Incompatibility of endurance- and strength-training modes of exercise

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DUDLEY, GARY A., AND RUSDAN DJAMIL. *Incompatibility of endurance- and strength-training modes of exercise.* J. Appl. Physiol. 59(5): 1446–1451, 1985.—Twenty-two male and female subjects trained for 7 wk for endurance (*group E*), for strength (*group IS*), or for both strength and endurance (*group C*) to evaluate the effect of concurrent performance of both modes of training on the in vivo force-velocity relationship of human muscle and on aerobic power. Endurance training consisted of five 5-min sessions three times a week on cycle ergometer with a work load that approached the subject's peak cycle-ergometer O_2 uptake (peak CE $\dot{V}O_2$). Strength training consisted of two 30-s sets of maximal knee extensions per day performed on an isokinetic dynamometer three times a week at a velocity of 4.19 $rad \cdot s^{-1}$. *Group C* performed the same training as *groups IS* and *E*, alternating days of strength and endurance training. Subjects (*groups C* and *IS*) were tested pre- and posttraining for maximal knee-extension torque at a specific joint angle (0.52 rad below horizontal) for seven specific angular velocities (0, 0.84, 1.68, 2.81, 3.35, 4.19, and 5.03 $rad \cdot s^{-1}$). *Groups C* and *E* were tested for peak CE $\dot{V}O_2$ pretraining, at 14-day intervals, and posttraining. *Group IS* showed significant increases in angle-specific maximal torque at velocities up to and including the training speed (4.19 $rad \cdot s^{-1}$). *Group C* showed increases ($P < 0.05$) at velocities of 0, 0.84, and 1.68 $rad \cdot s^{-1}$ only. Peak CE $\dot{V}O_2$, when expressed in relative or absolute terms, increased ($P < 0.05$) ~18% for both *groups E* and *C*. This response was linear for *group E* ($r = 0.98$, $P < 0.01$) and for *group C* ($r = 0.99$, $P < 0.01$). The results indicate that concurrent training for strength and endurance does not alter the increase in aerobic power induced by endurance training only. In contrast, concurrent training reduces the magnitude of increase in angle-specific maximal torque at fast, but not slow, velocities of contraction.

muscle force-velocity relationship; aerobic power

CONVENTIONAL STRENGTH and endurance modes of exercise training induce distinctly different adaptive responses when performed independently. Typically, strength-training programs involve large muscle group performance of high-resistance low-repetition exercises to increase the force output ability of skeletal muscle (1, 23). In contrast, endurance-training programs utilize low-resistance high-repetition exercises such as bicycling or running to increase maximum O_2 uptake ($\dot{V}O_{2\,max}$) (18, 21). Endurance training does not increase the force output ability of muscle (9), and training for strength induces little or no increase in $\dot{V}O_{2\,max}$ (9, 11, 14). Obviously the nature of the adaptive response to training is specific to the training stimulus.

In contrast to the wealth of information describing the physiological responses to strength (1, 7) or endurance training (7, 12), data describing their compatibility are sparse. Recently, Hickson (9) found that concurrent training for strength and endurance reduced the ability for strength development but did not compromise gains in $\dot{V}O_{2\,max}$. It is not known whether this altered adaptive response was dependent on contraction velocity as velocity-specific measurements of muscle strength were not made. This is important because the velocity of contraction has a substantial impact on the force output ability of human skeletal muscle (2, 17, 24). In addition, the compatibility of strength training at high velocities where maximal power output occurs and of endurance training remains undetermined. The purpose of the present study, therefore, was to evaluate the influence of concurrent high-velocity isokinetic strength and endurance training on the in vivo force-velocity relationship of human muscle and on aerobic power. This was accomplished by assessing the influence of training essentially the same major muscle group (knee extensors) with a cycle ergometer and an isokinetic loading dynamometer on maximal knee-extension torque at a specific angle for seven angular velocities. Alterations in cycle-ergometer (CE) $\dot{V}O_{2\,max}$ were also examined.

METHODS

Testing procedures. Twenty-two volunteers (14 females and 8 males) participated in this study (Table 1). They were university students or staff who had not trained regularly for 3 mo prior to this study. Informed consent was obtained from each subject before the study. No attempt was made to alter their physical activity beyond the training sessions. Prior to testing and training each subject was familiarized with equipment to be used. They were also instructed in the procedure of obtaining carotid pulse rate, which would serve as an index of endurance-training intensity (19).

For each subject performing endurance-type training, $\dot{V}O_{2\,max}$ was determined during exercise on a cycle ergometer as described previously (6, 16). Briefly, an incremental load test was performed 1 day before and 2 days after training. The initial work load of 60 W (60 rpm) was performed for a duration of 1 min. Thereafter, the exer-

TABLE 1. *Descriptive statistics of subjects of the three different groups*

Group	n	Age, yr	Ht, cm	Weight, kg	
				Pretraining	Posttraining
Endurance	10	20.6±0.5	166.6±1.6	61.6±2.4	61.7±2.4
Combination	6	22.2±1.8	164.0±5.6	59.8±5.1	61.2±4.8
Isokinetic	6	25.7±2.4	170.4±5.1	67.3±5.5	68.1±4.9

Values are means ± SE.

cise intensity was increased by 30 W each minute until 60 rpm could no longer be maintained. The attainment of $\dot{V}O_{2\,max}$ was established by the leveling off of $\dot{V}O_2$ with increasing exercise intensity for these tests. Every 14 days during training CE $\dot{V}O_{2\,max}$ was determined during the last exercise bout of that day so that training would not be compromised. The subjects were tested at exercise intensities (supramaximal) that resulted in volitional exhaustion in 3–5 min. The subject was retested if he or she maintained the effort for more than 5 min. CE $\dot{V}O_{2\,max}$ was established as the highest $\dot{V}O_2$ obtained for these tests. $\dot{V}O_2$ was determined every 30 s during each test using a Beckman Metabolic Cart (see Ref. 25). Calibration of the instrument was carried out using gases of known concentrations before each test. $\dot{V}O_{2\,max}$ measured on a cycle ergometer is generally lower than that obtained on a treadmill for sedentary subjects. Thus CE $\dot{V}O_{2\,max}$ represents peak $\dot{V}O_2$ rather than true $\dot{V}O_{2\,max}$, and is termed peak CE $\dot{V}O_2$ (20).

Measurement of maximal torque at a specific angle for seven velocities was used to assess strength improvements. Tests were conducted 1 day before and 2 days after training using a 50-rpm Cybex II isokinetic loading dynamometer (Cybex Division of Lumex, Bay Shore, NY) essentially as described by Caiozzo et al. (2). The dynamometer was calibrated on each testing day by placing known weights at the end of the lever arm, which was of a given length, and then allowing the arm to move about the input axis at an angular velocity of 0.52 rad$\cdot$s^{-1}. Velocity calibration was done by determining the number of revolutions obtained in 1 min at angular velocities of 1.05, 2.09, and 3.14 rad$\cdot$s^{-1}.

The subjects were tested for maximal knee-extension torque at a specific angle for seven angular velocities; 0, 0.84, 1.68, 2.51, 3.35, 4.19, and 5.03 rad$\cdot$s^{-1}. The subject was stabilized in a sitting position on a sturdy bench with firm back support using thigh, hip, and chest straps. The input axis of the dynamometer was aligned with the subject's knee joint and the ankle strapped to the lever arm. The subjects were instructed to hold metal handles attached to the sides of the test bench during the tests. Vertical and horizontal displacement and lever arm length were held constant for each subject during each test and training session to ensure machine-subject alignment. The lever arm was positioned 0.52 rad (30°) below horizontal for the isometric test (0 rad$\cdot$s^{-1}). This position served as the test angle (see Ref. 2). Once the subject was situated properly, he or she was instructed to gradually increase isometric force to a maximum. Contractions were initiated 0.44 and 0.61 rad before the test angle for contraction velocities of 0.84 and 1.68 rad$\cdot$s^{-1}, respectively (see Ref. 2). For the remaining angular velocities, 2.51, 3.35, 4.19, and 5.03 rad$\cdot$s^{-1}, contractions started at ~1.74 rad of flexion. The legs were fixed at these specific starting angles by a leg-angle positioning device.

Starting from the angles noted above, the subjects were instructed to exert a maximum effort until full knee extension was reached. Maximal torque values produced at the test angle were registered on a strip-chart recorder equipped with a specific-angle registering pen. The recorder had a paper speed and frequency response of 100 mm$\cdot$s^{-1} and 0.05–40 Hz.

The experimental conditions were administered randomly and each subject performed four contractions at each velocity with ~10 s of rest between trials. The highest torque value at each angular velocity was used for data analyses. Tests were performed using the right leg. Test-retest reliability of torque measurements before and after training was 0.95 or greater, independent of contraction velocity.

Training. Subjects were randomly assigned to one of three training groups: *group E*, cycle training for endurance; *group IS*, isokinetic training for strength; or *group C*, concurrent training for endurance and strength. *Groups E* and *IS* performed training programs that were designed to induce substantial increases in peak CE $\dot{V}O_2$ and muscular strength, respectively. Compromised responses in *group C* to concurrent training for strength and endurance would therefore be detectable. Endurance training was done as interval training on a Monark cycle ergometer (Monark Cresientab, Vanber, Sweden) three times per week (alternate days) for 7 wk. The exercise consisted of five 5-min sessions with a 5-min rest recovery between sessions. Mean power output of the initial training sessions was 168.3 ± 10.5 and 159.8 ± 8.9 (±SE) W for *groups E* and *C*, respectively, and increased ~8 W each week. The sessions were designed to elicit peak CE $\dot{V}O_2$ during *min 4* or *5*, however, if the effort became too severe the resistance was adjusted to complete the designated time period. The first 30 s of each session served as a warm-up. Exercise intensity was evaluated by palpation of the carotid pulse rate (19), with consistent values of 180 beats/min or greater during *min 4* or *5*. Subjects maintained a pedal frequency of 60 rpm during training.

Strength training of the knee extensors was done on a Cybex II isokinetic loading dynamometer three times a week (alternate days) for 7 wk. The subjects trained at an angular velocity of 4.19 rad$\cdot$s^{-1}, the speed at which maximal power output occurs in untrained college-age individuals (17). The training sessions consisted of two sets of knee extensions done with maximal voluntary efforts for 30 s (26–28 contractions) with a 5-min rest between sets. The subjects initiated contractions at ~1.74 rad of flexion. Adjustments of the apparatus and positioning and stabilization of the subjects were standardized as previously described. Training was done on both legs.

The subjects that concurrently trained for endurance and strength performed the same protocols as *groups E* and *IS*. Training was done six times a week, alternating days of endurance and isokinetic strength training. All training sessions were supervised.

Statistical analyses. The force-velocity relationship data were analyzed using a two-way analysis of variance, three-factor mixed design with repeated measures on two factors. The relationship between training duration and peak CE $\dot{V}O_2$ was analyzed using linear regression. Other data were analyzed using a two-way analysis of variance for repeated measures. Post hoc multiple-comparison analyses were made using the Scheffé method. The 0.05 level of significance was used in all comparisons.

RESULTS

Peak CE $\dot{V}O_2$ increased significantly after training for *group E*, when expressed in relative (38.8 ± 2.4 to 45.1 ± 3.0 $ml \cdot kg^{-1} \cdot min^{-1}$, 16.2%) and absolute (2.39 ± 0.15 to 2.78 ± 0.18 $l \cdot min^{-1}$, 16.9%) terms (Fig. 1). It also increased significantly for *group C* (37.5 ± 0.77 to 44.5 ± 2.1 $ml \cdot kg^{-1} \cdot min^{-1}$, 18.7%, and 2.24 ± 0.05 to 2.72 ± 0.13 $l \cdot min^{-1}$, 20.9%) (Fig. 2). There were no significant differences in these responses between the two groups. The increases in peak CE $\dot{V}O_2$ for *groups E* and *C* were linear ($r = 0.98$ and 0.99, respectively, $P < 0.01$) during the 7-wk training period (Figs. 1 and 2). Furthermore, the rate of increase was similar between these groups.

Strength improvements exhibited different patterns in *groups IS* and *C*. In *group IS*, training resulted in significant improvements in maximal torque at each angular velocity tested except 5.03 $rad \cdot s^{-1}$ (Fig. 3). These changes represent mean increases ranging from 38.4 N·m (25.8%) at 0.00 $rad \cdot s^{-1}$ to 10.4 N·m (11.6%) at 4.19 $rad \cdot s^{-1}$ (Table 2, Fig. 3). Significant gains in strength occurred at speeds 0.00, 0.24, and 1.68 $rad \cdot s^{-1}$, only, for *group C* (Fig. 4). The mean increases in torque corre-

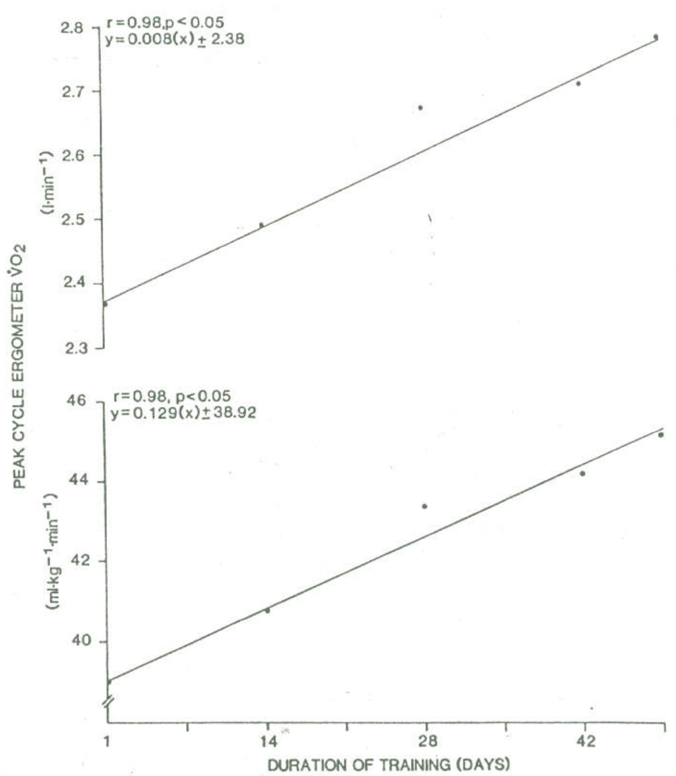

FIG. 1. Relationship between peak cycle-ergometer O_2 uptake ($\dot{V}O_2$) and training duration for *group E*.

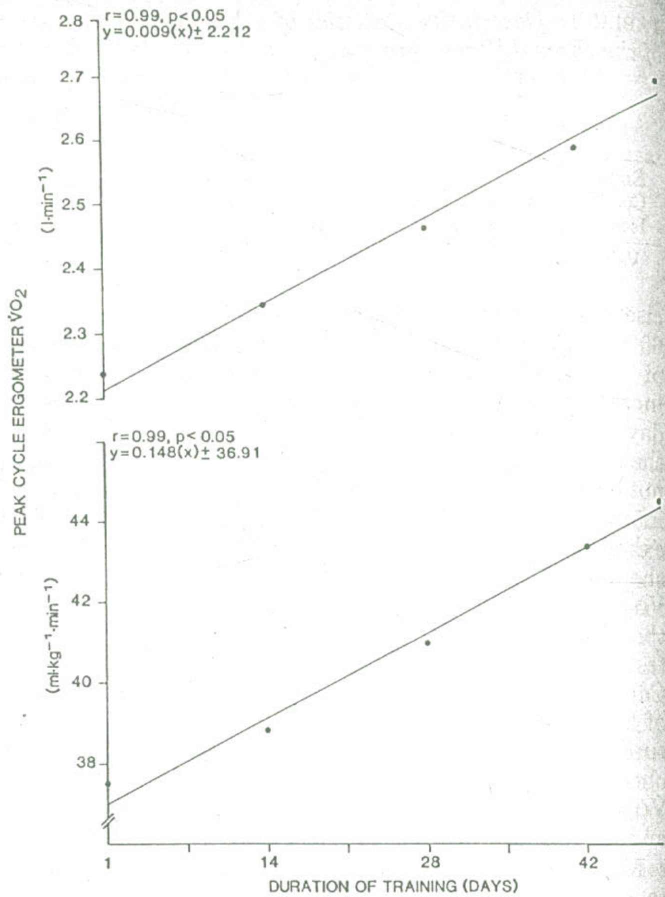

FIG. 2. Relationship between peak cycle-ergometer O_2 uptake ($\dot{V}O_2$) and training duration for *group C*.

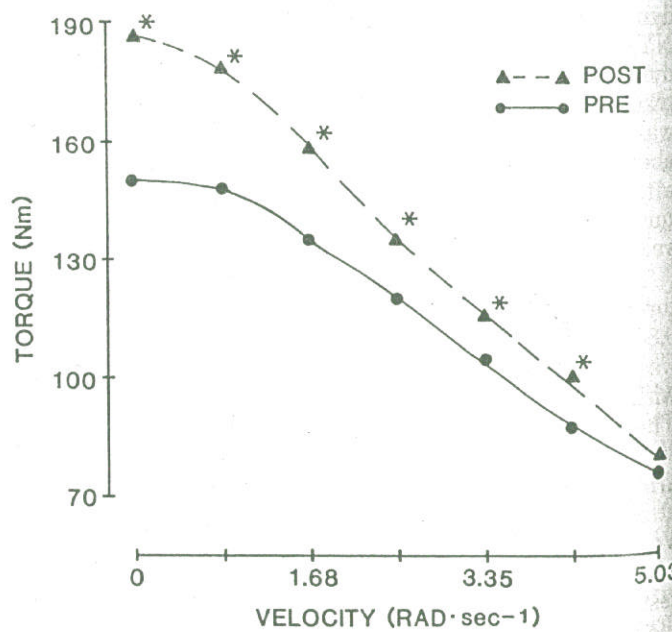

FIG. 3. Average maximal torque of knee extensor muscles plotted against velocity of contraction before and after training for *group IS*. * Significant improvement pre- vs. posttraining, $P < 0.05$.

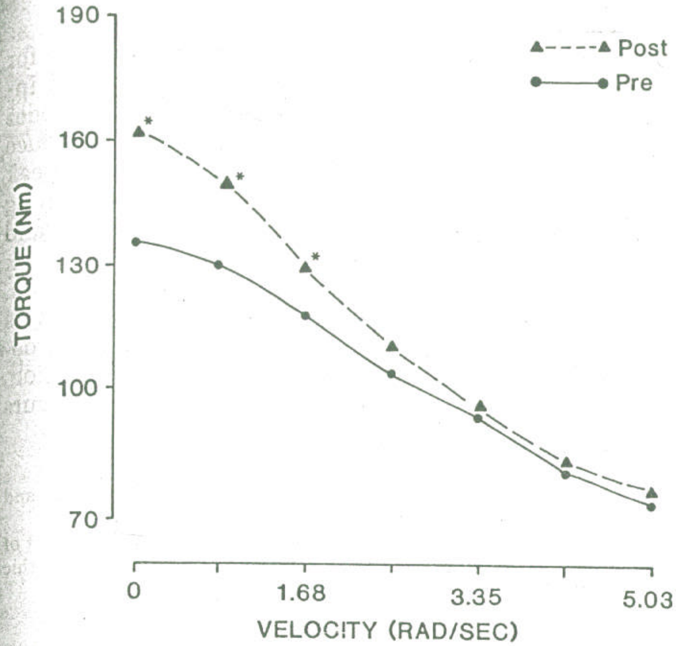

FIG. 4. Average maximal torque of knee extensor muscles plotted against velocity of contraction for *group C* before and after training. * Significant improvement pre- vs. posttraining, $P < 0.05$.

TABLE 2. *Percent improvement in peak torque at each test speed*

Test Speed, $rad \cdot s^{+1}$	*Group IS*	*Group C*
0.00	25.8±5.3	20.0±6.9
0.84	22.8±4.6	16.5±6.3
1.68	17.1±2.3	10.0±2.2
2.51	12.3±1.8	6.0±4.5
3.35	10.0±3.2	1.2±3.4
4.19	11.6±2.9	1.1±2.3
5.03	5.3±3.2	3.0±3.0

Values are means ± SE.

sponding to these velocities were 26.1, 14.2, and 11.7 N·m representing relative improvements of 20.0, 16.5, and 10.0% (Table 2, Fig. 4).

DISCUSSION

Our interest in the present study was to determine whether individuals can adapt to strength and endurance training when these distinct modes of exercise training are performed concurrently. We felt it was important to require substantial involvement of the same major muscle group (knee extensors) in both types of training (15) and to employ programs that induce substantial adaptive responses when performed independently. Our subjects performed high-intensity interval training using a cycle ergometer when training for endurance, high-velocity isokinetic contractions when training for strength, or both when training for strength and endurance. Peak CE $\dot{V}O_2$ was measured to determine the magnitude of the adaptive response to endurance training (3, 20), and adaptations to strength training were assessed by measuring maximal torque at a specific joint angle for seven angular velocities (2, 17, 24). This approach provided the opportunity to assess alterations of the in vivo force-velocity relationship of the knee-extensor muscles, since muscle strength was determined at the same muscle length for each angular velocity of contraction (2, 17, 24). We did not measure peak torque irrespective of joint angle, because it occurs at progressively smaller angles, and thereby shorter muscle lengths, as contraction velocity increases (17, 22). In addition, muscular strength in the group training for endurance and peak CE $\dot{V}O_2$ in the group training for strength were not measured, because strength training does not alter aerobic power (9, 11, 14) and endurance training does not alter muscular strength (9).

The results of the present study and those of Hickson (9) indicate that concurrent training for endurance and strength does not alter the ability to adapt to endurance training. *Group E*, which trained for endurance, and *group C*, which trained for strength and endurance, showed changes in peak CE $\dot{V}O_2$ of similar magnitude and linearity (Figs. 1 and 2). This was true when peak CE $\dot{V}O_2$ was expressed in relative or absolute terms. Thus it appears that performance of both modes of training concurrently does not alter the adaptability of the factors that govern increases in peak CE $\dot{V}O_2$.

The linear increase in peak CE $\dot{V}O_2$ deserves further discussion. The present study and others (10, 16) show a constant increase in peak CE $\dot{V}O_2$ when training intensity is maintained relative to improvement. The average weekly increases (0.055 and 0.068 $l \cdot wk^{-1}$ for *groups E* and *C*, respectively) found in the present study are approximately one-half of those reported previously by us (16) and others (10). This probably reflects the reduced frequency of training per week used in the present study (3 times) than past studies (6 times) (10, 16). The magnitude of increase in peak CE $\dot{V}O_2$ (~18% in absolute terms) is also impressive because our subjects trained for only 25 min three times a week for 7 wk. This response indicates that the most important training variable for increasing aerobic power is training intensity (18). In addition, the linear nature of the adaptive response to this type of endurance training (continually intensified training stimulus) indicates that the magnitude of increase in peak CE $\dot{V}O_2$ does not diminish as improvements occur.

Although it appears that strength training does not alter the ability to adapt to endurance training, the opposite is not the case. The results of the present study and those of Hickson (9) show that concurrent training for strength and endurance reduces the ability to increase muscle strength. Our results also show that this response is dependent on contraction velocity. *Groups IS* and *C* both showed significant increases in angle-specific torque after training, but the nature of their responses was quite different. *Group C* showed significant improvements in torque at angular velocities of 0, 0.84, and 1.68 $rad \cdot s^{-1}$ only (Fig. 4). In contrast, *group IS* showed significant improvements at speeds up to and including the training speed, 4.19 $rad \cdot s^{-1}$ (Fig. 3). Thus concurrent training for strength and endurance does not alter the increase in muscle strength in the slow-velocity high-force region of the in vivo force-velocity relationship of human muscle.

However, this type of training reduces the ability to increase strength in the high-velocity low-force region of this same relationship.

Increases in muscle strength have been related to adjustments in neural and/or intrinsic muscle properties (1, 2, 5, 13). Caiozzo et al. (2) have suggested that a tension-limiting mechanism of neural origin is a major factor which governs training-induced increases in muscle strength at slow, but not fast, speeds of contraction. Concurrent training for strength and endurance appears not to alter the adaptability of this mechanism. *Groups C* and *IS* both showed significant increases in peak torque in the slow-velocity high-force region of the in vivo force-velocity relationship.

Neural factors independent of the neural tension-limiting mechanism originally described by Perrine and Edgerton (17) and/or intrinsic muscle properties appear to govern strength development at fast velocities of contraction (2, 13). It appears that concurrent training for strength and endurance alters the adaptability of one and/or both factors. *Group IS*, but not *group C*, exhibited significant increases in peak torque at fast velocities of contraction. It is difficult, however, to attribute this altered adaptive response to a specific factor important to strength development.

Hickson's subjects, who trained concurrently for strength and endurance, performed 11 training sessions a week for a total training time of over 7 h (9). They also performed both modes of training 5 consecutive days a week. We were concerned that this approach to concurrent training may have resulted in residual fatigue (4, 8), and that this may have contributed to the reduced improvement in muscular strength. Our training programs were therefore designed to minimize the development of residual fatigue. We reduced the number of training sessions and the total training time per week by ~50 and 75%, respectively. In addition, strength and endurance training were not performed on consecutive days. It is therefore probable that the development of residual fatigue and its consequent limitation to improvement, if evident, were much less in the present than past study (9).

In the present study, *groups C* and *IS* showed significant improvements in peak torque in the slow-velocity high-force region of the in vivo force-velocity relationship. These results suggest that training at 4.19 $\text{rad}\cdot\text{s}^{-1}$ does result in adjustments of a neural tension limiting mechanism. In contrast, Caiozzo et al. (2) found minimal increases in angle-specific torque in this region of the relationship when training at the same velocity. These different adaptive responses probably reflect the different training programs employed. Our subjects performed as many contractions as possible (~60 total) in two 30-s work bouts separated by 5 min of rest. Their subjects performed 20 contractions (2 sets of 10) with 10 s of rest between each contraction and with 10 min of rest between each set. Subjects in both studies trained three times a week but our program duration was substantially greater (7 vs. 4 wk). Thus our subjects performed more contractions (~5-fold) of a different nature (rapid in succession in contrast to intermittent) from theirs, even though both trained at the same contraction velocity.

In summary, it appears that concurrent training for strength and endurance, which requires substantial involvement of the same major muscle group in both modes of training, does not compromise the ability to induce increases in peak CE $\dot{V}O_2$. However, the gains in peak CE $\dot{V}O_2$ will be no greater than when endurance training only is performed. In contrast, concurrent strength and endurance training reduces the ability to increase peak torque at fast, but not slow, velocities of contraction. This response suggests that endurance training alters the adaptability of the factors that govern strength development at fast, but not slow, velocities of contraction. The mechanism or mechanisms by which this occurs remain to be determined.

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