patent pending). The results of this study do not constitute endorsement of this product by the authors or the National Strength and Conditioning Association. The current contact information of the corresponding (lead) author is: The Miracle Workout, LLC, P. O. Box 2221, Boulder, CO 80306-2221, e-mail training@MiracleWorkout.com.

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