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Abstract

For optimal sports performance, many athletes will require a range of physical qualities including strength, power, and aerobic capacity. Subsequently, training is likely to contain periods where concurrent development of fitness components is required and can typically be classified into two simple training paradigms, endurance and strength training. In order to optimise training, the interaction of these fitness components should be considered as endurance training may interfere with strength training sessions via conflicting molecular signaling which may blunt optimal muscular development. At present, there are a range of conflicting recommendations inthe literature, due to the challenges of comparing different training studies and the variables which impact upon the magnitude of adaptation; including volume, intensity (load), rest, sequencing, and concurrent training goals. Most importantly, the overall training stress should be considered to reduce cumulative fatigue and minimise the potential negative effect on strength adaptations via dampened hypertrophic responses. Inter-session rest should be maximized wherever possible to reduce the interaction between competing molecular signalingpathways and provide opportunity to refuel as excesive bouts of training when fuel depleted mayrestrict subsequent training intensities and blunt any potential adapatations. When training sessions must be completed in close proximity, sequencing should consider the desired training adaptations. If strength adaptations are priority, training sessions should be sequenced, strength-endurance to maximise the strength stimulus. Overall, optimal planning during concurrent training is a complex interaction between a range of variables where strength and conditioning professionals should be

conscious of a series of factors and select a training regime that minimises the interference effect within the constraints of their own training logistics.

Introduction

Successful sports performance is multifaceted and includes optimal preparation of skill, tactics, and physical qualities. Activities such as marathon running and weightlifting have clear physicalqualities at opposite ends of a continuum. For example, a marathon runner requires excellent aerobic capacity with elite athletes typically demonstrating maximum oxygen consumption(V̇O$_2$max) values of 70-85 ml·kg^{-1}·min^{-1} (Joyner & Coyle, 2008), while in contrast, weightlifting necessitates high levels of muscular force, and as a result, a greater cross-sectional area (CSA) oftype II muscle fibers (Aagaard et al., 2011; Fry et al., 2006). Therefore, the amount of time dedicated to enhancing strength and power qualities by the endurance athlete is markedly lowerthan that dedicated by the weightlifter, just as the time dedicated to aerobic qualities is lower for the weightlifter compared to the marathon runner.

Many sports require a range of physical qualities including both strength/power and aerobic capacity for optimal performance. For instance, in a single rugby union match, it may benecessary for a player to accelerate past their opponent in a line break (acceleration and power), ruck and maul in offensive and defensive plays (muscular mass and strength), and cover large distances tackling opponents throughout (aerobic capacity). Therefore, training for rugby and many other team sports requires multiple physical qualities, which often need to be developed concurrently (Chiwaridzo, Ferguson, & Smits-Engelsman, 2016). Typically these qualities are classified into two simple training paradigms, endurance and strength training. Endurance training is commonly denoted by low-moderate (~ 70%˙O_2max) intensity and high volume training which places greatest demand on oxidative metabolism, and promotes adaptations specific to enhanced oxygen uptake and delivery such as increased mitochondrial and capillary density (Baar, 2014). In contrast, strength training is characterised as high intensity (≥80% one repetition maximum) and low volume, and places greater demand on anaerobic metabolism and promotes adaptations enhancing muscle CSA and neuromuscular efficiency to enhance force production (Farup et al., 2012). Herein lays the concern, as concurrent strength and endurance training promotes diverse physiological adaptations (Nader, 2006), it is important that strength and conditioning coaches and sport scientists have appropriate physiology knowledge to optimise programming, and thus training adaptations. The aim of this chapter is to discuss the adaptive response to concurrent exercise and identify how periodisation can minimise the interference effect of diverse adaptations.

The Interference Effect

An interference effect has been reported when strength and endurance exercises are performedconcurrently (Hickson, 1980). The cause appears to be linked to the differing physiological responses and adaptations to strength and endurance training, possibly due to the high volume and long duration that is often associated with endurance based training (Wilson, et al., 2012).It is presumed that endurance exercise interferes with resistance exercise sessions (via residual fatigue and/or substrate depletion) and therefore blunts any muscular developments e.g.,muscle fibre type alterations and architectural adaptations (Leveritt & Abernethy, 1999; Murlasits, Kneffel, & Thalib, 2018).

Neural Development

It has been well documented that increases in maximal strength during the initial weeks of strength training can be largely attributed to the increased motor unit activation of the trained agonist muscles (Häkkinen et al., 1998; Häkkinen, Kraemer, Newton, & Alen 2001a; Häkkinen, etal., 2001b). It has also been demonstrated that strength training, performed concurrently with endurance training may have no detriment to neuromuscular characteristics in elite endurance populations with no resistance training experience (Mikkola, Rusko, Nummela, Paavolainen, & Häkkinen, 2007; Paavolainen, Häkkinen, Hamalainen, Nummela, & Rusko 1999; Støren, Helgerud, Stoa, & Hoff, 2008; Taipale et al., 2010) and recreationally resistance-trained men (Jones,Howatson, Russell, & French, 2013). Häkkinen et al., (2003) demonstrated that alongside large increases in maximal force, there was an increase in the maximum integrated electromyographysignal (EMG) in the leg extensor muscles during a concurrent training programme lasting 21 weeks. Increases in EMG amplitudes via strength training would result from an increased numberof active motor units and/or an increase in their rate coding (Sale 1992). However, there are conflicts in the literature, where an interference effect has been demonstrated, it is purported to manifest as: 1) alterations in the neural recruitment patterns of skeletal muscle (Chromiak & Mulvaney, 1990; Gergley, 2009); 2) limitations in force generation (Rhea et al., 2008; Rønnestad,Hansen & Raastad, 2012); and 3) increased neuromuscular fatigue from increased training demands of high volume endurance training (Davis, Wood, Andrews, Elkind, & Davis, 2008; Pattison, Drinkwater, Bishop, Stepto & Fyfe 2020).

Interestingly, any impairments were less evident in the early stages of training (first 4 weeks), which may indicate that there is aprogressive interference to neuromuscular function with prolonged concurrent training periods (Pattison et al. 2020). These findings have been supported via a meta-analysis that indicated whilst muscular power increased, the magnitude of change was lower in concurrent trained groups (ES = 0.55) than in strength only trained groups (ES = 0.91) (Wilson et al., 2012). It is speculated that forces at high contraction velocities i.e., movements that need 'explosive'strength with high levels of rate of force development (RFD), are affected more by endurance training than force at low contraction velocities (Dudley & Djamil, 1985; Wilson et al., 2012). Therefore, in sports that require explosive strength development and/or maintenance, coupled with endurance capabilities, decrements in muscular power may be likely and a result of impaired contraction velocity or RFD (Häkkinen et al., 2003).

Muscular Development

Following periods of concurrent training, skeletal muscle CSA has been found to be depressed (Bell, Petersen, Wessel, Bagnall, & Quinney 1991) and within the total CSA, it has been evidencedthat individual muscle fibers have hypertrophied to a lesser degree (Kraemer et al., 1995; Bell, Syrotuik, Martin, Burnham, & Quinney, 2000). Mikkola, Rusko, Izquierdo, Gorostiaga & Häkkinen(2012) postulates that during bouts of concurrent training, optimal adaptation of trained musclesto both strength and endurance training stimulus may not be morphologically or metabolically possible. It has been theorised that an increased catabolic state of skeletal muscle could lead to a reduced change in the CSA

(Kraemer et al., 1995; Bell et al., 2000). In support of this, it has beendiscussed that there is a likely impact of testosterone and cortisol interference due to mixed endocrine responses to training, where strength training stimulates an increase in testosterone and prolonged endurance training increases basal levels of circulation cortisol (Taipale et al., 2010; Taipale & Hakkinen, 2013). In addition, endurance training may decrease muscle fiber size in order to accommodate increases in capillary and mitochondrial density (Sale, MacDougall, Jacobs & Garner, 1990). This may be due to the oxidative stress imposed on the muscle and the requirement to optimise the kinetics of oxygen transfer because of the additional endurance training (Häkkinen et al., 2003). Furthermore, a lack of development in muscle CSA during concurrent training could be attributed to overtraining induced by chronic muscle glycogen depletion (down regulating the signaling cascade required for protein accretion, as well as reducing training performance) and an increase in catabolic hormones (Mikkola et al., 2012). Further analysis demonstrates that potential interferences to muscle hypertrophy during concurrent training are more prominent when strength training is concurrently performed with running compared to cycling (Wilson et al., 2012). This is likely explained by greater levels of muscle damage in running (eccentric muscle action) and thereby reducing the development of muscle tissue via competing demands for tissue regeneration via the inflammatory process (Clarkson & Hubal 2002; Wilson et al., 2012).

Molecular signaling

Excessive bouts of endurance exercise are known to reduce rates of protein synthesis for several hours following the cessation of training (Rennie & Tipton, 2000). Molecular signaling research has evidenced that during (and following) endurance training the metabolic signaling pathways that are linked to substrate depletion and calcium release and uptake into the sarcoplasmic reticulum are activated (Coffey & Hawley, 2007). The secondary messenger Adenosine Monophosphate-activated Kinase (AMPK) is activated, as its role is to increase mitochondrial function to enhance aerobic capacity via the breakdown of glycogen and fatty acids to fuel activity (Rose & Hargreaves, 2003). However, this activation inhibits the mammalian target of Rapamycin (mTOR), whose role is to mediate skeletal muscle hypertrophy through upregulationof protein synthesis via activation of ribosome proteins (Bodine, 2006). Knowledge of this signaling system informs us that in conditions of low glycogen and high concentration of calciumand Adenosine monophosphate (AMP) (as would occur during aerobic training), would activate the AMPK pathway, thus protein accretion (via the mTOR pathway) is significantly reduced (Figure 6.1). Therefore, strength training in a fatigued state may not be best practice.

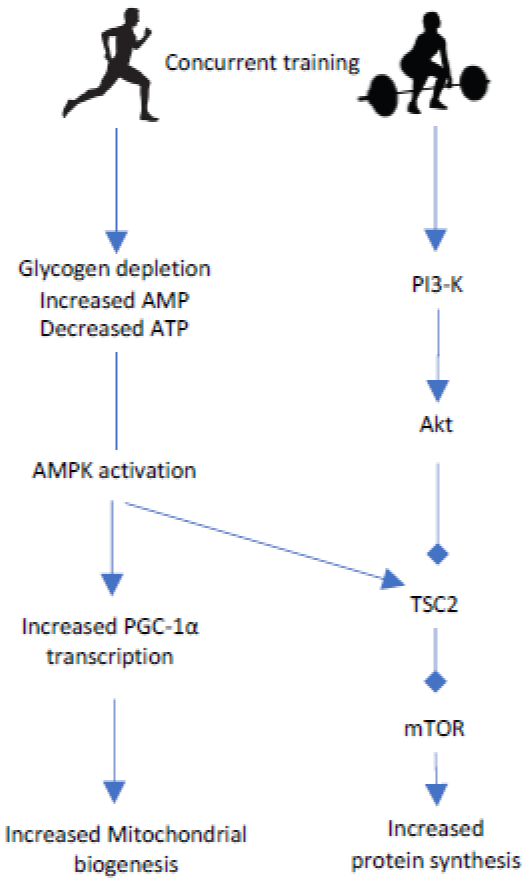


Figure 1 Putative adaptive pathways in response to the concurrent programming of endurance and resistance exercises in a training program. Diamonds represent inhibition of a pathway and arrows represent activation. Adenosine monophosphate (AMP); Adenosine monophosphate kinase (AMPK); Adenosine triphosphate (ATP); Peroxisome proliferator-activated receptor-γ coactivator-1α (PGC-1α); Phosphoinositide 3-kinase (PI3-K); Tuberous sclerosis complex 2 (TSC2); Mammalian target of rapamycin (mTOR) .

Cardio-Respiratory Development

There is empirical evidence that in elite endurance athletes, strength training can lead to enhanced long-term (> 30-minutes) and short-term (< 15-minutes) endurance capacity (Aagaard& Andersen 2010). Investigations into adaptations of cardiorespiratory function have indicated that there are no differences in the magnitude of adaptation when endurance training iscompleted in isolation or concurrently with strength training (Bell et al., 2000; McCarthy, Pozniak,& Agre 2002). The greatest impact on cardiorespiratory adaptations arise when peripheral adaptations (e.g. capillary and mitochondrial density) are blunted. As the volume and intensity of resistance training increase, competition for contractile protein synthesis (promoting an increase in fibre size and muscle CSA) and an increase in glycolytic enzymes exist (Docherty & Sporer 2000). More recent focus on cardiorespiratory adaptations has investigated the acute effects of concurrent training on oxidative metabolism (Alves et al., 2012; Kang et al., 2009). Alves et al., (2012) did not observe differences in mean values of ˙O_2 or heart rate (HR) during endurance exercise performed prior to or following a strength training session. However, Kang et al., (2009) demonstrated greater mean values for participant’s ˙O_2 when endurance exercisewas performed following strength training compared with endurance exercise only. There are a number of methodological differences that can explain these results, i.e., intensity of enduranceexercise; strength exercises chosen, and populations used. The positive effects of strength training for endurance athletes may occur independently to changes in cardiorespiratory development (Paavolainen et al., 1999) and could be due to improvements in rate of force development (RFD) that aide improvements in exercise economy. An improved force profile mayaugment RFD and the time required to produce the desired force for each movement reducing ground contact time (GCT) (Hoff, Gran, & Helgerud, 2002; Paavolainen et al., 1999; Sedano, Marín, Cuadrado, & Redondo, 2013). Moreover, an enhanced force profile can augment the utilization of elastic energy in the muscle-tendon system, decrease GCT and reduce the demandon ATP production, thus improving exercise economy (Wilson and Lichtwark, 2011).

Underlying all these proposed mechanisms, it may be that there is an individual response that iscoupled to an athlete's training experience (Fyfe & Loenneke 2017). When comparing moderatetrained athletes with well-trained athletes, it has been evidenced that higher activation of molecular mechanisms leading to both myofibrillar and mitochondrial protein synthesis occur inless trained populations regardless of the concurrent nature of the training (Nader, von Walden,Liu, Lindvall, Gutmann, Pistilli & Gordon 2014; Perry, Lally, Holloway, Heigenhauser, Bonen & Spriet 2010). This is attributed to the philosophy that in less developed athletes, any stimuli mayinduce significant alterations to a cells homeostasis and, therefore, lead to greater training-induced adaptations and that endurance based athletes could be considered less developed in strength parameters and therefore the interference effect is a reduced factor in their training development.

Training Strategies to Minimise Interference

Training Periodisation

Periodising a training programme (which should include the planning of all tactical and technicaltraining) for a sport that includes a range of physical qualities and planning of multiple training units within a training day, microcycle, and mesocycle, needs to be cautiously managed to minimise the interference effect; as one training unit may inhibit adaptations to a prior or subsequent training unit. In addition, the inclusion of training units such as technical and tacticalskills within the sport may provide enough stimuli to maintain or enhance physical qualities and such training stressors should be considered in the periodised plan to optimise fitness and minimise fatigue (Issurin, 2010, 2003; Suarez-Arrones et al., 2014).

Wong, Chaouachi, Chamari, Dellal, & Wisloff (2010) investigated a concurrent training programme using professional football players during an 8-week preseason. Programming prioritisied 1 repetition maximum (1RM) half back squat and Yo-Yo Intermittent Recovery Test (YYIRT) performance, alongside sport specific tactical and technical training units. The experimental group completed twice weekly strength training units and 8 minutes of high intensity running sessions (low volume) on the same day, additional to their normal 6-8 weekly soccer training units. Whereas the control group completed their normal 6-8 weekly soccer training units. Results demonstrated significant improvements for the experimental group in 1RM half back squat (+25Kg) and YYIRT (+298m) but only the YYIRT (+137m) for the control group. Similarly, Enright, Morton, Iga, & Drust (2015) demonstrated half back squat 1RM improvementsduring a 5-week in-season concurrent training programme that included strength training,soccer-specific endurance training, technical, and tactical sessions. In this study design, all groupscompleted a concurrent training protocol and sequencing was manipulated. Training groups either completed strength-endurance or endurance-strength, separated by ~ 1hour. Regardless of sequence, both groups significantly improved half back squat 1RM by 10.3% and 19.1% respectively. However, the more pronounced changes and larger increase observed in the E+S training situation may suggest that the concurrent training sequence, in association with recovery duration between training bouts coupled with nutrient availability may be able to modulate significant changes in physical performance measures. These applied research examples demonstrate minimal interference effect and suggest that within professional sport, both strength and aerobic measures can be augmented with concurrent training programmes over prolonged periods.

With regards to maximizing strength training adaptations for strength and power based athletes(contact sport), Appleby, Newton, & Cormie (2012) assessed strength over a 2-year period in professional rugby union players. Findings indicate increases in strength are highly related to increases in lean body mass and the magnitude of improvement is related to initial strength level. However, the degree of strength improvement diminishes with increased strength, training experience (4–7 years), and if athletes do not have the capacity to increase lean body mass (Baker, 2013). Consequently, it is important to recognise methodological differences in concurrent training research. Comparing athletes with a low resistance training age to well- trained strength athletes is unwise as the stimulus for adaptation is different. Longitudinal research where strength based athletes have participated in concurrent training (Appleby, et al.,2012; Baker, 2013; Stodden & Galitski, 2010) have typically dedicated specific training periods such as preseason (Appleby, et al., 2012) or off-season (Stodden & Galitski, 2010) to hypertrophydevelopment and included a minimum of 3 resistance training sessions per week for thismesocycle. This form of block / emphasis based periodisation enables a large training stimulus tobe applied to well-trained athletes. During in-season, training frequency is reduced to a minimumof one session per week to maintain physiological adaptations made in the pre and off-season. In Appleby et al. (2012) and Stoden & Galitski, 2010 studies, 1RM strength improved within yearone and year two, alongside the inclusion of speed, agility, aerobic capacity, technical, and tactical training units. This in-season reduction in strength training frequency demonstrates wellthought-out programming with regards to concurrent training volume and periodisation. As such,there is no decrease in strength, which is a positive outcome in this scenario (Baker, 2013). A review on the development, retention, and decay of strength in trained athletes further confirmthese programming variables, suggesting that to maintain strength, 1-2 training units per week are required (McMaster, Gill, Cronin & McGuigan, 2013); this low frequency stimulus could be sufficient due to athletes undertaking substantial doses of high / rapid force generating activities during technical and tactical training sessions. Interestingly, it also speculated that a detraining period of 3 weeks has minimal effect on muscular strength (McMaster et al., 2013). This providesvaluable programming information with regards to the duration of strength training residuals andthe potential for programming adjustments such as, an opportunity to reduce resistance trainingvolume and implement a tapering strategy, or increase training volume to target another physicalquality.

For successful periodisation within sports where concurrent training is required, it would beprudent to determine off-season and in-season periods to establish specific training goals. Furthermore, determining preseason and in-season mesocycle goals would help focus programming and lessen the interference effect of physiological adaptations of diverse physical qualities. For example, Garcia-Pallares, Sánchez-Medina, Carrasco, Díaz, & Izquierdo, (2009) demonstrated in elite kayakers that strength and endurance qualities can be trained concurrentlywith positive performance outcomes. The distinctive aspect of this research was coupling hypertrophy training with aerobic training at 90% of $^{\cdot}O_{2max}$ in the first mesocyle and strengthtraining and maximal aerobic power training (high intensity aerobic training, between 90% and 100% of $^{\cdot}O_{2max}$) in the second mesocycle. Rationale for this was due to the physiologicaladaptations expected, hypertrophy (increase in contractile proteins synthesis) and aerobic power training (increase in oxidative capacity modulated by changes to oxidative enzymatic reactions)promote opposing adaptations at a peripheral level (Garcia-Pallares et al., 2009). Emphasising fitness qualities in this manner has the potential to limit the interference effect based on specific physiological adaptations. The use of transition or detraining periods from strength training units within programming may also be beneficial as: 1) this period may enable restoration andsupercompensation, and 2) another training unit may be prioritised without detrimental effectsto strength (McMaster et al., 2013; Sedano et al., 2013). Special attention should be consideredin regards to the type of sport, for example contact sports may necessitate a need forhypertrophy and an increased frequency of resistance training units whilst minimising theamount of aerobic training units completed.

Training Session Sequencing

One opportunity to manipulate training variables and reduce interference may be through the sequencing of training units within a microcycle. In programmes that include both strength and endurance based training stimuli in the same session, the training response may be different depending on whether endurance or strength training is performed first. In a recent meta- analysis, Eddens, van Someren & Howaston (2018) included 10 studies directly comparing intra-session exercise sequence and the interference effect. Resutls identified that performing resistance training first enhanced the improvement in lower-body dynamic strength within prolonged concurrent training programmes (weighted mean difference, 6.91% change; 95% CI 1.96 to 11.87 change; p=0.006). Similar findings were also reported by Murlasits, Kneffel & Thalib(2018) whose meta-analysis directly compared strength and endurance training sequence on performance measures and identified a significantly different effect size of 3.96 kg (95%CI: 0.81 to 7.10 kg), indicating the superiority of the strength-prior-to-endurance order. Interestingly, Ratamess et al., (2016) demonstrated endurance training performed 10 minutes before strengthtraining resulted in 9.1– 18.6% fewer repetitions performed compared to strength training only. Therefore, it is plausible that the order effect is explained by residual fatigue, with the stress of the preceding endurance training acting to inhibit the quality of the strength training session.

Training Recovery

Insufficient recovery between training sessions may limit the desired adaptations from previous training. Residual fatigue from aerobic training may reduce the quality of strength training sessions by alterations in neural recruitment patterns (Chromiak & Mulvaney, 1990; Gergley, 2009), inhibit force generation capacity (Rhea et al., 2008; Rønnestad, et al., 2012) or neuromuscular fatigue (Leveritt & Abernethy, 1999; Davis et al., 2008). For example, Robineau, Babault, Piscione, Lacome, & Bigard, (2016) concluded that strength and power adaptations wereinhibited unless at least 6-hours recovery was allowed between training sessions (strength followed by high intensity endurance exercise), however, a 24-hour recovery period was superiorto further reduce interference. Furthermore, Sale, MacDougall, Jacobs, & Garner, (1990) reported that strength and endurance training performed on the same day (alternating order) had no effect on muscle hypertrophy, but did cause a significant reduction in strength development in untrained men compared to separate day training (approximately 24 hours rest).It is likely that increasing recovery between sessions, reduces the magnitude of the interference effect as there is less disruption in post training signaling pathways (Lundberg et al., 2012) and an increased period for protein synthesis, restoration, and opportunity to replenish fuel stores (Chtourou et al., 2014).

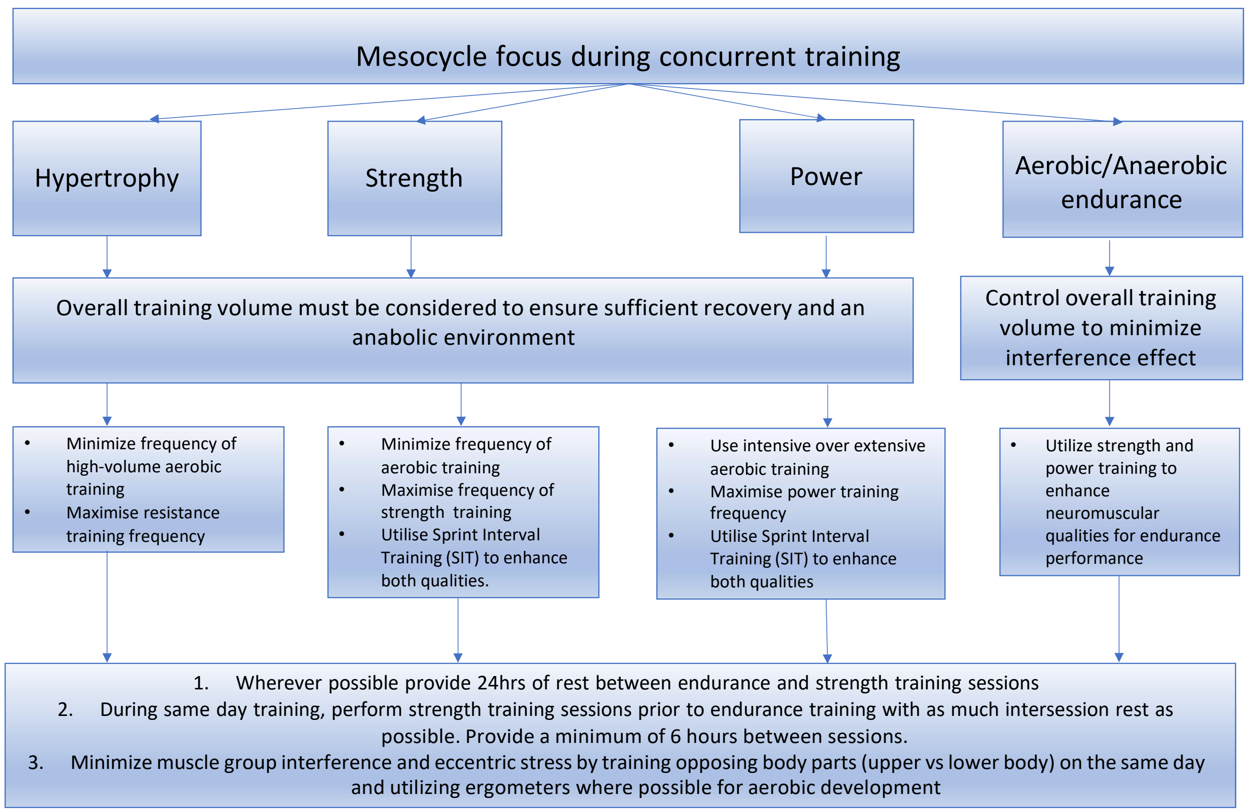
Further, the interference effect may also be increased when the same muscle groups are utilisedfor strength and endurance based training (Craig et al., 1991; Sporer & Wenger 2003). Sporer & Wenger (2003) report that lower body strength was significantly decreased for at least 8 hours after completion of a cycling sub maximal aerobic training session (36 mins cycling at 70% maximal power at˙O_2) and a cycling high intensity interval training session (3 mins work and 3mins rest at 95-100% of maximal power at˙O_2), with no difference between groups at any recovery time point. However, a meta-analysis, examining the interference of aerobic andresistance training suggests interference effects are primarily body part specific as performancedecrements were found in lower, but not upper-body exercise (Wilson et al., 2012). Therefore, athletes who engage in multiple strength training units per week, may benefit from utilising a split training routine where upper body strength training is completed on days that contain aerobic training sessions (given these predominately tax the legs).

Training Intensity

It may also be important to consider endurance training intensity as Chtara et al., (2008) and Davis et al., (2008) reported that interference is more likely to occur at aerobic training intensities close to maximal oxygen uptake. Ratamess et al (2016) investigated the acute response of strength performance initiated 10 minutes after four different endurance (running) protocols, these included: 1) continuous moderate intensity for 45 minutes, 2) continuous moderately high intensity for 20 minutes, 3) high-intensity intervals for 15 minutes (with 15 minutes of low- intensity in between), and 4) continuous moderately high intensity uphill for 20 minutes. Results demonstrated all endurance protocols observed a significant strength training performance deficit (repetitions) compared to strength training only. Interestingly, protocol 3 (most intensive) led to the greatest performance decrement followed by protocol 1 (most extensive). With regards to longer-term research, Varela-Sanz, Tumilil, Abreu & Boullosa (2018) investigated two matched volume concurrent training protocols of different training intensities for a duration of eight weeks. Subjects were randomly allocated to either: 1) a traditional training group who completed continuous running at 65-75 % of maximal aerobic speed (MAS) and 10-12 repetition maximum (RM) three times per week, or 2) a polarized group that combined brisk walking of 35- 40% MAS and 15 RM twice weekly; and brisk walking at 35-40% MAS, 15 second intervals at 120% MAS and 5RM in the third session. Results demonstrated similar strength and endurance improvements for both groups, however, only the polarised group were able to maintain lower body explosive power by means of a jump test. In this regard, the results suggest that the polarized distribution of training attenuates the interference effect in respect to neuromuscular performance which may be due to a combination of factors such as a low weekly training frequency (4 rest days per week) or superior programming related to employing low intensity brisk walking and reduced frequency of high intensity training, thus limiting fatigue. Interestingly,it has also been reported that high intensity aerobic training may minimise the interference effectdue to the recruitment of high threshold motor units and a potential reduction in training volume. For example, Wong et al., (2010) reported significant improvements in strength, sprint speed, and aerobic performance after strength sessions were utilised concurrently with high intensity aerobic training (15:15sec at 120% MAS and passive recovery). Notably, this training allowed for approximately 5hrs between the morning strength session and the afternoon high intensity aerobic session, which may have also contributed to the significant adaptations found. High intensity interval training is discussed further in Chapter 4.

Training Frequency, Volume and Mode

Optimal training frequency is also important as a number of studies investigating concurrent training have reported varied conclusions on whether endurance training attenuates strength and power adaptations (Sale et al., 1990; Craig et al., 1991; Abernethy & Quigley, 1993; Hennessy& Watson, 1994; Kraemer et al., 1995; McCarthy, Agre, Graf, Pozniak, & Vailas,, 1995). Jones, etal., (2013) speculated that these differences may be linked to endurance training frequency as attenuated responses are more often reported in studies utilising a high (Craig et al., 1991; Hennessy & Watson, 1994; Kraemer et al., 1995) vs. a low training frequency (Abernethy & Quigley, 1993; McCarthy, et al., 1995; Sale et al., 1990). Jones, Howatson, Russell, & French, (2016) examined the effects of endurance training frequency in a six-week training intervention in which participants were randomly assigned to 1 of 4 experimental conditions: 1) strength training only, 2) concurrent strength and endurance training at a ratio of 3:1, 3) concurrent strength and endurance training at a ratio of 1:1, or 4) a control. Results demonstrated that an increase in the frequency of endurance training and total training volume within the concurrenttraining paradigm resulted in the attenuated development of lower-body strength when compared with strength training alone. Moreover, earlier work from the same research group demonstrated that recreationally trained men completing high frequency strength and muscularendurance training (both 3 x per week) resulted in lower strength and hypertrophy adaptations compared to groups performing strength only (3 x per week) or low frequency strength and muscular endurance training (3 x strength and 1 x endurance per week) (Jones et al., 2013). Subsequently, it may be important to evaluate the desired physiological outcome and manipulate strength to endurance training ratio dependent on the training goals. It seems prudent that should muscular strength or hypertrophy be a priority, the frequency and ratio of endurance training should be low, as endurance training frequencies of greater than three times a week have been shown to attenuate strength performance (Jones et al., 2013; Jones et al., 2016; Häkkinen et al., 2003; Izquierdo-Gabarren et al., 2005; Kraemer et al., 1995). It should be noted that methodological differences make comparing and contrasting frequency research problematic due to manipulation of the acute programme variables and the amount of permutations available which mainly effect training volume. Wilson et al., (2012) produced a meta-analysis of concurrent training studies that demonstrated negative significant and meaningful relationships between endurance training frequency, duration, and lower bodyadaptations in hypertrophy ($r = -0.26$; $r = -0.75$, respectively), strength ($r = -0.31$; $r = -0.34$, respectively) and power ($r = -0.35$; $r = -0.29$, respectively) indicating an interference effect. Whilst there were significant negative relationships, the majority are weak and suggest minimal interference effect for strength and power adaptations. Therefore, prescription of training loadsshould be monitored, as when concurrent training is necessary, the overall training load is likelyto be higher, in both frequency and duration, due to needing to meet this minimum-dose response of two different fitness qualities.



Summary

In summary, the concurrent training research provides equivocal findings on rate and magnitudes of adaptations (positive and negative in their manifestation) across a number of physiological variables including strength, power, and cardiorespiratory functions. This wide range of findings may be due to the wide range of acute programme variables contributing to the potential interference effect. Although it is not fully understood, the research seems to support that the interference effect has its greatest effect on strength development (via hypertrophicadaptations) and that the most likely mechanism of this interference is linked to the molecular signaling activated from the type of training undertaken. Athletes whom require high levels of muscular strength and hypertrophy, therefore, should endeavor to limit any long periods of concurrent training.

During the planning of training, overall periodisation including microcycles and mesocycles needto be cautiously managed to control fatigue and minimise the interference effect (see Figure 1 for recommendations). It would be prudent to determine off-season and in-season periods to establish specific training goals where as much focus can be placed on a single training outcomeas possible. It may also be optimum to reduce the frequency of endurance training (and stronglyconsider total accumulated fatigue) when hypertrophy adaptations are required. During trainingcycles where concurrent training is unavoidable, it would be sensible to consider the level of stimulus required of different modes of training and determine a minimal dose response. For example, detraining or transition periods of up to three weeks from strength training units may be beneficial to allow supercompensation and of other physical qualities, such as speed and agility to be prioritised.

Practical guidelines for concurrent training include, 24 hours of rest between strength and endurance training units, where this is not possible, 6-8 hours would be sufficient. In addition, muscle recruitment and mode of exercise should be considered, for example, where training necessitates two training units in one day, upper body strength could be coupled with on feetaerobic training. Alternatively, off-feet aerobic training (cycling, rowing, and ski-erg) could bematched with lower body strength training to minimise extensive eccentric stress. In scenarioswhere training sessions must be combined, and strength development is key, a strength-endurance order should be used. Finally, to maximise strength adaptations, two rest days shouldbe provided and endurance training frequency of less than three sessions per week is advised.

Applied Training Case Study

Given the necessity for numerous elite sporting populations to develop strength and aerobic capacity simultaneously, a significant demand has been placed upon the practice of effective concurrent training methods. Working within amateur or semi-professional sport this demand iseven more apparent due to varying external life commitments e.g. employment, especially thoseinvolving manual labour. Scheduling for appropriate adaptation with little time available to trainbecomes a challenge; therefore, there is a requirement to complete both strength and aerobic capacity training within a single training session. In this applied training case study, the population comes from an elite womens rugby team in the UK and their typical weekly in-seasonschedule can be seen in Table 1.

Table 1 Typical training week

Day	Combined Sessions (Semi Pro)	
Monday	18:00 – 19:00	Upper Body Strength
	19:00 – 20:00	Off Feet Conditioning
Tuesday	17:00 – 18:00	Lower Body Strength
	19:00 – 20:30	Combined Conditioning + Rugby
Wednesday	Active Recovery	
Thursday	17:00 – 18:00	Total Body Strength
	19:00 – 20:30	Combined Conditioning + Rugby
Friday	Active Recovery	
Saturday	Game Day	
Sunday	Day Off	

Due to logistical constraints in the training environment (squad size, floor space) this group of players were split into two training groups in one continuous 120-minute session. One group performed resistance training (RT) prior to aerobic capacity training (ACT), and the other group perform ACT prior to RT. Session content for all players was the same and training took place in-season three times per week. Table 2 provides the programming variables used during an 8 weektraining block to provide sufficient stimulus for the physiological adaptations required for performance in their sport.

Table 2 Programming for concurrent training over an 8-week block

Training Period			
Weeks	1-3	4-6	7-8
RT Workload			
Warm up			
Sets	2	3	3
Duration	3 mins	3 mins	4 mins
Recovery	30s	30s	30s
Main Exercises			
Sets Upper Body	3	3	3
Sets Lower Body	3	3	3
Repetitions	10	6	3
Intensity (% 1RM)	70%	80%	90%
Recovery	2 mins	3 mins	3 mins
Complementary Exercises			
Repetitions Plyometrics	6	6	6
Repetitions Hamstrings	6	6	6
ACT Workload			
Short Intervals	2 x 8 min of 30/30s	2 x 10 min of 30/30s	2 x 12 min of 30/30s
Sprint Intervals	4 x 30s all-out	6 x 30s all-out	8 x 30s all-out

Resistance training design

Every session began with a warm-up focused on movement skills. Strength-training includedexercises of the lower (squat, deadlift and lunges) and upper (bench press, chin up and bent-over row) body (Table 2). Training was divided into three periods during which the intensity progressively increased. The first period (weeks 1-3) aimed to prepare participants for maximalstrength training. The second (weeks 4-6) and the third (weeks 7-8) periods were designed to increase maximal strength (Table 2). Each set of squats was immediately followed by plyometric jumps. Exercises were alternated during each training session, alternating lower- and upper-body exercises. Players were free to change weight during the training period in order to achieve the programmed repetitions.

Aerobic capacity training design

Two different ACT sessions were performed outside on an artificial pitch. A specific 15 min warm-up, consisting of moderate, cruising and sprinting runs preceded each aerobic training session. The first consisted of short-intervals and included two sets of interval running. Players would alternate 30 s runs at 100% of their individual maximal aerobic speed (MAS) with 30 s of active recovery at 50% MAS, where MAS was obtained from a 1200 m test. The second sprint-interval included repetition of 30s running all-out efforts with 4 min of passive recovery.

Table 3 Mean (±SD) values for performance measures conducted in elite women's rugby players pre- and post- 8 weeks of concurrent training interventions.

Performance Test		**Pre**	**Post**	**% Change**
Squat 1RM (kg)	**RT-ACT group**	93.1 (15.3)	98.5 (14.2)*	5.5%
	ACT-RT group	97.5 (21.2)	101.5 (18.6)*	4.1%
Bench press 1RM (kg)	**RT-ACT group**	61.0 (12.9)	65.0 (12.8)*	6.5%
	ACT-RT group	60.7 (21.7)	63.1 (22.0)*	4.0%
Maximal Aerobic Speed (m/s)	**RT-ACT group**	3.5 (0.4)	3.7 (0.4)*	5.7%
	ACT-RT group	3.5 (0.4)	3.7 (0.5)*	5.7%

**Denotes a significant difference compared to baseline (p < 0.05)*

Player monitoring data (Table 3) highlights that despite having to schedule the team into differingorders of concurrent training they all demonstrated large positive adaptations in both strength and aerobic capacities over an 8 week block. From this applied training case study it is clear thatthe sequence in which concurrent training is performed within a 120 min training session has minimal impact on the player's physiological development. We can however, highlight from thisapplied example, that the greater improvements seen in the RT-ACT group are in line with concurrent training recommendations in relation to training order and weekly rest days.

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