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Concurrent Strength and Endurance Training

A Review

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Abstract

Concurrent strength and endurance training appears to inhibit strength development when compared with strength training alone. Our understanding of the nature of this inhibition and the mechanisms responsible for it is limited at present. This is due to the difficulties associated with comparing results of studies which differ markedly in a number of design factors, including the mode, frequency, duration and intensity of training, training history of participants, scheduling of training sessions and dependent variable selection. Despite these difficulties, both chronic and acute hypotheses have been proposed to explain the phenomenon of strength inhibition during concurrent training. The chronic hypothesis contends that skeletal muscle cannot adapt metabolically or morphologically to both strength and endurance training simultaneously. This is because many adaptations at the muscle level observed in response to strength training are different from those observed after endurance training. The observation that changes in muscle fibre type and size after concurrent training are different from those observed after strength training provide some support for the chronic hypothesis. The acute hypothesis contends that residual fatigue from the endurance component of concurrent training compromises the ability to develop tension during the strength element of concurrent training. It is proposed that repeated acute reductions in the quality of strength training sessions then lead to a reduction in strength development over time. Peripheral fatigue factors such as muscle damage and glycogen depletion have been implicated as possible fatigue mechanisms associated with the acute hypothesis. Further systematic research is necessary to quantify the inhibitory effects of concurrent training on strength development and to identify different training approaches that may overcome any negative effects of concurrent training.

Athletes involved in many sports often perform strength and endurance training concurrently in an effort to achieve adaptations specific to both forms of training. To date, research investigating the neuromuscular adaptations and performance improvements associated with concurrent strength and endurance training (subsequently referred to as concurrent training) has produced inconsistent results. Some studies have shown that concurrent training inhibits the development of strength and power but does not affect the development of aerobic fitness when compared with either mode of training alone.[1-5] Other studies have shown that concurrent training has no inhibitory effect on the development of strength or endurance.[6-9] However, it has also been shown that the development of aerobic fitness is compromised by concurrent training.[10] Discrepancies in the concurrent training literature most likely stem from the use of different training protocols in each individual study. For example, some studies have used isokinetic strength training protocols,[2,8,10] while others have employed isoinertial strength training.[1,3-6,9] The nature of endurance training also differs among studies. Running,[3-5] cycling,[2,6,9,10] rowing,[7,11] arm cranking[8] and a combination of running and cycling[1] have all been performed in the endurance training components of various concurrent training studies. To complicate matters further, most concurrent training protocols differ in the volume, intensity and speed of muscular contraction. Finally, the training age of study participants has differed among studies. The purpose of this paper is to review the concurrent training literature in order to identify the limitations of the research, discuss various hypotheses proposed to explain research findings and conclude with suggestions for future research.

1. Concurrent Training Studies

Investigations into the effects of concurrent training have typically compared changes in strength and endurance variables after strength training, endurance training and concurrent strength and endurance training (see tables I, II and III). Arguably, the most consistent finding to emerge from the concurrent training literature is that increases in strength and power during concurrent training are reduced when compared with strength training alone.[1-5,12-15] However, this is not always the case. Nelson et al.[10] reported that improvements in maximal oxygen uptake ($\dot{V}O_{2max}$) during the second half of a 20-week training programme were compromised during concurrent training when compared with endurance training alone. Moreover, a number of studies have found no interference to strength or endurance development as a consequence of concurrent training.[6-9,11]

Current research indicates that concurrent training can, on occasion, inhibit strength or endurance development. It is difficult to make clear statements as to under what conditions such inhibition occurs, as there are significant differences in the design of concurrent training studies. Some of these design issues are discussed in the following subsections.

Table I. Interference in strength development

Author	Design/training routine	Findings	Comments
Hickson[1]	10 weeks training 5 days per week S group: multiple sets of 5 repetitions, loads > 80% 1RM, range of lower limb exercises E group: high intensity cycling and running	S group ↑ by a greater margin than C group; ↑ $\dot{V}O_{2max}$ E ≈ C group	
Dudley & Djamil[2]	7 weeks training 3 days per week S group: 2 sets of 30-second isokinetic knee extensions 4.19 rad^{-1} E group: interval cycle ergometry of 5 x 5-minute bouts, 40 to 100% $\dot{V}O_{2max}$ C group: S and E alternate days	S group participants ↑ peak torque at speeds up to and including the training speed; C group ↑ peak torque at slower velocities (0 to 1.68 rad • s^{-1}) only; ↑ $\dot{V}O_{2max}$ E ≈ C group	
Hunter et al.[12]	12 weeks training 4 S and/or 4 E sessions per week C group trained S followed by E on same day twice a week, only 1 training modality on the remaining 4 days S group: 3 sets of 7 to 10 repetitions, upper and lower body exercises E group: running 75% HRR for 20 to 40 minutes	C group isoinertial S and endurance running training did not inhibit 1RM squat or bench press, but vertical jump height ↑ was not as great in C group as S group; ↑ $\dot{V}O_{2max}$ E ≈ C group; additional group of E trained participants produced similar strength and power ↑ to S group	Further analysis of 1RM squat data using effect size statistics[13] suggested improvements for S group were approximately double the ES observed for C group; training status may influence adaptations to C training
Hennessy & Watson[4]	8 weeks training 5 days per week - C S group: 3 days per week, periodised, at 70 to 105% 1RM E group: 4 days per week running, (3 sessions continuous, 1 fartlek) C group: irregular, S and E same day twice a week (order not reported), 1 day S only and 2 days E only	Lower but not upper body S development compromised; S group improved 20m sprint time and vertical jump height, whereas C group did not improve on these measures; ↑ $\dot{V}O_{2max}$ E ≈ C group	56 male rugby players with resistance training experience; reinforces inhibitory effects confined to concurrently trained limbs
Kraemer et al.[5]	12 weeks training with 4 group designs: C, S and E; C, E and upper body only S; S only; E only C group: 4 days per week, S and E same day E group: running, 80 to 100% $\dot{V}O_{2max}$ S group: heavy/light 4-day split routine, 3 x 10RM and 5 x 5RM	1RM S was inhibited in C group; only S group ↑ Wingate performance; ↑ $\dot{V}O_{2max}$ E ≈ C group	35 males from a single US Army base

C = concurrent; **E** = endurance; **ES** = effect size; **HRR** = heart rate reserve; **RM** = repetitions maximum; **S** = strength; $\dot{V}O_{2max}$ = maximal oxygen uptake; ↑ = increase.

1.1 Dependent Variable Selection

Why is attenuation of strength or endurance performance evident only in some concurrent training studies? Typically, the variation between studies is attributed to differences in the concurrent training interventions and/or the participants. However, consideration should also be given to the possibility that some dependent variables may be more sensitive than others to the effects of concurrent training. We recently completed an investigation addressing this question (unpublished data). Specifically, we compared the sensitivity of isoinertial, isometric and isokinetic strength indices to the effects of 6 weeks of strength, endurance, and concurrent strength and endurance training. Strength and endurance training involved 3 sets of upper and lower body exercises [4 to 10 repetitions maximum (RM)], and 5 5-minute bouts of cycling (40 to 100% $\dot{V}O_{2max}$), respectively. Strength parameters measured prior to and following training were the 1RM half squat, maximal isometric leg extension strength 0.78 rad from full extension, and maximal isokinetic extension torques 0.52 rad from full extension at 1.04, 3.12, 5.20 and 8.67 rad • s^{-1}. Strength, endurance and concurrent training differentially affected each strength index. Thus, it was evident that there were in fact differences in the level of sensitivity in the dependent variables as a consequence of strength, endurance and concurrent training. These results reinforce the notion that various strength indices do not monitor similar mechanistic events.[16] It is therefore suggested that dependent variable selection may affect the interpretation of concurrent and other training data.

1.2 Modality of Resistance Training

The majority of concurrent training studies involving isoinertial strength training demonstrate an inhibition in strength development.[1-5,12] This inhibition appears to be confined to the musculature involved in both the endurance and strength training components of the concurrent training programme.[3-5,12] Furthermore, all but one[9] of the studies involving isoinertial strength training that have measured indices of muscular power show that strength training alone increases muscular power, while concurrent training produces no improvement in muscular power.[4,5,12]

Concurrent strength and endurance training does not appear to affect the development of isokinetic strength at slow (< 1.68 rad • s^{-1}) speeds of muscular contraction.[2,10] However, lower body but not upper body isokinetic strength at fast (> 1.68 rad • s^{-1}) speeds of muscular contraction does appear to be inhibited.[2,8]

The effect of concurrent training on strength development in different muscle groups has not been systematically investigated. Lower body strength development appears to be compromised when the lower limbs are engaged in some form of simultaneous endurance training. However, concurrent training may not restrict the development of upper body strength.[8] Unfortunately, only one study conducted to date has examined upper body adaptations. Further research investigating upper body concurrent training involving different endurance and strength training modalities is necessary before any conclusions can be made regarding the effect concurrent training has on upper body strength development.

1.3 Modality of Endurance Training

All studies that have incorporated running as the endurance training modality have demonstrated an inhibition in strength development.[1,3-5] Interestingly, each of these studies involved a combination of running and isoinertial strength training. Studies which involve cycling have shown inconsistent patterns of interference.[2,6,9,10] The different strength training modalities used in these studies may be associated with the different patterns of interference observed. When endurance rowing and arm cranking is combined with strength training there appears to be no interference in strength development when compared with strength training alone.[7,8,11]

1.4 Training History

Strength development has been shown to be compromised after concurrent training in both trained[4,5] and untrained participants.[2,3] Equally, no inhibition in strength development has been observed after concurrent training in both trained[7] and untrained participants.[9]

Endurance athletes have been shown to have significantly greater increases in strength and power after concurrent training than a group of sedentary volunteers who performed the same concurrent training.[12] Unfortunately, this study did not include a group of endurance athletes who performed strength training in isolation. Thus, it is unclear whether previous endurance training either partially or fully negates any inhibitory effect on strength development associated with concurrent training. It has also been suggested that concurrent training may inhibit strength development in previously trained women but not men.[11]

On some occasions, resistance training has been shown to enhance parameters associated with endurance performance.[9,17-19] Interestingly, none of the concurrent training studies have shown clear evidence of an additive effect of concurrent training

Table II. Interference in endurance development

Author	Design/training routine	Findings	Comments
Nelson et al.[10]	20 weeks, S preceded E S group: 4 times per week, 3 sets of 6 repetitions, isokinetic knee extension and flexion, speed = 0.52 rad • s^{-1} E group: 4 times per week, continuous cycling, 75 to 85% HR_{max}, 30 to 60 minutes	S ↑ C ≈ S groups; $\dot{V}O_{2max}$ gains during second half of training programme compromised for C training compared to E only	$\dot{V}O_{2max}$ was measured on a treadmill, despite cycling as E training; it is unclear if this would have altered the results

C = concurrent; **E** = endurance; **HR_{max}** = maximal heart rate; **S** = strength; **$\dot{V}O_{2max}$** = maximal oxygen uptake; ↑ = increase.

(i.e. improvements in either strength or endurance that are greater after concurrent training than after strength or endurance training performed in isolation). However, it is possible that the benefits of concurrent strength and endurance training may be enhanced in previously endurance trained volunteers.

In summary, concurrent strength and endurance training inhibits the development of isoinertial strength when compared with strength training alone. Concurrent training also interferes with lower body isokinetic strength development at fast (> 1.68 rad • s^{-1}) but not slow (< 1.68 rad • s^{-1}) speeds of muscular contraction. The effect endurance training modality has on the interference of strength development associated with concurrent training is unclear. However, endurance running training combined with resistance training appears to inhibit isoinertial strength development when compared with isoinertial strength training alone. Participants with a history of endurance training may be less susceptible to any negative effects of concurrent training on strength development.

2. Proposed Mechanisms

Many concurrent training studies have found strength development is inhibited during concurrent strength and endurance training. However, few authors have attempted to address why this phenomenon exists. Overtraining has been suggested as a possible mechanism,[14] while Craig et al.[3] proposed both acute and chronic hypotheses to explain why normal adaptive responses are impaired during concurrent training.

2.1 Overtraining

The majority of concurrent training studies involve at least 3 experimental groups. These groups usually include a strength only, an endurance only and a strength and endurance (concurrent) training group. Typically, the concurrent training group will perform the same amount of endurance training as the endurance only group, as well as the same amount of strength training as the strength only group. Therefore, the concurrent training group participants have to contend with double the dose of training load of the other 2 groups.

It has been suggested that individuals performing concurrent strength and endurance training may become overtrained in comparison with others who are performing strength or endurance training alone.[14] It is thought that this overtrained state causes the concurrent training group to have less than optimal improvements in performance tests following training. Moreover, it has been argued that if overtraining was a factor during concurrent training, then both strength and endurance performance measures would be inhibited when compared with training for each exercise modality alone.[14] No concurrent training study has reported this finding. However, this argument presumes that the thresholds for the effects of overtraining to become apparent on strength and endurance measures are similar. This may not be the case and warrants further investigation prior to accepting this argument.

The results of Dudley and Djamil[2] imply that overtraining cannot be responsible for impairments in strength development associated with all concurrent training studies. The volume of endurance training in this study was 5 5-minute sessions on 3 days per week. The volume of strength training was only 2 30-second sessions on 3 alternate days per week. It is highly unlikely that the volume of training involved in this study was excessive enough to cause overtraining in the concurrent training group.

There is insufficient evidence to preclude overtraining as a mechanism for the inhibited adaptive response seen in some concurrent training studies. More focused research is required. There is a need for future concurrent training studies to incorporate measures of sympathetic and parasympathetic activation, as well as established psychological, strength and endurance markers of overtraining.[20]

2.2 The Chronic Hypothesis

The effects exhibited on muscle fibre hypertrophy, endogenous substrates, metabolic enzyme activity, contractile protein structure and capillarisation by strength training are markedly different, and sometimes opposite, from the adaptations associated with endurance training.[21,22] The chronic hypothesis suggests that skeletal muscle is placed in a situation of conflict when concurrent training is performed. The muscle is attempting to adapt to both forms of training. However, this is not possible because adaptations to endurance training are often inconsistent with adaptations observed during strength training. For example, endurance training has been shown to increase the activity of aerobic enzymes.[23,24] However, aerobic enzyme activity can be decreased after strength training.[25] The muscle is therefore unable to adapt optimally to either the strength or the endurance training stimulus. Thus, concurrent training elicits different adaptations at the skeletal muscle level from the adaptations normally observed when each mode of training is performed in isolation.

Evidence supporting the chronic hypothesis is limited, because few studies have measured physiological changes in response to concurrent strength and endurance training. This makes it difficult to pinpoint a chronic physiological mechanism responsible for causing an inhibition in strength development after concurrent training. Despite the relatively small amount of evidence, some authors have suggested specific skeletal muscle adaptations that may be modified during concurrent strength and endurance training.[14,15] These include changes to muscle fibre transformations and muscle hypertrophy, and changes in the pattern or efficiency of motor unit recruitment.

2.2.1 Muscle Fibre Type Transformations

Concurrent training has the potential to elicit rapid changes in the contractile character of the trained muscle that is different from those associated with strength or endurance training performed in isolation[26-29] The power output and force per unit area of myosin heavy chain isoforms (IIx > IIa > I) differs, and thus different training adaptations could modify strength development.[30,31] Recently, the relative myosin heavy chain IIa isoform content was shown to be significantly correlated with various strength indices.[32]

Concurrent training studies that have measured training-induced muscle fibre type transitions have reported little difference in fibre type change between concurrent and strength only training groups.[5,6,10] This minimal difference in fibre type transformation was also associated with a lack of interference in strength development with concurrent training in 2 studies.[6,10] However, in the third study, muscular strength and power have been shown to be inhibited by concurrent strength and endurance training even though the pattern of muscle fibre type transformation was unaffected by concurrent training.[5]

It must be remembered that all 3 studies used histochemical techniques to differentiate between muscle fibre types. Thus, subtle training-induced changes in the myosin heavy chain character of the muscle may have gone unnoticed, as this approach only detects the predominant isoform within a tissue sample. For example, the percentage increase in the proportion of fast twitch a (FTa) fibres observed during strength only training in the Kraemer et al.[5] study was larger (however not statistically significant) than the percentage increase observed in the concurrent training group (73 *vs* 39%). Transitions from fast twitch b (FTb) to FTa fibres appeared to occur in both groups, with FTb fibres almost non-existent in both groups at the end of the training period. Thus, it is assumed that a shift from type

Table III. No interference effects in concurrent strength and endurance training

Author	Design/training routine	Findings	Comments
Sale et al.[6]	22 weeks, 2 groups: S one leg and C the other; E one leg and C the other S group: 3 times per week, 6 sets of 15 to 20 repetitions leg press E group: 3 times per week, 5 x 3-minute cycle ergometer bouts, 90 to 100% $\dot{V}O_{2max}$	No interference with development of either S or E; number of reps at 80% 1RM improved most for C trained legs	Influence of central adaptation transfer between legs; Craig et al.[3] suggest a regional effect for C training
Bell et al.[7]	12 weeks, 2 experimental groups: S only and C S group: 3 times per week circuit fashion on hydraulic equipment, work : rest 1 : 1 E group: 3 times per week, continuous rowing ergometer, 40 to 55 minutes, 85 to 90% HR_{max}	C low velocity S and E rowing did not interfere with S ↑ compared to low velocity S only	Strength training group was also allowed to perform one E session per week; a comparison of 2 C regimens
Abernethy & Quigley[8]	7 weeks training 3 days per week S group: 2 sets of 30-second isokinetic elbow extensions E group: interval arm cranking of 5 x 5-minute bouts, 40 to 100% $\dot{V}O_{2max}$ C group: S and E on alternate days	No interference in S development	Suggested pattern of strength development in triceps differs from that for quadriceps during C training
McCarthy et al.[9]	10 weeks training, 3 days per week, S and E same day for C group, order rotated, < 20 minutes between modes S group: 3 sets of 6 repetitions, 6RM E group: continuous cycle ergometry, 50 minutes, 70% HRR	↑ in 1RM squat & bench press, vertical jump, isometric knee extension torque, C ≈ S groups; ↑ $\dot{V}O_{2max}$ E ≈ C group	Attributed lack of interference to reduced frequency of C training (i.e. 3 days per week compared to 5 to 6 days per week)
Bell et al.[11]	16 weeks training, 3 days per week S and E training, tests at 4 week intervals S group: 2 to 6 sets of 2 to 10 repetitions, 65 to 85% 1RM E group: continuous and interval ergometer rowing	C ≈ S groups for leg press ↑ in males; C group ↑ < S group ↑ for leg press in females; males had significant ↑ in cortisol levels for C and S groups after 8 weeks, subsequent 8 weeks S group returned to baseline but C group did not; females: both groups cortisol levels declined over first 8 weeks, then significant rise in both groups	Non-random participant assignment, i.e. university students in S group, rowers in C group; gender differences

C = concurrent; **E** = endurance; **HR_{max}** = maximal heart rate; **HRR** = heart rate reserve; **RM** = repetitions maximum; **S** = strength; **$\dot{V}O_{2max}$** = maximal oxygen uptake; ↑ = increase.

IIx to type IIa major histocompatibility complex (MHC) isoforms had occurred.

In summary, research to date suggests that concurrent training does not alter the normal transition of muscle fibre types associated with strength training alone. However, there is a need for further research in this area using more sensitive biochemical techniques to assess possible transformations in the contractile character of skeletal muscle associated with longer periods of concurrent training.

2.2.2 Muscle Fibre Hypertrophy

Strength training has been shown to increase the cross-sectional area of skeletal muscle.[33] Furthermore, the amount of force able to be generated by the muscle has been shown to be directly related to muscle fibre diameter.[34] Hypertrophy in both slow and fast twitch muscle fibres has been observed after strength training.[35,36] However, longitudinal and cross sectional studies have indicated that resistance training induces greater amounts of hypertrophy in FTa muscle fibres than slow twitch (ST) or FTb fibres.[37,38]

While resistance training causes greater fibre hypertrophy than endurance training, controversy exists over the extent of muscle fibre hypertrophy resulting from endurance training. This is largely due to the fact that a wide range of exercise intensities has been classified as endurance exercise.[21] However, unlike strength training, there appears to be no distinct pattern (there may be a variety of patterns) of fibre hypertrophy associated with endurance training. This suggests that concurrent strength and endurance training may elicit different patterns of fibre hypertrophy from those normally observed during either mode of training alone.

It has been demonstrated that concurrent strength and endurance training disrupts the pattern of muscle fibre hypertrophy normally associated with each individual mode of training alone.[5] In this study, strength training caused hypertrophy in ST, FTa and FTc fibres, while endurance training increased cross-sectional area of ST and FTc fibres only and concurrent training caused hypertrophy of FTa fibres only. This may have explained why leg strength in the concurrent group did not improve as much as the strength only group. Interestingly, the concurrent training group did not increase anaerobic power even though changes in FTa fibre hypertrophy were similar in the concurrent and strength training groups. These data highlight that the relationship between changes in fibre hypertrophy and changes in performance is complex in nature.

Nelson et al.[10] also reported that concurrent training interferes with fibre hypertrophy patterns associated with strength or endurance training alone. Significant increases in ST, FTa and FTb fibre areas were observed after concurrent and endurance only training. Strength only training increased the cross-sectional area of FTb fibres only. Surprisingly, strength development in this study was not inhibited by concurrent training, even though concurrent training disrupted fibre hypertrophy patterns. Thus, strength may have been maintained by neural mechanisms and/or alterations in MHC isoform expression.

Sale et al.[6] reported similar increases in gross muscle cross-sectional area during concurrent and strength only training. Increases in 1RM strength were also similar in the concurrent and strength only training conditions. This suggests that strength development is not inhibited when changes in gross muscle hypertrophy are similar in strength only training groups and concurrent training groups. However, the use of one leg for the strength condition and the contralateral limb for the concurrent condition leaves open the possibility that muscle hypertrophy in different fibre sub-populations and/or a contralateral effect may have occurred.

In summary, the effect concurrent strength and endurance training has on muscle fibre hypertrophy is unclear. Disruptions in the pattern of fibre hypertrophy in the various fibre type sub-groups are evident after concurrent training. However, this does not appear to be associated with any inhibition in strength development often observed after concurrent training. Future research which focuses on the absolute and relative effects of concurrent training on muscle hypertrophy may help to clarify the situation.

2.2.3 Endocrine Changes

Concurrent training which alters the balance of anabolic to catabolic hormones may reduce fibre hypertrophy and consequently strength development.[39] There is a growing body of literature investigating endocrine response to various forms of training. Typically, testosterone and cortisol (or their derivatives) have been used as markers for muscle anabolism and catabolism. Testosterone and cortisol levels have been shown to increase, decrease and stay the same following various bouts of endurance exercise.[40,41] These differences may not only be due to alterations in production as a consequence of different exercise regimens, but also to modifications in hepatic and renal clearance. Some, but not all, resistance training interventions have been shown to alter the testosterone : cortisol ratio in favour of anabolism.[42-46] Conceivably, the endurance element of concurrent training could create a more catabolic environment, and this in turn may inhibit strength development. It should be noted that the resistance element of concurrent training may also modify the endocrine environment normally associated with the endurance component of concurrent training.

There have only been a few concurrent investigations which have reported endocrine responses to concurrent training.[5,11] Interestingly, concurrent training has not been shown to reduce testosterone levels. In fact, Kraemer et al.[5] reported an increase in testosterone between the eighth and twelfth week of training. However, concurrent training has also been associated with an earlier increase in cortisol levels. While endocrine data provide a promising mechanistic link, strength development was not always inhibited in conditions where there was an elevation in cortisol. Thus, the current data indicate that further work into endocrine response to concurrent training is required and that the role of the anabolic-catabolic hormones in concurrent adaptation is complex.

2.2.4 Changes in Motor Unit Recruitment

Demands placed on the neuromuscular system during endurance and strength training require different patterns of motor unit activation. The recruitment of muscle fibres during endurance exercise is dependent on the intensity of the exercise.[47] Preferential recruitment of ST fibres occurs during low to moderate endurance activity.[48] Resistance training is generally characterised by muscular contractions producing near maximal levels of force. All muscle fibres within movement specific motor unit pools are recruited during this type of activity.[49] Furthermore, strength training increases the force of muscular contraction by enhancing co-ordination of motor unit recruitment.[50] It has been suggested that concurrent strength and endurance training may alter motor unit recruitment patterns associated with maximal voluntary contractions.[15] Endurance training has been shown to reduce vertical jump ability.[51] This may be due to endurance training reducing the capability of the neuromuscular system to rapidly generate force.[51] Therefore, it appears possible that concurrent training may interfere with the development of strength by impairing the ability of the neuromuscular system to make adaptations in the organisation of efficient motor unit recruitment patterns normally associated with strength training alone (for more discussion see section 2.3.1).

None of the concurrent training studies conducted thus far has investigated training-induced changes in motor unit recruitment. However, as discussed earlier in section 2.2.2, strength interference during concurrent training cannot be wholly attributed to inhibition of fibre hypertrophy or fibre type transformations. This suggests that alterations in motor unit recruitment may be partly responsible for the inhibition in strength development observed during concurrent training.

In summary, concurrent strength and endurance training does appear to elicit a different adaptive response from either strength or endurance training performed in isolation. Thus, the chronic hypothesis is appealing given that it provides a clear mechanism to explain the interactions between resistance and endurance training, despite the fact that data testing this hypothesis are limited in extent and precision.

2.3 The Acute Hypothesis

The acute hypothesis contends that residual fatigue from the endurance component of concurrent training compromises the ability to develop tension during the strength element of concurrent training.[3] The degree of tension developed by the muscle during training is a critical factor in producing optimal strength development.[52] If sufficient tension cannot be generated during the strength component of concurrent training, optimal strength development and adaptation may not occur. Thus, the acute hypothesis suggests that simply performing strength and endurance training concurrently does not necessarily cause impaired strength development. Rather, the scheduling of training sessions in a manner such that strength training quality is reduced because of residual fatigue from a previous endurance training session may be responsible for causing impaired strength development.

The acute hypothesis was proposed after an inhibition in lower body strength but not upper body strength was observed after combined running and weight lifting training.[3] It was suggested that the schedule of training, which involved running immediately before weightlifting, was responsible for the inhibition of lower body strength development.[3] It was offered that running produced residual muscle fatigue that did not allow volunteers to train their lower body as effectively as their upper body. Thus, the relative training overload was reduced. The reduced quality of the strength training stimulus in the concurrent training group compared with the strength only training group was considered to be responsible for the impaired strength development in the concurrent training group. It has also been suggested that the time required to give the body sufficient recovery between training sessions may be the limiting factor when attempting to induce simultaneous adaptations to strength and endurance training.[53]

When the order of training sessions is reversed, and strength training sessions immediately precede the endurance training sessions, the development of aerobic fitness has on occasion been impaired.[10] Therefore, it appears that some form of residual fatigue from a preceding training activity may reduce the quality of a subsequent training activity. This may then lead to an inhibition in the normal training-induced adaptive response associated with the second training activity.

Two studies have been conducted comparing concurrent strength and endurance training programmes with different organisation of training sessions.[54,55] Sale et al.[55] found that concurrent strength and endurance training conducted on alternate days produced larger strength gains than concurrent training performed on the same day. Participants in the same day condition in this investigation performed concurrent training on 2 days per week. Strength training preceded endurance training on 1 of these days. The order of training was then reversed on the second day.

Collins and Snow[54] also compared 2 concurrent training programmes that differed in the sequence of training. One group performed endurance training before strength training. This sequence was reversed in the other group. In contrast to Sale et al.,[55] they found that the sequence of training had no effect on the development of either strength or endurance. Frequency, intensity and duration of strength and endurance training were equal for both experimental groups in this study. However, Sale et al.[55] found that the total volume (weight lifted multiplied by number of repetitions) of strength training performed by the same day condition was less than the alternate day group. Consistent with this was the finding that the development of strength in the same day group was also less than the alternate day group.

Sale et al.[55] suggested that the ability of the alternate day group to lift progressively heavier weights was due to the fact that they had acquired strength training adaptations that caused their strength to improve as the training programme progressed. However, participants in the same day group may not have been able to lift as much weight because they were fatigued from the preceding bout of endurance exercise. These individuals performed concurrent training on 2 days a week, with endurance training preceding strength training on one occasion and strength training preceding endurance training on the other. The authors also suggested that the strength training stimulus may be reduced by an anticipatory effect when endurance training follows strength training. Unfortunately, these results cannot establish whether same day concurrent strength and endurance training inhibits strength development by directly interfering with the physiological process of adaptation to strength training, or by firstly reducing the strength training stimulus which then impairs the development of strength. However, these findings do suggest that there is a relationship between strength training stimulus and the amount of strength development.

Most studies that have compared concurrent strength and endurance training with either mode of training alone have failed to report the actual training volume and intensity performed throughout the study. An exception was Hennessy and Watson,[4] who reported that participants in the strength only training group performed a greater volume of strength training than the concurrent training group during the latter part of the training programme. Not surprisingly, the strength only group in this study increased strength development by a greater margin than the concurrent training group. Concurrent strength and endurance training sessions in this study were performed on the same day on 2 occasions each week. It is difficult to determine the mechanism responsible for the decrease in training volume in the concurrent training group as the order of training sessions was not reported. However, acute fatigue may be implicated.

Strength interference has been observed after concurrent training where strength and endurance sessions are performed on alternate days.[2] Residual fatigue may have still been a factor in this study, as it has been shown that recovery of strength after previous endurance activity may be incomplete after 25 hours.[56]

It has been shown that isoinertial strength development is greater when training sessions are spaced 48 hours apart when compared with training sessions spaced 72 hours apart.[57] This is despite evidence suggesting strength performance is reduced for up to 72 hours after an acute bout of strength exercise.[58] These results might appear to contradict the acute fatigue hypothesis of Craig et al.[3] However, the mechanisms underpinning and the effects of acute fatigue associated with resistance and concurrent training may differ. For example, research by Rooney et al.[59] suggests that the fatigue associated with resistance training may facilitate the activation of all the motor units associated with a particular movement. The acute fatigue associated with concurrent training may not be associated with a similar level of activation.

Abernethy[60] added further support to the acute fatigue hypothesis of Craig et al.[3] by demonstrating that prior endurance cycling significantly reduced the force produced by the leg extensors in subsequent isokinetic strength exercise. Recently, it has been shown that both isokinetic and isoinertial strength performance to be reduced when performed immediately after high intensity endurance cycling.[61] However, isokinetic, isometric and isoinertial strength performance remains optimal when performed 8 or 32 hours after endurance cycling.[62]

In summary, there is evidence to suggest that residual fatigue from a bout of prior endurance exercise inhibits the quality of subsequent strength exercise. However, it is unclear at this stage whether repeated acute reductions in strength training quality are responsible for causing impairments in strength development during concurrent strength and endurance training.

2.3.1 Fatigue Mechanisms Involved in the Acute Hypothesis

Identifying the physiological mechanisms responsible for producing residual fatigue associated with the acute hypothesis may enable concurrent strength and endurance training sessions to be scheduled such that strength training quality remains optimal. Although these potential fatigue mechanisms have yet to be systematically investigated, the effect of residual fatigue is localised to the concurrently trained muscle. A number of studies found that only lower body strength development and not upper body strength development was impaired during concurrent training.[3-5] Recent research has found that 6 hours following a 30-minute bout of intensive cycling, a significant reduction in maximal isometric strength was accompanied by a significant increase in the activation deficit associated with an interpolated twitch train (Bently D, personal communication). This, in combination with a reduction in the integrated electromyogram (iEMG) activity, suggests a centrally mediated fatigue. However, the iEMG : force ratio, which has been used as an index of central fatigue, was not altered by the bout of cycling. Moreover, the significant decrements in force associated with electrostimulation at all frequencies (10 to 100Hz) implicate peripheral factors in acute fatigue. A possible mechanism is alteration to the excitation-contractile process. It has been suggested that low frequency fatigue may be indicative of suppression of the process.[63] Bently (personal communication) reported such fatigue evident immediately (10 minutes) after the bout of cycling.

Other possible peripheral causes of acute fatigue include accumulation of metabolites (e.g. inorganic phosphate, lactic acid, ammonia) and depletion of energy substrates such as ATP, creatine phosphate and muscle glycogen.[64] It has been suggested that the decrease in muscle pH as a result of lactate accumulation is a major cause of fatigue in short duration exercise.[65] Elevated blood lactate levels are evident after high intensity endurance exercise.[66] Blood lactate usually returns to resting levels approximately 1 hour after cessation of exercise.[67] Strength has been shown to be reduced 4 hours after cessation of endurance exercise.[60] Furthermore, recovery of strength remains incomplete 25 hours after endurance activity.[56] Thus it would appear that reductions in strength are still evident well after pH levels have returned to normal. Therefore, it is unlikely that increased hydrogen ion accumulation as a result of lactic acid production is the fatigue mechanism involved in the acute hypothesis.

A number of studies have reported strength loss after inducing muscle damage by having volunteers perform unaccustomed eccentric exercise.[68-70] Therefore, it is possible that endurance exercise involving relatively large amounts of eccentric muscle activity may impair performance in a subsequent strength training session. However, this is unlikely to cause any long term impairment in strength development. Firstly, muscle damage occurs after unaccustomed exercise and repeated bouts of exercise (i.e. training sessions) result in little or no damage.[71] Secondly, exercise-induced muscle soreness is likely to be much greater after strength exercise than endurance exercise.[72] Thus, in a classic concurrent training study, the strength only group would also experience exercise-induced muscle damage. However, strength development in this group is often greater than the concurrent training group. Therefore, it appears unlikely that exercise-induced muscle damage is responsible for the residual fatigue associated with the acute hypothesis. However, as cellular mechanisms responsible for exercise-induced muscle damage are not well understood,[72] this fatigue mechanism should not be totally discounted at this stage. Interestingly, concurrent training studies involving strength and endurance training modalities with relatively large amounts of eccentric activity (running and isoinertial strength training), have consistently shown strength development to be inhibited.[1,3-5,12] Further research in this area is warranted.

Prolonged endurance activity causes a significant reduction in endogenous muscle glycogen levels.[48,73] The point at which an individual cannot continue endurance exercise has been associated with the exhaustion of intramuscular glycogen stores.[74] Furthermore, work capacity during endurance exercise is dependent on initial muscle glycogen levels.[75] While the importance of intramuscular glycogen as an energy substrate during endurance exercise is well documented,[76,77] the metabolism of muscle glycogen during strength training activity has received little attention in the research literature.

Muscle glycogen is an important energy substrate during resistance training activity.[78,79] Strength performance has been shown to be enhanced by carbohydrate supplementation during exercise.[80] Thus, it would seem plausible that reduced muscle glycogen would impair strength performance. Indeed, muscle glycogen depletion has been shown to reduce isometric strength performance.[81] In addition, a programme of carbohydrate restriction has been shown to reduce isoinertial but not isokinetic strength performance.[82] Conversely, isokinetic strength appears to be unaffected when muscle glycogen stores are reduced,[83] and it has been shown that glycogen depletion may not be responsible for reduced isometric strength performance 24 hours after endurance exercise.[84] However, low muscle glycogen appears to accentuate exercise-induced muscle weakness.[85]

Muscle glycogen depletion has not always been shown to reduce performance during strength training activity. It has been suggested that the nature of performance impairment during resistance activity may depend upon the extent to which glycogen is depleted in different muscle fibre types.[86] Therefore, it is difficult to speculate as to whether intramuscular glycogen depletion can be implicated as the fatigue factor involved in the acute hypothesis. However, it is clear that muscle glycogen depletion has the potential to impair certain measures of strength performance.

In summary, recent data suggest that central and peripheral factors may be implicated in the acute hypothesis. Regardless of the combination of factors, the effects of acute fatigue appear to be confined to the concurrently trained muscle. Recent data suggest that suppression of the excitation-contractile process may be implicated, although the temporal magnitude of this disruption appears small. There is some evidence to also implicate glycogen depletion in acute fatigue. More research in this area is required.

3. Conclusion

The purpose of this review was to compare concurrent training studies, identify limitations of the research and discuss possible mechanisms involved. Concurrent strength and endurance training appears to inhibit strength development when compared with strength training alone. Our understanding of the nature of this inhibition is limited at present. This is because of limited systematic concurrent training research endeavours. Many concurrent training research efforts are single study investigations which examine adaptations to specific forms of strength and endurance training. It is difficult to compare results of studies which differ markedly in a number of design factors including the mode, frequency, duration and intensity of training, training history of participants, scheduling of training sessions and dependent variable selection. It is recommended that individual laboratories focus on a particular training model and perform a series of investigations using this model. A consistent series of research studies may enable quantification of the inhibitory effects of concurrent training. Furthermore, by manipulating only certain training variables researchers may be able to identify different training strategies that may overcome any negative effects of concurrent training. At present, both chronic and acute hypotheses have been proposed to explain the phenomenon of strength inhibition during concurrent training. However, limited evidence exists for both hypotheses. Further mechanistic research is also necessary to identify other possible mechanisms responsible for the observed inhibition in strength development after concurrent training.

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