SPECIFIC TRAINING EFFECTS OF CONCURRENT AEROBIC AND STRENGTH EXERCISES DEPEND ON RECOVERY DURATION

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ABSTRACT

Robineau, J, Babault, N, Piscione, J, Lacome, M, and Bigard, AX. Specific training effects of concurrent aerobic and strength exercises depend on recovery duration. *J Strength Cond Res* 30(3): 672–683, 2016—This study aimed to determine whether the duration (0, 6, or 24 hours) of recovery between strength and aerobic sequences influences the responses to a concurrent training program. Fifty-eight amateur rugby players were randomly assigned to control (CONT), concurrent training (C-0h, C-6h, or C-24h), or strength training (STR) groups during a 7-week training period. Two sessions of each quality were proposed each week with strength always performed before aerobic training. Neuromuscular and aerobic measurements were performed before and immediately after the overall training period. Data were assessed for practical significance using magnitude-based inference. Gains in maximal strength for bench press and half squat were lower in C-0h compared with that in C-6h, C-24h, and STR. The maximal voluntary contraction (MVC) during isokinetic knee extension at $60°\cdot s^{-1}$ was likely higher for C-24h compared with C-0h. Changes in MVC at $180°\cdot s^{-1}$ was likely higher in C-24h and STR than in C-0h and C-6h. Training-induced gains in isometric MVC for C-0h, C-6h, C-24h, and STR were unclear. $\dot{V}O_2$peak increased in C-0h, C-6h, and C-24h. Training-induced changes in $\dot{V}O_2$peak were higher in C-24h than in C-0h and C-6h. Our study emphasized that the interference on strength development depends on the recovery delay between the 2 sequences. Daily training without a recovery period between sessions (C-0h) and, to a lesser extent, training twice a day (C-6h), is not optimal for neuromuscular and aerobic improvements. Fitness coaches should avoid scheduling 2 contradictory qualities, with less than 6-hour recovery between them to obtain full adaptive responses to concurrent training.

KEY WORDS endurance, neuromuscular, interference, resistance

INTRODUCTION

Improvement of physical performance is highly dependent on the type of training performed. The physiological responses to endurance training, which commonly consists of low-resistance and high-repetition exercises, involve cardiorespiratory (e.g., pulmonary diffusion, cardiac output) (14) and muscular (e.g., capillary and mitochondrial volume density, oxidative enzyme activity) adaptations (10). In contrast, strength training, which includes high-resistance and low-repetition exercises, causes muscle fiber hypertrophy and neural adaptations that improve the strength production capacity (15,33).

Because many sport activities require the execution of high-intensity efforts that may be repeated over time, athletes may be required to train for both strength and endurance simultaneously (13). However, previous studies showed that strength training combined with endurance exercises in a single program is known to impair strength and power gains in comparison with strength training alone (12,18,19,23,25). Hickson (19) was the first to provide evidence that such concurrent training attenuates the development of strength, in comparison with resistance training alone. Numerous studies have highlighted the impact of these interferences on maximal dynamic strength (25), speed running (23), and maximal torque, especially at fast angular velocities (12,39). Nevertheless, other conflicting results have also been published so that impairment in strength or power development in response to concurrent training remains a subject of debate (26,31,36). Most published observations disclose improvements in peak oxygen consumption and markers of aerobic capacity after concurrent training (8,9,12,16,18,19,31,36).

A recent and complete meta-analysis identified modality, duration, and frequency of endurance exercises as the main

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factors supporting the interferential effects of endurance training on the expected improvement of strength and power in response to resistance training (39). Moreover, the influences of several training factors such as (a) intensity and volume of endurance and strength exercises, (b) sequencing and timing of concurrent training sessions, and (c) timing of recovery periods between exercises have been previously addressed to minimize the interference (12,22,36). For example, training programs using serial concurrent exercises (i.e., sequential strength and aerobic exercises in every session) lead to lower responses of the peak torque of knee extensors and flexors when aerobic exercises precede strength as compared with the opposite (4). Although concurrent training programs in which strength precedes endurance within the same session are expected to lead to more favorable strength adaptations (4), the responses of strength power to such programs remain controversial (9,11,16).

Another important factor that might explain the interference effect of concurrent training programs that use serial exercises is the duration of the recovery period between strength and endurance exercises. To our knowledge, data describing the role played by the recovery delay between endurance and strength exercises on adaptations to concurrent training protocols are spare. It has been shown that a 24-hour recovery between strength and endurance sequences leads to higher maximal strength improvements than when both exercises are performed during the same training bout (35). However, it is not known whether a recovery period less than 24 hours maximizes the combined effects of endurance and strength training, especially on muscle strength and power development. Moreover, the optimal length of recovery periods has not been examined in concurrent training consisting of strength exercises followed by high-intensity endurance exercises. These questions are warranted because the training load in top-level sport, increased since several years, induced a twice-a-day organization of the training with sometimes no or only few hours between the concurrent sequences.

Therefore, the purpose of this study was to (a) investigate the impact of concurrent training when strength precedes endurance exercises on the gains in strength, power, and aerobic capacity and (b) determine whether the recovery between strength and high-intensity, interval-type exercises would influence the expected interference effect. It allowed giving helpful recommendations to coaches to harmonize the program of strength and endurance qualities. For that purpose, the physiological responses to a 7-week serial concurrent training program were compared with those observed after strength training only. Three concurrent training programs were tested with 0-, 6-, and 24-hour recovery delays between strength and endurance sequences. We hypothesized that gains in muscle performance would be better after a 6-hour recovery than if endurance bouts are performed immediately after strength exercises but would be lower than if sessions are separated by 24-hour recovery.

Methods

Experimental Approach to the Problem

The experiment was 10 weeks long with the first week dedicated to familiarization with all equipment and testing procedures, the second week involved the initial tests, the next 7 weeks the training programs, and the last week the final tests (Figure 1).

The independent variable was the treatment effect of 5 different 7-week training programs with 1 control group (CONT), 1 strength training group (STR), and 3 concurrent strength and endurance training groups. This last group consisted of 2 sequences a week of each quality. The only difference was the recovery delay between strength and endurance sequences. Strength training was always performed first and was followed directly (C-0h), 6 hours (C-6h), or 24 hours (C-24h) by endurance training. STR only completed the strength sequences. At least 72 hours elapsed between the 2 strength sequences for all training groups (C-0h, C-6h, C-24h, and STR). CONT did not train during the entire duration of the experimental protocol and only performed pretest and posttest. The dependant variables allowed evaluating neuromuscular and oxidative adaptations through field and laboratory tests. Regarding to the field tests, the 1 repetition maximum (1RM) of the lower limbs (half squat [HS]) and upper limbs (bench press [BP] and bench row [BR]) and the countermovement jump (CMJ) height allowed maximal strength and muscular power

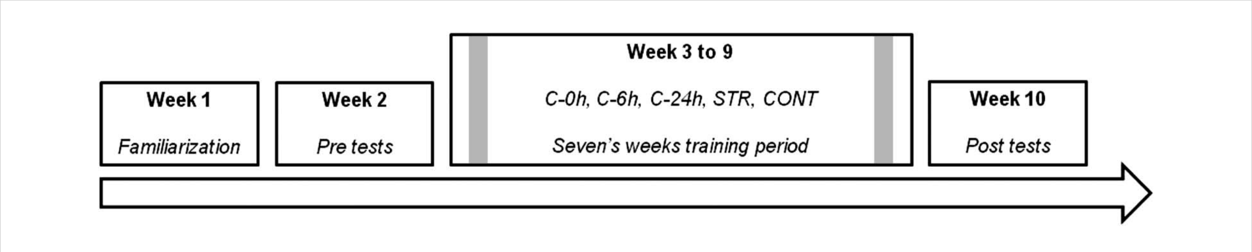

Figure 1. Experimental design of the study. The gray bars correspond to the 1 repetition maximum and countermovement jump tests. Maximal aerobic field test was only performed at the first training. CONT = control; C-0h = no recovery between sequences; C-6h = 6-hour recovery between sequences; C-24h = 24-hour recovery between sequences; STR = strength.

measurements, respectively. Laboratory tests allowed evaluating neuromuscular properties of the right knee extensors (maximal voluntary and electrically evoked torque, electromyography [EMG] activity and voluntary activation level) and the peak of the oxygen consumption ($\dot{V}O_2$) measured during a graded maximal running test. Throughout the experimental procedure, participants were asked not to change their dietary habits.

Subjects

Fifty-eight amateur rugby players volunteered for this experiment ([mean ± *SE*] age, 25.5 ± 0.4 years, ranging from 21 to 28 years). All were free from severe injuries for the last year. Their practice volume was ~4–5 hours per week with only minimal experience in resistance training. Volunteers were randomly assigned to 1 of the 5 experimental groups with 3 concurrent strength and endurance training groups, 1 strength training group, and 1 control group. Individual characteristics for the 5 groups are presented in Table 1. The entire experiment was performed during the summer off-season. Therefore, subjects performed only 1 of the 5 training programs. They were asked to restrict fatiguing efforts at least 2 days before each test session and were also advised to maintain their normal dietary intake throughout the study. No food supplement was administered during all the protocol duration. Subjects were informed about the design of the study and all signed a written consent form. The study was in agreement with the Helsinki statement and was approved by the Ethics Committee (ComEth) of Grenoble.

Field Tests

One Repetition Maximum and Countermovement Jump. Field tests were performed to measure gains related to training but also to finely determine appropriate work intensities for strength and endurance training. The 1RM for each exercise was evaluated at the beginning and at the end of the training program. To warm up, subjects performed 2 series with light loads for each exercise. Then, they began the 1RM test by performing series of only 1 repetition with progressively heavier weights until the 1RM was achieved. The precision was 2.5 kg for upper-limbs movements (BP and BR) and 5 kg for HS (20). Maximal power of the lower limbs was also measured at the beginning and end of training, using the CMJ with an Optojump system (Microgate, Bolzano, Italy). It was performed starting from a standing position, then squatting down to an individually defined knee angle, and finally, extending the knee in 1 continuous movement. Arms were kept on the hips to minimize the upper-body contribution. The position of the upper body was standardized to avoid flexion and extension of the trunk (27). Participants performed 3 trials, and only the highest jump was retained for analyses.

Graded Maximal Aerobic Field Effort. At the beginning of the training procedure, subjects were submitted to a graded maximal aerobic field effort to set individual velocities used during the aerobic training. Each test started at 8 $km \cdot h^{-1}$ for 2 minutes followed by 0.5 $km \cdot h^{-1}$ increments in velocity each minute. Heart rate (HR) was continuously measured using a portable HR monitor. This field test was conducted until exhaustion. Maximal HR was determined as the highest HR achieved during the test. The last velocity sustained for 1 minute was the maximal aerobic velocity (MAV).

Laboratory Tests

Neuromuscular Properties Measurements. Neuromuscular properties of the right knee extensors (maximal voluntary and electrically evoked torque, EMG activity, and voluntary activation level) were measured 1 week before and after the training on a previously validated Contrex isokinetic dynamometer (Medimex, Zürich, Switzerland) (30). Participants were seated upright on the dynamometer chair with an 85° hip angle. Velcro straps were applied tightly across the thorax and pelvis; the leg being fixed to the dynamometer lever-arm. The axis of rotation of the dynamometer was aligned to the lateral femoral condyle, indicating the anatomical joint axis of the knee. Arms were positioned on both sides of the chest with each handgripping handle. Leg extensions were conducted within a 90° range of motion (from 100° to 10° knee flexion; 0° corresponding to complete leg extension). For all torque measurements, appropriate corrections were made for the gravitational effect of the leg by recording and subtracting the resistive torque of the leg on relaxed subjects. Subjects were encouraged by investigators to push as hard as possible throughout the contractions.

Table 1. Characteristics of subjects.*†

	CONT (*n* = 10)	C-0h (*n* = 15)	C-6h (*n* = 11)	C-24h (*n* = 12)	STR (*n* = 10)
Age (y)	25.2 ± 3.5	24.3 ± 3.8	28.0 ± 4.5	24.8 ± 3.9	25.2 ± 4.4
Weight (kg)	88.3 ± 8.9	85.7 ± 11.5	90.4 ± 9.1	83.5 ± 14.9	90.8 ± 14.5
Height (cm)	182.5 ± 4.6	172.4 ± 41.7	180.9 ± 6.3	176.6 ± 6.8	180.7 ± 7.4

*CONT = control; C-0h = no recovery between sequences; C-6h = 6-hour recovery between sequences; C-24h = 24-hour recovery between sequences; STR = strength.

†The values are expressed in mean ± *SD*.

Each session began with the determination of the optimal electrical stimulation intensity for quadriceps muscles. Then, subjects performed a standardized warm-up composed of submaximal contractions: 8 concentric at $180°\cdot s^{-1}$, 6 concentric at $60°\cdot s^{-1}$, and 2 isometric at 75°. After warm-up, the quadriceps maximal voluntary torque (MVT) was measured in isometric and concentric conditions. Isometric contractions (MVC) were maintained ~6 seconds at a 75° knee flexion angle. Sets of 4 concentric contractions were performed at a $60°\cdot s^{-1}$ (MVC_{60}) and at a $180°\cdot s^{-1}$ (MVC_{180}). Two attempts were made for each condition with 2-minute recovery between trials. Maximal torque was retained for the isometric condition, and concentric torque was measured at 75°. Then, the ability to repeat maximal isometric contraction was evaluated by means of a fatiguing procedure that consisted of twenty 5-second maximal isometric contractions interspaced with 10-second recovery. Mean values of each contraction were retained for analyses. First, the mean muscular work was calculated by averaging the 20 MVC: $MVC_{mean} = \sum MVC/20$. Thereafter, muscle fatigability was measured by means of the following formula: $MVC_{dec}\ (\%) = 1-(MVC_{mean}/MVC_{best})\times 100$ with MVC_{best} corresponding to the highest MVC value of the 20 MVC. Torque, angular position, and EMG signals were digitized online (sampling frequency 2,000 Hz) using a Biopac system (MP 150, Biopac Systems, Inc., Santa Barbara, CA, USA) and stored on hard disk for further analyses.

Electromyographic Activity. Electromyographic activity was concomitantly measured and recorded with 3 pairs of silver chloride surface electrodes applied over the belly of the 3 superficial knee extensor muscles (vastus lateralis, vastus medialis, and rectus femoris). The interelectrode distance was 2 cm (center to center). The reference electrode was fixed to the right patella. Low impedance (<2,000 Ω) of the skin-electrodes interface was obtained by shaving, abrading with sandpaper, and cleansing with alcohol. Electromyographic signals were amplified with a bandwidth frequency ranging from 1 to 500 Hz (common mode rejection ratio = 90 dB, impedance = 100 MΩ, gain = 1,000) and recorded with a sampling frequency of 2,000 Hz.

Mechanical Properties and Voluntary Activation Level. Electrical neurostimulations were used to determine the mechanical properties of the knee extensors and the voluntary activation level by using the twitch interpolation technique (32). The cathode (ball probe, ~10-mm diameter) of the high-voltage stimulator (Digitimer DS7, Hertfordshire, United Kingdom) was pressed onto the femoral triangle over the femoral nerve and moved to the position giving the greatest visible contraction of the whole quadriceps muscle group. The anode (self-adhesive electrode, 10 × 5 cm) was positioned midway between the superior aspect of the greater trochanter and the inferior border of the iliac crest. To determine each subject's maximal stimulation intensity, a series of single square-wave stimuli (1-millisecond duration, 400-V maximal voltage) were delivered by progressively increasing the current until there was no further increase in the evoked isometric twitch response (75° knee flexion). The plateau in twitch torque, so obtained, was taken as the maximal stimulation intensity. The corresponding M-wave (EMG peak-to-peak amplitude) was quantified (3). A mean value was finally calculated by averaging the M-wave of the 3 superficial knee extensors. Then supramaximal stimulations (maximal intensity + 10%) were delivered with paired impulses (here called doublet; 10-millisecond interstimuli intervals) before, during (~4 seconds after the beginning of the contraction), and 5 seconds after (potentiated doublet) each MVC. Electrically evoked peak torque was quantified to determine contractile properties (doublet at rest before isometric contractions) and activation levels using the following formula: $\text{Activation level}\ (\%) = [1-(A\times(T\ stim/MVC))/B]\times 100$, with A = amplitude of the superimposed doublet, B = amplitude of the potentiated doublet, and T stim = voluntary torque when doublet is superimposed (38).

Aerobic Performance Tests. A graded maximal aerobic running test until volitional exhaustion was performed on a mechanical treadmill (Medical development S2500, Tecmachine filiale HEF groupe, Andrezieux-Boutheon, France) with simultaneous electrocardiogram, 1 week before and after the training program. The initial velocity was $5\ km\cdot h^{-1}$ and increased by $1\ km\cdot h^{-1}$ every minute. $\dot{V}O_2$ was measured continuously using a breath-by-breath analyzer (Oxycon pro; Jaeger, Wuerzburg, Germany). Peak $\dot{V}O_2$ was determined as the highest 300-second rolling average of $\dot{V}O_2$ during the test and was retained for the analyses.

Field tests, such as 1RM and CMJ were performed during the first and the last strength training. The graded maximal aerobic field test was only performed during the first aerobic training. Laboratory tests were performed 1 week before and after the training program.

Strength Training

Every session began with a warm-up focused on abdominals/core training. Strength training sessions consisted of 3–4 sets of 3–10RM of the lower limbs (HS and leg press [LP]) and upper limbs (BP and BR). Training was divided into 3 periods during which the intensity progressively increased. The first period (weeks 1–2) aimed to prepare participants for a maximal strength training by performing 3 or 4 series with 10 repetitions a set at 70% of the 1RM. The second (weeks 3–5) and the third periods (weeks 6–7) were designed to increase maximal strength performing 3 or 4 series with 6 and 3 repetitions a set close to 80 and 90% 1RM, respectively (Table 2). The 1RM was checked each week to regulate strength workload. Each set of HS, done on a guided machine, was immediately followed by plyometric jumps. Also, sets of LP were combined with eccentric exercises on hamstring muscles. Rest between sets ranged from 2

Table 2. Description of the strength training program.*

Weeks	1–2	3–5	6–7
Warm-up exercises			
Abdominals/core training (min)	2 × 3	3 × 3	3 × 3
Main exercises			
BP and BR series	3	3	3
HS and LP series	4	4	3
Repetitions	10	6	3
Intensity (% 1RM)	70	80	90
Recovery (min)	2	3	3
Complementary exercises			
Plyometrics	6	6	6
Hamstring	6	6	6

*BR = bench row; BP = bench press; HS = half squat; LP = leg press; 1RM = 1 repetition maximum.

to 3 minutes according to strength training recommendations (hypertrophic vs. maximal strength) (40). All contractions during upper-limbs exercises were performed in isoinertial conditions with free weights. The ones done during lower limbs exercises were performed with specific Cybex guided machines (Medway, MA, USA). Exercises were randomized during each training session, alternating lower- and upper-body tasks. In summary, strength training included 7 exercises: core training, BP, BR, HS, plyometric exercises, LP, and an eccentric hamstring exercise.

Aerobic Training

Aerobic exercises included three 6-minute sets of high intensity 15 s/15 s interval training on a field. Subjects, wearing cleats, alternated 15-second runs at 120% of their individual MAV with 15 seconds of passive recovery. A 5-minute warm-up, consisting of moderate to cruising runs, preceded each aerobic training session. Subjects wore an individual HR monitor (Polar Electro Oy, Kempele, Finland) during each session to assess the cardiac workload and to regulate the distance to cover during the 15-second efforts. Distance to cover for the next sessions was higher if HR was lower than the rate of 90% of the maximal HR.

Statistical Analyses

Data were assessed for practical significance using magnitude-based inference (21). We chose to use inferential statistics because traditional statistical methods often fail to indicate the magnitude of an effect, a factor that is typically more relevant for training prescription than any statistically significant effect. All data were log-transformed before analyses, to reduce bias arising from nonuniformity of error. We used 2 modified statistical spreadsheets from the sportsci.org

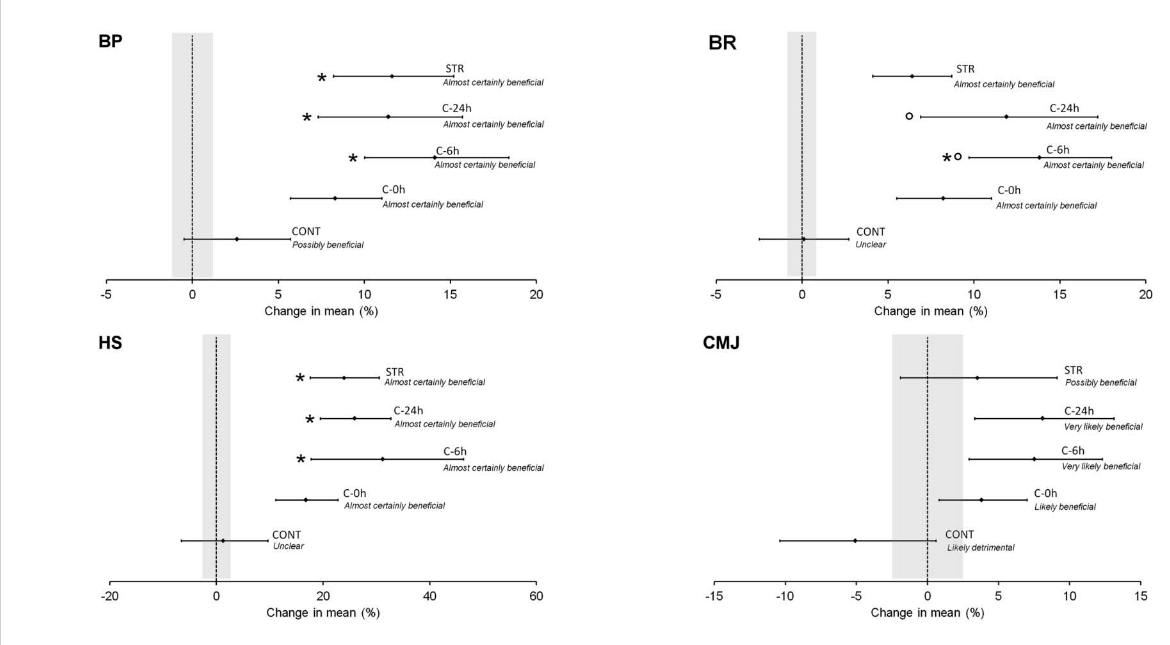

Figure 2. Within-group changes in mean for bench press, BR, half squat, and CMJ. Bars indicate uncertainty in the true mean changes with 90% confident interval. Trivial area was calculated from the smallest worthwhile change (see Methods). *Improvement was at likely (>75%) higher compared with C-0h group. °Improvement was at likely (>75%) higher compared with STR group. CONT = control; C-0h = no recovery between sequences; C-6h = 6-hour recovery between sequences; C-24h = 24-hour recovery between sequences; STR = strength; BR = bench row; CMJ = countermovement jump.

website of Hopkins to calculate within- and between-trial changes for each group. These spreadsheets calculated the standardized differences or effect sizes (ES; 90% confidence interval [CI]) using the pool *SD*. The magnitude of the change was interpreted by using values 0.3, 0.9, 1.6, 2.5, and 4.0 of the within-athlete variation (coefficient of variation [CV]) as thresholds for small, moderate, large, very large, and extremely large differences, respectively (21). In addition, we calculated probabilities to establish whether the true (unknown) values were lower, similar or higher than the smallest worthwhile change (SWC). This threshold was calculated for each parameter of the control group using its CV during the 9-week protocol. One third of CV was thought to represent the SWC (1). Quantitative chances of higher (beneficial) or lower (detrimental) differences were evaluated qualitatively as follows: <1%, almost certainly not; 1–5%, very unlikely; 5–25%, unlikely; 25–75%, possible; 75–95%, likely; 95–99%, very likely; >99%, almost certain. If the chance of higher or lower differences was >5%, the true value was assessed as unclear (20). Data in table and figures are presented as mean in change ± 90% CI. Results were considered as statistically significant above 75% (likely) chance of higher or lower differences.

All the measurements were moderate to highly reliable, with the intraclass correlation coefficient ranging from 0.85 to 0.97 in neuromuscular field tests, from 0.92 to 0.96 in neuromuscular properties measurements and corresponding to 0.84 in the aerobic performance test.

RESULTS

One Repetition Maximum and Countermovement Jump

One Repetition Maximum and CMJ performance changes are depicted in Figure 2. At the end of the protocol, 1RM BP almost certainly increased for the groups C-0h (prevalues vs. postvalues [mean ± *SD*]: 87.5 ± 22.2 vs. 94.5 ± 23.3 kg; change ± 90% CI, 8.3 ± 2.7%; ES, 0.32 ± 0.10, moderate to large), C-6h (76.1 ± 17.9 vs. 86.1 ± 16.4 kg, 14.1 ± 4.1%, 0.59 ± 0.17, large to very large), C-24h (74.2 ± 12.0 vs. 82.7 ± 13.8 kg, 11.4 ± 4.1%, 0.57 ± 0.20, moderate to very large), and STR (85.5 ± 13.8 vs. 95.3 ± 14.7 kg, 11.6 ± 3.4%, 0.60 ± 0.17, large to very large). Changes in the CONT group were possibly positive (80.6 ± 16.1 vs. 82.5 ± 16.0 kg, 2.6 ± 3.1%, 0.11 ± 0.14, trivial to moderate). The difference in change of 1RM BP performance was likely to almost certainly greater in the C-6h (change ± 90% CI, 7.4 ± 4.2%; ES, 0.31 ± 0.18, small to large), C-24h (4.8 ± 4.3%, 0.22 ± 0.19, trivial to large), and STR (5.0 ± 3.0%, 0.25 ± 0.18, trivial to large) groups than in the C-0h group at the end of the training period. Training-induced changes in 1RM BP between C-6h, C-24h, and STR were unclear.

Also, 1RM BR almost certainly increased in C-0h (84.0 ± 10.7 vs. 90.8 ± 11.6 kg, 8.2 ± 2.7%, 0.57 ± 0.18, large to very

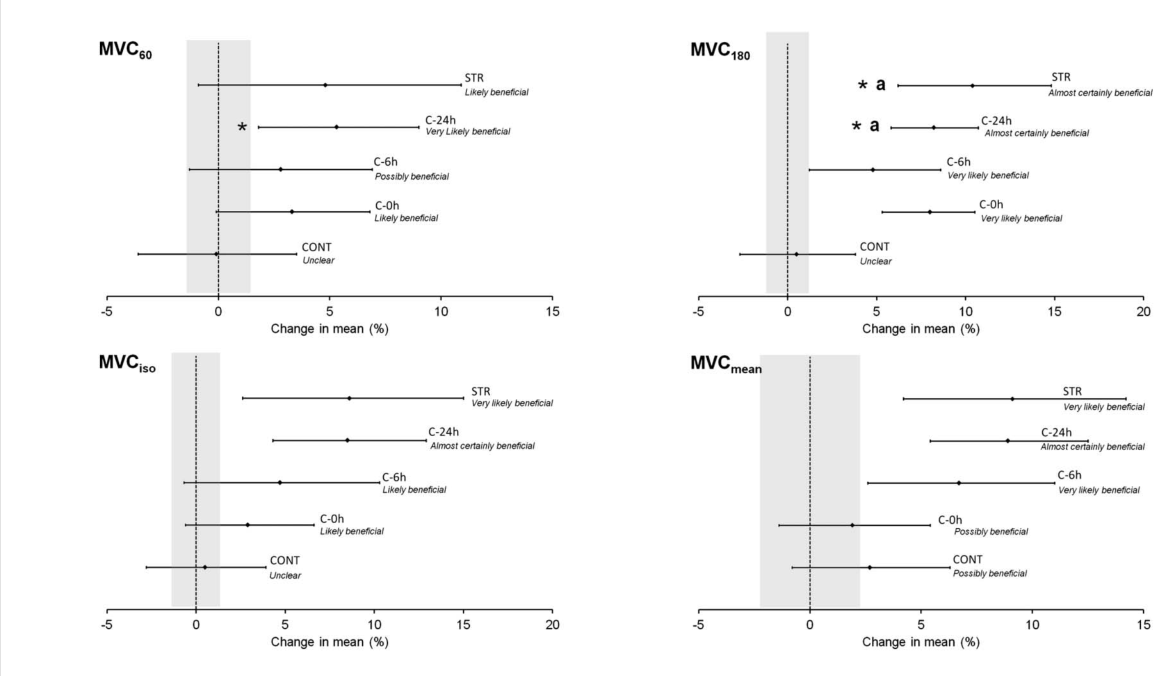

Figure 3. Within-group changes in mean for MVC_{60}, MVC_{180}, MVC_{isom}, and MVC_{mean}. Bars indicate uncertainty in the true mean changes with 90% confident interval. Trivial area was calculated from the smallest worthwhile change (see Methods). *Improvement was likely (>75%) higher compared with C-0h group. [a]Improvement was likely (>75%) higher compared with C-6h group. CONT = control; C-0h = no recovery between sequences; C-6h = 6-hour recovery between sequences; C-24h = 24-hour recovery between sequences; STR = strength; MVC_{iso} = maximal voluntary contraction in isometric condition; MVC_{60} = maximal voluntary contraction in concentric condition at 60°·s^{-1}; MVC_{180} = maximal voluntary contraction in concentric condition at 180°·s^{-1}.

large), C-6h (78.0 ± 10.9 vs. 88.4 ± 9.9 kg, 13.8 ± 4.1%, 0.22 ± 0.26, very large to extremely large), C-24h (77.5 ± 10.6 vs. 86.7 ± 10.9 kg, 11.9 ± 5.0%, 0.80 ± 0.33, large to extremely large), and STR groups (91.0 ± 10.0 vs. 97.0 ± 12.2 kg, 6.4 ± 2.3%, 0.45 ± 0.15, moderate to very large). Changes in the CONT group were unclear (88.6 ± 15.6 vs. 88.3 ± 13.3 kg, 0.1 ± 2.6%, 0.00 ± 0.14). The training-induced changes in 1RM BR performance were very likely and likely higher in the C-6h and C-24h than in the STR group, respectively (moderate to very large, 6.7 ± 4.5%, 0.47 ± 0.30; trivial to large, 6.0 ± 5.9%, 0.46 ± 0.42). Moreover, 1RM BR improvement was likely higher in C-6h than in C-0h group (trivial to very large, 4.7 ± 4.7%, 0.36 ± 0.36).

One repetition maximum HS almost certainly increased in C-0h (156.0 ± 20.3 vs. 182.0 ± 28.5 kg, 16.8 ± 5.7%, 1.05 ± 0.34, moderate to very large), C-6h (140.0 ± 26.5 vs. 184.1 ± 34.0 kg, 31.2 ± 13.5%, 1.28 ± 0.51, large to extremely large), C-24h (143.3 ± 23.6 vs. 180.0 ± 26.4 kg, 25.9 ± 6.4%, 1.45 ± 0.33, large to extremely large), and STR groups (152.5 ± 24.6 vs. 190.0 ± 38.4 kg, 23.9 ± 6.3%, 1.15 ± 0.28, large to very large). Changes in the CONT group were unclear (168.8 ± 35.6 vs. 169.4 ± 31.7 kg, 1.2 ± 7.8%, 0.05 ± 0.32). Improvements in 1RM HS performance were likely greater in the C-6h (12.8 ± 11.9%, 0.74 ± 0.69, trivial to very large), C-24h (8.3 ± 6.3%, 0.61 ± 0.47, trivial to large), and STR (6.6 ± 6.2%, 0.45 ± 0.43, trivial to large) groups than in the C-0h group at the end of the training period. Between C-6h, C-24h, and STR groups, differences in change were unclear.

Jump height increased likely in the C-0h group (33.7 ± 4.7 vs. 34.8 ± 3.8 cm, 3.8 ± 3.0%, 0.27 ± 0.21, trivial to small) and very likely in the C-6h (29.4 ± 3.9 vs. 31.5 ± 3.8 cm, 7.5 ± 4.6%, 0.51 ± 0.31, small to moderate) and C-24h groups (32.6 ± 5.0 vs. 35.1 ± 4.4 cm, 8.1 ± 4.8%, 0.48 ± 0.28, small to moderate). Improvement in STR group was possible (33.8 ± 5.4 vs. 35.2 ± 6.9 cm, 3.5 ± 5.4%, 0.22 ± 0.25, trivial to moderate). Jump height decreased likely in the CONT group (36.6 ± 5.1 vs. 35.0 ± 6.4 cm, −5.1 ± 5.3%, −0.26 ± 0.29, trivial to small). Differences between changes occurring in C-0h, C-6h, C-24h, and STR groups were unclear.

Torque Production Capacity and Neuromuscular Properties

MVC_{60} (Figure 3) increased likely in C-0h (227.1 ± 38.9 vs. 234.1 ± 38.3 N·m, 3.3 ± 3.4%, 0.17 ± 0.17, trivial to moderate) and STR groups (233.9 ± 39.9 vs. 246.3 ± 50.0 N·m,

TABLE 3. Pre-post values and qualitative effects.*†

	Prevalues	Postvalues	Change ± 90% confidence interval		Effect magnitude	
Peak twitch (N·m)						
CONT	115.4 ± 10.3	117.0 ± 13.3	1.1 ± 5.7	Unclear	0.10 ± 0.47	Trivial
C-0h	102.2 ± 16.2	102.3 ± 15.8	0.3 ± 2.2	Unclear	0.01 ± 0.13	Trivial
C-6h	102.7 ± 18.4	103.6 ± 16.9	1.1 ± 3.3	Unclear	0.06 ± 0.19	Trivial
C-24h	98.1 ± 18.7	99.0 ± 18.4	1.0 ± 3.5	Unclear	0.05 ± 0.17	Trivial
STR	113.8 ± 21.2	114.7 ± 24.2	0.3 ± 3.3	Unclear	1.1 ± 0.14	Trivial
M-wave amplitude (mV)						
CONT	6.4 ± 1.6	6.7 ± 1.2	5.7 ± 12.3	Possible	0.23 ± 0.45	Small
C-0h	6.1 ± 2.5	6.3 ± 2.2	63 ± 14	Possible	0.14 ± 0.30	Trivial
C-6h	5.8 ± 1.5	5.8 ± 1.2	−0.2 ± 17.6	Unclear	−0.01 ± 0.60	Trivial
C-24h	6.1 ± 1.3	6.2 ± 1.7	0.9 ± 11.0	Unclear	0.04 ± 0.41	Trivial
STR	5.9 ± 0.9	6.1 ± 1.8	2.2 ± 18.0	Unclear	0.09 ± 0.65	Trivial
MVA (%)						
CONT	89.9 ± 5.9	90.6 ± 3.5	1.0 ± 6.4	Unclear	0.15 ± 0.98	Trivial
C-0h	93.4 ± 4.0	95.3 ± 3.8	2.1 ± 2.4	Unclear	0.46 ± 0.52	Small
C-6h	94.5 ± 3.3	96.1 ± 2.5	1.7 ± 1.8	Possible	0.50 ± 0.49	Small
C-24h	**93.2 ± 5.6**	**95.6 ± 3.5**	**2.8 ± 2.2**	**Probably**	**0.50 ± 0.38**	**Small**
STR	94.5 ± 3.2	95.8 ± 2.8	1.3 ± 2.2	Possible	0.37 ± 0.60	Small
MVC_{dec} (%)						
CONT	13.3 ± 5.3	10.9 ± 4.9	−21.7 ± 31.4	Unclear	−0.41 ± 0.56	Small
C-0h	14.5 ± 4.3	13.8 ± 4.5	−7.7 ± 27.9	Unclear	−0.21 ± 0.70	Small
C-6h	14.4 ± 6.4	12.4 ± 6.0	−13.0 ± 31.4	Unclear	−0.20 ± 0.45	Trivial
C-24h	15.8 ± 6.5	15.1 ± 4.8	0.2 ± 22.3	Unclear	1.1 0.53	Trivial
STR	16.8 ± 5.4	16.6 ± 3.1	3.3 ± 35.6	Unclear	0.09 ± 0.84	Trivial

*C-0h = no recovery between sequences; C-6h = 6-hour recovery between sequences; C-24h = 24-hour recovery between sequences; STR = strength; CONT = control; MVC = maximal voluntary contraction; MVA = maximal voluntary activation; M-wave amplitude was the average of the 3 superficial knee extensors (vastus lateralis, vastus medialis, and rectus femoris).

†Pre and post values are expressed as mean ± *SD*.

Bold values highlight a significant effect.

4.8 ± 5.7%, 0.21 ± 0.26, trivial to large) to very likely in the C-24h group (218.9 ± 39.7 vs. 231.2 ± 45.0 N·m, 5.3 ± 3.5%, 0.25 ± 0.16, small to large). Improvement in C-6h group was possible (223.6 ± 36.2 vs. 228.6 ± 30.2 N·m, 2.8 ± 4.1%, 0.16 ± 0.24, trivial to moderate), whereas change was unclear in the CONT group (233.4 ± 46.3 vs. 231.6 ± 39.3 N·m, −0.1 ± 3.5%, 0.00 ± 0.14). Changes were likely higher in C-24h compared with C-0h group (3.9 ± 4.4%, 0.21 ± 0.24, trivial to large). There was no other between-group difference in training-induced change.

MVC_{180} (Figure 3) increased very likely in C-0h (183.6 ± 25.3 vs. 191.3 ± 28.4 N·m, 8.0 ± 2.7%, 0.25 ± 0.13, small to moderate) and C-6h groups (173.9 ± 29.4 vs. 181.5 ± 25.4 N·m, 4.8 ± 3.6%, 0.28 ± 0.21, trivial to large), and almost certainly in C-24h (168.8 ± 27.6 vs. 182.5 ± 28.1 N·m, 8.2 ± 2.4%, 0.46 ± 0.13, moderate to very large) and STR groups (184.2 ± 30.2 vs. 204.6 ± 41.5 N·m, 10.4 ± 4.2%, 0.46 ± 0.18, moderate to very large). Changes in the CONT group were unclear (191.2 ± 25.4 vs. 192.2 ± 26.0 N·m, 0.5 ± 3.2%, 0.03 ± 0.20). The changes of MVC_{180} were likely higher in C-24h (3.8 ± 3.5% and 4.2 ± 4.0%, 0.23 ± 0.22 and 0.25 ± 0.24, respectively, trivial to large) and STR (5.9 ± 4.7% and 6.3 ± 5.1%, 0.33 ± 0.27 and 0.32 ± 0.26, respectively, trivial to very large) than in the C-0h and C-6h groups. No other between-group difference in enhanced performance was detected.

MVC_{iso} (Figure 3) increased likely in C-0h (278.6 ± 53.7 vs. 287.3 ± 58.2 N·m, 2.9 ± 3.5%, 0.13 ± 0.16, trivial to moderate) and C-6h groups (279.1 ± 51.3 vs. 291.2 ± 50.0 N·m, 4.7 ± 7.4%, 0.23 ± 0.26, trivial to moderate), almost certainly in C-24h (274.8 ± 57.5 vs. 296.2 ± 54.3 N·m, 8.5 ± 4.2%, 0.36 ± 0.18, small to very large), and very likely in STR group (297.5 ± 62.6 vs. 324.3 ± 73.1 N·m, 8.6 ± 6.0%, 0.31 ± 0.21, small to very large). Changes in the CONT group remained unclear (288.3 ± 39.9 vs. 289.5 ± 38.7 N·m, 0.5 ± 3.3%, 0.03 ± 0.21). Differences between changes occurring in C-0h, C-6h, C-24h, and STR groups were unclear.

Change in MVC_{mean} performance (Figure 3) was possibly positive in C-0h (206.2 ± 32.0 vs. 220.0 ± 33.2 N·m, 1.9 ± 3.3%, 0.09 ± 0.16, small to moderate) and CONT groups (218.9 ± 38.8 vs. 223.8 ± 43.7 N·m, 2.7 ± 3.5%, 0.11 ± 0.14, trivial to moderate). Differences between changes occurring in C-0h and CONT groups remained unclear. MVC_{mean} (Figure 3) increased very likely in C-6h (205.3 ± 29.1 vs. 224.5 ± 38.3 N·m, 6.7 ± 4.1%, 0.39 ± 0.24, small to large) and STR groups (219.1 ± 42.6 vs. 225.7 ± 47.3 N·m, 9.1 ± 4.9%, 0.42 ± 0.22, moderate to large), and almost certainly in C-24h group (227.1 ± 39.5 vs. 248.0 ± 46.1 N·m, 8.9 ± 3.5%, 0.49 ± 0.19, moderate to very large). Differences between changes occurring in C-6h, C-24h, and STR groups remained unclear. No significant changes occurred in MVC_{dec}, a marker of muscle fatigability, in any of experimental groups (Table 3).

Changes in electrically evoked peak torque and M-wave amplitude remained unclear in all experimental groups (Table 3). Maximal voluntary activation levels increased likely after the concurrent training in the C-24h group (93.2 ± 5.6 vs. 95.6 ± 3.5%, 2.8 ± 2.2%, 0.50 ± 0.38, trivial to moderate).

$\dot{V}O_2$peak

Changes in $\dot{V}O_2$peak are reported in Figure 4. $\dot{V}O_2$peak increased likely in C-0h (4,359 ± 429 vs. 4,525 ±

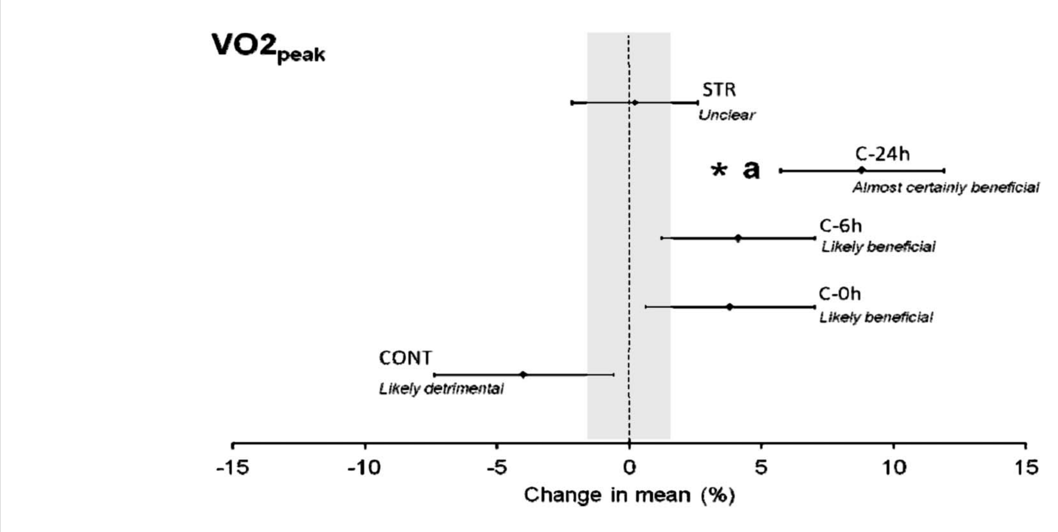

Figure 4. Within-group changes in mean for $\dot{V}O_2$peak. Bars indicate uncertainty in the true mean changes with 90% confident interval. Trivial area was calculated from the smallest worthwhile change (see Methods). *Improvement was likely (>75%) higher compared with C-0h group. [a]Improvement was likely (>75%) higher compared with C-6h group. CONT = control; C-0h = no recovery between sequences; C-6h = 6-hour recovery between sequences; C-24h = 24-hour recovery between sequences; STR = strength.

547 ml·min, 3.8 ± 0.6%, 0.27 ± 0.22, trivial to moderate) and C-6h groups (4,449 ± 494 vs. 4,636 ± 564 ml·min, 4.1 ± 1.2%, 0.30 ± 0.21, trivial to moderate) and almost certainly in C-24h group (4,064 ± 419 vs. 4,419 ± 405 ml·min, 8.8 ± 5.7%, 0.81 ± 0.28, moderate to large). Increased $\dot{V}O_2$peak values in response to physical training, were likely higher in C-24h than in the C-0h (5.2 ± 5.1%, 0.40 ± 0.40, trivial to large) and C-6h (3.5 ± 3.6%, 0.29 ± 0.30, trivial to moderate) groups. There was no difference in adaptive changes observed in both C-0h and C-6h groups.

DISCUSSION

The aim of the present study was to determine whether the recovery delay between strength and endurance training sessions altered the physiological adaptations to a 7-week concurrent training program. The main findings of this study were that (a) strength, power, and aerobic maximal capacity would be reduced when strength preceded endurance exercises and (b) the interferential effect of concurrent training would differ according to the duration of the recovery period that separated training sessions. The training-induced interferential effect seemed to occur when short recovery delays were imposed between strength and endurance training, i.e., with 0-hour but also, at least partly, with 6-hour recovery (C-0h and C-6h groups, respectively) compared with resistance exercise only. Beyond few distinctions between groups, it seemed there were various interferences depending on the outcome and muscle group.

In this study, the concurrent training consisted in a combination of both strength and aerobic exercises performed in a specific order, with strength training before high-intensity interval running sessions. The effects of high-intensity interval-type running sessions performed concurrently with strength exercises on the muscular torque remain controversial. It has been shown that when high-intensity endurance exercises precede strength sessions, the strength performance and volume of work that can be performed are impaired (29,37) but the intrasession sequencing order of such exercises failed to influence the development of strength and power (9). Regarding these conflicting results on the effects of high-intensity endurance exercise on strength production capacity, the training program chosen in this study consisted of strength exercises followed by high-intensity endurance exercises, a condition that was expected to be less deleterious for the volume of work that can be maintained during the strength sessions.

The optimal duration of recovery periods required between aerobic and strength training sessions to ensure a constant volume of work during strength sessions has been previously examined (36,37). It was concluded that the work that can be performed on the lower limbs during the strength sessions was diminished for up to 8 hours (37). Results of this study show that a recovery period of 6 hours between exercises when strength precedes high-intensity aerobic exercises would allow similar adaptive responses of voluntary strength of lower and upper limbs than during strength-only training. Moreover, a 24-hour recovery period seemed to be necessary for full aerobic development and to observe similar responses of the torque production capacity to those in the strength-only group. Whether aerobic exercises after strength exercises would negatively affect the molecular signaling promoting muscle hypertrophy and regulators of the mitochondrial biogenesis has been recently examined (2). The authors found no alteration in the responses of the main signaling pathway involved in muscle growth when a moderate-intensity endurance exercise was performed after resistance exercise, but the specific effects of high-intensity aerobic exercise remain to be examined.

The interference of strength adaptations of our present concurrent trainings corroborated many previous studies (12,16,18,19,23,24). Compared with these, we demonstrated the interference effect with a reduced training volume (7 weeks with 4 sessions a week). In comparison, Hickson outlined this phenomenon with a 10-week training program, whereas no attenuation of the maximal strength development was found after the first 7 weeks (duration of our protocol). The negative effect of aerobic work on the maximal strength development only occurred during the last 3 weeks of the experimental training (weeks 8–10). Other studies showed this interference effect after training programs of at least 8 weeks duration (5,16,18,19,23). Also, we seemed to observe attenuations of strength development with low-frequency training (2 sequences of each quality per week), whereas the majority of the studies showing the interference effect were at least made up of 3 trainings of each quality per week (5,12,18,19,23,39). Therefore, our findings, with low recovery delay between sequences, provide elements in favor of enhanced interference making strength and endurance sequences incompatible when performed within a single training program, even with a low training volume. Similar results after low concurrent training volume that highlighted the role played by high-intensity aerobic exercises on the reduced development of strength and power have been previously published (9). Together with that study, our results would suggest that high-intensity interval exercises performed after strength sessions impair the development of strength and power, especially when short recovery periods separate training sessions.

The present strength training program was expected to lead to strength and power gains in both lower and upper limbs. Surprisingly, we observed smaller gains in BR maximal strength for STR than concurrent training groups. This might be explained by a group effect. The higher initial values for STR compared with the other groups would induce a smaller range for improvement. Another interesting finding of the present study was that high-intensity interval running sessions impaired strength gains of not only lower limbs muscles, as expected, but also of upper-limbs muscles, as shown by the lower BP 1RM values in C-0h group, in comparison with C-6h, C-24h, and STR groups. These results contrast with reports from other studies in which the interference effect of concurrent training was only observed for leg muscles (18,28). Such lack of agreement with existing experimental data might be attributed to differences in training duration, type of aerobic exercise, and total work volume.

Quadriceps MVT was measured under both isometric and concentric conditions at slow and fast angular velocities (60 and 180°$\cdot$s^{-1}). The results would demonstrate a higher interference effect at fast than at slow angular velocity. Our results were in agreement with the existing literature data (12), which emphasized improvement in maximal torque at slow velocities of contraction (from isometric to 96°$\cdot$s^{-1} concentric contractions) after a similar concurrent strength and endurance training. The training status of the participants could explain these results. Participants, not accustomed to heavy weight were exposed to a tension-limiting mechanism of neural origin (7) at slow velocities. Strength training, whether performed alone or combined with endurance, seemed to eliminate this mechanism. Thus, we can expect to measure more strength gains at slow than fast velocities of contraction with such no strength-familiarize participants. In this study, subjects were only slightly familiarized with heavy weightlifting training. This might explain the differences in strength gains between slow and fast angular velocity. Moreover, in our study, multijoint explosive-type exercises such as CMJ did not induce any interference. Such results contrast with another study (23) that demonstrated smaller increases in power and explosive qualities, measured by a vertical jump test, without any attenuation of slow contractions as shown by the 1RM BP and HS. In this case, the negative effect on explosive multijoint movement was obtained with 12 weeks of high-frequency training (6 sequences a week) while we used a markedly lower working volume. Therefore, the hypothesis supported by a few studies (18,23), emphasizing that concurrent training has a predominant negative effect on strength production at fast velocity and explosive qualities, is partially confirmed in our study. It appeared that single-joint isokinetic movements would be just as sensitive to interferential effects as multijoint movements.

A recent meta-analysis (39) interested in synthesizing overall ES for strength, endurance, and concurrent training groups, for strength production capacity of lower limbs. The main results showed mean overall ES of lower-body strength was equal to 2.12 (95% CI: 1.27–2.97) and 2.13 (95% CI: 1.07–3.19) for strength training only and concurrent training groups, respectively. In this study, mean ES of lower-body strength was significantly lower, close to 0.3. The differences in gains could be explained by the type of exercise used during the training program. Recently, Hartmann et al. (17) have reported that partial squat is less effective than deep squat for increasing vertical jump performance or isometric strength. So, we likely would have obtained better gains of knee extensor maximal strength if we had used deep squat as main exercise of lower limbs.

Consistent with the principle of training specificity, no increase in $\dot{V}O_2$peak occurred in STR group, whereas we observed significant gains of $\dot{V}O_2$peak for all the concurrent training groups with higher improvements in C-24h group. Most studies showed that concurrent training led to endurance adaptations including gains in oxidative potential (12,18,19,24,36). However, studies with contrasting results emphasized a lower aerobic development, demonstrated by an attenuation of maximal aerobic power, $\dot{V}O_2$peak or citrate synthase activity, after concurrent training (34). As for strength improvements, a long recovery delay between sessions, i.e., up to 24 hours, seemed to be necessary to minimize the interference on the oxidative potential development. Our impairments in $\dot{V}O_2$peak gains in C-0h and C-6h groups could be explained by an acute neuromuscular fatigue induced by the strength exercises. This residual fatigue may reduce the quality of endurance training and lead to a reduction in aerobic potential development over time. As previously mentioned with strength gains, the meta-analysis of Wilson et al. (39) showed us higher mean ES for $\dot{V}O_2$max with values of 1.36 (95% CI: 0.35, 2.36) and 1.56 (95% CI: 0.49, 2.63) after endurance and concurrent training group, respectively. We could explain these differences by the type of training used during the program. High-intensity interval training such as short interval training (15 s/15 s) seems to be less effective to improve $\dot{V}O_2$peak. However, this type of training seems to induce higher neuromuscular and anaerobic glycolytic adaptations (6), which could have a significant effect on running economy, time to failure, and workload during a time trial. No assessment of these parameters is a limitation of this study.

In conclusion, our study shows that the interference phenomenon of high-intensity, interval-type running training on strength development would depend on the recovery delay between training sessions. Indeed, daily training without recovery between sequences (C-0h) and, to a lesser extent, training twice a day (C-6h) did not seem to be fully optimal for strength, power gains, and $\dot{V}O_2$peak responses, unlike to daily training with 24-hour recovery between sessions.

PRACTICAL APPLICATIONS

These results suggest that strength and conditioning coaches should avoid scheduling 2 contradictory qualities (strength vs. endurance), with less than 6 hours of recovery between them, whereas a 24-hour recovery period between exercises is required to obtain a full neuromuscular and oxydative adaptative response to concurrent training. In summary, it does not seem to be recommended to program strength and endurance sequences within the same day regardless the order and the delay between the sessions. According to us, it is more efficient to isolate each type of sequence.

In team sports, like rugby, coaches also have to program specific technical and tactical training. These can induce high aerobic solicitation similar to those measured after following traditional endurance training. In addition, specific team sports training could be interferential on strength development if they are always scheduled close to weightlifting sequences. In fact, the monitoring of the specific technical and tactical training load and the induced physiological responses, by means of global positioning system technology, and portable HR monitor is necessary. It could allow regulating the intensity of the specific training and so, to avoid interference in the strength development. For example, it could be possible to do a technical training without intense movements close to a strength sequence.

In this study, we used high-intensity interval training that is regularly used in team sports. Other types of high-intensity aerobic exercises can be regularly performed such as sprint interval and repeated sprint training. Therefore, further studies could measure the effect of these types of aerobic training on strength adaptations within concurrent training.

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