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ORIGINAL ARTICLE

Endurance and neuromuscular changes in world-class level kayakers during a periodized training cycle

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Abstract This study was undertaken to analyze changes in selected cardiovascular and neuromuscular variables in a group of elite kayakers across a 12-week periodized cycle of combined strength and endurance training. Eleven world-class level paddlers underwent a battery of tests and were assessed four times during the training cycle (T0, T1, T2, and T3). On each occasion subjects completed an incremental test to exhaustion on the kayak-ergometer to determine maximal oxygen uptake (VO_{2max}), second ventilatory threshold ($VT2$), peak blood lactate, paddling speed at VO_{2max} (PS_{max}) and at $VT2$ (PS_{VT2}), stroke rate at VO_{2max} and at $VT2$, heart rate at VO_{2max} and at $VT2$. One-repetition maximum (1RM) and mean velocity with 45% 1RM load ($V_{45\%}$) were assessed in the bench press (BP) and prone bench pull (PBP) exercises. Anthropometric measurements (skinfold thicknesses and muscle girths) were also obtained. Training volume and exercise intensity were quantified for each of three training phases (P1, P2, and P3). Significant improvements in VO_{2max} (9.5%), VO_2 at $VT2$ (9.4%), PS_{max} (6.2%), PS_{VT2} (4.4%), 1RM in BP (4.2%) and PBP (5.3%), $V_{45\%}$ in BP (14.4%) and PBP (10.0%) were observed from T0 to T3. A 12-week periodized strength and endurance program with special emphasis on prioritizing the sequential development of specific physical fitness components in each training phase (i.e. muscle hypertrophy and $VT2$ in P1, and maximal strength and aerobic power in P2) seems effective for improving both cardiovascular and neuromuscular markers of highly trained top-level athletes.

Keywords Concurrent training · Resistance training · Endurance performance · Canoeing · Exercise testing · Periodization

Introduction

It is generally accepted by coaches and sport scientists that to maximize physiological adaptations and to avoid overtraining, proper handling of training program variables, including the intensity, frequency and volume of exercise, is required. This is especially important in sports where both endurance and strength need to be simultaneously enhanced to optimize performance (e.g. kayaking). Because strength and endurance training elicit distinct and often divergent adaptive mechanisms (Nader 2006; Sale et al. 1990a), the concurrent development of both fitness components in the same training regime can lead to conflicting neuromuscular adaptations.

This potential conflict has been referred to as an 'interference phenomenon' and it was first described by Hickson (1980), who observed compromised strength development, when strength and endurance training were applied concurrently. However, results of subsequent research have been equivocal, with studies both supporting

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(Bell et al. 2000; Craig et al. 1991; Dudley and Djamil 1985; Hennessy and Watson 1994; Kraemer et al. 1995) and questioning (Häkkinen et al. 2003; Hunter et al. 1987; McCarthy et al. 1995, 2002; Sale et al. 1990a) the universal nature of such interference. Several factors such as initial training status of the subjects, exercise mode, volume, intensity and frequency of training, scheduling of sessions, and dependent variable selection may influence the level of interference and explain the contradictory results of these studies (Docherty and Sporer 2000; Leveritt et al. 1999; Sale et al. 1990a). A detailed examination of the existing research on this topic seems to indicate that the volume, especially the frequency of training, may play a critical role in the adaptations consequent to concurrent training (Häkkinen et al. 2003; Izquierdo et al. 2005; McCarthy et al. 2002).

For example, most of the studies have reported concurrent training to be detrimental for strength gains only, when training frequency was higher than 3 days per week (Dudley and Djamil 1985; Hennessy and Watson 1994; Hickson 1980; Hunter et al. 1987; Kraemer et al. 1995). The neuromuscular mechanisms related to power production and explosive strength development seem to be the most affected by the simultaneous training of strength and endurance (Dudley and Djamil 1985; Häkkinen et al. 2003; Hennessy and Watson 1994; Kraemer et al. 1995). By comparison, the majority of current research supports the contention that concurrent training does not alter the ability to adapt to endurance training (Docherty and Sporer 2000; Hickson et al. 1988). Indeed, a number of studies have concluded that the addition of resistance training to ongoing exercise regimens of well-trained endurance athletes is beneficial and results in improved endurance performance (Hickson et al. 1988; Mikkola et al. 2007; Millet et al. 2002). Nevertheless, the question of which is the best way of sequencing sessions targeted at different goals, for the simultaneous development of strength and endurance, remains complex and not satisfactorily solved.

There exists some evidence to support that periodized resistance training programs can result in greater strength gains than non-periodized programs (Fleck 1999; Willoughby 1993). Non-linear or undulating models in which short periods of high volume are alternated with short periods of high intensity training are thought to optimize strength gains (Baker et al. 1994). Unfortunately, there are very few studies in the scientific literature that have explored the effects of periodized training on sports with great demands of both strength and endurance, and even fewer that have done so using elite athletes as subjects. Based on evidence from existing research (Docherty and Sporer 2000; Leveritt et al. 1999, 2000; Sale et al. 1990b; Sporer and Wenger 2003), we chose to structure a periodized program aimed at minimizing the possible interference effects in the simultaneous training of the strength and endurance components of physical fitness. Therefore, it was the purpose of the present study to examine the effects brought about by a 12-week periodized program of combined strength and endurance training on selected neuromuscular and cardiovascular parameters in a group of world-class level kayakers.

Methods

Subjects

Eleven male world-class, flat-water kayak paddlers (all of whom were finalists at the World Championships, including two Olympic gold-medalists) volunteered to take part in this study. Mean (SD) characteristics of participants were as follows: age 26.2 (2.8) years; height 1.83 (0.07) m; body mass 86.2 (5.2) kg; training experience 12.4 (2.1) years, annual paddling volume 4,220 (354) km. Subjects had at least 3 years of familiarization with the testing procedures used in this investigation, and they followed their respective training routines under strict supervision from coaches and sport scientists from the Royal Spanish Canoeing Federation. No physical limitations or musculoskeletal injuries that could affect training were reported. Kayakers underwent a complete medical examination (including ECG) that showed all were in good health condition. The study, which was conducted according to the declaration of Helsinki, was approved by the *Bioethics Commission* of the University of Seville, and written informed consent was obtained from all subjects prior to participation.

Previous training

Prior to entering the experimental phase of this study, participants had completed a 5-week transition period during which no specific paddling or resistance training was undertaken. Only some recreational physical activities (sport games plus cycling or swimming at low intensities) were performed.

Experimental design and testing sequencing

All subjects followed the same training program during the 12-week duration of the study. Subjects reported to the laboratory on four separate occasions (T0, T1, T2 and T3) throughout the intervention in order to assess the selected cardiovascular, neuromuscular and anthropometric parameters. Testing was completed on three consecutive days: anthropometry and maximal incremental exercise test on the kayak ergometer (day 1), one repetition maximum (1RM) strength (day 2) and power testing (day 3). No strenuous exercise was undertaken 24 h before reporting to the laboratory for testing. The same warm-up procedures and protocol for each type of test were repeated in subsequent occasions, and all testing sessions were performed at the same time of day (10–12 h) and under similar environmental conditions (20–22°C and 55–65% humidity). In a pilot study, the inter-test reliability for measuring maximal oxygen uptake (VO_{2max}), second ventilatory threshold ($VT2$), and HR at VO_{2max} (HR_{max}) was assessed by performing two incremental paddling tests to volitional exhaustion, separated by 3 weeks, on a kayak ergometer on 12 elite junior male kayakers, of international competitive level in the 500 m and 1,000 m sprint flat-water events. No significant differences were observed between the 3-week measurements in the endurance variables analyzed. Paddling testing variables showed reliability coefficients ranging from 0.92 to 0.98. The coefficients of variation (CV) for VO_{2max}, $VT2$, and HR_{max} ranged between 3.2 and 5.1%. The test–retest intraclass correlation coefficients for all strength/power variables used in this study were greater than 0.93 and CV ranged from 0.9 to 2.9%. No control group was used because including such a group while studying elite athletes could be considered highly unethical, since withholding important training stimuli would be detrimental to the athletes' progress (Kraemer 2005).

Anthropometry

Anthropometric measurements included: standing height, body mass, skinfold thicknesses (triceps brachii, subscapular, suprailiac, abdominal, anterior thigh, medial calf, supraspinale and biceps brachii), and muscle girths (chest, forearm, thigh, calf), and were performed by the same experienced investigator in accordance with guidelines from the International Society for the Advancement of Kineanthropometry (ISAK). Height was measured to the nearest 0.1 cm during a maximal inhalation, and body mass to the nearest 0.1 kg using a calibrated scale (Seca 714, Hamburg, Germany); skinfold thicknesses and muscle girths were assessed, respectively, by using a skinfold caliper (accurate to 0.2 mm) and flexible measurement tape (1 mm), all from the Harpenden range of anthropometric instruments (Holtain Ltd., UK).

Maximal incremental exercise test

After a 5-min warm-up at a speed of 9 $km\ h^{-1}$, subjects completed an incremental paddling test to volitional exhaustion on a kayak ergometer (Dansprint ApS, Denmark). The first stage was set at a speed of 11.5 $km\ h^{-1}$, and the speed increment was 0.5 $km\ h^{-1}$ each minute. Each kayaker freely adjusted his stroke rate (SR) as needed, while this rate was continuously recorded by means of a stroke counter (Interval 2000, Nielsen-Kellerman, USA). Heart Rate (HR) was monitored using standard HR telemetry (S610i, Polar Electro Oy, Finland) and recorded every 5 s. Paddlers were encouraged to make a maximal effort and complete as many stages as possible. The test concluded when: (a) the subject voluntarily stopped paddling, or (b) he was unable to maintain the imposed speed. Breath-by-breath gas analysis was conducted throughout using an automated Jaeger Oxycon Pro system (Erich Jaeger, Germany). The gas analyzers were calibrated using a 4.95% CO_2–95.05% N_2 gas mixture (BOC Gases, Surrey, UK), and the volume sensor using a 3-L calibration syringe. $VT2$ was determined from gas exchange measurements using the criteria of an increase in both ventilatory equivalents ($V_E \cdot VO_2^{-1}$ and $V_E \cdot VCO_2^{-1}$ ratios) and a decrease in the end-tidal carbon dioxide tension ($P_{ET}CO_2$). Two independent and experienced observers made $VT2$ determinations. If there was disagreement between the two, a third observer was brought in. VO_{2max} was defined as the average of the two highest single consecutive 15-s VO_2 mean values attained toward the end of the test. The following variables were determined for each paddler: O_2 uptake at $VT2$ (VO_2 at $VT2$), $VT2$ as a percentage of VO_{2max} [$VT2$ (%VO_{2max})], HR_{max}, HR at $VT2$ (HR_{VT2}), SR at VO_{2max} (SR_{max}), SR at $VT2$ (SR_{VT2}), paddling speed at $VT2$ (PS_{VT2}) and paddling speed at VO_{2max} (PS_{max}). Capillary whole blood samples were taken from each kayaker's earlobe during test recovery (minutes 1, 3, 5, 7 and 10) to determine peak lactate concentration ($[La^-]_{peak}$) using a miniphotometer (LP20, Dr. Lange, France).

Maximal strength and muscle power assessment

1RM was determined in the bench press (BP) and prone bench pull (PBP) using free weights. These were chosen because they are typical resistance training exercises used in the sport of canoeing, and are useful to assess strength and power in the opposing upper-body muscle actions of pushing and pulling. Warm-up consisted of 5 min of stationary cycling at a self-selected easy pace, followed by 5 min of static stretching and upper-body joint mobilization exercises. After a 3-min recovery, a set of six repetitions with the estimated 60% 1RM load, and another set of 2–3 repetitions with the estimated 80% 1RM load for each exercise were performed. Thereafter, each subject performed 3–5 more one-repetition sets with 5-min recovery pauses until his 1RM load could be determined with a precision of 2.5 kg. After two failed attempts at the same load, the test was terminated. The heaviest load that each subject could properly lift, without any external help, was considered to be his 1RM.

On the following day, mean concentric velocity with 45% of the previously determined 1RM load ($V_{45\%}$) was assessed for both exercises. This load was chosen since it has been proved to be very close to the load that maximizes the average mechanical power output for isoinertial upper-body resistance exercises (Cronin and Sleivert 2005; Izquierdo et al. 2002). After an identical warm-up, subjects performed two sets of three repetitions with the 45% 1RM load, using a 5-min recovery pause between sets. Mean velocity was recorded by means of a linear position transducer (MuscleLab, Ergotest Technology, Oslo, Norway). The mean velocity of the three best repetitions for each subject was registered as the $V_{45\%}$. In the BP, subjects lay supine on a flat bench, with their feet resting flat on the floor, and hands placed on the barbell slightly wider (5–7 cm) than shoulder width. After lowering the barbell to the chest, they pushed upwards, at maximum velocity, to the full extension of their elbows. The subjects were not allowed to bounce the bar off their chests or raise the shoulders or trunk off the bench. If this occurred, the trial was rejected and subsequently repeated. In the PBP, paddlers were instructed to lie prone and place their chin on the padded edge of a high bench. The pulling phase began with both elbows in full extension, while the barbell was grasped with hands shoulder-width apart or slightly wider (4–5 cm). The participants were instructed to pull with maximum effort until the barbell struck the underside of the bench, after which it was again lowered to the starting position. In both exercises, subjects' positions on the bench and grip widths were measured so that they could be reproduced on every lift.

Periodized training program

The training cycle was divided into three consecutive training phases. Phases one (P1: from T0 to T1) and two (P2: from T1 to T2) had a duration of 5 weeks, while the final phase (P3: from T2 to T3) lasted only 2 weeks. Two prioritized targets per fitness component (endurance and strength) were chosen to selectively work upon in each phase: P1, VT2 and muscle hypertrophy; P2, maximal aerobic power and maximal strength; and P3, specific kayaking racing pace and maximal power output. Testing was undertaken in the first week of each phase (T0, T1, and T2) and again at the 13th week, right after the completion of the training program (T3). Athletes exercised daily, except one full rest day per week. Strength training sessions were preferentially arranged prior to endurance sessions; when this was not possible, sufficient recovery time (6–8 h) was allowed before undertaking resistance training. Compliance with training requirements was excellent for all participants.

Endurance training

Three training zones were identified according to the exercise intensity: zone 1 (Z1), light intensity, below VT2; zone 2 (Z2), moderate intensity, between VT2 and 90% of VO_{2max}; and zone 3 (Z3), high intensity, between 90% and 100% of VO_{2max}. No higher, supramaximal intensities were used in this study. A description of the characteristics of endurance exercise modes used for training each intensity zone is provided in Table 1. The relative contribution of each of these intensities to the total training volume for each phase was markedly different (Fig. 1). Volume and intensity were carefully controlled and quantified for each training session throughout the full 12-week training cycle. The main variables used for endurance training monitoring were: time spent (hours) and distance covered (km) for volume; and HR and paddling speed for intensity. Distance and speed were registered by means of a GPS receiver (Garmin 201, Garmin Ltd., USA). Total time devoted to endurance training was 52.7 ± 1.9 h in P1, 49.5 ± 1.5 h in P2 and 21.5 ± 0.8 h in P3. Number of endurance training sessions per week ranged from 10 to 15.

Resistance training

Exercise type, loading intensity, number of sets and repetitions as well as rest pauses were different for each training phase (Table 2), and subjects completed three strength training sessions per week. Training to repetition failure was deliberately avoided, and paddlers were constantly encouraged to perform each repetition at maximal concentric velocity, regardless of the load being lifted. Eccentric actions were always performed in a slow controlled manner, lowering the weights in approximately 3 s. In maximal power training sessions (P3), each set was terminated when mean velocity decreased by more than 10% of the best (fastest) repetition's mean concentric velocity. In all strength training sessions, volume was recorded using total load lifted (kg) and number of repetitions completed. Intensity was assessed as percentage of 1RM, and mean concentric velocity in each repetition as measured by the linear position transducer. All training was supervised by professional coaches with several years of experience in the training of kayakers and canoeists. Total strength training volume was 15.6 ± 0.8 h and 2,430 ± 42 repetitions during P1, 13.2 ± 0.7 h and 660 ± 13 repetitions during P2, and 8.4 ± 0.5 h and 520 ± 14 repetitions during P3. The relative contribution of each strength training type to the total training volume in each phase is shown in Fig. 2.

Table 1 Description of the endurance training modes used for each intensity zone

Intensity zone	Total volume (min)	Sets	Repetitions	Work period (min)	Rest period (min)	Intensity (%$VO_{2\max}$)
Z1	70–120	1	1–3	20–90	1–3	70–80
Z2	40–90	1–4	1–10	5–20	1–4	80–90
Z3	20–60	2–5	4–8	1–8	2–8	90–100

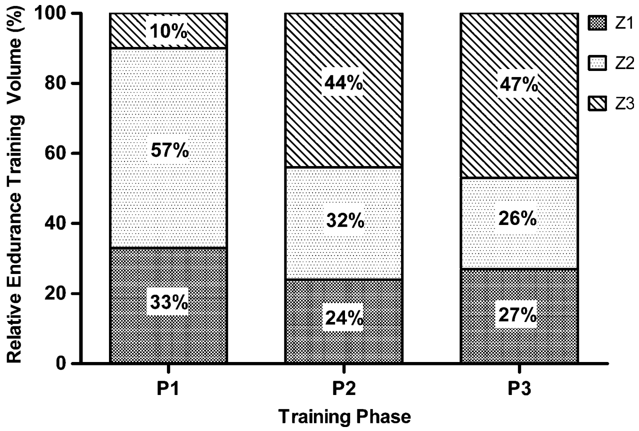

Fig. 1 Relative contribution of each exercise intensity zone to the total endurance training time performed in each phase. *Z1* light intensity below $VT2$, *Z2* moderate intensity between $VT2$ and 90% of $VO_{2\max}$, *Z3* high intensity between 90 and 100% of $VO_{2\max}$

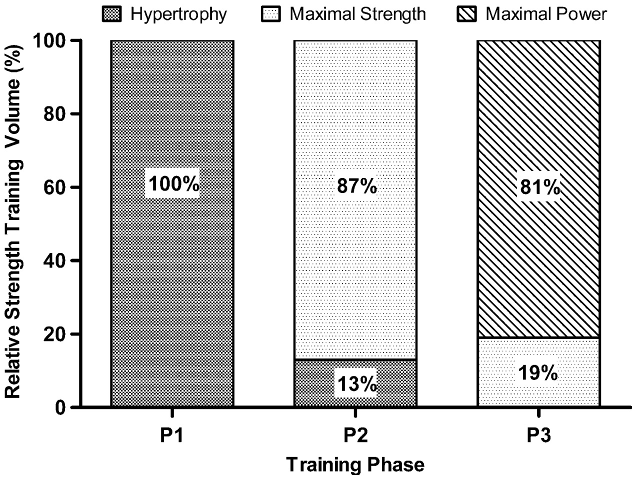

Fig. 2 Relative contribution of each strength training type used in this study to the total training volume in each phase

Statistical analysis

Standard statistical methods were used for the calculation of mean values and standard deviations (SD). The Kolmogorov–Smirnov test was applied to determine the nature of the data distribution. Because a normal distribution was confirmed, repeated measures ANOVA was used to evaluate changes in selected variables over the 12-week training period (T0-T1-T2-T3). Tukey's post hoc test was used to identify the source of any significant differences. Significance was accepted at the $P < 0.05$ level.

Results

Anthropometric changes

Changes in anthropometric measurements are reported in Table 3.

Cardiovascular and endurance performance changes

$VO_{2\max}$ increased by 3.5% from T0 to T1 ($P = 0.063$) and by 5.3% from T1 to T2 ($P < 0.01$), while no significant differences in $VO_{2\max}$ were observed from T2 to T3. VO_2 at $VT2$ increased significantly between T0 and T1 (12.4%, $P < 0.01$) but decreased by 4.3% from T1 to T2 ($P < 0.05$). $VT2$ (%$VO_{2\max}$) significantly increased from T0 to T1 (8.6%, $P < 0.01$), while it decreased 9.0% ($P < 0.01$) when comparing T1 to T2. $PS_{\max}$ improved at T1 (2.1%, $P < 0.05$), T2 (2.0%, $P = 0.068$) and T3 (2.0%, $P < 0.05$). No significant differences were observed for the rest of the variables analyzed ($HR_{\max}$, HR_{VT2}, $SR_{\max}$, SR_{VT2}, and $[La^-]_{\max}$) (Table 4; Fig. 3).

Strength and power changes

From T0 to T1, 1RM improved significantly (9.7 and 7.7% for BP and PBP, respectively, $P < 0.01$), while $V_{45\%}$

Table 2 Types and characteristics of resistance training

	Exercises	Sets	Repetitions	Load (%1RM)	Rest (min)
Hypertrophy	Bench press, prone bench pull, squat, shoulder press, pull ups	4–5	8–10	70–75	2
Maximal strength	Bench press, prone bench pull, squat	3–4	3–4	85–90	4
Maximal power	Bench press, prone bench pull	4–5	5–8[a]	45	4

[a] Each subject performed the maximum possible number of repetitions until mean concentric velocity dropped by more than 10% of the fastest repetition velocity within that set

Table 3 Changes in anthropometric parameters

	T0	T1	T2	T3
Body mass (kg)	86.0 ± 4.4	88.1 ± 4.8	85.9 ± 4.5	85.6 ± 4.6
Sum of four skinfolds[a] (mm)	35.5 ± 2.9	34.0 ± 2.3	$29.0 \pm 2.1^{\#}$	$34.3 \pm 2.3^{£}$
Sum of eight skinfolds[b] (mm)	67.4 ± 5.1	63.5 ± 4.3	$53.5 \pm 3.9^{\#}$	$63.8 \pm 4.5^{£}$
Thigh girth (cm)	56.4 ± 1.8	58.2 ± 1.6	57.6 ± 1.6	57.3 ± 1.8
Chest girth (cm)	105.2 ± 3.8	109.2 ± 3.9*	107.5 ± 3.4	107.1 ± 3.9
Forearm girth (cm)	28.6 ± 1.1	29.3 ± 1.1	28.9 ± 1.3	28.7 ± 1.1
Calf girth (cm)	36.0 ± 0.7	37.2 ± 0.9	37.0 ± 1.0	37.0 ± 0.9

Data is expressed as mean ± SD

* Significantly different ($P < 0.05$) when comparing T0 to T1

[#] Significantly different ($P < 0.05$) when comparing T1 to T2

[£] Significantly different ($P < 0.05$) when comparing T2 to T3

[a] Triceps brachii, subscapular, supraspinale, abdominal

[b] Four skinfolds + biceps brachii, suprailiac, anterior thigh, medial calf

Table 4 Changes in selected physiological and performance variables across the 12-week training programme

	T0	T1	T2	T3
PS_{max} (km h^{-1})	14.5 ± 0.3	14.8 ± 0.2*	15.1 ± 0.3	$15.4 \pm 0.2^{£\dagger}$
PS_{VT2} (km h^{-1})	13.6 ± 0.2	13.9 ± 0.2*	14.1 ± 0.2	$14.2 \pm 0.3^{\dagger}$
$[La^{-}]_{peak}$ (mmol L^{-1})	12.5 ± 3.3	11.8 ± 2.5	12.8 ± 2.2	13.0 ± 2.8
HR_{max} (beats min^{-1})	194 ± 8	188 ± 8	189 ± 10	189 ± 7
HR_{VT2} (beats min^{-1})	175 ± 7	172 ± 7	171 ± 6	172 ± 6
SR_{max} (strokes min^{-1})	104 ± 5	101 ± 9	101 ± 7	103 ± 8
SR_{VT2} (strokes min^{-1})	88 ± 4	84 ± 6	85 ± 5	85 ± 7

Data is expressed as mean ± SD

* Significantly different ($P < 0.05$) when comparing T0 to T1

[£] Significantly different ($P < 0.05$) when comparing T2 to T3

[†] Significantly different ($P < 0.05$) when comparing T0 to T3

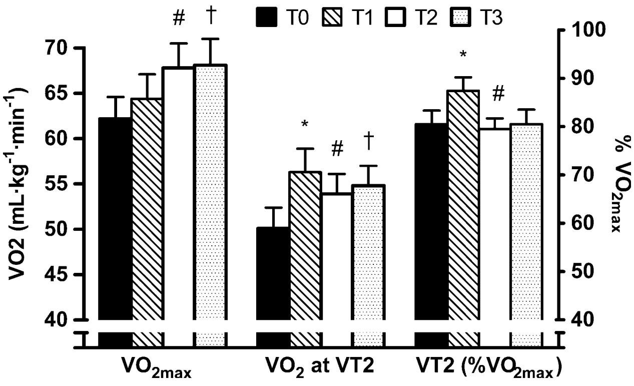

Fig. 3 Changes in VO_{2max} and $VT2$ across the 12-week training programme. Data is presented as mean ± SD. Significant difference: $^{*}P < 0.05$ from T0 to T1, $^{\#}P < 0.05$ from T1 to T2, $^{\#}P < 0.05$ from T1 and T2, $^{\dagger}P < 0.05$ from T0 to T3

remained unchanged in both bench press and prone bench pull exercises. Between T1 and T2, no significant changes were observed in 1RM values, while $V_{45\%}$ improvement was close to statistical significance (5.3%, $P = 0.077$ for BP and 4.6%, $P = 0.082$ for PBP). From T2 to T3, 1RM values significantly decreased by 4.6 and 4.5% ($P < 0.05$) respectively for BP and PBP. Simultaneously, $V_{45\%}$ significantly improved by 11.0% ($P < 0.01$) in BP and 7.1% ($P < 0.01$) in PBP. When comparing T0 and T3 values for these variables, significant improvements were found in 1RM values for BP (4.2%, $P < 0.05$) and PBP (5.3%, $P < 0.05$). Significant increases were also observed in $V_{45\%}$ for both bench press (14.4%, $P < 0.001$) and prone bench pull exercises (10%, $P < 0.001$) (Fig. 4).

Discussion

This study details the changes in selected endurance, anthropometric and strength-related parameters of world-class level kayakers across a 12-week periodized training cycle. The results are important and unique due to the internationally elite level of the athletes, the very high

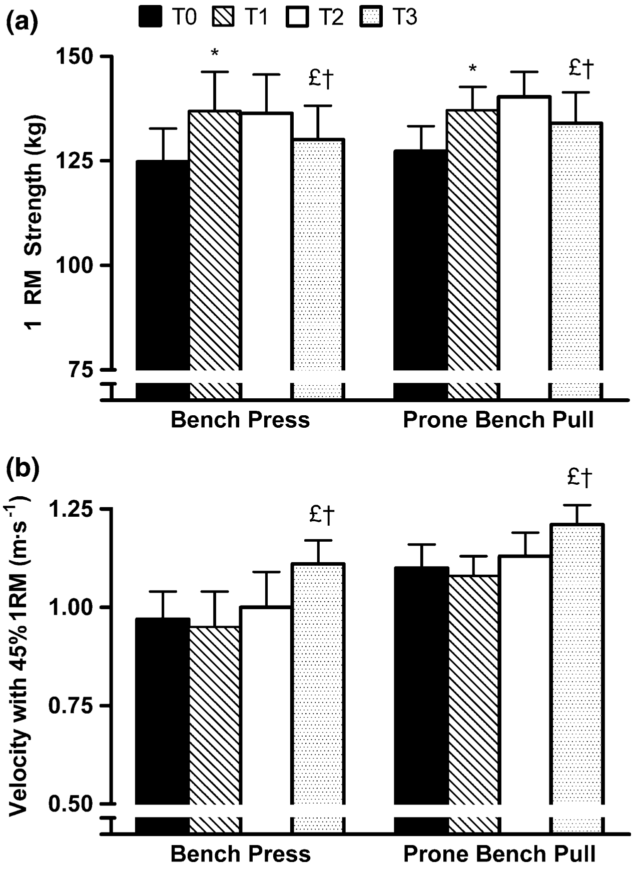

Fig. 4 Changes throughout the 12-week training programme in 1RM strength (**a**) and mean concentric velocity attained with 45% 1RM load (**b**) in the bench press and prone bench pull exercises. Data is presented as mean ± SD. Significant difference: $^{*}P < 0.05$ from T0 to T1, $^{£}P < 0.05$ from T2 to T3, $^{\dagger}P < 0.05$ from T0 to T3

demands of strength and endurance of their sport discipline as well as the scarcity of this type of study in the literature. The main finding of the present study was that 12-week of periodized training was effective for inducing significant gains in both strength and muscle power as well as endurance performance, showing that it is possible to simultaneously develop these different physical fitness components in a relatively short period of time and at a world-class level of performance.

It has been previously reported that a properly designed and implemented periodization scheme could be the best approach to minimize the potential interference effects in simultaneous strength and endurance training (Baker 2001; Docherty and Sporer 2000). However, little is known about what would be the optimal structure for such periodization during sports requiring both strength and aerobic performance (e.g. Olympic kayaking). According to the model proposed by Docherty and Sporer (2000), we chose to prioritize the fitness components to sequentially develop in each training phase so that potential interferences in the simultaneous training of strength and endurance could be minimized. In particular, the periodized training program used in this study deliberately avoided mixing the specific training objectives of muscle hypertrophy (i.e. strength training objective at P1) and maximal aerobic power (i.e. endurance training objective at P2), because these are thought to be two modes of training that lead to opposite physiological adaptations at the peripheral level that prevent the body from optimally and simultaneously adapting to both of them (Leveritt et al. 1999). Thus, while hypertrophy training would be attempting to increase contractile protein synthesis in the muscle, causing considerable metabolic and hormonal stress at the cellular level, training for aerobic power would require the muscle to increase its oxidative capacity (Docherty and Sporer 2000; Sale et al. 1990a). On the contrary, training at lower aerobic intensities (75–85% $VO_{2\max}$) such as those usually employed to improve the $VT2$ would induce more centrally mediated adaptations that would be expected to cause much less interference with the method of strength development via muscle hypertrophy (P1). The cited model also predicts less interference when concurrently training for maximal strength/power and aerobic power (P3), because the training stimulus for increasing strength would be mainly directed at the neural system (increased motor unit firing rate and changes in synchronization, recruitment of higher threshold motor units, etc.), not placing high metabolic demands on the muscle. Therefore, it appears that the manipulation of training intensity in each training phase is critical to avoid potential interferences in concurrent training (Docherty and Sporer 2000).

Although the total volume of endurance training was very similar for the first 5-week training phases (52.7 h for P1 and 49.5 h for P2), training intensity was markedly different. While in P1 most of the training volume was devoted to improving the $VT2$ (57% of total training time in Z2), aerobic power development was favoured in P2 (44% of total training time in Z3). The specificity of training appears to be reflected in the observed cardiovascular changes observed within every training phase. Thus, VO_2 at $VT2$ was the variable that improved the most in P1 (12.4%), whereas $VO_{2\max}$ increased more than any other cardiovascular variable in P2 (5.3%) (Fig. 3). The $VO_{2\max}$ mean value of 68.1 mL kg^{-1} min^{-1} reached after the 12-week training intervention is significantly higher than that obtained by other authors with high-level kayakers using similar ergometry testing protocols (i.e. mostly in the 54–60 mL kg^{-1} min^{-1} range) (Bishop et al. 2002; Fry and Morton 1991; Tesch et al. 1983; Van Someren and Oliver 2002). Although the endurance training performed in P1 was not directly focused towards the development of aerobic power (Fig. 1), the almost significant improvement in maximal aerobic power (3.5%) after this training phase (Fig. 3) is probably due to subjects exhibiting a particularly low initial level because of the previous 5-week transition period. As mentioned above, a 5.3% mean improvement in VO_{2max} was obtained in P2, after increasing training time devoted to aerobic power (i.e. from 5.3 to 21.8 h of training in Z3) for these already highly trained athletes. The observed changes in VO_{2max} in only 12 weeks of training (9.5% increase from T0 to T3; Fig. 3) are of similar magnitude to those of 8.0% described in a previous study (Tesch et al. 1976) with international-level kayakers and canoeists after a longer training period (8 months).

Similarly, the specificity of endurance training around the $VT2$ during P1 (57% of total training time in Z2; Fig. 1) brought about important increases in VO_2 at $VT2$ (12.4%). In P2, coinciding with an important reduction in training time spent at Z2 (only 32% in this intensity zone), VO_2 values at $VT2$ significantly decreased by 4.3%; whereas no changes for this variable were observed in P3. After completing the 12-week training cycle, $VT2$ ($\%VO_{2max}$) was identical to the starting value (80.5%), despite the fact that VO_2 at $VT2$ was significantly higher (increasing from 50.1 to 54.8 mL kg^{-1} min^{-1} from T0 to T3) (Fig. 3).

Variables closely related to actual kayaking performance, such as PS_{max} and PS_{VT2} increased steadily and similarly throughout the training cycle until reaching an improvement of 6.2 and 4.4% between T0 and T3, respectively (Table 4). It is noteworthy that PS_{max} improved from 15.1 to 15.5 km h^{-1} in the final 2 weeks (P3). The peak blood lactate concentration found after the incremental test to exhaustion on the kayak ergometer (13.0 ± 2.8 mmol L^{-1}) was comparable to the values reported in the literature (Bishop et al. 2002; Tesch et al. 1976, 1983) for similar top-level kayakers (i.e. 13–16 mmol L^{-1}), and occurred at between 5 and 7 min of recovery in all subjects.

The improvements in 1RM values for the bench press exercise (9.7%; Fig. 4), after 5-week of hypertrophy-oriented strength training performed in P1, are comparable to those described for this exercise for moderately strength-trained athletes following similar concurrent training routines in elite junior basketball and soccer players (from 5.2 to 9.6%) (Drinkwater et al. 2005, 2007), or handball players (16%) (Marques and González-Badillo 2006) after 6-week training. This notable increase in maximal strength was obtained even though only very modest levels of hypertrophy were detected in such a short training phase; thus, chest girth was the only variable to significantly increase during this period (Table 3). Unfortunately, MRI or other more sensitive measurements to ascertain the extent of possible hypertrophic changes were not performed in the present study. The greatest improvements in $V_{45\%}$ (11% in BP and 7% in PBP) clearly occurred after P3, where 80% of total resistance-training volume was spent on specifically working with maximal power output loads for upper-body exercises (Fig. 4). During this type of training, the number of repetitions performed in each set was carefully controlled by monitoring the velocity of each repetition and giving immediate feedback to the athlete. The set was stopped when velocity dropped by more than 10% of the fastest repetition mean concentric velocity (Table 2). This made it possible to attain very high power output values in only a few selected repetitions, as already suggested by some authors (Baker and Newton 2007; Izquierdo et al. 2006b; Tidow 1995), as an effective strategy for improving maximal power in highly trained elite athletes. By contrast, maximal dynamic strength decreased considerably in P3 (4.5% in both exercises; Fig. 4) even though 20% of total training time during this phase was of maximal strength type (Fig. 2). This could be explained by the significantly reduced volume and intensity of training during this final tapering phase, perhaps suggesting that high-intensity stimuli are needed in order to maintain maximal strength gains in these highly trained athletes. The 1RM strength values, together with the high VO_{2max} and VO_2 at $VT2$ found in this study confirm the huge requirements of aerobic power and strength of Olympic sprint kayaking.

Despite the time devoted to endurance training being, on average, more than triple that of resistance training, strength and power markers improved consistently throughout the study. Together with the above-mentioned strategy of prioritizing the development of two target fitness components (i.e. one for strength and another for endurance) in each training phase, the simultaneous improvement in strength and endurance markers observed in the present study may be explained by other factors which we believe helped to reduce conflicting adaptations in the concurrent training of strength and endurance. One important aspect was controlling for training volume and, especially, limiting the frequency of resistance training to only three sessions per week because, as already addressed in the introduction, higher frequencies have proved to compromise strength gains in most concurrent training studies. Research has also highlighted the importance of the order and timing of the aerobic and strength training sessions in order to minimize possible interference effects (Leveritt et al. 1999, 2000; Sale et al. 1990b; Sporer and Wenger 2003). Thus, insufficient recovery between training sessions might limit simultaneous adaptations to strength and endurance training. 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 (Leveritt et al. 1999) and/or reducing the absolute volume of strength training that could be performed in such condition (Sale et al. 1990b). Additionally, acute changes in metabolic activity have been reported to be altered by a preceding bout of endurance exercise (Leveritt et al. 2000). Consequently, and following the suggestions outlined by Sporer and Wenger (2003), we decided to schedule strength sessions before endurance sessions or, when not feasible, to separate both types of training sessions by at least 6–8 h to allow for restoration and glycogen repletion.

Two other aspects that we purposely introduced in the design of the training program were the avoidance of strength training sessions leading to muscle failure and the emphasis placed on performing each repetition explosively, with maximal intended concentric velocity. These measures are based on suggestions from previous research (Cronin and Sleivert 2005; Folland et al. 2002; Izquierdo et al. 2006a), and are aimed at maximizing adaptations in the neural component of strength as well as trying to avoid excessive fatigue or mechanical and metabolic strain, which could negatively influence the quality of subsequent training sessions. In the study of Sale et al. (1990b), although same day concurrent resistance and aerobic training induced very similar levels of muscle hypertrophy to those obtained when training strength and endurance on different days, strength gains were significantly higher in the latter case. Therefore, it seems likely that neural adaptations are impaired when combining strength and endurance in the same training session, so that to improve neuromuscular performance and make the most of strength training, sessions must be undertaken in a well-rested, unfatigued state. One may also speculate that similarly to the concurrent strength and endurance program performed in the present study, the shortest events of kayaking, canoeing and rowing could benefit from periodized programs, where emphasis is placed on developing maximal strength and maximal muscle power in certain phases of the training cycle.

A final aspect worth noting has to do with the specific modality of exercise used in strength and endurance training. In the few studies that have used upper-body exercise modalities of resistance and endurance training, there appeared to be no interference in strength development, when concurrent training was compared with strength training alone (Leveritt et al. 1999), whereas the 'interference phenomenon' described by Hickson (1980) was relative to lower body exercise, in which muscle strength is not a limiting factor. It remains to be determined whether there exist differences in concurrent training when training upper or lower-body musculature.

In summary, a 12-week periodized strength and endurance training program with special emphasis on prioritizing the development of specific physical fitness components in each training phase (i.e. muscle hypertrophy and *V*T2 in P1, and maximal strength and aerobic power in P2) seems effective in improving both cardiovascular and neuromuscular markers of highly trained top-level athletes.

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