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Effects of the Concurrent Training Mode on Physiological Adaptations and Performance

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Introduction

The physiological challenges induced by aerobic and resistance training performed concurrently gained popularity since the initial study by Robert C Hickson [1]. However, while he clearly showed dramatically impaired maximal strength development after already a few weeks of training, it is often neglected that the training volume in this study consisted of 11 weekly training sessions—much more than is typically performed in recreational athletes. Moreover, the large number of training sessions performed ultimately led to the recovery between subsequent training sessions being very short but residual fatigue was not considered as a possible cause for the compromised changes in muscle strength.

Almost 40 years later, convincing evidence has emerged that the training mode indeed is considered a crucial component in explaining the "interference" phenomenon. Especially the recovery between subsequent training sessions appears to determine the magnitude of adaptations induced by concurrent training [2, 3] but some evidence also exists for adaptations being specific to the intra-session sequence, at least in certain subject populations [4, 5]. In this context, a clear distinction of terminology needs to be made when interpreting the literature of concurrent training. While the "interference effect" generally refers to the magnitude of adaptations obtained by concurrent training as compared to aerobic or strength training only [1], the "order effect" commonly describes the interaction of aerobic and strength training performed in close proximity with different exercise sequences (i.e., commencing with aerobic or resistance training, respectively) [6, 7].

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On a further note, numerous cross-sectional studies were carried out especially during the past decade, aiming at elucidating the acute neuromuscular, hormonal or cardiorespiratory effects of concurrent aerobic and strength training sessions. While in these studies often rather strong claims towards possible long-term adaptations are made, very often these findings do not actually translate into performance adaptations observed after multiple weeks or months of training. Thus, this chapter aims at critically discussing the acute and chronic effects of different modes of concurrent aerobic and strength training by combining findings of cross-sectional and longitudinal study designs. Special reference will be given to effects of the exercise sequence within one training session and the importance of recovery between subsequent training sessions. Moreover, as the molecular signaling pathways of aerobic and strength exercise have been discussed elsewhere in this book, this chapter will focus on neuromuscular, cardiorespiratory and hormonal aspects, as well as the specific exercise performance.

The "Acute Hypothesis"

The initially observed impaired strength development during high volume concurrent aerobic and strength training (i.e., "interference") may be explained both by a chronic and an acute hypothesis. Hickson [1] suggested that compromised strength development may occur due to the inability of muscles to adapt to both forms of exercise simultaneously. Craig et al. [8], on the other hand, proposed that during training programs in which aerobic and strength training are performed in close proximity, residual fatigue from the first exercise will detrimentally affect the quality of the subsequent loading, possibly compromising long-term adaptations.

The "acute hypothesis" is supported by studies reporting that the recovery from strenuous exercise may depend on the exercise intensity and/or volume and may take up to multiple days [9–11]. Thereby the magnitude of neuromuscular fatigue may be much larger following strenuous types of strength loadings [9] compared to prolonged aerobic exercise [11]. This is interesting because concerns are typically raised especially with regard to the detrimental effects of residual fatigue induced by aerobic exercise on subsequent strength performance rather than possible acute effects of strength loading on aerobic performance (e.g., [12]). The effects of an initial bout of exercise on subsequent aerobic or strength performance have been discussed elsewhere in this book.

Acute Effects of the Intra-session Sequence on Force Responses

Even though the interest in concurrent training methods has increased tremendously over the past decade, the literature concerning the acute responses to concurrent aerobic and strength loadings (i.e., either performing endurance exercise followed by strength loading or vice versa) is sparse. Obviously the most important indices for possible exercise sequence-dependent responses would be differences in neuromuscular fatigue. However, surprisingly only very few studies have compared the overall force responses to concurrent exercise loadings. In these investigations, similar declines in maximal and rapid force production were observed in both recreational endurance athletes [13] and previously untrained men [6, 14] and women [15], following strenuous strength loadings combined with moderate intensity endurance running or cycling. Moreover, force levels returned to baseline already after 24 h in all of these studies.

In our own studies, [6, 14, 15] the loading consisted of mixed hypertrophic, maximal and explosive exercise bouts combined with continuous endurance cycling at anaerobic threshold intensity. While the overall magnitude of muscular fatigue was similar following both exercise sequences, the contribution of force loss by strength or endurance exercise was specific to the exercise order performed [6, 14]. Endurance cycling performed before the strength loading led to a reduction in maximal force of ~10% while in the opposite order aerobic exercise did not further reduce force production. Hence, while strength loadings may produce neuromuscular fatigue when performed both before and after endurance exercise, endurance cycling does not seem add to the overall magnitude of fatigue, considering a certain level or pre-fatigue is achieved. Similar findings are actually also shown in studies investigating the acute neuromuscular responses to prolonged strength loadings only [9, 16] but the underlying causes may be manifold. For example, during endurance cycling of moderate intensity both type I and type IIa fibers are typically active [17] and it is likely that strength loading activates high threshold motor units characterized by high fatigability, while subsequent endurance cycling may only recruit fatigue-resistant slow twitch fibers [18], apparently not increasing the magnitude of overall fatigue.

Acute Effects of the Intra-session Sequence on Hormonal Responses

Acute exercise-induced reductions in force production are typically accompanied by temporary alterations in hormonal concentrations. While the association between acutely increased hormone concentrations and muscle growth were questioned in a recent review paper [19], several studies have shown statistically significant correlations between basal and/or loading-induced concentrations of e.g., circulating testosterone and the chronic development of muscle mass and strength during strength training [20–24]. These findings provide at least some evidence for a supporting role of acute endocrine alterations in long-term physiological adaptations and may also help explaining distinct adaptations to concurrent aerobic and strength training.

When comparing existing studies concerning the acute hormonal responses to concurrent loadings (i.e., aerobic and strength exercise performed within the same training session), it should be noted that the magnitude of hormonal responses is typically associated with the characteristics of the exercise session (i.e., exercise intensity and volume) and, thus, findings may be specific to the concurrent training session performed. Comparing findings of previous studies, it appears that the acute growth hormone responses (22-kDa) may consistently be larger when concurrent loadings are commenced with strength exercise in previously untrained men [6] and women [15], using a similar mixed-strength training protocol combined with stationary cycling exercise. One theory explaining these findings may lay in an accumulation of fatty acids induced by the aerobic exercise, which might suppress the endocrine release of growth hormone [25]. Consequently, one may hypothesize that strength exercise performed prior to aerobic training optimizes the anabolic milieu, required for neuromuscular adaptations to take place. Although such assumptions are not supported by acute testosterone accumulation in these studies, in previously untrained men we have shown that testosterone concentrations may be dramatically reduced for up to 48 h when strength exercise is preceded by endurance cycling [6]. Furthermore, no acute increases in cortisol concentrations were observed in either of the concurrent loadings, while significant reductions were observed for up to 48 h in both groups.

Reduced hormone concentrations during recovery have generally been linked with an upregulation of androgen receptors accompanied by increased target tissue uptake or an inhibited production of these hormones in the releasing gland or at the hypothalamus level [16, 26]. Unfortunately, we were not able to study the target receptor kinetics and, thus, the meaning of these findings remains speculative [26]. Along with attenuated growth hormone responses, however, it is likely that aerobic training performed prior to strength exercise may prolong the needs for recovery as opposed to the opposite exercise order due to the observed reduced testosterone concentrations.

Importantly, our findings were quite different compared to those observed in other studies in recreationally strength-trained [27] and concurrent endurance and strength athletes [28], performing hypertrophic resistance loadings combined with endurance cycling [27] and running [28]. Both of these studies showed acute increases in testosterone concentrations following the exercise sequence commencing with aerobic training. Furthermore, Cadore et al. [27] showed that the cortisol concentrations were elevated after the first exercise modality (endurance and strength, respectively) in both loading sequences but returned to baseline during the second exercise (strength and endurance, respectively), while Rosa et al. [28] observed increased cortisol and growth hormone concentrations following both loading conditions. While the authors of these studies concluded that the anabolic environment was optimized when endurance exercise preceded bouts of strength training, it appears that the hormonal responses to combined exercise sessions seem to differ between trained and untrained populations. This hypothesis is indeed supported by our data showing that after 24 weeks of exercise sequence-specific concurrent training, the initial reductions in recovery testosterone concentrations in the group which performed aerobic prior to strength training were diminished [14]. Furthermore, as opposed to previously untrained subjects, in trained individuals performing endurance exercise prior to strength training may in fact provide a cumulative anabolic stimulus (although the opposite exercise order was not performed in this study) [29]. This was e.g., shown by the activation of molecular signaling pathways required for muscle growth and would aid explaining the increased testosterone concentrations following this exercise sequence in the studies by Cadore et al. and Rosa et al.

Acute Effects of the Intra-session Sequence on Cardiorespiratory Responses

Currently very little is known on the cardiorespiratory responses to concurrent loading sessions and typically the data are limited to excess post-exercise oxygen consumption (EPOC). These findings, however, remain equivocal and at least from a physiological point of view it remains uncertain why the exercise sequence would affect overall EPOC responses. Di Blasio et al. [30] found the magnitude of EPOC to be similar in previously untrained women performing aerobic followed by strength training and vice versa. However, in physically active men both no differences [31, 32] and a greater EPOC response following the exercise order commencing with aerobic exercise [33] were observed. The latter finding may at least in part be explained with a rather low endurance exercise intensity and volume (25 min at 70% of VO_{2max}) in this study, in fact being comparable to an active recovery strategy and, thus, enhancing lactate removal [34]. Interestingly, the EPOC response following alternating endurance and resistance exercise (i.e., 3 × 10 min of treadmill running, each followed by 1 set of 8 exercises of circuit training) has been shown to be larger than that observed when endurance and strength exercise were performed subsequently [30] but the reasons for this phenomenon remain to be investigated.

Chronic Adaptations to Same-Session Combined Training

The findings stemming from cross-sectional study designs provide at least some indications for possible exercise sequence-specific adaptations, when long-term concurrent aerobic and strength training is performed. However, it appears that these findings translate only in very few cases into the findings of chronic training studies. This is likely attributed to factors which may be controlled well in laboratory conditions but will affect training over multiple weeks or months (i.e., sleeping habits, nutrition, psychological stress, daily activities). Table 14.1 provides a summary of studies dealing with the exercise sequence of concurrent training in healthy subjects performing regular aerobic and strength training.

Recently two meta-analyses were published on this topic [47, 48] and both of these investigations provided quite similar conclusions, indicating that dynamic strength development may be optimized when strength training is performed prior to aerobic training, while the exercise sequence may not matter seem to for morphological [47] or cardiorespiratory adaptations [47, 48]. Referring to Table 14.1, however, it appears that in fact only very few studies have provided statistical evidence for this claim. Moreover, it can be noted that the currently available studies differ

Table 14.1 Literature review on current studies investigating the "order effect" of prolonged concurrent aerobic and strength training in healthy subjects

Study	Subjects	Training duration	Training mode	Cardiorespiratory function ($p < 0.05$)	Neuromuscular function ($p < 0.05$)	Between-group difference ($p < 0.05$)
Collins and Snow [35]	Untrained men and women ES ($n = 15$) SE ($n = 15$)	7 weeks	3 day week^{-1} E: 20–25 min running at 60–90% of heart rate reserve S: Whole body, 2 × 3–12 repetitions at 50–90% of 1 RM	ES ↑ SE ↑	ES ↑ SE ↑	C: No N: No
Gravelle and Blessing [36]	Active women ES ($n = 6$) SE ($n = 7$)	11 weeks	3 day week^{-1} E: 45 min at 70% of VO_{2max} S: Lower body 2–4 × 6–10 RM	ES ↑ SE →	ES ↑ SE ↑	C: Yes N: No
Chtara et al. [37]	Male sport students ES ($n = 10$) SE ($n = 10$)	12 weeks	2 day week^{-1} E: Interval running on an indoor track at 100%vVO_2max with recovery of 60%vVO_2max (duration 50% of time to exhaustion) S: Whole body circuit including strength-endurance and explosive protocols	ES ↑↑ SE ↑	N/A	Yes
Chtara et al. [38]	Male sport students ES ($n = 10$) SE ($n = 10$)	12 weeks	2 day week^{-1} E: Interval running on an indoor track at 100%vVO_2max with recovery of 60%vVO_2max (duration 50% of time to exhaustion) S: Whole body circuit training, including strength-endurance and explosive protocols	N/A	ES ↑ SE ↑	No

Cadore et al. [4]	Untrained older men ES ($n = 13$) SE ($n = 13$)	12 weeks	3 day week^{-1} E: Cycling, 20–30 min continuous at 80–90 of heart rate at second ventilatory threshold, interval cycling 6 × 4 min at second ventilatory threshold S: Whole body, 2–3 × 6–20 RM	ES ↑ SE ↑↑	ES ↑ SE ↑↑	C: No N: Yes
Cadore et al. [39]	Untrained older men ES ($n = 13$) SE ($n = 13$)	12 weeks	3 day week^{-1} E: Cycling, 20–30 min continuous at 80–90 of heart rate at second ventilatory threshold, interval cycling 6 × 4 min at second ventilatory threshold S: Whole body, 2–3 × 6–20 RM	N/A	ES ↑ SE ↑↑	Yes
McGawley and Andersson [40]	Semi- and fully professional soccer player ES ($n = 9$) SE ($n = 9$)	5 weeks	3 day week^{-1} E: SIT 5–60 s at 90–95% HRmax, HIIT 4–5 min, (rest not defined) S: 2–3 × 5–10 repetitions at 75–90% 1 RM and 3 × 3–20 repetitions jumps with bodyweight	ES ↑ SE ↑	ES ↑ SE ↑	C: No N: No
Davitt et al. [41]	Inactive young women ES ($n = 13$) SE ($n = 10$)		4 day week^{-1} E: 30 min at 70–80% of HR reserve (not specified if performed as running or cycling) S: Whole body, 3 × 8–12 repetitions at 90–100% of 1 RM	ES ↑ SE ↑	ES ↑ SE ↑	C: No N: No

(continued)

Table 14.1 (continued)

Study	Subjects	Training duration	Training mode	Cardiorespiratory function ($p < 0.05$)	Neuromuscular function ($p < 0.05$)	Between-group difference ($p < 0.05$)
Wilhelm et al. [42]	Untrained older men ES ($n = 11$) SE ($n = 12$)	12 weeks	2 day week^{-1} E: 20 min cycling at 85–95 of HR at the second ventilator threshold S: Whole body, explosive strength with 2–3 × 8–18 RM	ES ↑ SE ↑	ES ↑ SE ↑	C: No N: No
Schumann et al. [43]	Untrained men ES ($n = 16$) SE ($n = 18$)	24 weeks	2–3 day week^{-1} E: 30–50 min, continuous and HIIT cycling, progressively increasing from aerobic threshold intensity to anaerobic intensity S: Whole body, 2–4 × 15–20 repetitions at 40–60% of 1 RM, 2–5 × 8–10 repetitions at 80–85% of 1 RM, 2–5 × 3–5 repetitions at 85–95% of 1 RM	ES ↑ SE ↑	ES ↑ SE ↑↑	C: No N: No
Makhlouf et al. [44]	Male elite soccer players ES ($n = 14$) SE ($n = 15$)	12 weeks	2 day week^{-1} E: 2 × 12–16 × 15 s at 110–120% of maximal speed S: Whole body 3 × 5–10 RM	ES ↑ SE ↑	ES ↑ SE ↑	C: No N: No
Eklund et al. [15]	Untrained women ES ($n = 15$) SE ($n = 14$)	24 weeks	2–3 day week^{-1} E: 30–50 min, continuous and HIIT cycling, progressively increasing from aerobic threshold intensity to anaerobic intensity S: Whole body, 2–4 × 15–20 repetitions at 40–60% of 1 RM, 2–5 × 8–10 repetitions at 80–85% of 1 RM, 2–5 × 3–5 repetitions at 85–95% of 1 RM	ES ↑ SE ↑	ES ↑ SE ↑	C: No N: No

Küüsmaa et al. [45]	Untrained men ES ($n = 21$) SE ($n = 21$)	24 weeks	2–3 day week^{-1} E: 30–50 min, progressive continuous (65–80% HRmax) and HIIT (85–100% HRmax) cycling S: 2–3 × 10–20 repetitions at 40–70% of 1 RM, 3–4 × 10–15 repetitions at 70–85% of 1 RM, 3–5 × 3–8 repetitions at 85–95%	ES ↑ ↑ SE ↑	ES ↑ SE ↑	C: Yes N: No
Cadore et al. [46]	Untrained elderly men ES ($n = 12$) SE ($n = 13$)	12 weeks	3 day week^{-1} E: Cycling, 20–30 min continuous at 80–90 of heart rate at second ventilatory threshold, interval cycling 6 × 4 min at second ventilatory threshold S: Whole body, 2–3 × 6–20 RM	ES ↑ SE ↑	N/A	No

E endurance exercise, *S* strength exercise, *C* indices of cardiorespiratory function, *N* indices of neuromuscular function, *RM* repetition maximum, *HR* heart rate, ↑ Significant increase in either of the outcome variables being classified as "neuromuscular" or "cardiorespiratory" ($p < 0.05$), *Note*: Larger increases in one group denoted by "↑↑" may not necessarily lead to a statistical between-group difference ($p < 0.05$)

quite drastically in the study design and population studied, providing a rather heterogeneous sample for a meta-analysis.

Based on our study showing exercise order-specific differences in hormonal responses, one may expect commencing training with strength exercise to induce superior neuromuscular adaptations as compared to the opposite exercise order, due to maintained recovery testosterone concentrations in this group [6]. However, when subjects systematically continued training with a periodized endurance and strength training program for 24 weeks, adaptations in muscle hypertrophy and dynamic strength were similar in the two groups [14, 43]. Moreover, no statistical associations between the acute changes in growth hormone or testosterone concentrations and the magnitude of maximal strength gains or hypertrophy were observed.

These findings are in line with several previous studies in young men and women with various training backgrounds (Table 14.1) [15, 35, 36, 38, 40, 41, 43–45]. Unfortunately, while the initial reduction in testosterone concentrations in our study [6] was no longer observed after 24 weeks of training [14], the exact time line for these adaptations cannot be ruled out by the study design. Furthermore, it needs to be acknowledged that the training frequency in our (as well as in most other previous studies) was rather low (i.e., 2–3 weekly combined training sessions), allowing for at least 2 full days of rest between consecutive training sessions, while the initial reductions in testosterone were observed for 48 h only [6, 14]. It remains, thus, unknown whether performing concurrent training sessions more frequently will actually lead to sequence-specific training adaptations.

While maximal exercise performance did not seem to be affected by the order of exercise, we actually did observe at least small differences in neural adaptations between the groups [5]. During isometric knee extension, the EMG of vastus lateralis statistically increased only in the group commencing training with strength, while the magnitude of improvement was much smaller in the opposite exercise sequence. Supporting these findings, a statistically significant correlation between changes in voluntary activation (assessed by the superimposed twitch technique) and strength performance was observed in the group commencing with endurance training during the latter 12 weeks of the training program, where about half of the subjects actually decreased both isometric strength and voluntary activation. In line with this, in the same group no statistically significant increases in rapid force production were observed [43], indicating indeed at least to some extent neural inhibition when aerobic exercise continuously precedes strength training, despite no differences in maximal strength performance. This finding is in line with studies in older men, in which it was shown that the force per unit of muscle mass of knee extensors increased to a larger extent when strength training was performed before endurance training [4]. Similarly, lower body strength gains and improved neuromuscular economy (normalized EMG at 50% of peak torque) were found when strength training preceded endurance training compared to the opposite exercise sequence, while no differences in muscle thickness were observed [39].

With regard to cardiorespiratory adaptations, studies have found limited increases in VO_{2max} following the order commencing with strength training in young women [36] and men [37, 45], while others have found no statistical between-group differences in young subjects [15, 35, 40, 41, 43, 44]. Interestingly, while in old men no differences in VO_{2max} and absolute as well as relative cycling economy were observed [4, 46], the load at the first ventilatory threshold was statistically increased only in the group commencing the training with strength exercise [4]. This finding was opposed to our own study in which we showed improved cycling economy when training was commenced with aerobic exercise in previously untrained women but not men [3]. As in the study by Cadore et al. [4] also neuromuscular performance was optimized following the exercise order commencing with strength training, the authors concluded that improved muscular strength beneficially affected cycling economy at least in some intensities. This was somewhat confirmed by the finding of larger individual responses when commencing training with aerobic exercise [46] and may indicate that the training sequence may be important to optimize training adaptations both in women and in elderly men, as has been described in depth elsewhere in this book.

Chronic Adaptations to Same-Session Combined Training Versus Concurrent Training Performed on Separate Days

While so far the adaptions in respect to the exercise sequence were discussed, findings from these studies do not allow drawing conclusions on whether performing aerobic and strength training in close proximity may actually induce distinct adaptations when compared to combined training performed on separate days. From a practical point of view, splitting aerobic and strength exercise onto alternating days may reduce residual fatigue between aerobic and strength training sessions but at the same time may reduce overall recovery time due to a higher training frequency when total training volume is matched. Indeed, the evidence underlying this concern is still rather sparse but especially during the past 5 years studies concerning this question were carried out.

Already an early study by Sale et al. [49] reported that previously untrained subjects training on different days improved strength performance over 20 weeks to a larger extent than those subjects performing both modes within the same session, even though both training groups improved both fast and slow twitch fiber area and muscle size to a similar extent. More recently, the benefits of a longer recovery time between the two distinct exercise modes were nicely demonstrated by a study of Robineau et al. [2] and have been described in detail elsewhere in this book. Briefly, it was shown that a recovery of at least 6 h between strength and aerobic training sessions may optimize overall strength gains, while for aerobic performance even 24 h might be required.

The findings of these previous studies were at least somewhat well in line with results obtained by our group. In previously untrained subjects, we showed that performing a periodized aerobic and strength training program on separate days nearly doubled the magnitude of cardiorespiratory adaptations as compared to volume-matched combined training performed within the same training session, while no difference in dynamic strength or muscle mass was observed [3, 50]. It should, however, be noted that the initial values of maximal oxygen consumption were significantly lower in the group performing concurrent training on separate days. While this was accounted for in the statistical analysis, initial lower cardiorespiratory fitness provides a much larger window/potential for physiological adaptations induced by training and may, thus, have at least in part be contributed to the much larger changes in VO_{2max} in this group.

The distinct changes in cardiorespiratory adaptations in our study were accompanied by significant reductions in total fat mass, exclusively observed in the group performing concurrent training on separate days [50]. While the effects of such training regimen on body composition and health were beyond the scope of this chapter, it is likely that these adaptations were at least in part explained by the frequency of acute peaks in fat oxidation, despite a similar total training volume. In line with this, it was previously shown that the accumulated EPOC response following split sessions (i.e., a 2 h training session split into 2 × 1 h of aerobic exercise) was much larger than that observed following a volume and time-matched single training session [51], indicating training frequency to be an important variable to consider when planning concurrent training programs.

When comparing concurrent training performed on alternating days or within the same training session, possible differences may also be observed between alternating days and either of the two exercise sequences only (i.e., aerobic exercise performed prior to or after strength exercise). Makhlouf et al. [44] found that adolescent soccer players' adaptations in countermovement jumping height were significant only when concurrent training was performed on separate days or within the same session, commencing with strength training but not vice versa. This observation is not surprising as in both scenarios strength training was performed in a "recovered" state or at least not immediately preceded by aerobic exercise. While not reflected in overall strength performance, these findings are somewhat in line with a study of our group in which we showed that the neural adaptations are optimized when strength training is performed on separate days or at least prior to aerobic training [5].

Summary

This chapter aimed at providing a summary on the acute physiological and performance responses and adaptations to concurrent aerobic and strength training, with special reference to the training mode. Current literature provides evidence for distinct acute physiological responses, appearing to be specific to the sequence of concurrent training sessions. However, these different responses may not necessarily be reflected in force responses, requiring more advanced tools for monitoring. This is for example shown by reduced hormone concentrations for up to 48 h, which are especially pronounced when strength training is preceded by aerobic exercise. However, even though some indices of neural inhibition may be observed when aerobic training is consistently performed prior to strength exercise the acute sequence-specific differences may not translate into performance gains after prolonged training. Thus, considering that aerobic and strength exercise are to be performed in the same training session the exercise order may not be crucial for physiological adaptations when sufficient recovery (i.e., >48 h) is provided between subsequent training sessions. However, in order to optimize gains in physical fitness both in men and women, aerobic and strength exercises should be separated by 6–24 h.

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