REVIEW ARTICLE

Sports Med 2011; 41 (4): 329-343
0112-1642/11/0004-0329/$49.95/0

Strategies to Optimize Concurrent Training of Strength and Aerobic Fitness for Rowing and Canoeing

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Abstract

During the last several decades many researchers have reported an interference effect on muscle strength development when strength and endurance were trained concurrently. The majority of these studies found that the magnitude of increase in maximum strength was higher in the group that performed only strength training compared with the concurrent training group, commonly referred to as the 'interference phenomenon'. Currently, concurrent strength and endurance training has become essential to optimizing athletic performance in middle- and long-distance events. Rowing and canoeing, especially in the case of Olympic events, with exercise efforts between 30 seconds and 8 minutes, require high amounts of maximal aerobic and anaerobic capacities as well as high levels of maximum strength and muscle power. Thus, strength training, in events such as rowing and canoeing, is integrated into the training plan. However, several studies indicate that the degree of interference is affected by the training protocols and there may be ways in which the interference effect can be minimized or avoided. Therefore, the aim of this review is to recommend strategies, based on research, to avoid or minimize any interference effect when training to optimize performance in endurance sports such as rowing and canoeing.

Proper planning of training programme variables, including intensity, frequency and volume of exercise, is required to maximize physiological adaptations and to avoid overtraining in elite athletes. This is especially important in most cyclic sports (i.e. disciplines that require repeated continuous movements similar to others such as running, walking, swimming, rowing, cross-country skiing, cycling and canoeing), where both aerobic fitness and muscle strength need to be simultaneously enhanced to optimize performance. Strength has been defined as the ability of the muscle to exert maximal force or torque at a specified velocity.[1] However, it varies for different muscle actions such as eccentric, concentric and isometric. Therefore, an infinite number of values for strength of muscles may be obtained as related to the type of action, the velocity of the action and the length of the muscles. Muscle power, which is a function of the interaction between the force applied and the speed of contraction, is associated with the explosiveness of the muscles (i.e. the ability to develop a great deal of force in a short period of time, termed the rate of force development).[1]

On the other side, the aerobic endurance performance depends on two main fitness components: (i) the highest rate of oxygen consumption ($\dot{V}O_2$) attainable during maximal or exhaustive effort (maximal $\dot{V}O_2$ [$\dot{V}O_{2max}$]); and (ii) the anaerobic threshold (AT): the $\dot{V}O_2$ level above which aerobic energy production is supplemented by anaerobic mechanisms during exercise, resulting in a sustained increase in lactate concentration and metabolic acidosis.[2] For highly trained athletes the AT is normally placed at 80–90% of the $\dot{V}O_{2max}$.

Several studies have shown the effectiveness of concurrent training programmes in enhancing the performance of endurance athletes (e.g. running economy, increases of the speed at lactic threshold or improvements in the jump capability).[3-11] Previous research demonstrates that both rowing and canoeing, especially in the case of Olympic events (200, 500, 1000 and 2000 metres) with exercise efforts between 30 seconds and 8 minutes require high levels of maximal aerobic and anaerobic capacities, as well as maximum muscle strength and power.[12-20] In both sports, recent studies found performance improvements following concurrent training programmes in highly trained athletes, such as paddling speed and paddling power output at maximal and submaximal intensities, as well as lactic acid concentrations at submaximal intensities.[15,21-23]

Some of the mechanisms that may be responsible for these improvements in performance during concurrent training are as follows:[24] (i) increased strength that may improve mechanical efficiency, muscle coordination, and motor recruitment patterns;[25] (ii) an overall increase of strength that can facilitate changes and corrections in the technical model;[4] or (iii) increased muscular strength and coordination that may reduce the relative intensity of each cycle enabling the athlete to conserve energy.[26]

In recent decades, many researchers have focused on studying the effects of the combined strength and endurance training programmes on physical performance. The results of several studies have shown that 10–12 weeks of concurrent training, with a weekly frequency between 4 and 11 sessions, with intensities ranging from 60% to 100% of $\dot{V}O_{2max}$ for endurance and from 40% to 100% of one-repetition maximum (1RM) for resistance training, resulted in increases ranging from 6% to 23% in $\dot{V}O_{2max}$ and 22% to 38% of maximum strength.[27-29] In the majority of these studies the increases in maximum strength were higher in the group that performed only strength training compared with the concurrent training group. This potential conflict has been referred to as an 'interference phenomenon' because a compromised strength development was observed when strength and endurance training were applied concurrently.[27] In contrast, the majority of current research supports the contention that concurrent training does not alter the ability to positively adapt to endurance training.[3,6,30]

Several studies have identified different factors that can influence the level or degree of interference generated by concurrent training.[29-33] These factors include the initial training status of the subjects, exercise mode, volume, intensity and frequency of training, scheduling of sessions and the dependent variable being investigated.

In particular, the initial training status of subjects may play a critical role in the adaptations produced by concurrent training.[34] Most research studies have analysed the concurrent training adaptations in untrained subjects[27,35-43] or moderate to well trained participants.[3-5,28,44-46] However, very few researchers have focused on studying the effects of concurrent training for elite and highly trained athletes who require high levels of strength and endurance for successful performance, such as rowers and paddlers.[15,21-23] This often requires concurrent strength and endurance training, which has become an integral part of training programmes for middle- and long-distance events. Despite all of the experimental studies, there is a lack of practical information that enables coaches to design an effective training plan to optimize performance in sports with high demands for muscle strength and aerobic fitness. Therefore, the aim of this review was to identify the optimal combinations of training programme variables in order to avoid or at least minimize the negative effects of concurrent training in elite rowers and paddlers.

1. Literature Search

SciELO, Science Citation Index, National Library of Medicine, MEDLINE, Scopus, SportDiscus®, CINAHL, ProQuest, ScienceDirect and Google Scholar databases were searched from January up to 11 April 2010 for articles published from original scientific investigations. Search terms included various combinations of the keywords 'concurrent training', 'rowing', 'canoeing', 'kayak', 'training periodization', 'training to failure', 'training volume', 'repetitions', 'sets', 'resistance training', 'strength training' and 'endurance training'. The names of authors cited in some studies were also utilized. Hand searches of relevant journals and reference lists obtained from articles were also conducted in the libraries of the Studies, Research and Sports Medicine Center, Government of Navarra, Pamplona, Spain. Such combinations resulted in the inclusion of 89 original research articles addressing the effects of concurrent training in elite and well trained subjects.

Search criteria were as follows: (i) English peer-reviewed scholarly journals only; (ii) dissertations, theses and conference proceedings were excluded; and (iii) studies must refer to the effects of concurrent strength and endurance training and manipulation of training programme variables in well trained or highly trained athletes.

2. Interference Phenomenon during Concurrent Training

Because strength and endurance training elicit distinct and often divergent adaptive mechanisms,[33,47] the concurrent development of both fitness components in the same training regimen can lead to conflicting neuromuscular adaptations; as a result, different studies have found compromised adaptation of strength, especially muscle power, when both attributes were trained at the same time as endurance.[15,27-29,36,37,45,48]

Although, historically, strength training has been a fundamental aspect of all short-term cyclic sports, the majority of middle- and long-distance cyclic disciplines have considered resistance training a potential enemy for physical performance enhancement. Indeed, the majority of middle- and long-distance coaches have considered strength training a potential detriment to performance and have only included it for specific parts, such as starts and changes of pace. Most of the studies with elite and highly trained athletes have found interference effects when strength and endurance were trained concurrently (table I).

The interference of strength development during concurrent training has been classically explained by the following mechanisms:[47,49-51] (i) reductions in the motor unit recruitment and decreases of rapid voluntary neural activations;[27,37,48,52] (ii) chronic depletion of muscle glycogen stores;[53,54] (iii) skeletal muscle fibre-type transformation from IIb to IIa and from IIa to I;[55,56] (iv) overtraining produced by imbalances between the training and recovery process of the athlete;[52,57] and (v) decreases in the cross-sectional area of muscle fibres and in the rate of muscle force production[28] due to the reduction in total protein synthesis following endurance training.[58,59]

Table I. Concurrent training effects on well trained and highly trained subjects

Study (y)	No. of subjects; sex; description	Age (y) [mean or range]	Study design/training routine	Duration (wk)	Findings
Mikkola et al.[5] (2007)	19; M; well trained cross-country skiers	23.1	Equal total training volume in both CT and ET groups, but 27% of total ET volume was replaced by explosive ST in CT group	8	No changes occurred in $\dot{V}O_{2max}$ and electromyography in either ET or CT groups. The steady-state $\dot{V}O_2$ decreased only in the CT group (–7%). No significant differences were detected in maximal isometric and concentric force between groups
Rønnestad et al.[6] (2010)	23; M and F; well trained cyclists	27–30	ET group: normal ET CT group: heavy ST (from 10RM to 4RM) twice a wk, plus normal ET	12	Wingate peak power output (8.7%), W_{max} during incremental test (4.4%), power output at 2 mmol/L [La$^-$] (3.7%) and mean power output during a 40 min all-out trial (6%) increased only in CT group. Both groups increased their $\dot{V}O_{2max}$ (6.0% ET in the group and 3.3% in the CT group)
Millet et al.[8] (2002)	15; M; elite triathletes	21–24	ET group: normal ET CT group: heavy weight training 2 d/wk at 90% of 1RM, plus normal ET	14	Improvements in maximum strength (17–25%) were detected only in the CT group. Running economy and hopping power were significantly greater in the CT than in the ET group. No significant differences were detected in $\dot{V}O_{2max}$ or other cardiorespiratory parameters between groups
Paavolainen et al.[9] (1999)	18; M; elite distance runners	23–24	Equal total training volume for both CT and ET groups, but 32% of total ET volume in the CT group was replaced by sport-specific explosive ST	9	5 km run time decreased in the CT group (–3.1%). Improvements in running economy (8.1%) and maximal anaerobic velocity were detected only in the CT group. Sprint (3.6%) and jump performance (4.7%) increased in the CT and decreased in the ET group (–2.4% and –1.7%). $\dot{V}O_{2max}$ increased in the ET group (4.9%), but no changes were observed in the CT group
Saunders et al.[10] (2006)	15; M; elite distance runners	23–25	ET group: normal ET CT group: concurrent plyometric training (3 d/wk) plus normal ET	9	Improvements in running economy (4.1%) were found only in the CT group. No significant differences in other strength and power measures between groups were detected
Spurrs et al.[11] (2003)	17; M; well trained distance runners	25.0	ET group: normal ET CT group: concurrent plyometric training (2–3 d/wk) plus normal ET	6	Decreases in 3 km run time (–2.7%) and improvements in running economy (4.1–6.6%) were detected only in the CT group
Izquierdo-Gabarren et al.[15] (2010)	43; M; highly trained rowers	22–27	Four groups: 4RF, 4NRF, 2NRF and control. All groups performed the same ET	8	4NRF group experienced larger gains in 1RM strength and muscle power output (4.6% and 6.4%, respectively) than the 4RF and 2NRF groups. 4NRF and 2NRF groups experienced larger gains in specific rowing performance compared with those found after 4RF
García-Pallarés et al.[22] (2009)	11; M; world-class, flat-water kayak paddlers	26.2	12 wk divided in three different phases. First phase focused on the development of muscle hypertrophy and anaerobic threshold. Second phase focused on maximum strength and MAP. Third phase focused on tapering	12	Significant improvements were detected in $\dot{V}O_{2max}$ (9.5%), $\dot{V}O_2$ at VT_2 (10%), 1RM (4–5%) as well as in the velocity with maximal power loads (10–14%)

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Table I. Contd

Study (y)	No. of subjects; sex; description	Age (y) [mean or range]	Study design/training routine	Duration (wk)	Findings
García-Pallarés et al.[23] (2010)	14; M; world-class, flat-water kayak paddlers	25.2	Full season of combined resistance and ET; 72% of total training volume was periodized ET and 28% periodized resistance training	43	Significant improvements were detected in $\dot{V}O_{2max}$ (8.8%), 1RM (6–12.5%) as well as in the velocity with maximum power loads (7–15.3%)
Hennessy and Watson[45] (1994)	56; M; well trained rugby players	23–24	ST group: 3 d/wk periodized resistance training. ET group: 4 d/wk, three continuous running sessions at low- to moderate-intensity plus one fartlek session. CT group: 5 d/wk, ST plus ET	8	1RM gains were detected in ST (16.7–20.9) and CT (5.4–14.5%) groups, but not in the ET group. Improvements in vertical jump (5.5%) and sprint (1.3%) were detected only in the ST group. Increases in estimated $\dot{V}O_{2max}$ were detected in CT (7.3%) and ET (10.8%) groups, but not in the ST group
Mikkola et al.[46] (2007)	18; M; 7; F; well trained distance runners	16–18	Equal total training volume in both CT and ET groups, but 19% of total ET volume was replaced in the CT group by explosive ST	8	Improvements in maximum dynamic (4%) and isometric (8%) strength were detected only in the CT group. Significant better results were detected in anaerobic performance in the CT group. No significant differences between groups were detected in $\dot{V}O_2$ at maximal and submaximal intensities as well as in serum hormone concentrations

2NRF = two exercises leading to not to repetition failure; **4NRF** = four exercises leading to not to repetition failure; **4RF** = four exercises leading to repetition failure; **CT** = concurrent training; **ET** = endurance training; **F** = female; **[La⁻]** = lactate concentration; **M** = male; **MAP** = maximal aerobic power; **RM** = repetition maximum; **ST** = strength training; $\dot{V}O_2$ = oxygen consumption; $\dot{V}O_{2max}$ = maximal oxygen consumption; VT_2 = second ventilatory threshold; W_{max} = peak power.

Leveritt et al.[29] proposed two main reasons for this interference phenomenon occurring during concurrent training. First, the chronic hypothesis suggests that the musculoskeletal tissue cannot adapt metabolically and morphologically simultaneously, mainly due to differences in the type and fibre size of the tissue when strength training is carried out in isolation or combined with endurance training. Second, the acute hypothesis contends that residual fatigue produced by endurance training reduces the ability of muscles to generate force. Strength training with residual fatigue may compromise the quality of the training, which may lead to a decline in strength development over a training cycle.

Because of the high demands for muscle strength and aerobic fitness in events such as rowing and canoeing, it seems necessary to identify the optimal combination of training variables to avoid or minimize the potential negative effects of concurrent training. In light of recent studies, the following sections will identify strategies and training programmes that have proven effective in controlling potential interference effects when strength and aerobic fitness are developed concurrently.

3. Concurrent Training Strategies to Minimize Interference

3.1 Training Periodization

Non-linear or undulating periodized resistance training programmes, in which short periods of high volume are alternated with short periods of high intensity, can result in greater strength gains.[60-62] Nevertheless, presently, the sequence and distribution of the optimal training loads for sports in which concurrent training is required to achieve success in competition, has not yet been identified.

Block periodization, the current trend in the training periodization for highly trained athletes, emphasizes the need to reduce the duration of the training phases and cycles, as well as the use of highly concentrated training loads focused on the consecutive development of a minimal number of motor and technical abilities.[21,63-65] This periodization model has been developed in response to a number of negative effects that occur in elite athletes following the use of the traditional periodization model. This traditional model has been dominant for over 30 years in almost all sports and performance levels, and still remains in force. The guidelines for this model are based on the simultaneous development of many fitness components during the same training phase (e.g. aerobic capacity, maximal aerobic power [MAP], maximum strength) and, therefore, this model does not provide sufficient workload to enable the correct development of selected fitness components.[21,64-66]

In a recent study,[22] a 12-week periodized cycle of combined strength and endurance training with special emphasis on prioritizing the development of two specific physical fitness components in each training phase (i.e. muscle hypertrophy and AT in one phase and maximum strength and MAP in the other phase), was effective for improving both cardiovascular and neuromuscular markers of top-level kayakers. In this study, approximately 50% of total paddling volume during each phase was devoted to the development of one endurance target. In addition, between 80–100% of the total strength training volume of each phase was devoted to the development of one strength target (figure 1).

In another study, the same group[21] compared training-induced changes in selected endurance and performance variables following two main training periodization models (i.e. traditional vs block periodization) in elite kayakers. Compared with traditional periodization guidelines, block periodization involved about half of the total training volume, but with ~10% higher workload accumulation over the selected training targets (45–60% of total training volume). The results demonstrated that during short training phases, (5 weeks) block periodization resulted in a more effective training stimulus for the improvement of kayaking performance (paddling speed, stroke rate and power output) when compared with a traditional approach in elite-level paddlers (figure 2).

These findings suggest that short training phases (5 weeks) using highly concentrated training loads (>50% of the total training volume) and which focus on the development of only two target fitness components in each training phase (i.e. one for strength and another for endurance), result in a more effective training stimulus for the improvement of performance in highly trained athletes when compared with a more traditional training approach.

3.2 Training Volume and Frequency

The frequency of training may play a critical role in the adaptations created during concurrent

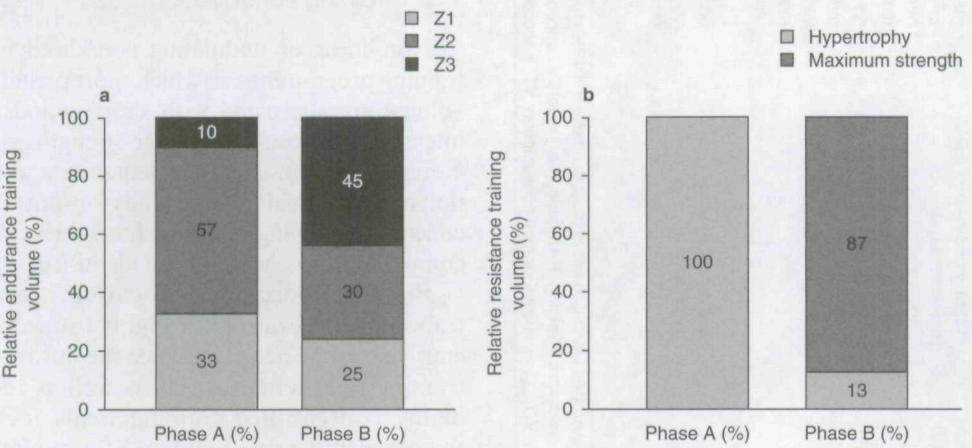

Fig. 1. (**a**) Relative contribution of each exercise intensity zone to the total endurance training time; and (**b**) relative contribution of each strength training type to the total resistance training volume performed in each phase. $\dot{V}O_{2max}$ = maximal oxygen consumption; VT_2 = second ventilatory threshold; **Z1** = light intensity below second VT_2; **Z2** = moderate intensity between VT_2 and 90% of $\dot{V}O_{2max}$; **Z3** = high intensity between 90% and 100% of $\dot{V}O_{2max}$.

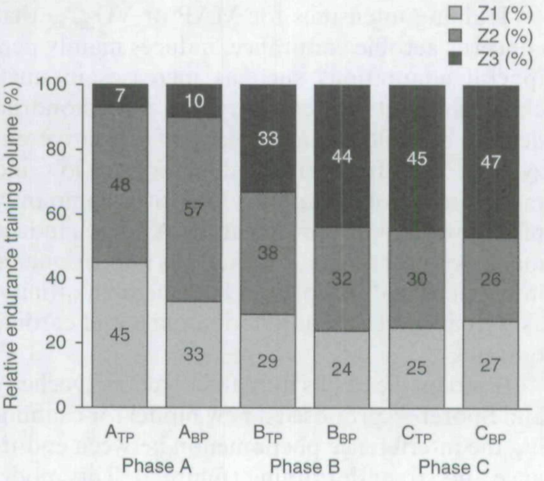

Fig. 2. Relative contribution of each exercise intensity zone to the total endurance training volume performed in each phase of both training periodization models (reproduced from García-Pallarés et al.,[21] with permission from Springer Science + Business Media). $\mathbf{A_{TP}}$, $\mathbf{B_{TP}}$ **and** $\mathbf{C_{TP}}$ = A, B and C phases of traditional periodization approach; $\mathbf{A_{BP}}$, $\mathbf{B_{BP}}$ **and** $\mathbf{C_{BP}}$ = A, B and C phases of block periodization approach; $\dot{\mathbf{V}}\mathbf{O_{2max}}$ = maximal oxygen consumption; $\mathbf{VT_2}$ = second ventilatory threshold; **Z1** = light intensity below second VT_2; **Z2** = moderate intensity between VT_2 and 90% of $\dot{V}O_{2max}$; **Z3** = high intensity between 90% and 100% of $\dot{V}O_{2max}$.

training.[39,48,67] Similarly, the total number of weeks that athletes undergo this concurrent training regimen also appears to be related to the level of interference that is generated.[48,68] Most of the studies have reported concurrent training to be detrimental for only strength gains when training frequency was higher than 3 days per week.[27,28,37,45,69] In studies where the training frequency did not exceed 3 days per week, increases in maximum strength were detected following concurrent training periods between 8 and 16 weeks,[15,22,67] and ≥20 weeks.[23,48]

The manipulation of other variables that make up the design of strength training such as the number of exercises, the number of repetitions per set or the number of sets per exercise, is another widely studied issue. Several researchers have concluded that the strength training-induced adaptations, such as muscle hypertrophy or nervous system improvements, depend largely on the total number of repetitions performed by the subject.[15,70-72] It has been observed that during strengthening programmes with trained subjects a moderate training volume (i.e. 10 weeks with <85% of the total volume that athletes can tolerate), is a more effective and efficient stimulus for increasing strength than conducting a maximum or close to maximum number of repetitions in a given training cycle.[70,71]

With regard to the number of repetitions performed per set, recent studies conducted with concurrent training programmes in kayakers[22] and rowers[15] showed that a moderate strength training volume (approximately 50% of the maximum number of repetitions that can be performed in a set) were effective for increasing strength and power. Izquierdo-Gabarren et al.[15] found that during an 8-week periodized cycle of combined strength and endurance training that incorporated three to five sets in four global and multi-joint exercises (prone bench pull, seated cable row, lat pulldown, power clean) produced significant increases in strength, muscle power and rowing performance in highly trained rowers. In 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 programme. It is especially important when both strength and aerobic endurance need to be concurrently enhanced.

To achieve optimal adaptations in muscle strength and power, as well as to minimize interference phenomenon with endurance training, it is not recommended to perform a training frequency in excess of three strength training sessions per week. To maximize the strength training adaptations and to avoid overtraining, the optimal number of exercises and repetitions to perform during each session need to be individually adjusted. A training volume close to 3–5 sets in 4–6 specific and multi-joint exercises, during 10–12 week training cycles, seems to be an adequate stimulus for optimal strength development in highly trained rowers and kayakers.

3.3 Optimal Combination of Strength and Endurance Training Intensities

For a large number of sports, optimization of physical performance depends on the concurrent development of a small number of strength and endurance capabilities. Traditionally, the specific strength improvement on rowing and canoeing has been conducted under the guidelines of two classical methods: (i) local muscle endurance (LME) and hypertrophy with moderate-to-high load (i.e. 6–12RM) and high-volume, multiple-set programmes with short-to-moderate rest periods between sets; and (ii) maximum strength and power with high load (i.e. 1–6RM), multiple-set programmes with long rest periods between sets.[73] Moreover, several research papers show that aerobic performance in Olympic events for both sports (rowing and canoeing) depends mainly on the development of anaerobic threshold (AT) and $\dot{V}O_{2max}$ or MAP.[13,17,22]

Training for maximum strength (intensities >85% 1RM) and maximal power (maximum power loads) induce mainly central adaptations. These adaptations include improvement of the neural component through increased motor unit firing rate and changes in synchronization, recruitment of higher threshold motor units, decreased co-contraction of antagonists and lower metabolic demands at the muscle level.[74] In addition, training for LME and hypertrophy requires intensities that range between 70% and 80% 1RM and induce mainly peripheral adaptations. These adaptations are highlighted by increases in the contractile protein synthesis that promotes an increase in fibre size and muscle cross-sectional area, as well as an increase of glycolytic enzymes. However, these training stimuli also produce declines in capillary and mitochondrial density, as well as a considerable metabolic and hormonal stress at the cellular level.[30,74]

Training intensities for MAP or $\dot{V}O_{2max}$ that concerns aerobic endurance, induces mainly peripheral adaptations such as increases in muscle glycogen stores, capillary and mitochondrial density as well as an increase of oxidative enzymes.[30,75,76] In contrast, adaptations to low and moderate aerobic training intensity, commonly related with improvements at the AT level, induce mainly central adaptations such as improvements in pulmonary diffusion and haemoglobin affinity, as well as increases in blood volume and cardiac output.[30,77]

Based on the results from these studies, Docherty and Sporer[30] proposed a new model for examining the interference phenomenon between endurance and strength training (figure 3). This model suggests that blending the specific training objectives of muscle hypertrophy for strength (LME) and MAP for endurance should be avoided (strength and power) due to these two training modes inducing opposite physiological adaptations at the peripheral level, interferences that prevent the body from optimally and simultaneously adapting to both.[29] In contrast, training at lower aerobic intensities (75–85% $\dot{V}O_{2max}$), such as those usually employed to improve the AT, induce more central adaptations than would be expected to cause much less interference with LME training. The cited model also predicts less interference when concurrently training for maximum strength and power and MAP because the training stimulus for increasing strength would be mainly directed at the neural system, not placing high metabolic demands on the muscle[30] (figure 4).

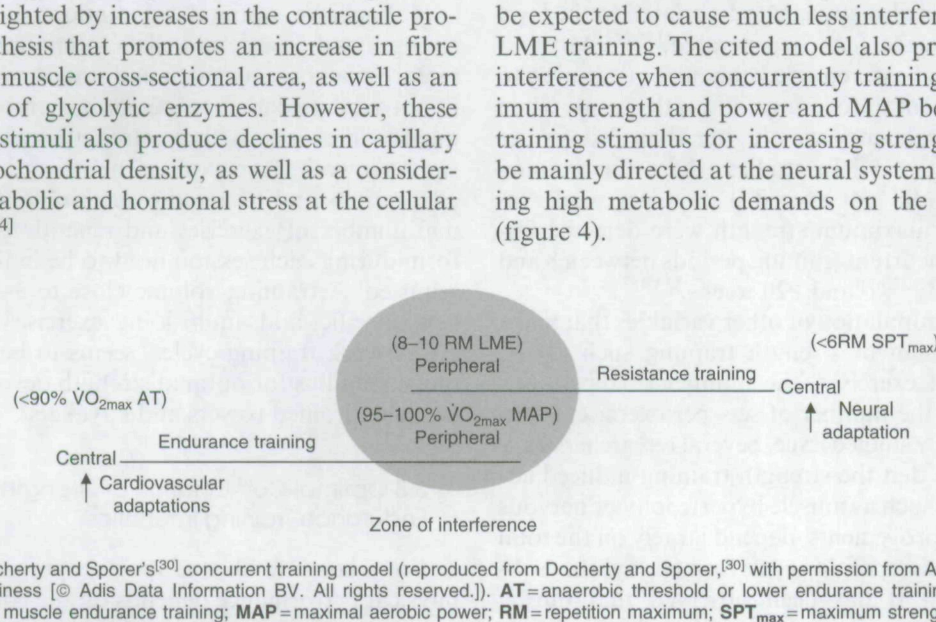

Fig. 3. Docherty and Sporer's[30] concurrent training model (reproduced from Docherty and Sporer,[30] with permission from Adis, a Wolters Kluwer business [© Adis Data Information BV. All rights reserved.]). **AT** = anaerobic threshold or lower endurance training intensities; **LME** = local muscle endurance training; **MAP** = maximal aerobic power; **RM** = repetition maximum; **SPT_{max}** = maximum strength and power training; **$\dot{V}O_{2max}$** = maximal oxygen consumption; ↑ indicates increase.

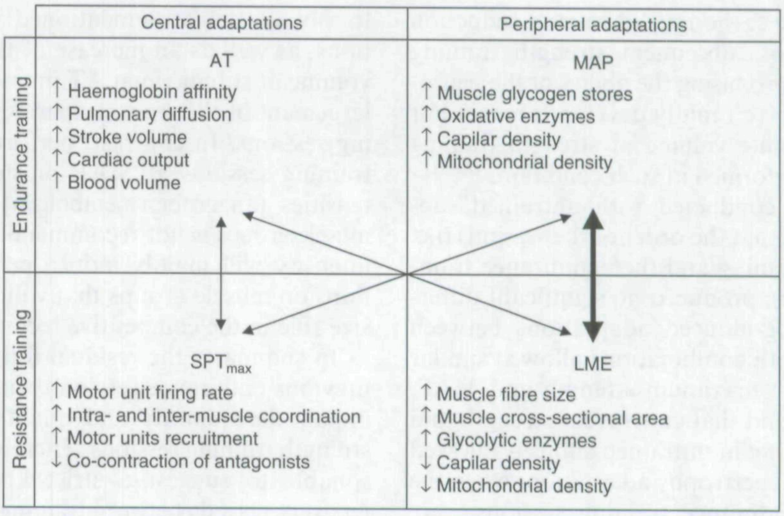

Fig. 4. Optimal combination between resistance and endurance training intensities. **AT** = anaerobic threshold or lower endurance training intensities; **LME** = local muscle endurance training; **MAP** = maximal aerobic power; **SPT$_{max}$** = maximum strength and power training; ↑ indicates increase; ↓ indicates decrease.

Unfortunately, very few studies have examined the effects of different concurrent training programmes in trained subjects to confirm or reject this theoretical model.[30] de Souza et al.[78] assessed the effects of AT and MAP intensity on maximum strength (1RM) and strength endurance (defined as the maximum number of repetitions performed with 80% of 1RM) in a group of experienced strength-trained athletes. The results showed that a continuous low intensity and moderate duration AT did not produce any interference on the subsequent strength session. Nevertheless, intermittent MAP exercise produced an acute interference effect on strength endurance, while maximum strength was not affected by this aerobic exercise mode.

To the authors' knowledge, the study of García-Pallarés et al.[22] is the first reported publication that examined the effects of a concurrent training programme that followed the Docherty and Sporer[30] model in elite athletes. In this study, two consecutive phases (5 weeks) of concurrent training in elite kayakers, with special emphasis on prioritizing the development of two specific physical fitness components in each training phase (i.e. muscle hypertrophy and AT in phase A and maximum strength and MAP in phase B) produce great increases in maximum strength (close to 10%), as well as increases in $\dot{V}O_{2max}$ (MAP) and $\dot{V}O_2$ at the second ventilatory AT >9%.

In summary, it seems necessary to avoid the simultaneous development of LME (8–10RM) and aerobic power, due to both training intensities inducing opposite adaptations on the same peripheral components. Therefore, during a concurrent training approach, endurance training at the AT level or at lower intensities should be associated with SPT$_{max}$ intensities. Due to the compatible training-induced adaptations associated with the MAP, LME and SPT$_{max}$ intensities, no interference effects should be expected during the concurrent development of these fitness components.

3.4 Sequence of Concurrent Training Sessions

Several studies have highlighted the importance of the sequence and timing of the aerobic and strength training sessions in order to minimize possible interference effects.[22,29,36,79-81] 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 sessions by compromising the ability of the neuromuscular system to rapidly develop force and/or reduce the absolute volume of strength training that could be performed in such conditions.[79-81]

Two studies conducted with untrained subjects[82,83] found that the order of the sessions (i.e. first strength training and then endurance training or *vice versa*), produced no significant differences in training-induced adaptations between groups, since both combinations allowed similar improvements in maximum strength and MAP. Sale et al.[80] found that concurrent strength and endurance training in untrained subjects allowed similar muscle hypertrophy adaptations when the strength and endurance training sessions were conducted on the same or on different days. Nevertheless, in this study, the strength gains were significantly higher in the group that performed the training sessions on different days. Similarly, in well trained athletes,[81] following an aerobic endurance training session, strength performance remained significantly decreased for at least 8 hours after completion of the endurance session. In a recent study,[22] highly trained kayakers achieved significant improvements in aerobic power, and maximum strength and muscle power by placing the strength sessions before the endurance sessions or, when not feasible, separating both types of training sessions by at least 6–8 hours to allow for restoration and glycogen repletion.

From a similar point of view, several studies have detected interference in strength gains during concurrent training only when the same muscle groups were used for both resistance and endurance training.[36,81] As already addressed in section 3.3, aerobic training intensities not exceeding AT produce mainly central adaptations. This is a critical success factor for Olympic rowing and canoeing, due to improvements in pulmonary diffusion and haemoglobin affinity, as well as increases in blood volume and cardiac output.[77] By conducting extra endurance training sessions at submaximal AT intensities and by not involving specific muscle groups (e.g. cycling for paddlers), this may allow high-level athletes to obtain the aforementioned central adaptations, as well as an increase of the total training volume at submaximal AT intensities and an enlargement of the recovery periods between training sessions. In contrast, performing endurance training sessions at MAP or supramaximal intensities (anaerobic metabolism) on non-specific muscle groups is not recommended. This training intensity will mainly induce peripheral adaptations on muscle groups that will not have a decisive role in the competitive technique model.

In summary, the residual fatigue caused by a previous endurance session could reduce and/or impair the quantity and quality of subsequent strength training sessions. Therefore, it seems reasonable to suggest a strict knowledge of the recovery periods between training sessions; in particular, for highly trained athletes, the strength training sessions should be placed before the endurance sessions or at least separating both types of training sessions by more than 8 hours. Performing extra endurance training sessions at submaximal intensities and employing mainly non-specific muscle groups, may allow high-level athletes to achieve central adaptations, while the specific muscle groups recover for subsequent sessions of greater intensity.

3.5 Number of Repetitions with a Given Load: Training to Failure versus Not to Failure

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.[84,85] Thus, the role of 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, in order to understand the physiological mechanisms underlying training-induced gains in strength and power. Most of these researchers have focused on studying the mechanisms and effects that training leading to repetition failure have on muscle strength and power, as well as the effects on the athlete's performance.[15,86-89]

Short-term training (<9 weeks) leading to 'repetition failure' produces greater improvements in strength when compared with a 'not to repetition failure' training approach in trained subjects.[87,89] However, other studies have concluded that training to repetition failure may not be necessary for optimal strength gains, since the incurred fatigue reduces the force that a muscle can generate.[85,87,88] 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.

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 maximum strength and muscle power output[85] (figure 5).

In highly trained male rowers,[15] an 8-week, linear-periodized, concurrent strength and endurance training programme, using a moderate number of repetitions not to repetition failure, provided a favourable environment for achieving greater enhancements in strength, muscle power and rowing performance when compared with higher training volumes of repetition to failure (figure 6).

Likewise, in two studies performed with elite kayakers and with concurrent training, a periodized training cycle of 12 weeks[22] and a pre-competitive training phase of 47 weeks[23] allowed paddlers to achieve great improvements in maximum strength and power when a not to repetition failure training approach was employed.

In summary, a concurrent strength and endurance training programme using a moderate number of repetitions for not to repetition failure training provides a favourable environment for achieving greater enhancements in strength, muscle power and specific performance when compared with higher training volumes of repetition to failure. The training for the not to repetition failure approach speeds up recovery from strength training, allowing rowers and paddlers to execute subsequent endurance training sessions with a superior performance.

4. Conclusions

Several strategies or mechanisms have proven effective in reducing the interference phenomenon of concurrent strength and endurance training, especially in rowing and canoeing where both capabilities need to be developed simultaneously to optimize performance as follows:

- Short training phases (5 weeks) using highly concentrated training loads (>50% of the total training volume) focusing on the concurrent

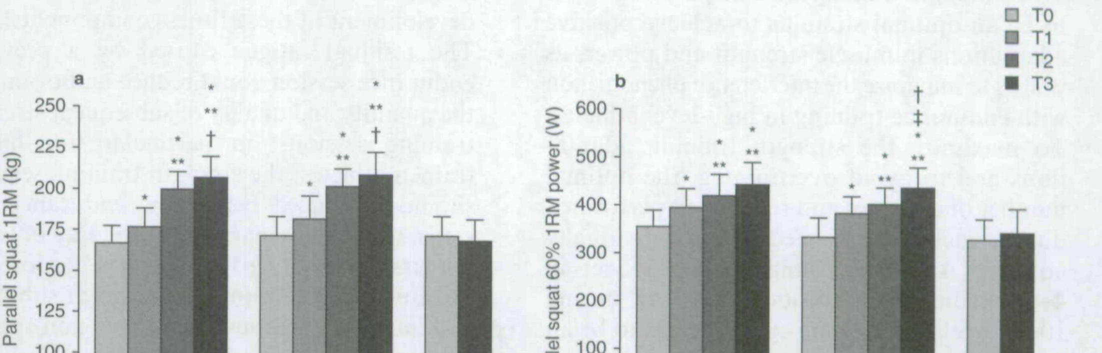

Fig. 5. (**a**) Maximal parallel squat strength; and (**b**) parallel squat muscle power during the experimental period (reproduced from Izquierdo et al.,[85] with permission from The American Physiological Society). **1RM** = one-repetition maximum; **NRF** = not to repetition failure group; **RF** = repetition to failure group; T0 = timepoint before training; T1 = timepoint after 6 wk of training; T2 = timepoint after 11 wk of training; T3 = timepoint after 16 wk of training. * $p < 0.05$ from the corresponding timepoint T0; ** $p < 0.05$ from the corresponding timepoint T1; † $p < 0.05$ from the corresponding timepoint T2; ‡ $p < 0.05$ from relative change at timepoint T2 between the groups.

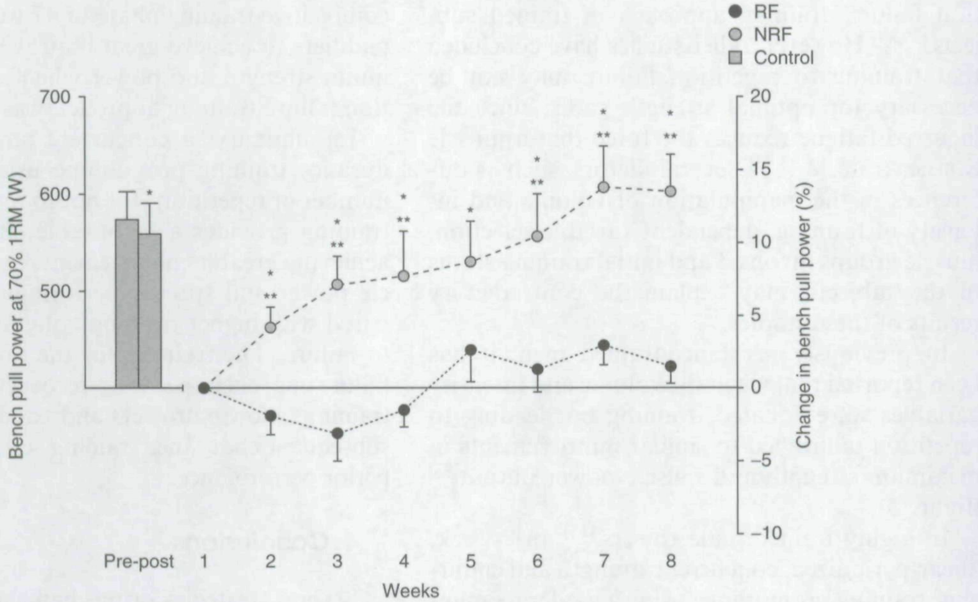

Fig. 6. Changes in muscle power output with an absolute load corresponding to 70% of one-repetition maximum (1RM) in bench pull during the experimental period (reproduced from Izquierdo-Gabarren et al.,[15] with permission from Lippincott Williams and Wilkins). **NRF** = not to repetition failure group; **RF** = repetition to failure group; * $p < 0.05$ from wk 1; ** $p < 0.05$ from corresponding value of RF.

development of one strength and one endurance target, can provide a more effective training stimulus for the improvement of performance in highly trained athletes when compared with a traditional training approach.

- Three strength training sessions per week seems to be an optimal stimulus to achieve positive adaptations in muscle strength and power, as well as to minimize the interference phenomenon with endurance training in high-level athletes. To maximize the strength training adaptations and to avoid overtraining, the optimal number of exercises and repetitions performed during each session need to be individually adjusted. A training volume close to 3–5 sets in 4–6 specific and multi-joint exercises, during 10–12 weeks of training cycles, seems to be an adequate stimulus for an optimal strength development in highly trained rowers and kayakers.
- Avoidance of the simultaneous development of LME (8–10 RM) and aerobic power can reduce the interference phenomenon due to both training intensities inducing opposite adaptations on the same peripheral components. In contrast, due to the compatible training-induced adaptations associated with strength and power and aerobic power, as well as the compatible effects of MAP, LME and strength and power intensities, no interference effects should be expected during the concurrent development of these fitness components.
- The residual fatigue caused by a previous endurance session could reduce and/or impair the quantity and quality of subsequent strength training sessions; in particular, for highly trained athletes, the strength training sessions should be placed before the endurance sessions, or at least separating both types of training sessions by more than 8 hours. Performing extra endurance training sessions at submaximal intensities that involve mainly non-specific muscle groups, may allow high-level athletes to achieve muscle peripheral adaptations, while the specific muscle groups recover for subsequent sessions of greater intensity.
- The training to repetition failure approach should be avoided in athletes at any performance level. A concurrent strength and endurance

training programme using a moderate number of repetitions for not to repetition failure training provides a favourable environment for achieving greater enhancements in strength, muscle power and specific performance when compared with higher training volumes of repetition to failure. The training for the not to repetition failure approach speeds up recovery from strength training, allowing rowers and paddlers to perform subsequent endurance training sessions of higher quality.

Acknowledgements

No sources of funding were used to assist in the preparation of this review. The authors have no conflicts of interest that are directly relevant to the content of this review.

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