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Human Kinetics
BRIEF REVIEW

Concurrent Training for Sports Performance: The 2 Sides of the Medal

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The classical work by Robert C. Hickson showed in 1980 that the addition of a resistance-training protocol to a predominantly aerobic program could lead to impaired leg-strength adaptations in comparison with a resistance-only training regimen. This interference phenomenon was later highlighted in many reports, including a meta-analysis. However, it seems that the interference effect has not been consistently reported, probably because of the complex interactions between training variables and methodological issues. On the other side of the medal, Dr Hickson et al subsequently (1986) reported that a strength-training mesocycle could be beneficial for endurance performance in running and cycling. In recent meta-analyses and review articles, it was demonstrated that such a training strategy could improve middle- and long-distance performance in many disciplines (running, cycling, cross-country skiing, and swimming). Notably, it appears that improvements in the energy cost of locomotion could be associated with these performance enhancements. Despite these benefits, it was also reported that strength training could represent a detrimental stimulus for endurance performance if an inappropriate training plan has been prepared. Taken together, these observations suggest that coaches and athletes should be careful when concurrent training seems imperative to meet the complex physiological requirements of their sport. This brief review presents a practical appraisal of concurrent training for sports performance. In addition, recommendations are provided so that practitioners can adapt their interventions based on the training objectives.

Keywords: strength and aerobic training, neuromuscular performance, middle- and long-distance performance

Athletic events and sport-specific actions range in duration between a few seconds (eg, jumps, throws, sprints, accelerations) and several hours (eg, marathon running, race walking, open water swimming). Such a wide range in competition duration and/or distance makes the relative contribution of anaerobic and aerobic pathways to power production highly variable. In many instances, both explosive actions relying mostly on instantaneous muscular strength and power, and more repetitive actions of a predominantly aerobic nature, can make significant contributions to sports performance. It was recently suggested that combined sprint and endurance performance in a group of well-trained cyclists (road, team pursuit, and track sprint; amateur to Olympic athletes) was mainly determined by oxidative capacity, muscle (vastus lateralis) capillarization, gross efficiency, muscle volume, and fascicle length.[1] Concurrent strength and aerobic training (AT) is therefore an integral part of many competitive athletes' preparation process in both individual and team sports. However, coaches and athletes need to be aware of how these forms of training may interact with each other and/or interfere with the desired adaptations.

Side 1: The Effects of Concurrent Training on Neuromuscular Performance

Chronic Effects

While pursuing his postdoctoral studies, Robert C. Hickson gradually included some running sessions to his habitual strength-training program. This anecdote later led to a research project, which became a seminal paper in the field of concurrent training (CT).[2] The 10-week protocol[3] included one AT group, one resistance training (RT) intervention, and a CT group that completed all AT and RT sessions. Participants in the RT group (n = 8) had to complete a lower body maximal strength-training protocol (3–5 sets of 5 repetitions at approximately 80% of 1-repetition maximum [1RM]) 5 d/wk. In the AT intervention (n = 8), the program consisted of 3 weekly interval training sessions to develop maximal aerobic power (6 repetitions of 5 min at an intensity close to maximal oxygen uptake [VO_2max] on a cycle ergometer) and 3 weekly sessions with a focus on aerobic endurance (30–40 min of continuous treadmill running as fast as possible). Therefore, participants in the CT group (n = 7) had to complete 11 sessions, with a typical recovery period of 2 hours between RT and AT. Surprisingly, the exact training sequence for this CT group was not reported.

Hickson's study showed a significant reduction in lower body strength gains for CT in comparison with RT, later referred to as the interference phenomenon.[4,5] Briefly, a constant progression in strength gains was observed for both CT and RT until weeks 6 to 7. Afterward, although the improvements in strength maintained a linear trend in the RT group, a decrease was observed in the CT group, which led to a significant difference between the 2 groups regarding the postprotocol relative improvement in maximal strength (44% vs 25%). Interestingly, no negative effects of this concurrent intervention were reported with regard to VO_2max.

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While the first obvious flaw of this study relates to the training load, which was dramatically increased in the CT group, potentially leading to an important fatigue state compromising potential adaptations, later studies revealed that the addition of AT to an RT mesocycle could be accompanied with setbacks in terms of strength and neuromuscular power adaptations. Indeed, a meta-analysis including 21 studies revealed that lower body neuromuscular power was particularly compromised after such a training regimen.[6] Interestingly, it was reported that when AT consisted of running exercises, the interference was more pronounced in comparison with cycling activities. The authors speculated that these results could be due to the important eccentric phase involved in running, potentially increasing muscle damage and reducing strength and power adaptations. In addition, a dose–response relationship was described, with AT duration and frequency negatively associated with neuromuscular performance.

To explain this interference phenomenon, both chronic and acute hypotheses have been suggested.[7] While the acute hypothesis referred to the residual fatigue induced by AT, leading to a reduced ability to develop tension during the strength-training component, the chronic hypothesis stated that the interference was due to different physiological adaptations (eg, muscle activation, muscle fiber type, hypertrophy, glycogen stores depletion) elicited by both training modalities. Indeed, AT and RT are typically associated with 2 extremes of an effort duration/energy metabolism continuum.[2] From a muscle fiber perspective, the complex nature of combined sprint and endurance performance has been highlighted with the observation of an inverse relationship between muscle fiber size and oxidative capacity.[1] At the molecular level, it was originally thought that the activation of the AMP-activated protein kinase (AMPK) by AT could inhibit the mammalian target of rapamycin (mTOR), which is activated by RT.[8] Consequently, this molecular cascade would then reduce the protein synthesis typically associated with RT.[2] However, this potential mechanism was discarded, considering that such a divergent cascade (AT:AMPK and RT:mTOR) seems too simplistic[9] and that the activation of AMPK was reported to have minimal effects on mTOR in humans.[10] Although a molecular approach could not fully explain the interference effect observed after CT, insights about the participants' training status were recently added to this discussion. Coffey and Hawley[11] suggested that a CT modality was detrimental mainly in trained individuals looking for more specific exercise adaptations. According to this model, beginners would be less affected by such a CT mesocycle since, at this stage, training adaptations are more general with any increase in physical activity showing a potential to induce large changes in molecular adaptations, no matter the exercise modality.[11] In support of this statement, their review highlighted that untrained individuals could improve muscle mass after AT, whereas RT could enhance oxidative capacity in beginners.[11] Coffey and Hawley[11] also suggested that the extremes found in the effort duration/energy metabolism continuum (eg, Olympic weight lifter vs marathon runner) are only truly observed after many years of specific training. Therefore, these highly trained individuals would need greater and, importantly, more specific training loads to increase the adaptation response, which could make these individuals more vulnerable to CT. However, this training status hypothesis might be partially questioned, considering that no differences between training groups (untrained vs trained) were observed for strength development during CT.[6] Although many questions are still debated, readers interested in molecular adaptation mechanisms and methodological considerations are invited to consult review articles published on the topic.[9,12]

Contrary to this interference hypothesis, a report published in 2013 suggested that the hypertrophic response was not altered by the addition of AT to an RT mesocycle.[13] Indeed, in this study, 10 moderately trained men completed a 5-week training protocol, which included 15 AT sessions and 12 RT sessions. A novel aspect of this protocol was that each participant had one leg performing only RT, whereas the other leg performed AT + RT. Importantly, RT was conducted 6 hours after the AT session, which consisted of 40 minutes of 1-legged cycling at an intensity corresponding to 70% of the maximal power measured during an incremental test. After 40 minutes, the power was increased so that participants would reach exhaustion within 1 to 5 minutes. The RT included 4 sets of 7 concentric–eccentric knee extensions on a flywheel ergometer, and participants were asked to produce a maximal effort on each repetition. During the 5 weeks of training, the power output during the RT sessions increased similarly in both legs (27% vs 28%). Partially in line with the original study conducted by Hickson,[3] the results also revealed that the endurance performance (time to exhaustion, TTE) was not altered by this training regimen. Actually, there was a tendency ($P = .052$) for a time × group interaction in favor of the CT intervention (TTE improvements: +29% vs +19%). However, this study showed that strength and power performance adaptations were similar in both legs. In addition, it was found that the quadriceps muscle volume increased more after the CT intervention in comparison with the RT regimen.

While these results could question the interference hypothesis, some methodological issues should be raised. First, the interference phenomenon described in the original paper by Hickson[3] was apparent only after 6 to 8 weeks of training. Therefore, it could be argued that a 5-week protocol was not long enough to induce any chronic fatigue leading to interference. Second, a recovery period of 6 hours was implemented in this 5-week protocol, whereas only 2 hours separated both training modalities in the original paper. Moreover, the observation that AT could lead to an advantage in terms of muscle hypertrophy is not that surprising, especially considering that a cycling activity was part of the intervention.[10,14] Importantly, equivalent or even greater quadriceps hypertrophy has been reported in CT studies lasting between 5 and 21 weeks.[15] Although detrimental effects of a CT intervention could be observed for muscle hypertrophy when both modalities are presented in close succession, it seems that a rest period of at least 6 to 24 hours is needed to optimize the outcomes.[15]

Interestingly, in a meta-analysis highlighting the interference phenomenon,[6] a theoretical model was suggested to avoid such a negative impact when athletes, because of the complex nature of their discipline, need to train for both aerobic and strength development. This model put forward the benefits of sprint training as a method to improve VO_2max[16] without compromising strength gains as RT and sprint training share similar outcomes.[6] This hypothesis was partially verified in a study published by Cantrell et al[17] in 2014. This 12-week protocol included a strength-training intervention (upper and lower body, 3 sets, 4–6 repetitions, twice weekly) and a concurrent regimen, which consisted in a sprint protocol (4–6 all-out cycling efforts lasting 20 s each, with a 2-min recovery period between repetitions) added to the RT intervention. Both training modes were separated by 24 hours. Whereas VO_2max was significantly improved only in the CT group, no differences were observed between interventions for maximal force (1RM, upper and lower body), showing improvements in both scenarios. However, since only recreationally active participants were included, more studies with athletes are needed before concluding firmly. These preliminary results were recently included in a meta-analysis verifying the effects of concurrent high-intensity interval training (HIIT) and RT on strength and hypertrophy in inactive, active, and trained participants.[18] This analysis suggested that an interference effect could be observed on lower body muscular strength (1RM) with relative changes being greater after an RT regimen (23.9%) in comparison with a HIIT + RT protocol (19.4%). Interestingly, no significant differences on lean body mass and upper body maximal strength were reported between interventions (RT or RT + HIIT). Contrary to previous research,[6] these results suggested that a cycling intervention could lead to more strength impairments than a running program but the authors did not provide any insights about potential mechanisms. Therefore, more studies are needed to elucidate this question about the most appropriate AT modality in a CT regimen. This meta-analysis also emphasized the importance of recovery, whereas protocols with more than 24 hours between training stimulations showed no interference on strength gains. Importantly, it has to be mentioned that to be considered as HIIT, intensities needed to be greater than 80% of maximal heart rate, superior to 100% of lactate threshold or above 90% of VO_2max, which represents a vast range if we consider that the upper limit would be sprint (all-out) exercises.

Consequently, it appears that the interference phenomenon originally described by Hickson[3] in 1980 could be reduced or less apparent as long as training parameters are planned appropriately. Clearly, the acute organization of training sessions seems to be crucial. Indeed, training sequence, rest periods between AT and RT, and AT volume and intensity were identified as variables that could play a key role in this interference phenomenon.[9]

Manipulating Training Variables

An original study published in 2003 addressed these questions regarding acute organization of training sessions.[19] After completing a VO_2max test and a 1RM protocol, a sample of 16 athletes (varsity and recreational) was divided into 2 groups based on AT intensity. While one group completed HIIT (6 × 3 min at 95–100 of maximal aerobic power, 3 min of recovery between bouts), the other participants went through a low-intensity continuous training (36 min at 70% of maximal aerobic power). Both protocols were executed on a cycle ergometer. Before the AT, all participants completed a control RT session, which consisted in 4 sets (bench press, leg press) at an intensity corresponding to 75% of the 1RM. Critically, for each set, participants were asked to execute repetitions until exhaustion. This RT session was thereafter executed 4, 8, and 24 hours after the AT session. Therefore, including the 2 testing sessions (1RM + VO_2max), participants had to visit the laboratory on 9 occasions: 3 AT and 4 RT sessions. Interestingly, the results revealed that, for the leg press exercise, the number of repetitions executed 4 and 8 hours after AT was significantly lower than in the RT control condition. It is only after a 24-hour recovery period that the number of repetitions got back to the values observed during the initial RT session. In addition to these observations, this study showed that the bench press performance (number of repetitions) was not altered by the AT session. Moreover, no effects of AT intensity were observed. Therefore, these results suggest that, when the objective is to optimize the number of repetitions in an RT session, participants should avoid AT for at least 8 hours if the same muscle groups are involved.

However, these results were challenged by a study showing that an RT session (leg press + knee extension; 2 sets of 7 repetitions, maximal efforts on a flywheel ergometer) performed 6 hours after an AT bout (40 min of legged cycling at 70% of maximal power output) did not compromise molecular responses leading to protein synthesis, whereas performances in lower body power were similar to an RT session without prior AT.[20] Nevertheless, it could be argued that the latter protocol did not require participants to execute RT exercises until exhaustion. Furthermore, a recent meta-analysis including 10 studies conducted mainly with untrained participants reported that an RT–AT training sequence was more profitable on lower body dynamic maximal strength than the opposite scenario.[21] Interestingly, no differences between sequences (RT–AT or AT–RT) were reported for lower body isometric strength, hypertrophy, maximal aerobic capacity, and body fat percentage. In this meta-analysis, protocols were at least 5-week long, and rest periods between training modalities were not longer than 15 minutes. Unfortunately, due to insufficient data, lower body power outcomes were not assessed.

Taken together, the above results provide evidence that an acute bout of AT repeatedly performed with minimal rest (<15 min, potentially up to 24 h) prior to an RT session could be detrimental, even in untrained participants, for optimal dynamic maximal strength development when the same muscle groups are involved in both training modes. This could be explained, at least partly, by a reduced number of repetitions performed during the RT session as a consequence of residual fatigue.[19] Training status represents another potential variable that could play a role in this effect.[11] In addition to these observations, it seems that hypertrophy, maximal aerobic capacity, and body fat percentage are not altered by the acute training sequence.

Training Recommendations to Optimize the Effects of CT on Neuromuscular Performance

Interference between AT and RT:

- CT could be associated with compromised neuromuscular performance.
- For the moment, it is difficult to conclude on the most appropriate AT modality (running vs cycling) because both were associated with the interference effect.
- AT duration, frequency, and temporal proximity with RT are negatively associated with neuromuscular performance.
- Training status is suggested to be an important variable, but more results are necessary before confirming this hypothesis.

Manipulating training variables when the main objective is related to neuromuscular performance:

- Protocols shorter than 6 weeks might not induce interference.
- Sprint training seems to represent a good option to improve VO_2max and avoid interference.
- AT should be performed at least 8 hours before RT if the same muscle groups are involved in both modalities and if the objective is to maximize the number of repetitions executed during RT.
- The RT–AT sequence seems to be more beneficial for lower body maximal strength than the opposite (AT–RT).
- Hypertrophy could be improved with CT after 5 to 21 weeks when a rest period of 6 to 24 hours is presented between training modalities, especially if cycling is the AT modality.

Side 2: The Effects of CT on Middle- and Long-Distance Performance

Chronic Effects

In his seminal article published in 1980, Hickson[3] wrote: "The results of this study suggest that there is little or no benefit for endurance athletes to strength train at the same time." Although such a statement might appear quite disconnected from the knowledge acquired in the area over the past 40 years, it is important to mention that this quote mainly refers to VO_2max, which was the only aerobic performance index assessed in this research. However, Hickson et al[22] subsequently contributed new insights suggesting that the above quote was inappropriate. Indeed, in 1988, a new paper provided some evidence that the addition of an RT program could amplify endurance performance. In that study, 8 endurance-trained athletes (6 males and 2 females) completed a 10-week RT mesocycle in addition to their usual AT program (running + cycling). No control group was included, but participants had between 3 and 12 years of endurance training experience and had been training regularly (running–cycling) for a minimum of 3 to 4 months prior to the implementation of the RT phase. Importantly, initial testing was conducted to show that participants were in a steady-state level of performance (TTE) before the beginning of the RT mesocycle. RT was then held 3 times per week, with the main objective to develop lower body maximal strength (3 sets of 5 repetitions at an intensity of 80% of 1RM). Importantly, RT was completed at least 1 hour prior to any AT session. RT sessions were separated by at least 24 to 48 hours. In addition to maximal strength and VO_2max tests conducted before and after the intervention, participants had to complete TTE tests, which were long (cycling at 80%–85% of VO_2max) and short (exhaustion within 5–8 min in cycling and running tests). This study revealed that participants improved short-term endurance performance by 11% and 13% in average (cycling and running, respectively). In addition, in the long-term cycling endurance test, participants improved their performance by 20%, in average. Considering that VO_2max was not modified after this training regimen, other performance variables definitely benefited from this intervention.

Since the classical work of di Prampero et al,[23] it is well accepted that middle- and long-distance performance is determined not only by VO_2max but also by aerobic endurance and the energy cost of locomotion (ECL). Interestingly, in a monograph publication dedicated to marathon performance, it was indicated that the latter determinant was a forgotten but crucial factor in elite running performance.[24] In support of this argument, it was shown that East African runners who dominate international competitions[25] are particularly economical runners in comparison with Europeans and American runners.[24] In addition to this observation, a case study presenting physiological parameters of the women's marathon world record holder highlighted the importance of ECL.[26] Throughout a 10-year span, running speed at VO_2max was shown to improve in parallel to a reduction in ECL, whereas VO_2max was not modified. A recent analysis conducted with cyclists showed that gross efficiency was a crucial factor in explaining combined sprint and endurance performance.[1] Taken together, these observations emphasize the importance of ECL as a performance factor in middle- and long-distance events, which accentuate the importance of identifying training strategies potentially resulting in a lower ECL.

In 1999, an important paper was published showing that explosive strength training resulted in improvements in 5-km running performance.[27] During 9 weeks, a group of elite cross-country runners replaced 32% of their normal running sessions by plyometric exercises and dynamic weight training. A correlation analysis revealed that changes in ECL were associated with modifications in 5-km performance ($r = -.54$, $P < .05$). Later, our research group compared plyometric exercises to dynamic weight training in a sample of recreational runners, replicating these beneficial effects on ECL with an interaction in favor of the plyometric intervention.[28] Although these explosive strength-training methods showed benefits on ECL, it is important to mention that maximal strength training could also lead to improvements in ECL.[29] Typically, RT interventions will result in ECL improvements ranging from 2% to 8%.[30]

A recent meta-analysis[31] suggested that a CT mesocycle was associated with improvements (net standardized mean difference = 0.52; 95% confidence interval, 0.33–0.70) in middle- and long-distance performance (events >75 s) in a variety of disciplines (running, cycling, cross-country skiing, and swimming). Interestingly, while VO_2max and aerobic endurance (eg, lactate or ventilatory thresholds) were not altered by such a training intervention, it was reported that ECL was significantly enhanced (net standardized mean difference = 0.65; 95% confidence interval, 0.32–0.98). In addition, training protocols with more than 24 sessions resulted in greater benefits on ECL than lower-volume programs. Importantly, protocols of at least 6 to 8 weeks with a focus on maximal force and explosive RT were associated with greater benefits.[32] It was recently proposed that increased absolute strength would result in a running pattern executed at a lower (muscle contraction) relative intensity. Therefore, recruitment of higher threshold motor units would be reduced, eventually producing more economical behavior.[33] However, the contention that reductions in ECL resulting from RT lead to improvements in middle- and long-distance performance was recently challenged.[34] Indeed, it seems that not all studies reporting an improvement in ECL are associated with a clear performance enhancement. In addition, to our knowledge, no intervention studies allowed to establish a clear cause/effect relationship between improvements in ECL and middle- and long-distance performance. Such an observation might not be completely surprising considering that the physiological variables in the classical study by di Prampero et al[23] explained approximately 72% of the performance variability in a cohort of runners from the Geneva marathon. Therefore, improvements in ECL could be unnoticed from a performance perspective, considering that other factors might alter the final outcome. Nevertheless, with the available scientific literature, it appears that CT leading to a reduction in ECL might be a plausible mechanism for explaining, at least partly, the observed improvements in middle- and long-distance performance. In support of this suggestion, it was shown that a reduction in ECL is accompanied by an elevation of maximal aerobic speed, even in the absence of a VO_2max enhancement.[23] Therefore, such a phenomenon could help the runner achieve a faster absolute speed during a race. Besides the effects of CT on ECL, it was reported that this training modality could improve neuromuscular capacity, anaerobic metabolism, and sprint performance leading to an overall improvements in middle- and long-distance performance.[27,35] Although it seems that less research has been conducted in that domain, one could argue that these metabolic and neuromuscular enhancements could be particularly important for specific portions of the race, such as hilly sections of a course and final sprints. More precisely, it was suggested that maximal strength training is a key method to improve middle- and long-distance performance.[31] While a combination of methods (submaximal, maximal, and power RT) could be associated with performance benefits, it is suggested that a long-term periodized plan should optimize training adaptations.[36] Interestingly, as pointed out recently,[1] RT methods with an emphasis on plyometric and eccentric contractions could be advantageous considering the importance of muscle fascicle length for combined sprint and endurance performance.

Manipulating Training Variables

Although the interference phenomenon was first suggested to describe the reduction in strength gains after a CT protocol compared with an RT-only regimen,[4,5] it seems that CT could also lead to acute alterations on certain variables pertaining to the aerobic pathway, potentially leading to impairments in middle- and long-distance performance. Indeed, muscle damage, muscle soreness, neural fatigue, and glycogen depletion induced by an RT session could acutely reduce endurance performance (time trial, TTE and ECL). Consequently, an inappropriate training periodization repeating such negative patterns will lead to RT-induced suboptimization of endurance performance (RT-SEP).[37] In line with this framework, a study published in 2001 revealed that an acute bout of RT was associated with significant impairments in ECL.[38] In this study conducted with 9 distance runners (10-km time of 37:03 [6:09] min), participants had to complete 4 treadmill running sessions to assess ECL, with the first being considered as the control condition and the remaining 3 sessions implemented 1, 8, and 24 hours after a low-volume, high-intensity RT session (6 exercises, upper and lower body, 3 sets at an intensity corresponding to 8RM). When compared with the control condition, it was shown that ECL increased by 2.6% (2.3%) when RT was performed 1 hour prior to the treadmill running session. Importantly, ECL showed a tendency toward elevated values in comparison with the control condition up to 24 hours after the RT session. Interestingly, these impairments in ECL were accompanied by a reduction in contractile properties of the quadriceps femoris. Another study replicated a similar pattern, highlighting the acute detrimental effects of RT on ECL.[39] In that investigation, 14 trained runners (10-km time <37 min) were randomized into one of the 2 following sequences: AT 6 hours after RT or the opposite. ECL and TTE tests were conducted 24 hours after the first training session (or 18 h after the second one). Results showed that the RT–AT sequence led to impairments in ECL, which were not observed for the AT–RT sequence. Moreover, TTE performance was reduced similarly for both RT–AT and AT–RT.[39] Consequently, it was suggested that a recovery period of more than 24 hours should be implemented between CT sessions and the following endurance performance.[39] Considering the above observations that aerobic and endurance performance could be acutely compromised after RT, it seems crucial to understand what could be the long-term effects of different training sequences on middle- and long-distance performance. Two recent meta-analyses concluded that the intrasession training sequence had no effect of maximal aerobic capacity (VO_2max).[21,40] It seems nevertheless important to highlight that VO_2max is definitely not the only performance factor related to middle- and long-distance events. In 2005, a study with 48 recreational athletes showed that, after a 12-week protocol with 2 sessions weekly, participants included in the AT–RT sequence improved 4-km time trial, TTE, and maximal aerobic speed more than participants included in other training regimen (RT–AT sequence, AT only, RT only, or a control group). While it reinforces the importance of RT as a useful stimulus for middle- and long-distance performance, it also suggests that a sequence effect could be observed, at least when considering multiple factors pertaining to endurance performance.[41]

Training Recommendations to Optimize the Benefits of CT on Middle- and Long-Distance Performance

Middle- and long-distance athletes could benefit from CT:

- In addition to their normal training regimen, middle- and long-distance athletes (running, cycling, cross-country) could benefit from the addition of RT.
- Training should focus on the individual athlete and his/her training status.
- Maximal strength appears as a crucial training stimulus, whereas plyometric/explosive training and a focus on eccentric contractions could be advantageous if implemented appropriately in the training plan.
- In a long-term periodization, it is suggested that a combination of methods (submaximal strength, maximal strength, and power training) should be implemented to optimize RT adaptations.
- ECL could be improved (2%–8%), whereas no significant modifications are reported for either aerobic endurance or VO_2max.
- CT interventions including more than 24 RT sessions seem particularly advantageous for the ECL.
- CT could also enhance combined performance through improvements in anaerobic metabolism and neuromuscular capacity leading to faster sprints.

Manipulating training variables when the main objective is related to middle- and long-distance performance:

- RT could acutely increase the ECL and decrease TTE for up to 24 hours, and it is suggested that the accumulation of these negative effects could lead to suboptimization of endurance performance.
- To optimize long-term time-trial performance, TTE, and maximal aerobic speed, it seems that the AT–RT sequence is more beneficial than the opposite (RT–AT).

Conclusion

The combination of cardiovascular and neuromuscular solicitations within the same training program, and occasionally within the same training session, appears to be a compulsory path to achieve high performance in many sports. However, this strategy is not without risks and may occasionally have a deleterious effect on one or more determinants of performance. The purpose of this short review was to describe the physiological adaptations induced by combined training and to identify the conditions that should be fulfilled to be efficient. Although acute and chronic adaptations that are likely to change performance in one direction or the other are relatively well identified, it appears from this review that there is no universal rule to make sure that performance will improve. As is often the case, success is a matter of balance—balance in the choice of methods and their articulation within the session (the microcycle and the macrocycle), but also balance between the physiological profile of the athlete, the additional benefits that can be expected from a combined training, and the risk of injury or overreaching. Here, as for most facets of training, the key is individualization.

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