# CONCURRENT TRAINING ENHANCES ATHLETES' CARDIOVASCULAR AND CARDIORESPIRATORY MEASURES

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## ABSTRACT

Davis, WJ, Wood, DT, Andrews, RG, Elkind, LM, and Davis, WB. Concurrent training enhances athletes' cardiovascular and cardiorespiratory measures. *J Strength Cond Res* 22(5): 1503–1514, 2008—We evaluated the effects of concurrent strength and aerobic endurance training on cardiovascular and cardiorespiratory adaptations in college athletes and compared two concurrent exercise (CE) protocols. Separate experiments were performed on 30 women (mean age 19.6 years) and 20 men (20.4 years). In both experiments, subjects were divided into two groups (serial CE and integrated CE) matched for initial physical condition and trained in a vigorous 3-day per week CE program of 9 (men) to 11 (women) weeks. The two CE training protocols were equilibrated for exercise mode, intensity, and volume, differing only in the timing and sequence of exercises. During training, serial CE discernibly ($p < 0.05$) increased cardiovascular adaptation in women, indicated by reduction ($-5.7\%$) in active heart rate (HR) (HR/aerobic exercise intensity), whereas integrated CE discernibly reduced active HR in women ($-10.7\%$) and men ($-9.1\%$). Before and after comparisons in the larger sample of women showed that serial CE discernibly reduced systolic and diastolic blood pressure (BP) ($-8.7\%$ and $-14.0\%$, respectively), increased estimated $\dot{V}O_2$max (18.9%), and produced a trend ($0.10 > p > 0.05$) toward reduced resting HR ($-4.9\%$). Integrated CE in women discernibly reduced systolic and diastolic BP ($-13.2\%$ and $-12.6\%$, respectively), increased estimated $\dot{V}O_2$max (22.9%), and produced a trend toward reduced resting HR ($-2.4\%$). Integrated CE produced discernibly larger gains than serial CE or a trend for four of six training adaptations. Effect sizes were generally large (60.0% of discernible differences). We conclude that, for cardiovascular and cardiorespiratory adaptations in athletes, strength and endurance training are compatible and that exercise timing and sequence significantly influence training adaptations, complimenting our previous similar conclusions for strength, muscle endurance, body composition, and flexibility.

**KEY WORDS** combined exercise, integrated interference, heart rate, blood pressure, aerobic capacity, $\dot{V}O_2$max, resistance, range of motion

## INTRODUCTION

Several investigators have reported that concurrent exercise (CE), in which strength and aerobic endurance training are included in the same training sessions or program, interferes with muscle strength or power adaptations (14,20,21,31,40). Reduction in strength or power adaptations in response to concurrent strength and aerobic endurance training has been termed the interference effect, hypothesis, or phenomenon (20,21). Several other investigators, however, could not confirm the interference hypothesis (3,4,5,16,23), and several have reported the opposite, namely, a complimentary or synergic effect of concurrent strength and aerobic endurance training on muscle strength (17), muscle endurance (22,30), and athletic performance (4,18,24,28,33,38).

To clarify the effects of concurrent strength and aerobic endurance training and to identify the necessary and sufficient conditions for their compatibility, we evaluated in a companion article (13) the strength and muscle endurance adaptations induced by two CE protocols, serial CE and integrated CE (Figure 1). We found that an 11-week, 3-days per week training program of serial CE significantly enhanced strength and muscle endurance, body composition, and flexibility in well-conditioned women athletes (13). Integrated CE generally produced discernibly greater training adaptations than serial CE, and these adaptations exceeded those published by other investigators for single-mode (strength) training of athletes (13). These results suggest possible synergy, not interference, between strength

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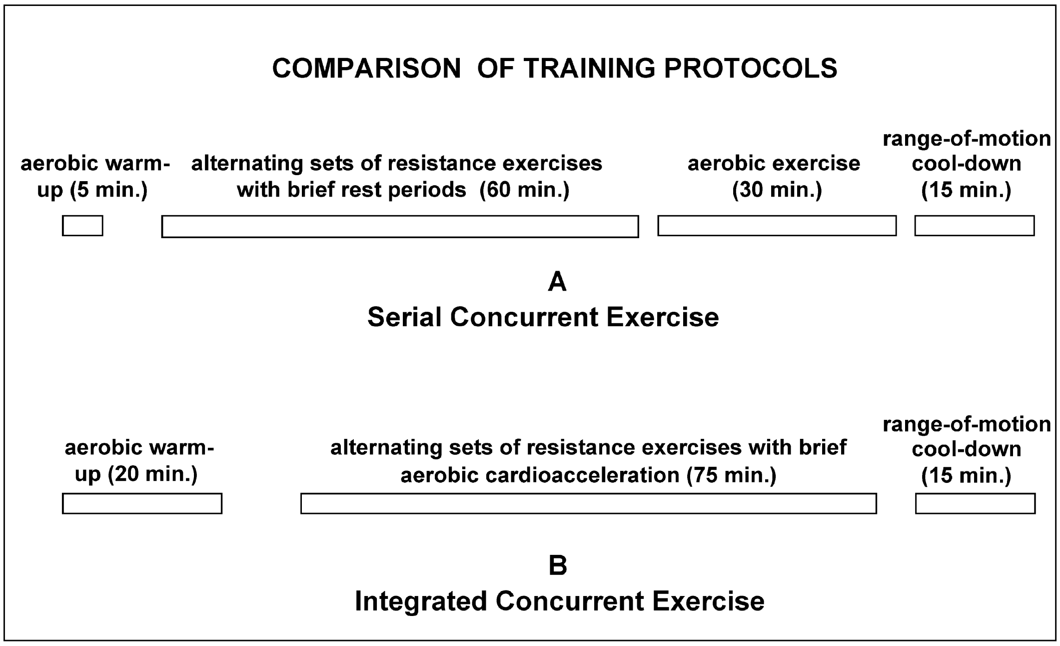

**Figure 1.** The two training protocols employed in this study, serial concurrent exercise (CE) (*A*) and integrated CE (*B*) (from reference 13). The length of each *horizontal bar* is proportional to the duration of the corresponding component. The width of spaces between bars is not significant.

and endurance training. These results do not contradict the findings of previous investigators who have demonstrated interference using different subjects, methods, and experimental designs; instead, these results encourage exploration of the necessary and sufficient conditions for compatibility versus interference of concurrent strength and endurance training.

In this article, we extend our earlier analysis of strength, muscle endurance, and other measures (13) to cardiovascular and cardiorespiratory adaptations. Most previous studies report that concurrent strength and aerobic endurance training did not interfere with aerobic endurance adaptations (14,20,21,23,43), although some report interference (16) or synergy (9,30,34), i.e., reduction or disproportionate enhancement, respectively, of maximal aerobic capacity. To our knowledge, there have been no previous studies of the effects of concurrent strength and aerobic endurance training on cardiovascular adaptation as measured by active HR, i.e., HR relative to the intensity of aerobic exercise, and no previous studies of the effects of CE on BP in athletes. We hypothesized that, as in the case of strength and muscle endurance adaptations (13), cardiovascular and cardiorespiratory measures would show discernible adaptations for serial CE and integrated CE, and larger adaptations for integrated CE than serial CE.

## METHODS

### Experimental Approach to the Problem

The rationale for these hypotheses is our earlier findings that integrated CE produces less delayed-onset muscle soreness and, by inference, faster muscle recovery than serial CE (12), as well as greater strength and muscle endurance adaptations (13). The enhanced strength and muscle endurance adaptations induced by CE would be expected to accompany and/or cause greater cardiovascular and cardiorespiratory adaptations through physiological mechanisms described in the Discussion. We tested these hypotheses using data from the same subjects and experiment as in our earlier papers (12,13). In the present report, training variables related to cardiovascular and cardiorespiratory fitness were measured and compared during a 9-week training program in men, and before, during, and after an 11-week training program in the larger sample of women.

### Subjects

The subjects were college athletes who were part of the same experiments described in previous articles (12,13). All subjects signed an informed consent statement, and the university's institutional review board approved this research program before its implementation. Subject demographics were reported earlier (12) and were not discernibly different between the serial CE and integrated CE group.

### Procedures

In each experiment, both groups (serial CE, integrated CE) undertook vigorous concurrent training 3 days per week entailing aerobics, three sets each of nine resistance exercises, and a range of motion (ROM; stretching and bending) cool down. Training took place in 1 hour and 50 minutes exercise sessions conducted 3 days per week for 9 (men) or 11 (women) weeks. Two CE protocols were employed: serial and integrated. Serial CE is the sequential performance in each training session of different modes of exercise (resistance, aerobic, and ROM) (Figure 1A). Integrated CE is repeated alternation in each training session among different modes of exercise, particularly resistance and aerobic exercise, so that they interact repeatedly and more directly (Figure 1B).

The most significant difference between these two concurrent protocols is heart rate (HR) during resistance exercises (12,13). In the serial CE protocol, HR was relatively low during weight training, averaging 31.9% (women) and 35.1% (men) (12,13) of HR reserve (HRR), calculated using the Karvonen method (1) and corresponding to "light" intensity aerobic exercise (1). In the integrated CE protocol, preresistance aerobic cardioacceleration increased HR during sets of resistance exercises to higher levels, averaging 62.5% (men) and 64.8% (women) of HRR (12,13) and corresponding to "vigorous" intensity aerobic exercise (1). The serial CE and integrated CE protocols were balanced carefully for exercise mode, volume, intensity, duration, and other relevant variables (12,13). Only the timing and sequence of exercises differed between the two groups (Figure 1).

General procedures for this experiment were as described previously (12,13), including pretraining instruction and assessments, training, and posttraining assessments and debriefing. Pretraining instruction was provided uniformly for both serial CE and integrated CE groups in the nine resistance exercises used during training (three sets each, eight to 12 repetitions per set) and in the use of the Borg scales (7), which were used to regulate progression. Athletes advanced in repetitions to 12, then reverted to eight repetitions using heavier weight (10 lbs for lower body, 5 lbs for upper body), when exertion during the final (third) set was "strong" or less and perceived pain was "weak" or less (12). If exertion exceeded "strong" or if perceived pain exceeded "weak," the weight and repetitions for the corresponding exercise were maintained unchanged in the following exercise session. The source of any pain reported as greater than "weak" was clarified before allowing the subject to continue the exercise program.

Pretraining assessments reported included estimated maximal aerobic capacity ($\dot{V}O_2$max), resting HR, and systolic and diastolic BP. $\dot{V}O_2$max was estimated using a graded exercise test (1) and automated with a Technogym treadmill (The Technogym Wellness Company, Gambettola, Italy). Systolic and diastolic BP were measured from the left arm using an OMRON HEM-630 arm cuff placed over the radial artery while subjects were seated silently and alone in a quiet room with their left arm elevated and supported at heart level. Systolic BP and diastolic BP were each measured twice in a period of 5 minutes, and the mean was recorded. Resting HR was recorded at the same time as BP as the mean of two consecutive measurements. Estimated $\dot{V}O_2$max, muscle strength (one-repetition maximum [1-RM] weight) and endurance (the number of repetitions to failure at 50% of 1-RM) data were used to implement the matched-pairs design based on initial physical condition, as detailed previously (12,13). Following matching, subjects were assigned at random to serial CE and integrated CE groups (12,13). This procedure ensured similar starting points for the two groups in each experiment.

During training, average HR of each subject during the aerobic and resistance phases of each workout was recorded by subjects on their workout logs using cardiotelemetry (Polar A-5 HR transmitter and wrist receiver). Steady-state treadmill velocity in miles per hour was recorded during the aerobic phase of training as the measure of the intensity of aerobic exercise. During training, subjects increased the treadmill velocity for the next exercise session whenever their mean HR declined noticeably from the previous training session, with the goal of sustaining mean HR during the aerobic phase of each training session approximately in the middle of their vigorous HR training window, i.e., 60–84% of HRR. Mean normalized HR (active HR) was determined by dividing the mean HR in beats per minute by the mean treadmill velocity in miles per hour. Such normalization was essential because any decline in nonnormalized mean HR could have resulted simply from a decline in exercise intensity (treadmill velocity), rather than from cardiovascular adaptation. Normalization of HR to exercise intensity ensured that any decline in active HR was caused exclusively by cardiovascular adaptation.

At the end of the 11-week concurrent training program in women (posttraining), the same measurements that were made during the pretraining phase of the experiments were repeated in the same sequence by the same investigators and following the same standardized protocols (1). Before and after evaluations were performed only for the women because withdrawal of some men subjects immediately before posttraining measurements reduced posttraining sample sizes below those required for statistical validity.

### Statistical Analyses

Data management and analysis were as detailed previously (12,13). The Wilcoxon matched-pairs sign-ranked test was used for most comparisons of means. Student's *t*-test (two-sample unequal variance) was used for comparisons of active HR during training because there were insufficient subjects in the men's group near the end of the training program to sustain a matched-pair analysis. Directional (one-tailed) statistical tests were used throughout because the hypotheses tested predicted the direction of change. Most measurements were made double-blind, i.e., neither the measurer nor the subject knew the group identity of subjects. The exceptions were single-blind measurements of resting HR and BP in the posttraining session, made by an investigator who knew the group identity of each subject. Effect size (ES) was calculated and characterized as recommended (42).

## Results

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

### Cardiovascular Adaptations

Mean resting HR in the women serial CE group declined by 4.9% during the 11-week training program, from 63.8 to 60.7 $b{\cdot}min^{-1}$, representing a trend toward reduction (Wilcoxon test, $n = 15$, $p = 0.052$). Effect size (ES) was small (0.33). In the integrated women CE group, the mean resting HR declined by 2.4%, from 63.5 to 62.0 $b{\cdot}min^{-1}$, also representing a trend toward discernible reduction (Wilcoxon test, $n = 15$, $p = 0.056$), and effect size was small (0.22). Serial CE therefore produced a 51.0% larger reduction in mean resting HR than integrated CE in women, which was not discernibly different (Wilcoxon test, $n = 14$, $p = 0.34$).

Cardiovascular adaptation during the training program was evaluated in both women and men by analyzing the change in HR relative to exercise intensity (normalized HR) during the aerobic phase of each exercise session (HR/treadmill velocity in units of $b{\cdot}min^{-1}$/mph). Graphing this measure of active HR as a time series (active HR versus exercise session) reveals an apparently downward trajectory over the training program in both women (Figure 2) and men (Figure 3), signifying a continuous reduction in HR relative to exercise intensity, i.e., a steady increase in cardiovascular adaptation during the training program.

To evaluate this apparent increase in cardiovascular adaptation statistically, the mean active HR during the last 10 exercise sessions of the training program was compared with mean active HR during the first 10 exercise sessions in both serial CE and integrated CE groups in both genders. In women (Figure 4A), the mean active HR decreased discernibly in both the serial CE group (5.7% reduction; $t$-test, $n = 10$, $p = 0.00047$) and the integrated CE group (10.7% reduction; $t$-test, $n = 10$, $p = 0.00000015$). ES was large

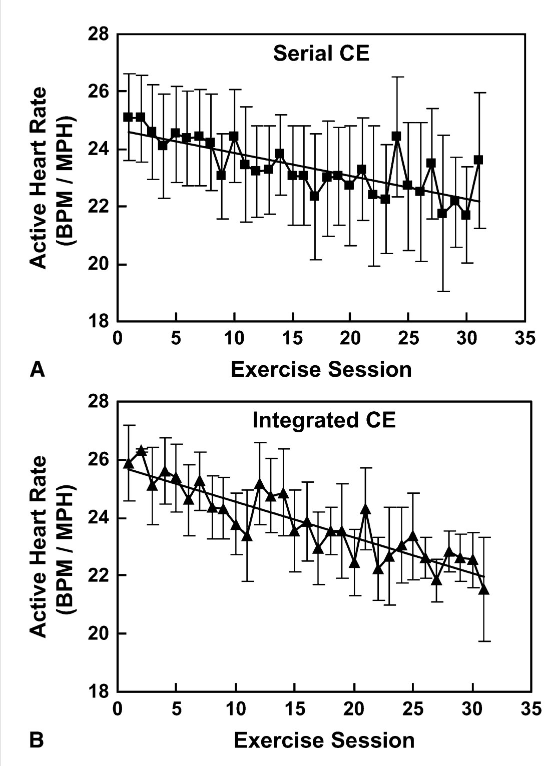

**Figure 2.** Mean active heart rate in women athletes normalized for aerobic exercise intensity (treadmill velocity) during the aerobic phase of successive training sessions during an 11-week concurrent exercise (CE) training program. *A*, serial CE group; *B*, integrated CE group. Error bars designate two *SEM* The *straight line* is the best fit linear curve included to highlight the downward trajectory of normalized HR during training.

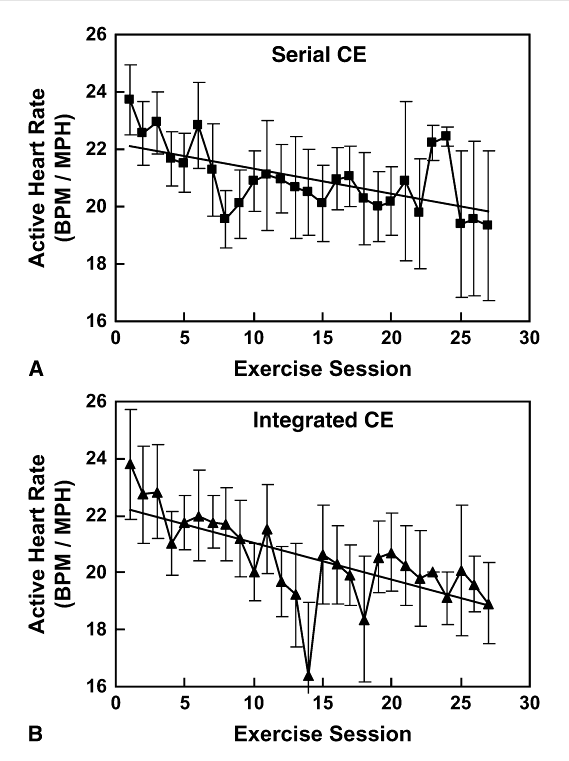

**Figure 3.** Mean active heart rate in men athletes normalized for aerobic exercise intensity (treadmill velocity) during the aerobic phase of successive training sessions during a 9-week concurrent exercise (CE) training program. *A*, serial CE group; *B*, integrated CE group. Error bars designate two *SEM* The *straight line* is the best fit linear curve included to highlight the downward trajectory of normalized HR during training.

in both cases (2.57 and 3.29, respectively). In men (Figure 4B), the mean active HR did not change discernibly in the serial CE group (1.5%; *t*-test, $n = 10$, $p = 0.36$) but declined discernibly in the integrated CE group (9.1% reduction; *t*-test, $n = 10$, $p = 0.00041$), where the ES was large (1.64). Inspection of active HR data in averaged serial men CE group (Figure 3A) reveals anomalous countertrends in averaged data during the first 10 exercise sessions (workouts 8–9) and the last 10 exercise sessions (workouts 23 and 24), which were accompanied by small sample sizes. The outliers comprising these countertrends reduced mean active HR during the first 10 exercise sessions and increased mean active HR during the last 10 exercise sessions. Therefore, the apparent absence of cardiovascular adaptation as measured by active HR during serial CE in men may be the result of these chance outliers in relatively small samples.

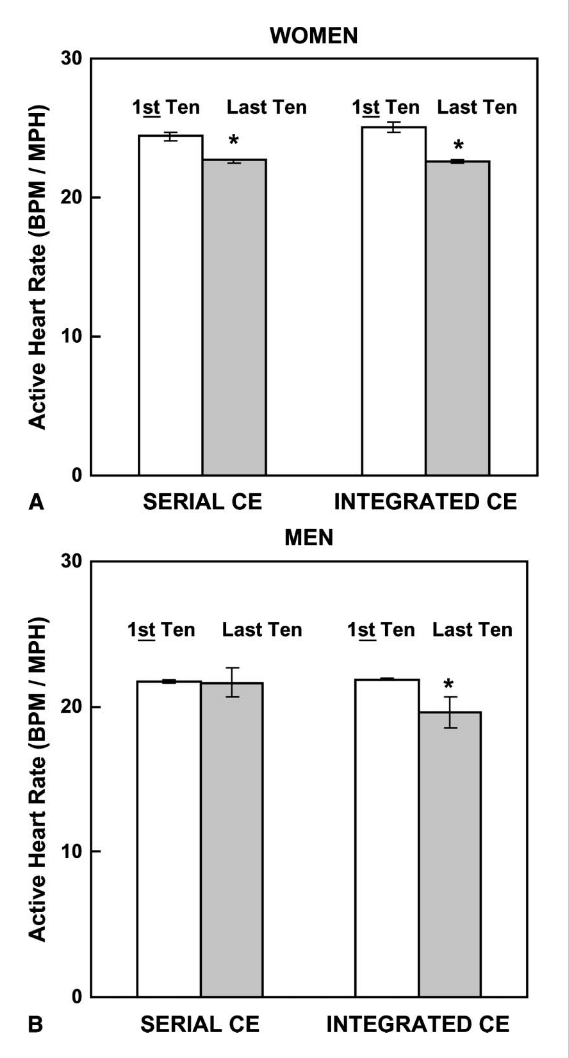

**Figure 4.** Mean active heart rate during the aerobic phase of the first 10 training sessions (*open bars*) and the last 10 training sessions (*shaded bars*) in women (*A*) and men (*B*). *Discernible differences in the last 10 training sessions ($p < 0.05$).

Comparison of serial CE and integrated CE with respect to active HR shows that, by this measure of cardiovascular adaptation during training, integrated CE was more effective than serial CE in both genders (Figure 5A). Integrated CE was 89.0% more effective than serial CE in women (Figure 5B), which was discernible (*t*-test, $n = 10$, $p = 0.0014$) and 735.9% more effective in men, also discernible (*t*-test, $n = 10$, $p = 0.007$). For both women and men, ES was large (2.0 and 15.7, respectively). This large difference in percent gain in the men is most likely exaggerated by the aforementioned chance outliers in the serial CE group.

### Blood Pressure

Mean systolic BP in the women serial CE group declined by 11 mm Hg (8.7%) during the 11-week training program (Figure 6 A and C). The posttraining mean systolic BP in the serial CE group was discernibly smaller than the pretraining

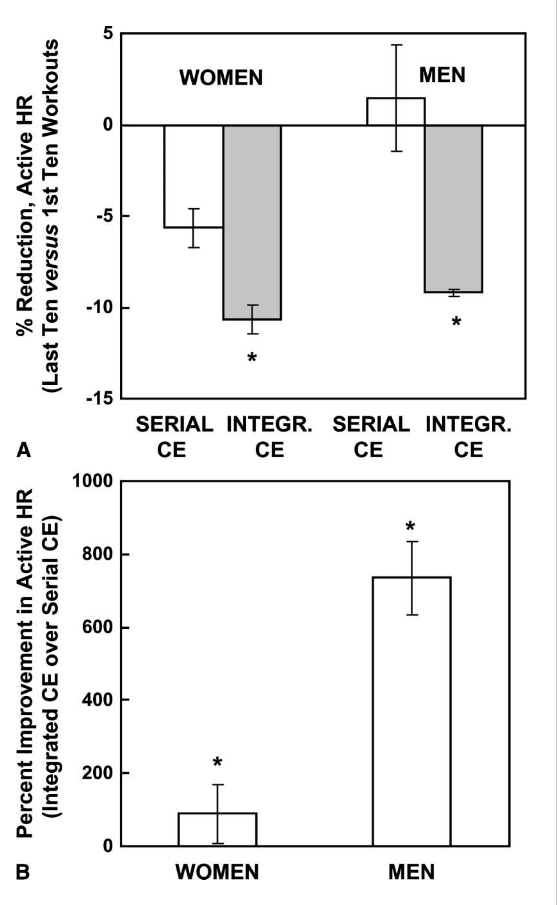

**Figure 5.** Percent difference in cardiovascular adaptation (active heart rate) during training compared for serial concurrent exercise (CE) and integrated CE in women and men (*A*). *Open bars*, serial CE; *shaded bars*, integrated (integr.) CE. *B*, Percent improvement of integrated CE over serial CE in both genders. *Discernible differences at $p < 0.05$.

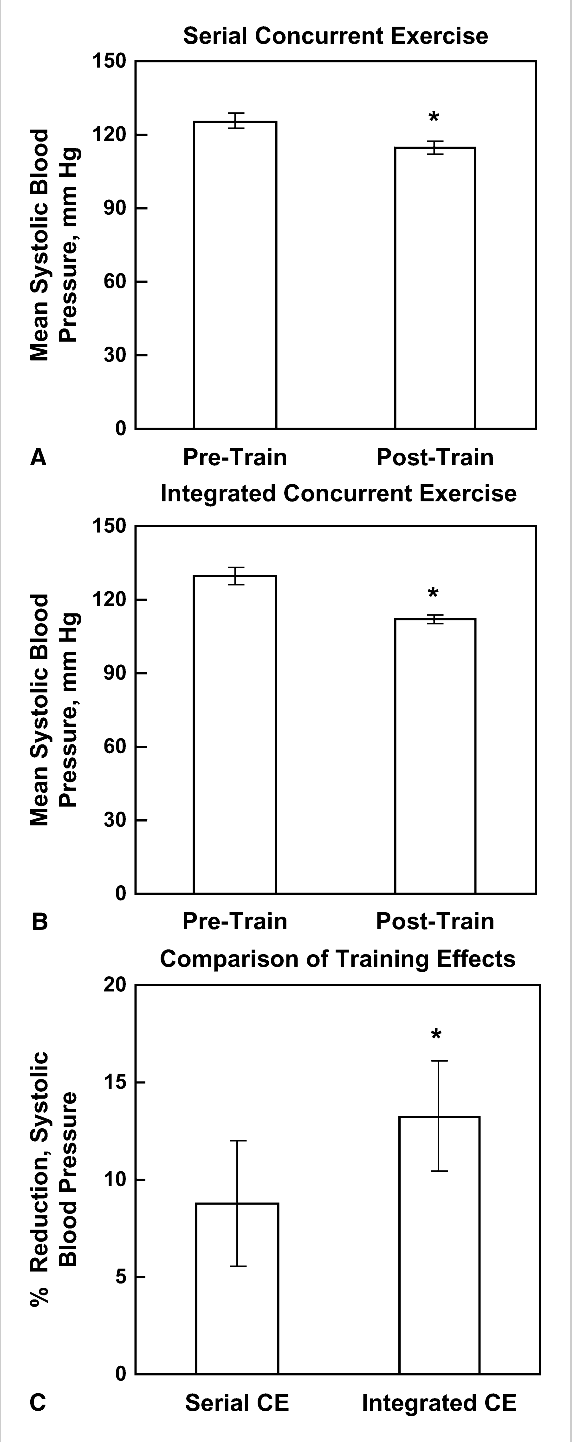

**Figure 6.** Mean systolic blood pressure before (Pre-Train) and after (Post-Train) a vigorous 11-week concurrent exercise (CE) training program in women athletes. *A*, serial CE group; *B*, integrated CE group; *C*, comparison of the two groups. *Discernible differences ($p < 0.05$) between post training and pre training (*A* and *B*) and between integrated CE and serial CE (*C*).

mean (Wilcoxon test, $n = 15$, $p = 0.012$), and ES was moderate (0.92). Mean systolic BP in the women integrated CE group decreased by 17 mm Hg (13.2%) over 11 weeks (Figure 6 B and C). The posttraining mean was discernibly smaller than the pretraining mean in the integrated CE group (Wilcoxon test, $n = 15$, $p = 0.001$), and ES was large (1.28). Integrated CE in women therefore induced a 51.7% greater mean decline in systolic BP than serial CE (Figure 6C), discernibly larger (Wilcoxon test, $n = 15$, $p = 0.03$), and ES was small (0.42).

Mean diastolic BP in the women serial CE group decreased by 11 mm Hg (14.0%) during the 11-week training program (Figure 7 A and C). The posttraining mean diastolic BP was discernibly smaller than the pretraining mean (Wilcoxon test, $n = 15$, $p = 0.001$), and ES was large (1.24). Mean diastolic BP in the women integrated CE group decreased by 10 mm Hg (12.6%) over 11 weeks (Figure 7 B and C). The posttraining mean was discernibly smaller than the pretraining mean (Wilcoxon test, $n = 15$, $p = 0.0009$), and ES was large (1.05). Integrated CE in women therefore induced a 10% smaller decline in diastolic BP, which was indiscernible (Wilcoxon test, $n = 15$, $p = 0.41$) (Figure 7C).

### Estimated Maximal Aerobic Capacity

Mean $\dot{V}O_2$max in the women serial CE group increased by 18.9 % (Figure 8 A and C) during the 11-week training program. The posttraining mean was discernibly larger than the pretraining mean (Wilcoxon test, $n = 14$, $p = 0.006$), and ES was moderate (0.93). Mean estimated $\dot{V}O_2$max in the women integrated CE group increased during the 11-week training program by 22.9% (Figure 8 B and C). The posttraining mean was discernibly larger than the pretraining mean (Wilcoxon test, $n = 12$, $p = 0.001$), and ES was large (1.31). Integrated CE in women therefore yielded a 21.2% greater increase in $\dot{V}O_2$max than serial CE (Figure 8C), constituting a trend toward larger adaptation in the integrated CE group (Wilcoxon test, $n = 12$, $p = 0.07$), and ES was small (0.25).

## DISCUSSION

The main finding of this study is that, in well-trained college athletes, vigorous serial and integrated concurrent strength and aerobic endurance training (Figure 1) conducted 3 days per week over a period of 9 weeks (men) to 11 weeks (women) produced discernible cardiovascular and cardiorespiratory adaptations. Integrated CE generally produced larger adaptations than serial CE, and effect sizes were generally large (60% of comparisons) (Table 1). We reported previously (13) that CE enhances strength, muscle endurance, body composition, and flexibility, and that integrated CE was more effective than serial CE in producing these adaptations. The present study extends these conclusions to cardiovascular and cardiorespiratory adaptations for the same subjects and experiments. These results collectively demonstrate compatibility rather than interference between strength and endurance training in athletes.

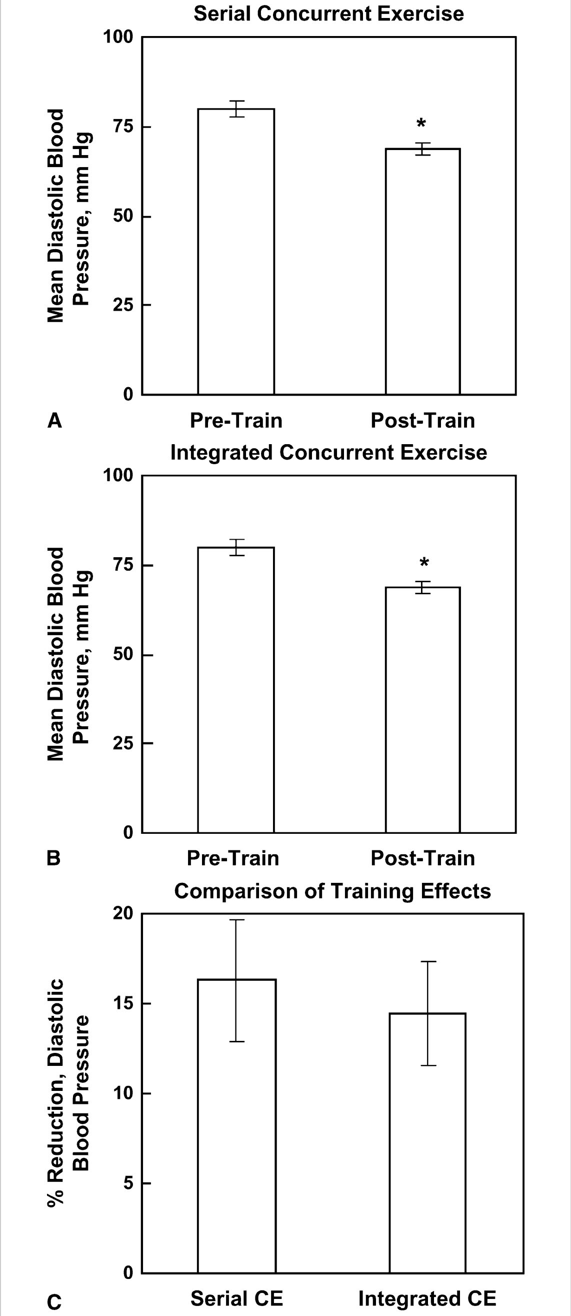

**Figure 7.** Mean diastolic blood pressure before (Pre-Train) and after (Post-Train) a vigorous 11-week concurrent exercise (CE) training program in women athletes. *A*, serial CE group; *B*, integrated CE group; *C*, comparison of the two groups. *Discernible differences ($p < 0.05$) between post training and pre training (*A* and *B*).

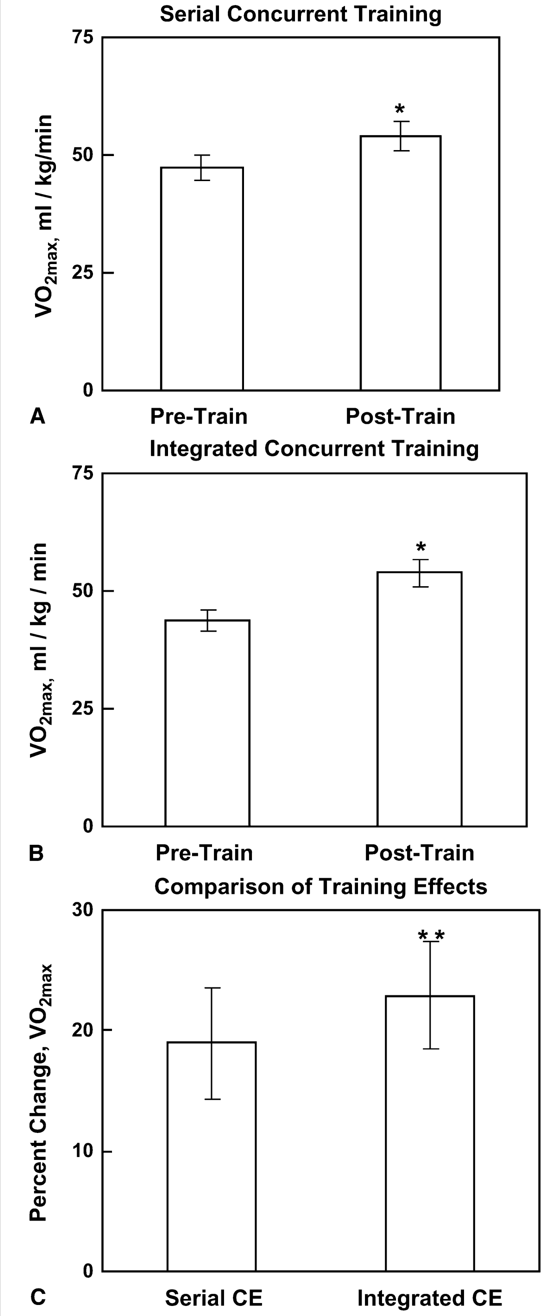

**Figure 8.** Mean estimated maximum aerobic capacity ($\dot{V}O_{2}max$) before (Pre-Train) and after (Post-Train) a vigorous 11-week concurrent exercise (CE) training program in women. *A*, serial CE group; *B*, integrated CE group; *C*, comparison of the two groups. *Discernible differences ($p < 0.05$) between post training and pre training (*A* and *B*). ** Trend toward discernible difference ($0.1 > p < 0.05$) between integrated CE and serial CE.

The cardiovascular and cardiorespiratory adaptations obtained in this study exceed those reported by other investigators for single-mode (strength or endurance) or concurrent training in athletes by up to an order of magnitude (Table 2). Comparison with the findings of other investigators suggest that the CE protocols used here produce greater adaptations than single-mode strength or endurance training alone, i.e., that concurrent strength and endurance

**TABLE 1.** Summary and comparison of training adaptations observed in this study.

| Training adaptation | Gender | Serial CE | ES | Integrated CE | ES | Percent difference | ES |
|---|---|---|---|---|---|---|---|
| Resting HR | Women | −4.9%† | S | −2.4%† | T | −51.0% | – |
| Active HR | Women | −5.7%* | L | −10.7%* | L | 90.0%‡ | L |
| Active HR | Men | 1.5% | – | −9.1%* | L | 735.9%‡ | L |
| Systolic BP | Women | −8.7%* | M | −13.2%* | L | 51.7%‡ | S |
| Diastolic BP | Women | −14.0%* | L | −12.6%* | L | −10.0% | – |
| $\dot{V}O_2max$ | Women | 18.9%* | M | 22.9%* | L | 21.2%§ | S |

Numbers in "Serial CE" and "Integrated CE" represent the percent differences between post-and pretraining means ([(Post − Pre)/(Pre)] × 100), except for active HR, in which the number represents changes observed during training (last 10 exercise sessions versus the first 10 exercise sessions). Numbers under "Percent difference" represent the percent changes in training adaptations of integrated CE compared with Serial CE ([(Integrated − Serial)/(Serial)] × 100).

ES = effect sizes; L = large; M = moderate; S = small; T = trivial; CE = concurrent exercise; HR = heart rate; BP = blood pressure.

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

†Trends ($0.10 > p > 0.05$) between pre- and posttraining.

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

§Trend toward a larger effect ($0.10 > p > 0.05$).

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

training have synergic rather than simply neutral effects on training adaptations. Testing this hypothesis requires further studies in which the adaptations induced by integrated CE are compared with the adaptations of matched control groups of subjects that receive single-mode strength training and single mode endurance training, which was beyond the scope of this study.

This investigation compared two concurrent training protocols that differed only in exercise timing and sequence (12,13). Because one protocol (integrated CE) generally induced discernibly greater adaptations than the other (serial CE) (Table 1), the timing and sequence of exercises significantly influences cardiovascular and cardiorespiratory adaptations, as we reported previously for adaptations in strength, muscle endurance, body composition, and flexibility (13). Previous investigators found that conducting endurance training before strength training in a concurrent exercise protocol with sports students improved maximal aerobic capacity more than the reverse sequence and more than endurance training alone (9). A similar result has been reported for healthy women non-athletes (30). In the present study, we found the same; when aerobic exercise preceded strength training (integrated CE), cardiovascular and cardiorespiratory adaptations were greater than when strength training preceded aerobic exercise (serial CE) (Table 1). This convergence of independent results suggests that performing aerobics before strength training in a concurrent protocol enhances aerobic endurance adaptations through synergic interactions and yields larger adaptations than performing strength training before aerobics. The additional stimulus of increased HR during resistance exercises (integrated CE) further enhanced aerobic endurance adaptations. The present results therefore add to the evidence that exercise timing and sequence within training sessions significantly influence cardiorespiratory adaptations ($\dot{V}O_{2max}$) and extends this conclusion to cardiovascular adaptations (HR, BP).

**TABLE 2.** $\dot{V}O_2max$ adaptations (% change) in athletes and individuals trained recreationally for 1 year or more in strength (S), endurance (E), and concurrent (C) training programs observed by other investigators.

| S | Age (yrs) | Dur (wks) | Freq (d/wk) | E | Age (yrs) | Dur (wks) | Freq (d/wk) | C | Age (yrs) | Dur (wks) | Freq (d/wk) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| −1.8% | 20.4 | 12.8 | 2.8 | 9.0% | 20.7 | 11.0 | 2.4 | 5.6% | 23.7 | 10.7 | 3.4 |

Adaptations were averaged across 16 training groups (nine male, five female, one mixed-gender, one unreported) from eight published studies (seven studies on athletes, one study on sport students).

Dur = mean duration of exercise programs; Freq = mean frequency of training sessions.

All percent changes represent percent differences in $\dot{V}O_2max$ values after training compared with before ([(Post − Pre)/ (Pre)] × 100). Means were computed from the following references: S (4,9,29,36); E (4,9,35,39); C (9,18,24,36).

Limited previous data on the effect of CE on resting HR have documented moderate declines in the resting HR of non-athletes (30), as found also in the present study with athletes. To our knowledge, no previous study has evaluated the impact of CE on active HR, i.e., cardiovascular adaptation during aerobic exercise as measured by HR relative to aerobic exercise intensity. In the present study, cardiovascular adaptation as measured by a decline in active HR was discernible in both serial CE and integrated CE groups in women and in the integrated CE group in men. Inability to detect a decline in active HR in the men serial CE group probably resulted from chance outliers in the relatively small men's sample size (see Results). In both genders, adaptation in active HR was greater for the integrated CE group than for the serial CE group, which is again attributable to the timing and sequence of exercises and specifically to the aerobic elevation of HR immediately before resistance training in the integrated CE group but not the serial CE group. Little or no difference between genders was therefore evident for cardiovascular adaptations during training in this study, as we reported previously for the elimination of delayed-onset muscle soreness (DOMS) by integrated CE in these subjects (12).

We evaluated before and after changes in BP and estimated aerobic capacity only in the larger group of women athletes because of the relatively small posttraining sample size in men. There are few comparative data published on BP in athletes, but in non-athletes, strength and aerobic endurance exercise both reduce BP. Some studies suggest that resistance training alone induces little (3–4%) (26) or no (11) reduction in BP. A meta-analysis of 72 studies on healthy non-athlete adults showed a mean reduction from endurance training of 3.0 (systolic) and 2.4 (diastolic) mm Hg (15), with comparable reductions from 12 studies of resistance training (15) and greater reductions in hypertensive subjects (15,27). Moreover, there is increasing consensus that strength training alone reduces aortic compliance (6,25,41), which is associated with increased systolic BP (6,8). In a single study of the effects of concurrent strength and endurance training on BP in healthy women non-athletes (30), the concurrent group showed approximately the same decline in resting diastolic BP (6.7 mm Hg) as the endurance group (5.8 mm Hg). The data from non-athletes therefore suggest that strength, endurance, and concurrent training all induce a similar but modest decline in BP.

To our knowledge, no previous study has evaluated the effects of concurrent strength and endurance exercise on BP in athletes. The present study shows that systolic and diastolic BP in women athletes were discernibly reduced by both serial CE and integrated CE. These reductions exceed declines reported for endurance training alone in non-athletes by a factor of up to 4 and exceed the reduction in diastolic BP reported from a single previous study of concurrent training in non-athletes (30) by a factor of 2. Systolic BP was reduced discernibly more by integrated CE than serial CE, whereas diastolic BP was reduced discernibly and equally by serial CE and integrated CE. The present findings therefore add to existing evidence (10,25) that the weak or potentially adverse effects of strength training alone on BP (and possibly on aortic compliance) may be enhanced or ameliorated by concurrent training, particularly integrated CE.

Numerous studies have evaluated the effects of endurance training on maximal aerobic capacity. In untrained individuals, conventional submaximal endurance training produces gains in maximal aerobic capacity of 15–20%, with greater gains associated with longer training programs (19). In the most highly trained endurance athletes, however, gains in maximal aerobic capacity are typically negligible to small unless high-intensity interval training is utilized (32). In a 14-week training program with well-conditioned triathletes, for example, neither CE nor endurance training increased $\dot{V}O_{2max}$ (36). Although data on endurance adaptations as measured by maximal aerobic capacity in athletes are sparse, analysis of available studies reveals that the gains in estimated maximal aerobic capacity induced here by serial CE (Table 1) exceed those reported in athletes for single-mode strength or endurance training and concurrent training by up to an order of magnitude or greater (Tables 1 and 2). Integrated CE in particular induced $\dot{V}O_2$max training adaptations approximately 2.5 times greater than published values for adaptations from endurance training alone in athletes (Tables 1 and 2).

The physiological mechanism(s) by which integrated CE induces larger cardiovascular and cardiorespiratory training adaptations than serial CE are unknown. Some of the results of integrated CE as reported in the present study can be explained, however, by the same peripheral mechanisms we postulated earlier to account for the elimination of DOMS (12) and the disproportionate enhancement of strength and muscle endurance adaptations by integrated CE in this cohort (13). We proposed the hypothesis that integrated CE–and in particular the elevated HR during resistance exercises–increases short-term muscle perfusion and therefore accelerates the flux of nutrients and metabolic wastes across the sarcolemma, and simultaneously induces long-term angiogenesis of skeletal muscle, which further amplifies sarcolemmal flux (12). The same physiological mechanism(s) would be expected to enhance oxygen transfer to muscle tissue and therefore increase estimated maximal aerobic capacity in response to integrated CE but not serial CE, as observed in the present study. Similarly, increased volume of the peripheral vascular bed from enhanced angiogenesis in skeletal muscle would be expected to amplify the reduction of systolic but not diastolic BP by integrated CE but not serial CE, also as observed in the present study.

Central mechanisms, however, could also account for some of the results of this study. Differential increase in aortic compliance (6,8,10,25,27,41), for example, would be expected to preferentially reduce systolic BP (6) compared with diastolic BP, as found in the integrated CE group. Central mechanisms seem more likely to account for the observed decreases in resting and active HR in both CE protocols, as well as the observed differences between serial CE and integrated CE. These cardiovascular effects could result from enhanced cardiac hypertrophy and/or ventricular and aortic compliance changes induced by integrated CE that in turn cause increased ejection fraction and/or increased cardiac output. Integrated CE may enhance cardiac hypertrophy more than serial CE by repeated recruitment of the vascular muscle pump (44) and/or by enhanced perfusion of cardiac muscle during integrated CE. Alternatively, or additionally, the stimulus of repeated cardioacceleration during integrated CE may build cardiac strength and aerobic capacity disproportionately in comparison with serial CE through the same unknown physiological mechanism(s) that underlies high-intensity interval training in athletes (32).

## PRACTICAL APPLICATIONS

This study has four practical applications. First, the results extend to cardiovascular and cardiorespiratory measures the evidence that concurrent strength and aerobic endurance training are compatible rather than antagonistic in athletes. This conclusion does not contradict the demonstration of the interference effect by previous investigators, who used different subjects, methods, and experimental designs (see Introduction). Instead, our results help to clarify the necessary and sufficient conditions for the compatibility of strength and endurance training. We conclude that interference is evident primarily if not exclusively when training intensity-including both training frequency and program duration–is greater than appropriate for the physical condition of subjects, and when the timing and sequence of exercises is not optimal (13). In conjunction with our previous report (13) and the findings of other investigators (see Introduction), the present results support the prescription of CE, as recommended by United States national training, certifying, and medical organizations (1, 2, 37) for the specific program and subject variables summarized above and reviewed previously (13).

The second practical application of this study is the demonstration that exercise timing and sequence during concurrent training significantly influence training adaptations in well-conditioned subjects, as shown previously by others for aerobic endurance in sport students (9) and healthy women non-athletes (30). Such a convergence of independent results suggests that aerobic endurance adaptations are maximized by concurrent training in which aerobic endurance exercise precedes strength training rather than the reverse sequence, as shown previously for strength and muscle endurance adaptations (13). The present results also show that increased HR during strength training (integrated CE) enhances aerobic endurance adaptations in athletes.

The third practical application of this study is related to our finding that integrated CE reduces systolic BP discernibly more than serial CE. This result suggests that integrated CE is more effective as a therapy for the management and treatment of hypertension than other concurrent training protocols, including serial CE. Comparison of the present results with those of other investigators suggests further that integrated CE may be more effective than conventional single-mode strength or endurance training for the control and amelioration of hypertension.

The fourth practical application of this study is the further documentation of a new training protocol, integrated CE, in which HR is increased aerobically before each set of anaerobic exercises. We reported in the companion article (13) that this protocol enhances strength, muscle endurance, and other adaptations in athletes. The present results provide the additional demonstration that integrated CE generally elicits larger cardiovascular and cardiorespiratory adaptations than serial CE and larger adaptations than those reported by other investigators for single-mode (strength or endurance) training in athletes. The same physiological mechanisms shown here to enhance cardiovascular and cardiorespiratory adaptations during vigorous integrated CE training of athletes presumably operate to lesser degrees during moderate and light integrated CE training in a broader population. Therefore, the integrated CE training protocol has the potential to improve training and rehabilitation outcomes at all levels.

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