Concurrent Endurance and Strength Training Not to Failure Optimizes Performance Gains

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ABSTRACT

IZQUIERDO-GABARREN, M., R. GONZÁLEZ DE TXABARRI EXPÓSITO, J. GARCÍA-PALLARÉS, L. SÁNCHEZ-MEDINA, E. S. S. DE VILLARREAL, M. IZQUIERDO. Concurrent Endurance and Strength Training Not to Failure Optimizes Performance Gains. *Med. Sci. Sports Exerc.*, Vol. 42, No. 6, pp. 1191–1199, 2010. **Purpose**: The purpose of this study was to examine the efficacy of 8 wk of resistance training to failure versus not to failure training regimens at both moderate and low volumes for increasing upper-body strength and power as well as cardiovascular parameters into a combined resistance and endurance periodized training scheme. **Methods**: Forty-three trained male rowers were matched and then randomly assigned to four groups that performed the same endurance training but differed on their resistance training regimen: four exercises leading to repetition failure (4RF; n = 14), four exercises not leading to failure (4NRF; n = 15), two exercises not to failure (2NRF; n = 6), and control group (C; n = 8). One-repetition maximum strength and maximal muscle power output during prone bench pull (BP), average power during a 20-min all-out row test (W_{20min}), average row power output eliciting a blood lactate concentration of 4 mmol·L^{-1} ($W_{4mmol·L^{-1}}$), and power output in 10 maximal strokes ($W_{10strokes}$) were assessed before and after 8 wk of periodized training. **Results**: 4NRF group experienced larger gains in one-repetition maximum strength and muscle power output (4.6% and 6.4%, respectively) in BP compared with both 4RF (2.1% and −1.2%) and 2NRF (0.6% and −0.6%). 4NRF and 2NRF groups experienced larger gains in $W_{10strokes}$ (3.6% and 5%) and in W_{20min} (7.6% and 9%) compared with those found after 4RF (−0.1% and 4.6%), whereas no significant differences between groups were observed in the magnitude of changes in $W_{4mmol·L^{-1}}$ (4NRF = 6.2%, 4RF = 5.3%, 2NRF = 6.8%, and C = 4.5%). **Conclusions**: An 8-wk linear periodized concurrent strength and endurance training program using a moderate number of repetitions not to failure (4NRF group) provides a favorable environment for achieving greater enhancements in strength, muscle power, and rowing performance when compared with higher training volumes of repetitions to failure in experienced highly trained rowers. **Key Words:** TRAINING INTENSITY, OPTIMAL TRAINING VOLUME, DOSE–RESPONSE VOLUME, TRAINING TO REPETITION FAILURE

Coaches and researchers with an interest in sports requiring both strength and aerobic endurance (e.g., rowing) have attempted to design and to implement periodization schemes aimed to minimize the potential interference effects traditionally associated with concurrent training (2,5). Several studies have shown that short-term repeated high-intensity concurrent resistance and endurance training may compromise the magnitude of strength and power development (7,15,24). It is also believed that for optimal strength and endurance enhancement, special attention should be paid to the order and timing of the training sessions. Thus, residual fatigue from a previous endurance session may cause a reduction in the quality of subsequent strength training by compromising the ability of the neuromuscular system to rapidly develop force (26) and/or reducing the absolute volume of strength training that could be performed in such a condition (35). The manipulation of resistance training volume (i.e., number of exercises per session, repetitions per set, or sets per exercise) is another issue that has received considerable research attention. Indeed, it has been suggested that the main effect (i.e., neural, hypertrophic, metabolic, and hormonal responses) and subsequent adaptations to resistance training partially depend on the total number of repetitions performed by an individual (1,11,12,22). Moderate increase in training volume has been shown to lead to further improvement in strength (1,11,12,33). However, it appears that once a given "optimal" volume is reached, further increases in training volume do not yield any significant gains and can even lead to reduced performance in experienced resistance-trained subjects (11,12). Unfortunately, the question of which is the optimal training volume for the simultaneous development of strength and endurance for sports requiring great demands of both components of physical fitness (e.g., rowing) remains unresolved.

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The number of repetitions performed with a given load may impact the extent of muscle damage and cause subsequent decrements in velocity and force production (20,21). Thus, the role played by training leading to repetition failure (inability to complete a repetition in its full range of motion) has been of interest to coaches and sport scientists to understand the physiological mechanisms underlying training-induced gains in strength and power. Short-term training (<9 wk) leading to repetition failure produces greater improvements in strength (6,34) when compared with a not to failure training approach. However, other studies have concluded that training to failure may not be necessary for optimal strength gains because the incurred fatigue reduces the force a muscle can generate (8,25,37). Likewise, in previously resistance-trained men, it has been reported that when the volume and intensity variables were equated, training not leading to repetition failure led to similar improvements in maximal strength and muscle power output (20) compared with training leading to failure. In light of these observations, we hypothesized that resistance training performed with the same intensity but not leading to failure (i.e., half the maximum number of repetitions that could be performed per set leading to failure) and with either identical (i.e., same number of exercises per session) or reduced volume (i.e., half the number of exercises per session) would lead to similar gains in maximal strength to training to repetition failure but to greater gains in power output and attenuate compromised strength and cardiovascular development when strength and endurance training were applied concurrently. Therefore, the purpose of this study was to examine the effect of three different 8 wk of resistance training interventions that manipulated training volume (moderate volume to failure, moderate volume not to failure, and low volume not to failure) for increasing upper-body strength and power as well as some cardiovascular variables in a group of well-trained rowers who underwent a combined resistance and endurance periodized training scheme.

METHODS

Experimental Design and Approach to the Problem

A longitudinal research design using three different resistance training volumes (i.e., sets × repetitions) performed with the same intensity (progressing from 10RM to 4RM) but with a different number of exercises (4 vs 2 exercises) and a different number of repetitions per set (i.e., leading to failure vs not leading to failure) was used to parcel out differential training adaptations in strength and power gains as well as to analyze rowing performance changes during concurrent strength and endurance training. In an attempt to minimize the effect of potential confounding variables, relative load (percentage of one-repetition maximum (1RM)) and average intensity and frequency of training were controlled by equating their values among the treatment groups. Such adjustments were critical to the study design because it has been suggested that differences in overall training intensity and volume influence performance adaptations (12,20). After baseline testing, subjects were matched according to physical characteristics, muscle strength and power indexes, and rowing performance and then randomly assigned to one of four groups: four exercises leading to repetition failure (4RF; n = 14), four exercises not leading to failure (4NRF; n = 15), two exercises not to failure (2NRF; n = 6), or a control group (C; n = 8). The control group did not undergo any resistance training but continued their usual traditional rowing training, similar to that performed by the three resistance training groups. All groups were assessed on two occassions: before (PRE) and after (POST) the 8-wk training intervention.

Subjects

This study involved a group of 43 trained male rowers with 12.1 ± 5 yr of regular training and competition experience in traditional rowing (Table 1). Traditional rowing competition is a fixed-seat rowing performed on the sea, the boat manned by 13 rowers, and a cox (23). All subjects participated in a Spanish traditional rowing league. Before inclusion in the study, all subjects were medically screened and appeared to be free from any orthopedic, cardiac, endocrinal, or medical problems that would rule out their participation or influence the results of the research. Each participant gave written informed consent to participate after the purpose and potential risks of the study were carefully explained. The study was conducted in accordance with the stipulations of the Declaration of Helsinki and was approved by the by the institutional review committee of the Instituto Navarro de Deporte.

TABLE 1. Characteristics of the periodized resistance training program performed by each group.

Group	Week	1	2	3	4	5	6	7	8	Total reps
	Sessions	2	2	2	2	2	2	2	2	
	Sets	3	4	3	4	3	4	3	4	
	Intensity (%1RM)	75	75	80	80	86	86	92	92	
4RF (n = 14)	Scheduled reps	10	10	8	8	6	6	4	4	
	Reps/session	120	160	96	128	72	96	48	64	784 × 2 = 1568
4NRF (n = 15)	Scheduled reps	5	5	4	4	3	3	2	2	
	Reps/session	60	80	48	64	36	48	24	32	392 × 2 = 784
2NRF (n = 6)	Scheduled reps	5	5	4	4	3	3	2	2	
	Reps/session	30	40	24	32	18	24	12	16	196 × 2 = 392

4RF, four exercises (prone BP, seated cable row, lat pulldown, and power clean) training to repetition failure group; 4NRF, four exercises (prone BP, seated cable row, lat pulldown, and power clean) training not to failure group; 2NRF, two exercises (prone BP and seated cable row) training not to failure group; reps, number of repetitions.

The study took place from March to April, at the end of the specific preparatory period. During the preceding months, the subjects had been training six times a week on average, with a typical training session duration of 120 min. The distribution of training was similar to that of Olympic rowing, with 60% of the specific training done in water, 20% of strength training in the gym, and 20% athletic training (i.e., running training at light and moderate intensities for cardiovascular conditioning). Furthermore, in the 5 months preceding the beginning of the study, the subjects took part in a resistance training program consisting mainly of typical free-weight exercises (i.e., including bench press, prone bench pull (BP), and back squat exercises) with three to five sets of 8–15 repetitions and a relative intensity of 50%–80% 1RM.

Brief Overview of Testing Procedures

All rowers were familiar with the testing protocol because they had been previously tested on several occasions in previous seasons for training prescription purposes. Furthermore, several warm-up muscle actions were recorded before the actual maximal, explosive, and endurance test actions.

Subjects were required to report to the laboratory on five separate occasions over a 2-wk period. Testing sessions were always carried out at the same time of day and under similar environmental conditions. During the first week, subjects visited the laboratory on three occassions, every other day, as a part of their regular testing program. Each rower was tested for one-repetition maximum (1RM) dynamic strength (day 1) and muscle power output (day 2) in the prone bench pull (BP) exercise. On the third day, anthropometric variables and power output in 10 maximal strokes ($W_{10\text{strokes}}$) were measured. In addition, during this first week, two endurance rowing sessions at low intensity (blood lactate concentration <2 mmol·L^{-1}) were performed 24 h before the testing session. During the second week, participants performed a progressive exercise test on a rowing ergometer (day 1) and a 20-min all-out test ($W_{20\text{min}}$; day 2). These sessions were interspersed with rest periods of a minimum of 48 h to limit the effects of fatigue on performance. Subjects were required to avoid any strenuous physical activity during the duration of the experiment and to maintain their dietary habits for the entire duration of the study.

Antropometry and Body Composition

Standing height (m), body mass (kg), percentage of body fat (%), and fat-free mass (FFM; kg) were determined for each subject. Height and body mass were measured using a self-calibrated scale (Año Sayol, Barcelona, Spain) and recorded to the nearest 0.5 cm and 0.1 kg, respectively. Whole-body fat was estimated according to the skinfold thickness method developed by Jackson and Pollock (32). Skinfold measurements were measured at seven sites (subscapular, tricipital, midaxillary, suprailiac, pectoral, abdominal, and anterior thigh) using a Harpenden skinfold caliper accurate to 0.2 mm (Holtain Ltd., Crymych, UK). A minimum of two measurements were taken at each skinfold site by the same highly skilled investigator. Fat-free mass (kg) was calculated as the difference between body mass and body fat.

Maximal strength and muscle power tests. A detailed description of the maximal strength and muscle power testing procedure can be found elsewhere (18,20). In brief, maximal upper-body strength was assessed using a one-repetition maximum BP ($1RM_{BP}$) action. The BP exercise (elbow and shoulder flexion) was chosen because it seems most specific to the rowing technique (27,29). Bilateral BP tests were performed with the use of standard free-weight equipment (Salter, Madrid, Spain). Subjects lay facedown on the bench with both elbows in full extension, arms completely stretched out and suspended perpendicularly at 90°, and barbell grasped with hands shoulder-width apart or slightly wider. On command, participants pulled with maximum effort until the barbell struck the underside of the bench, after which it was again lowered to the starting position. A manual goniometer (Q-TEC Electronic Co. Ltd., Gyeonggi-do, Korea) was placed at the elbow to standardize the range of motion. Warm-up consisted of a set of 10 repetitions with loads of 40%–60% of the perceived maximum. Thereafter, five to six separate single attempts with increasing loads were made until the subject was unable to flex the arms to the required position. The heaviest load that each subject could properly lift was considered to be his 1RM. The rest period between actions was always 2 min.

The upper-body power–load relationship was assessed in the BP using relative loads of 15%, 30%, 45%, 60%, 75%, 85%, and 100% of the previously determined 1RM ($W_{BP15\%} - W_{BP100\%}$). On command, the subjects were instructed to move the loads as fast as possible. Two concentric actions for each load were recorded, and that with the highest absolute power output value was taken for further analysis. The rest period between each trial was 2 min.

Each week during the intervention period, BP power output developed with the same absolute load (that corresponding to the 70% 1RM pretraining value) was assessed. This load was chosen because it has been proved to be very close to the load that maximizes the average mechanical power output for isoinertial BP resistance exercises (23). Four repetitions were performed as fast as possible with this fixed load, and the mean concentric power was retained for further analysis.

Bar displacement, mean concentric velocity, and peak and mean concentric power during BP actions were recorded by attaching a rotary encoder (FitroDyne; Fitronic, Bratislava, Slovakia) to one end of the barbell. The rotary encoder recorded the position and direction of the bar to an accuracy of 0.0003 m. Customized software was used to calculate power output for each repetition of BP performed throughout the range of motion. For comparison purposes,

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an averaged index of muscle power output with all the absolute loads examined was calculated for each group separately. The averaged index of muscle power in BP was calculated as the sum of the power values obtained under all experimental conditions ($W_{\text{index}_{\text{BP}}}$). In addition, maximal power output was defined as the maximum power obtained from all loads examined ($W_{\max_{\text{BP}}}$). The test–retest intraclass correlation coefficients for all anthropometric, strength, and power variables were greater than 0.93, and the coefficients of variation ranged from 0.92% to 1.9%.

Rowing ergometer performance tests. The rowers were fully familiar with the use of the wind-resistance braked rowing ergometer (Concept II, model D, Morrisville, VT). All evaluations were performed on a modified ergometer with a drag factor of 145, a static seat individually adapted to each rower, and legs in semiflexion (i.e., 160°). Subjects warmed up by rowing progressively for 15 min, finishing up with some strokes at maximal effort. The highest value displayed on the monitor of the ergometer when each subject rowed 10 strokes with maximal effort was considered to be his maximal rowing power (W_{10stroke}) (14). Then, they undertook two 10-stroke trials, separated by 5 min of rest. The best reading (that with the highest power output) was taken for further analysis.

Exercise tests on the ergometer were performed using an incremental step protocol, as defined by Ingham et al. (17). The subjects warmed up for 10 min. Power was initially set at 150–180 W, depending on the rowers' body mass, and increased thereafter by 25 W after each stage. Heart rate was continuously recorded using a heart rate monitor (RS 800G3, Polar Electro, Kempele, Finland). Capillary whole-blood samples were taken from the earlobe during each 30-s rest period to measure lactate concentration ([La^-]) using a miniphotometer (Dr. Lange LP-20, Düsseldorf, Germany). Individual data points for blood lactate values were plotted as a continuous function against time. The exercise lactate curve was fitted with a second degree polynomial function (r = 0.98–0.99, $P < 0.001$). From the equation describing the blood lactate response to exercise, the power output associated with a blood lactate concentration of 4 $\text{mmol}\cdot\text{L}^{-1}$ (W_{4mmol}) was interpolated. The W_{4mmol} exercise intensity has been shown to be an important determinant of endurance performance capacity (38). Stroke rate and ratings of perceived exertion according to Borg's 20-point scale were also measured (4).

A 20-min all-out test was carried out after a 15-min warm-up. On the basis of the results of the previous progressive test, the intensity the subjects had to maintain was calculated as 250–350 W per stroke. Rowers were strongly encouraged to maintain the maximum sustainable power output for 20 min. Actual power output values were recorded every 4 min and at the end of the test, then the average power during the 20 min (W_{20min}) was computed. During this time, the subjects covered distances of 5000–6300 m, with 35–40 strokes per minute, performing a total number of 675–725 total strokes.

Resistance and endurance rowing training programs. All resistance training sessions started with a general warm-up (ending with four repetitions in the BP with 70% 1RM performed with maximal intended concentric velocity) and included cooldown periods of 5–10 min of low-intensity aerobic and stretching exercises. A trained researcher carefully supervised each workout session and recorded the training compliance and individual workout data so that exercise prescriptions were properly administered (e.g., number of sets and repetitions, rest pauses, and movement velocity). Training compliance for this study was 100% of the scheduled sessions.

Treatment groups were required to perform dynamic resistance training twice per week for 8 wk. The approximate training session duration for each group was 30 min (2NRF), 45 min (4NRF), and 60 min (4RF). A minimum of 2 d elapsed between two consecutive training sessions. Four resistance training exercises (BP, seated cable row, lat pulldown, and power clean) were used for the 4RF and the 4NRF groups, whereas the 2NRF group only performed the first two (BP and seated cable row). In addition, all intervention groups performed some supplementary exercises (e.g., abdominal crunch, trunk extension) for core conditioning.

The three treatment groups followed an 8-wk linear periodization program of resistance training. One group performed four exercises always leading to repetition failure in each set (4RF), another group used the same four exercises but only completed half the maximum number of repetitions that could be performed per set (4NRF), whereas the third group performed both half the number of exercises and half the maximum number of possible repetitions within each set (2NRF). All groups used the same training intensity in each session. This intensity was continuously adjusted during the 8-wk period by the rowers' capacity to perform sets to failure (4RF group) or to maintain the expected movement velocity (4NRF and 2NRF, not to failure groups). Thus, for the 4RF group, in the case that a subject was unable to perform the concentric phase in its full range of motion, the load was slightly reduced (and the exercise immediately resumed) for subsequent repetitions. During a typical training session in the 4RF group, the training load was reduced two to three times to individually adjust the corresponding resistance to the true repetition maximum, whereas the load remained constant in the 4NRF and 2NRF groups.

A detailed summary of the resistance training volume and exercise intensity performed by each treatment group for each of the 8 wk is presented in Table 1. As already mentioned, all groups trained with the same relative loading intensity (%1RM) in each session, but training volume was distinctly manipulated for each of them. Thus, the 4NRF group performed a final training volume (total number of repetitions) that amounts to half that of the 4RF group. Likewise, the 2NRF group only performed half the total training volume completed by the 4NRF group. Subjects

TABLE 2. Subjects' physical characteristics before and after the training intervention.

	4RF (n = 14)	4NRF (n = 15)	2NRF (n = 6)	Control (n = 8)
Age (yr)	25.4 ± 4.2	26.7 ± 5.7	22.1 ± 3.6	27.3 ± 7.1
Training experience (yr)	10.7 ± 3.1	12.6 ± 5.7	10.5 ± 4.4	15.2 ± 6.3
Height (cm)	181.0 ± 3.7	182 ± 4.9	184.5 ± 4.5	183.3 ± 4.1
Body mass (kg)				
PRE	79.8 ± 5.3	83.2 ± 6.3	85.8 ± 6.6	82.7 ± 7.5
POST	77.6 ± 4.5*	81.1 ± 5.9*	83.1 ± 5.5*	81.6 ± 7.2*
Body fat (%)				
PRE	12.1 ± 1.3	12.3 ± 1.7	13.5 ± 2.2	11.8 ± 1.5
POST	11.2 ± 0.7*	11.5 ± 1.3*	12.3 ± 1.4	11.3 ± 1.2
FFM (kg)				
PRE	70.0 ± 4.3	72.9 ± 4.6	74.0 ± 5.2	72.9 ± 6.3
POST	68.8 ± 3.8*	71.7 ± 4.6*	72.8 ± 5.1*	72.3 ± 6.4*

Values are presented as mean ± SD.

* $P < 0.05$ vs PRE.

4RF, four exercises training to repetition failure group; 4NRF, four exercises training not to failure group; 2NRF, two exercises training not to failure group; C, control group; FFM, fat-free mass; PRE, before intervention; POST, after 8 wk of training.

were carefully instructed to always perform the concentric phases of all exercises at the highest possible velocity, whereas the eccentric actions were done at a low, controlled velocity.

Besides the resistance training program underwent by the 4RF, 4NRF, and 2NRF groups, during the 8-wk period, all four groups performed the same endurance regimen. This endurance program comprised two mesocycles with a 3:1-wk training to recovery load structure. Rowers averaged a total of 45 training sessions during which 460 min·wk^{-1} of aerobic exercise (including both ergometer and on-water rowing) were performed. On the basis of training diary records, 87% of the endurance sessions were performed at low intensity ([La$^-$] <2 mmol·L^{-1}), 7% between 2 and 4 mmol·L^{-1}, and 6% above 4 mmol·L^{-1}.

Statistical analyses. Standard statistical methods were used for the calculation of means and SD. One-way ANOVA was used to determine any differences among the four groups' initial strength, power, and rowing ergometer endurance performance. The training-induced effects were assessed using a two-way ANOVA with repeated-measures (groups × time). When a significant F value was achieved, Sheffé *post hoc* procedures were performed to locate the pairwise differences between the means. Absolute changes in selected parameters (i.e., strength, muscle power, and endurance rowing variables) were analyzed via one-way ANOVA. Statistical power calculations for this study

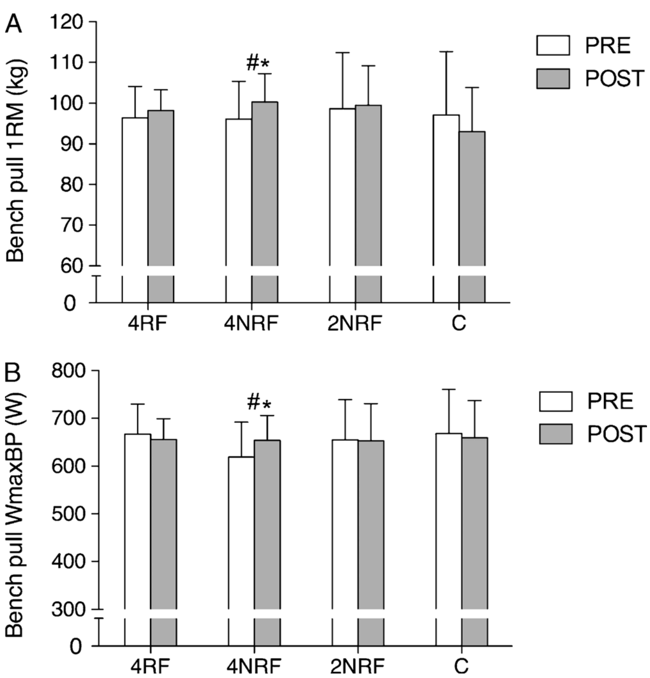

FIGURE 1—BP (A) maximal strength (1RM$_{BP}$) and (B) maximum power obtained from all loads examined ($W_{max_{BP}}$). *P < 0.05 from pretraining. #P < 0.05 from the relative change between groups. Data are presented as mean and SD.

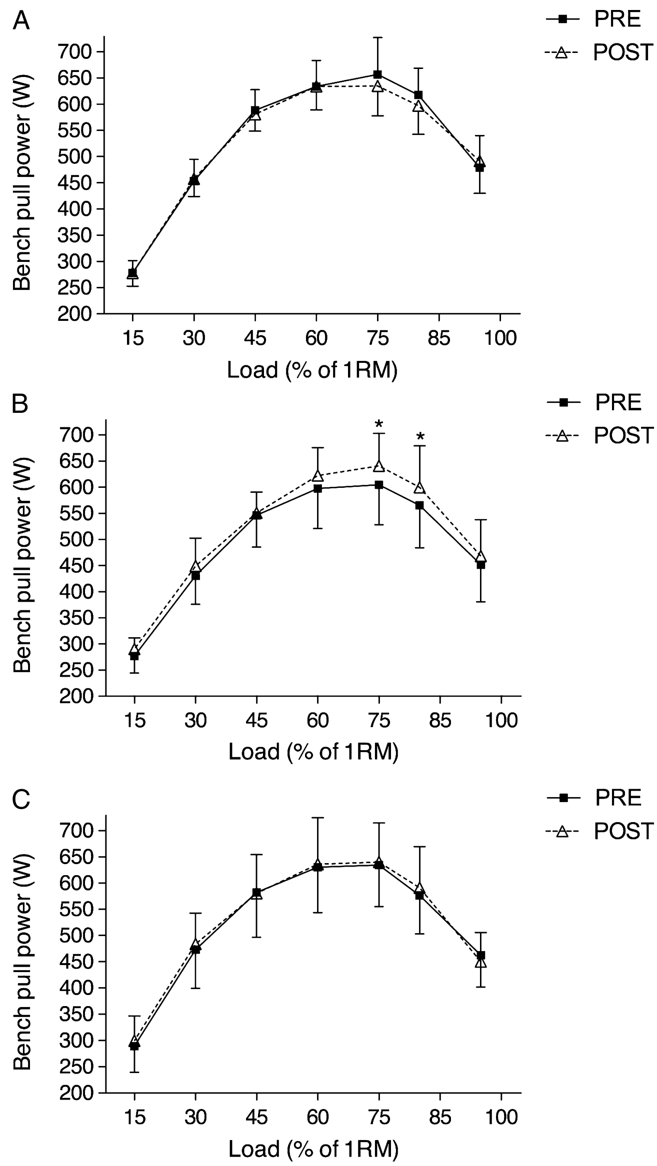

FIGURE 2—Mean ± SD muscle power output in the concentric BP action at different loads of individual maximal 1RM in 4RF (A), 4NRF (B), and 2NRF (C) group. *P < 0.05 from corresponding value at pretraining. Data are presented as mean and SD.

ranged from 0.75 to 0.80. The $P < 0.05$ criterion was used for establishing statistical significance.

RESULTS

Body composition. At the beginning of the training program, no significant differences were observed between groups in age, training experience, height, body mass, body fat mass, or FFM. A significant decrease in body mass, body fat, and FFM was observed after training in 4RF and 4NRF groups. After the intervention, a significant decrease was also observed for 2NRF and control groups in body mass and FFM, whereas no significant differences were observed in body fat (Table 2).

Maximal strength and muscle power output. At baseline, no significant differences were observed between groups in maximal strength ($1RM_{BP}$), maximal power at all loads (from 15% to 90% of $1RM_{BP}$; $W_{max_{BP}}$), and power output index in BP ($W_{index_{BP}}$). In the control group, no significant changes were observed from PRE to POST for any of the maximal strength and muscle power variables analyzed. After the training period, significant increases were observed in $1RM_{BP}$, $W_{max_{BP}}$, and $W_{index_{BP}}$ but only in the 4NRF group. Significant group × time interaction was observed for the $1RM_{BP}$, with a significantly larger magnitude of increase for 4NRF (4.6%) than that found in 4RF and 2NRF (2.1% and 0.6%, respectively) (Fig. 1A). Significant group × time interaction was observed for the $W_{max_{BP}}$ and $W_{index_{BP}}$ with a significantly larger ($P < 0.05$) magnitude of increase for 4NRF (6.4% and 5.2%, respectively) than that recorded in 4RF (−1.2% and −0.6%) and 2NRF (−0.3% and 2.2%) (Fig. 1B).

Significant increases were observed in muscle power output at 75% and 85% of $1RM_{BP}$ for the 4NRF group (Fig. 2B). A significant group × time interaction was observed in muscle power output at 75% and 85% of $1RM_{BP}$, with a significantly larger ($P < 0.05$) magnitude of increase for 4NRF (6.6% and 6.7%) than those recorded in 4RF (−3.1% and −2.7%) and 2NRF (0.8% and 1.4%) from PRE to POST training (Fig. 2, A–C).

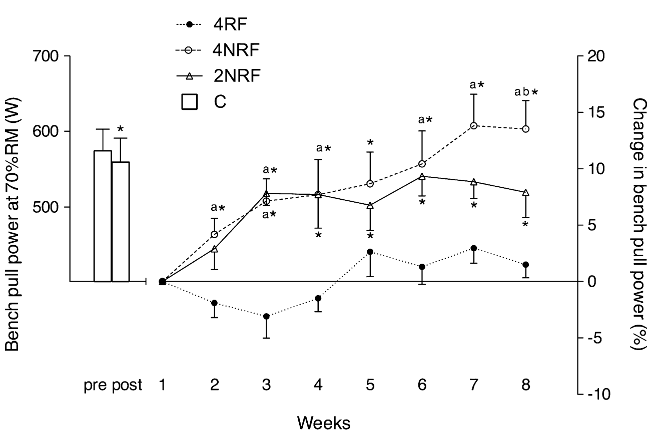

FIGURE 3—Mean ± SD muscle power output with an absolute load corresponding to the 70% of $1RM_{BP}$ during experimental period. *$P < 0.05$ from week 1. [a]$P < 0.05$ from corresponding value of 4RF. [b]$P < 0.05$ from corresponding value of 2NRF.

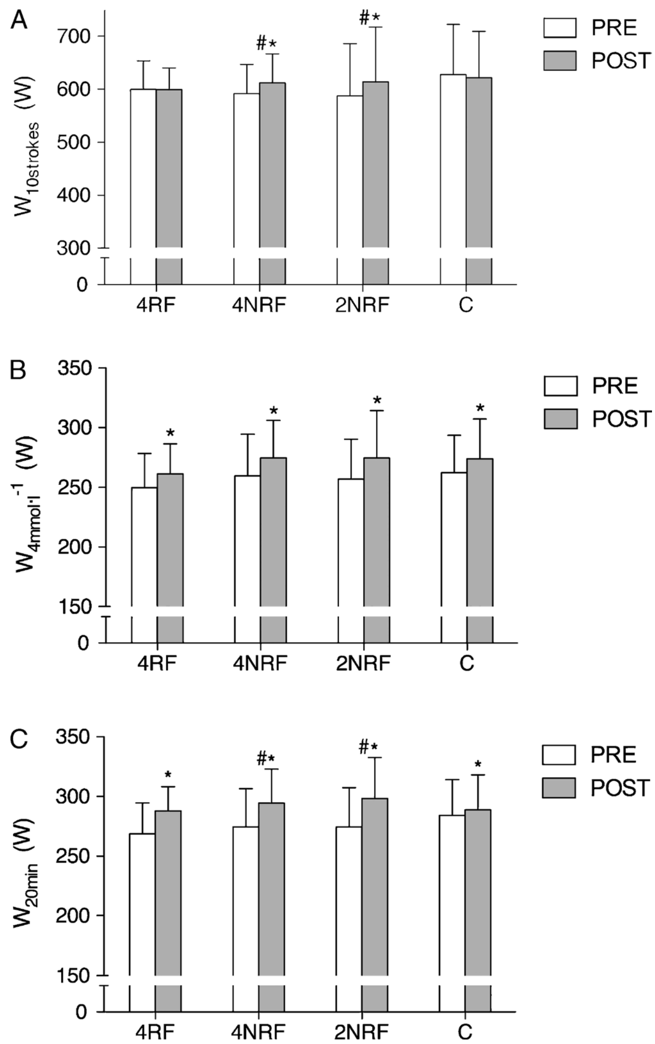

FIGURE 4—Mean ± SD power output of 10 strokes ($W_{10strokes}$) (A), which elicited a blood lactate concentration of 4 mmol·L^{-1} (B), and during 20 min of all-out test (W_{20min}) (C) attained in rowing ergometer during the experimental period. *$P < 0.05$ from pretraining. #$P < 0.05$ from relative change between the groups.

At baseline, no significant differences were observed in muscle power output with an absolute load corresponding to the 70% of $1RM_{BP}$. During the 8 wk of intervention, significant increases were observed in muscle power output with an absolute load corresponding to 70% of $1RM_{BP}$ at pretraining for 4NRF and 2NRF (Fig. 3), whereas no significant changes were observed in the 4RF group. In the control group, significant decreases (−2.6%) were observed from PRE to POST for this variable. Significant group × time interaction was observed in muscle power output with an absolute load corresponding the 70% of $1RM_{BP}$ at pretraining, with a significantly larger ($P < 0.05$) magnitude of increase for 4NRF (13.1%) than that recorded in 4RF and 2NRF groups (1.3% and 7.9%, respectively) (Fig. 3).

Performance in rowing ergometer. At baseline, no significant differences were observed between groups in rowing ergometer performance variables (i.e., $W_{4\mathrm{mmol}\cdot\mathrm{L}^{-1}}$ and $W_{20\mathrm{min}}$). $W_{10\mathrm{strokes}}$ increased significantly only in the 4NRF and 2NRF training groups. Significant group × time interaction was observed in $W_{10\mathrm{strokes}}$, with a significantly larger magnitude of change for 4NRF and 2NRF (3.6% and 5%) than that found for the 4RF (−0.1%) and control groups (−0.8%) (Fig. 4A).

$W_{4\mathrm{mmol}\cdot\mathrm{L}^{-1}}$ significantly ($P < 0.05$) increased in all groups after 8 wk of intervention period (Fig. 4B). No significant differences were observed in the magnitude of the change between groups (4NRF 6.2%, 4RF 5.3%, 2NRF 6.8%, and C 4.5%).

Significant increases were observed in $W_{20\mathrm{min}}$ for all groups (Fig. 4C). Significant group × time interaction was observed in $W_{20\mathrm{min}}$, with a significantly larger ($P < 0.05$) magnitude of increase for 4NRF and 2NRF (7.6% and 9%) than those recorded in 4RF (4.6%) and control groups (4.5%).

DISCUSSION

The two major findings of this study were that after 8 wk of combined resistance and endurance training, 1) the 4NRF group experienced larger gains in maximal strength and maximal power output, in absolute and relative terms, when compared with both 4RF and 2NRF groups; and 2) the 4NRF and the 2NRF groups improved $W_{10\mathrm{strokes}}$ and $W_{20\mathrm{min}}$ to a greater extent than the 4RF group, whereas no significant differences between groups were observed in the magnitude of changes in rowing power associated with a $[\mathrm{La}^{-}]$ of 4 $\mathrm{mmol}\cdot\mathrm{L}^{-1}$. These data seem to indicate that short-term resistance training using a moderate volume of repetitions not to failure enables a favorable environment for achieving greater enhancements in strength, muscle power, and rowing performance compared with higher training volumes of repetitions to failure. Therefore, our results suggest that to improve performance in sports with great demands of both muscle strength and aerobic endurance, a combined program of endurance and resistance exercise characterized by not training to repetition failure and performing only a moderate number of repetitions in each training session may be an effective and safe option for highly trained athletes.

Few studies have examined the different possibilities of manipulating resistance training volume for the concurrent development of strength and endurance in sports with great requirements of both fitness components (e.g., rowing). As already mentioned, moderate increases in training volume have been shown to lead to further improvement in strength (1,11,12,20,33). However, It appears that once a given "optimal" volume is reached, a further increase in training volume does not yield more gains and can even lead to reduced performance in experience resistance-trained subjects (11,12). The results of the present study tend to support this because only the 4NRF group led to significant increases in maximal strength and relative muscle power during a concurrent strength and aerobic training. In contrast, 2NRF and 4RF approaches did not provide an adequate stimulus for improving upper-body maximal strength and power during concurrent strength and endurance training, despite the training volume in 2NRF being 25% of that performed in 4RF. This seems to indicate that during concurrent strength and endurance training (i.e., row training), an optimal resistance training volume should be one that that elicits not only maximal strength and power gains but also an improvement in specific rowing performance. Thus, it is likely that performance could be compromised if this threshold volume were surpassed or drastically reduced, perhaps suggesting that moderate-volume high-intensity stimuli are needed to induce further power gains in highly trained athletes when the concurrent development of both strength and endurance are important.

Short-term isolated strength training programs (<9 wk) consisting of repetitions performed to failure have shown to lead to greater strength gains (6,34) compared with approaches not leading to failure in untrained subjects. On the contrary, other studies have shown that training to failure may not be necessary for optimal training gains (8,25,37). Several factors such as differences in the manipulation of volume and intensity of training, dependent variable selection, muscle groups involved, and initial training status of the subjects may explain the contradictory results of these studies. Recently, Izquierdo et al. (20) reported that training to failure and training not to failure resulted in similar gains in 1RM strength and muscle power output of the arm and leg muscles. That study was performed in a strength-trained population with a carefully equated and controlled volume and training intensity in the experimental groups. However, after a preceding peaking phase, training not leading to failure resulted in higher gains in muscle power compared with a training leading to failure approach. To the authors' knowledge, no studies have isolated the effects of performing sets leading to failure (or the number) in a multigroup experimental design while controlling other variables in a long-term training protocol in sports where both endurance and strength need to be simultaneously enhanced to optimize performance. The results of the present study suggest that short-term combined endurance and resistance training leading to failure do not provide an advantage for improving upper-body maximal strength and muscle power in highly trained rowers. In contrast, in the present combined training program, a not leading to failure and moderate training volume approach resulted in greater increases in maximal strength and muscle power gains of the upper-body musculature. This moderate increase (4%–6%) in maximal strength and muscle power was observed in spite of significant losses (~1.6%) in FFM in response to the combined endurance and resistance training intervention in all treatment groups (i.e., 4RF, 4NRF, and 2NRF). This pattern of results may be due to the very high physical demands placed on the athletes during the short-term high-intensity combined endurance rowing and strength training program.

APPLIED SCIENCES

Our findings are consistent with those of a previous study performed in trained subjects (24), which reported that combining strength and endurance training attenuates the muscle fiber hypertrophy produced by resistance training alone. Nevertheless, further research is required to optimize maximal strength and power development in the context of combined strength and endurance training.

Previous studies have also shown that short-term high-intensity concurrent resistance and endurance training may compromise the magnitude of strength and power development (7,15,24). The attenuated strength improvement usually observed in concurrent training has been attributed to the development of residual fatigue in the neuromuscular system (15) because of the high volume and training frequency (4–6 $d \cdot wk^{-1}$) typical of these combined programs, even during short-term training periods (<12 wk) (7,15,24). A trend toward attenuated strength adaptations with concurrent training could be also observed when a demanding amount of training volume and/or frequency was performed over a long period (3,13). However, when the training frequency is low (2–3 $d \cdot wk^{-1}$), there may be a synergistic effect between strength and endurance training in the observed increase in maximal strength during both short-term (<12 wk) (4,19,28) and long-term training periods (>20 wk) (13). Research has also documented that short-term repeated high-intensity training can lead to overtraining (9). Thus, residual fatigue from a previous aerobic session could cause a reduction in the quality of subsequent strength training by compromising the ability of the neuromuscular system to rapidly develop force (26) and/or by reducing the absolute volume of strength training that could be performed in such condition (10,35,36). Therefore, it appears that the manipulation of training volume and/or intensity is critical to avoid potential interferences in concurrent training (5,10,19), especially when high-intensity resistance training is performed concurrently with regular endurance rowing in well-trained athletes.

Tracking weekly time-course changes in the upper-body muscle power output developed with an absolute load corresponding to 70% 1RM pretraining value is a unique aspect of the present study that provides meaningful data for resistance training design during concurrent strength and endurance training. A moderate-volume training program performing each set not to muscular failure (i.e., 4NRF group) led to greater gains in power output, whereas no significant weekly gains in power were observed for the high-volume training to repetition to failure (i.e., 4RF) approach. These data indicate that training to failure for improving absolute upper-body muscle power may not provide a positive stimulus for optimal power development during concurrent training. Conversely, a moderate volume of training sets not performed to muscle failure made it possible to attain high power output values during a few selected repetitions and to minimize fatigue so that near-maximum neuromuscular drive and force could be applied to each repetition (20,21).

An interesting finding of the present study was that the periodized strength training program not leading to failure with moderate-volume (4NRF) and low-volume (2NRF) approaches induced greater gains in anaerobic rowing performance (e.g., $W_{10strokes}$) and average power during the 20-min all-out test (e.g., W_{20min}) than high-volume training to failure approach (4RF) or endurance only (control group). In addition, no significant differences between groups were observed in the magnitude of changes in stroke power associated with a blood lactate concentration of 4 $mmol \cdot L^{-1}$ ($W_{4mmol \cdot L^{-1}}$). These results are partially in agreement with those of previous studies, which showed that the addition of resistance training to ongoing exercise regimens of well-trained endurance athletes is beneficial and results in improved endurance performance (10,16,30,31). Similarly, it has recently been reported that a periodized training program can be effectively used for simultaneously developing strength and aerobic endurance in elite kayakers (10). Furthermore, our results also suggest that when training resistance volume is carefully controlled, high-volume program leading to failure does not yield improved aerobic gains and can even negatively affect rowing performance in highly trained endurance athletes. In contrast, this result may suggest that alternating exercise modes of moderate- or low-volume resistance training not leading to failure (e.g., 4NRF or 2NRF groups) combined with endurance training may help to increase training-induced aerobic gains compared with single endurance mode of training. Therefore, in the context of an 8-wk concurrent resistance and endurance rowing training cycle, highly trained rowers can enhance endurance gains by performing 50% or less of the maximum number of repetitions performed that could be completed in a given set while improving also neuromuscular function. By doing so, a moderate-volume training program performing each set not to muscular failure (i.e., 4NRF group) could be more efficient for also improving maximal strength and relative muscle power as well as providing a better stimulus for improving endurance performance during a concurrent strength and aerobic training cycle.

In conclusion, an 8-wk linear periodized concurrent strength and endurance training program using a moderate number of repetitions not to failure provides a favorable environment for achieving greater enhancements in strength, muscle power, and rowing performance when compared with higher training volumes of repetition to failure in experienced highly trained rowers. By contrast, both muscle strength and rowing performance could be compromised if a given threshold volume is surpassed or drastically reduced during a short-term training program, especially when both strength and aerobic endurance need to be concurrently enhanced.

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