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Abstract

Many sports require a range of physical qualities including strength, power and aerobic capacity for optimal performance. Subsequently, training is likely to contain periods where concurrent development of fitness components is required and will typically be classified into two training categories, endurance and strength training. In order to optimize training, the interaction of these fitness components should be considered as endurance training may interfere with resistance training sessions via conflicting molecular signaling which may blunt optimal muscular development. At present, there is a range of conflicting recommendations in the literature due to the challenges of comparing different training studies and the variables which impact upon the magnitude of adaptation; including volume, intensity, sequencing, rest and concurrent training goals. Most importantly, the overall training stress should be considered to limit cumulative fatigue and minimize 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 signaling pathways. Where required, strength training should be completed after aerobic endurance training to ensure overnight recovery facilitates strength based adaptations. 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 range of factors and select a training regime that minimized the interference effect but also fits with 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 physical qualities. For example, a marathon runner requires excellent aerobic capacity with elite athletes typically demonstrating $\dot{V}o_2$max values of 70-85 ml kg^{-1} min^{-1} (Joyner & Coyle, 2008). In contrast, weightlifting necessitates high levels of muscular force, and as a result, a greater cross-sectional area (CSA) of type 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 lower than that dedicated by the weightlifter, just as the time dedicated to aerobic qualities is lower for the weightlifter compared to the marathon runner.

There are many sports that 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 be necessary for a player to accelerate past their opponent in a line break (acceleration and power), ruck and maul in offensive and defensive plays (muscular size and strength), and cover great distances, tracking and tackling 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 training categories, endurance and strength training. Endurance training is commonly denoted by low 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 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 performed concurrently (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 (Leveritt & Abernethy, 1999).

Neural Development

It has been well documented that increases in maximal strength during the initial weeks of strength training can be attributed largely to the increased motor unit activation of the trained agonist muscles (Häkkinen et al., 1998; Häkkinen, Kraemer, Newton, & Alen 2001a; Häkkinen, et al., 2001b). It has been demonstrated that strength training, performed concurrently with endurance training has no detriment to neuromuscular characteristics in trained populations (Mikkola, Rusko, Nummela, Paavolainen, & Häkkinen, 2007; Paavolainen, Häkkinen, Hamalainen, Nummela, & Rusko 1999; Støren, Helgerud, Stoa, & Hoff, 2008; Taipale et al., 2010). Häkkinen et al., (2003) demonstrated that alongside large gains in maximal force, there was an increase in the maximum integrated EMGs in the leg extensor muscles during a concurrent training programme lasting 21 weeks. Increases in EMG amplitudes via strength training would result from the increased number of active motor units and/or an increase in their rate coding (Sale 1992). More recently, Jones, Howatson, Russell, & French (2013) reported no differences in neuromuscular responses between strength training and concurrent training interventions, which is in agreement with previous research stating neuromuscular characteristics are not fully inhibited by concurrent training (McCarthy, Agre, Graf, Pozniak, & Vailas, 1995; Mikkola, et al., 2007; Paavolainen et al., 1999). 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 (Leveritt & Abernethy, 1999; Davis, Wood, Andrews, Elkind, & Davis 2008). These findings have been supported via a meta-analysis that indicated whilst muscular power increased the magnitude of change was significantly 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). Therefore, in sports that require explosive strength development and/or maintenance, coupled with endurance capabilities, decrements in muscular power may be highly likely and that that decrements in power result from either impairment in 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 evidenced that 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 muscles to both strength and endurance training stimulus may not be morphologically or metabolically possible. It has been theorised that elevations in the catabolic hormonal 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 been discussed that there is a likely impact of testosterone and cortisol interference due to mixed endocrinal responses to training (Taipale & Hakkinen, 2013). Also, 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 partly due to the oxidative stress imposed on the muscle and the need to optimise the kinetics of oxygen transfer because of the addition of endurance training to strength 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 disruptions 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 potentially due to greater levels of muscle damage in running and thereby reducing the development of muscle tissue via competing demands for tissue regeneration via the inflammatory process (Clarkson & Hubal 2002).

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 (Rose & Hargreaves, 2003). However, this activation inhibits the mammalian target of Rapamycin (mTOR), whose role is to mediate skeletal muscle hypertrophy through upregulation of 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 calcium and AMP (as would occur during aerobic training), the AMPK pathway is activated and thus protein accretion (via the mTOR pathway) is significantly reduced. Thus strength training in a fasted or fatigued state may not be best practice.

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 is completed in isolation or concurrently with strength training (Bell et al., 2000; McCarthy, Pozniak, & Agre 2002). The greatest impact on cardiorespiratory adaptations come when the peripheral adaptations (e.g. capillary and mitochondrial density) are blunted when the demands of resistance training increase the competition for rises in contractile protein synthesis (promoting an increase in fibre size and muscle CSA) and an increase in glycolytic enzymes (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 VO_2 or HR during endurance exercise performed prior to or following a strength training session. However, Kang et al., (2009) demonstrated greater mean values for participants VO_2 when endurance exercise was performed following strength training compared with endurance exercise only. There are a number of methodological differences that can explain these differences, i.e. intensity of endurance exercise; 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 RFD that aide improvements in exercise economy. Further, improved RFD may reduce time to reach the desired force for each movement via reduced ground contact times. A shorter contraction time coupled with relative high force production would be likely to enhance the utilization of elastic energy in the muscle-tendon system in the lower body and could reduce the demand of ATP production, thus improving exercise economy.

Training Strategies to Minimise Interference

Training Periodisation

When periodising a training programme for a sport that includes a range of physical qualities, planning of training units within a training day, microcycle and mesocycle, needs to be cautiously managed to minimise the interference effect; one training session may inhibit adaptations to a prior or subsequent training unit. In addition, the inclusion of training units such as technical and tactical skills 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 minmise fatigue (Issurin, 2010, 2003; Suarez-Arrones et al., 2014).

In a recent study, an 8-week preseason concurrent strength and aerobic training programme (prioritising 1 repetition maximum (1RM) half back squat and Yo-Yo Intermittent Recovery Test) was effective at improving both cardiovascular and neuromuscular measures in professional soccer players (Wong, Chaouachi, Chamari, Dellal, & Wisloff, 2010). 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. Likewise, Sedano, Marín, Cuadrado, & Redondo (2013) demonstrated improved running economy, 3 km time trial and 1RM strength with concurrent training in elite endurance athletes. Here participants completed their normal 6 weekly endurance units (intervals x 3, moderate running 0.5-1.5h x 2 and fast running 0.5-1h x 1) with the inclusion of 2 weekly strength units over a 12-week training programme. Noticeably, both studies included two daily training units when resistance training was performed; during these days, resistance training units were performed in the morning prior to endurance units performed in the afternoon. Piacentini et al., (2013) also demonstrated similar results with concurrent training in highly trained master endurance athletes. Interestingly, these studies used linear periodisation patterns of increased intensity over time and demonstrated improvements in strength and endurance performance measures with no hypertrophy or concomitant changes to anthropometry. While these concurrent training studies demonstrate minimal interference effect to cardiovascular performance in aerobic endurance based sports, they conversely demonstrate endurance training may inhibit strength training adaptations such as muscle CSA to a greater degree. Therefore, consideration and appropriate planning must be applied when planning training blocks to stimulate muscle hypertrophy for collision sports where a goal of training is likely to be an increase in muscle mass.

With regards to maximizing strength training adaptations for strength and power based athlete, 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. Consequently, it is important to recognise methodological differences in concurrent training research. Comparing athletes with 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; Stodden & Galitski, 2010) have typically dedicated specific training periods such as preseason (Appleby, et al., 2012) or off-season (Stodden & Galitski, 2010) to hypertrophy development and included a minimum of 3 resistance training session per week for this mesocycle. This form of periodisation enables a large training stimulus to be applied to well-trained athletes. During in-season, training frequency reduced to a minimum of one session a week to maintain physiological adaptations made in pre and off-season. In both these studies, 1RM strength improved within year one and year two, alongside the inclusion of speed, agility, aerobic capacity, technical and tactical training units. A review (McMaster, Gill, Cronin & McGuigan, 2013) on the development, retention and decay of strength in strength and power based athletes confirm these programming variables, suggesting that to maintain strength, 1-2 training units per week are required. Interestingly, it also speculated that a detraining period of 3 weeks has no effect on muscular strength (McMaster et al., 2013). This provides valuable information in regards to the duration of strength training residuals and subsequent opportunities for tapering strategies or prioratising other training units.

For successful periodisation within sports where concurrent training is required, it would be prudent 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 concurrently with positive performance outcomes. The distinctive aspect of this research was coupling hypertrophy training with aerobic training in the first mesocyle and strength training and maximal aerobic power in the second mesocycle. The rationale for this was due to the physiological adaptations expected, hypertrophy (increase in contractile proteins synthesis) and aerobic power training (increase in oxidative capacity) promote opposing adaptations at a peripheral level (Garcia-Pallares et al., 2009). Periodising 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 and supercompensation and 2) another training unit may be prioritised without detrimental effects to strength (McMaster et al., 2013; Sedano et al., 2013). Special attention should be considered in regards to the type of sport, for example contact sports may necessitate a need for hypertrophy and an increased frequency of resistance training units whilst minimising the amount 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 on the same day, the training outcome may be different depending on whether endurance or strength-based training is performed first, and what fatigue may be carried from session to session (as mentioned in the molecular signaling section). Some studies have investigated the endocrine response to training sequencing as chronic physical adaptations are enhanced by optimal endocrine responses (Craig, Lucas, Pohlman & Stelling, 1991; Kraemer & Ratamess, 2005). However, these investigations have continually provided mixed conclusions. Cadore et al., (2012) reported strength training after endurance training resulted in increased testosterone levels compared to strength training prior to endurance. In addition, no change in cortisol response was reported, regardless of exercise sequencing. Goto, Ishii, Kizuka & Takamatsu, (2005) support endurance prior to strength training, as they found no difference in testosterone or cortisol concentration after resistance only or endurance training prior to resistance exercise. Moreover, Taipale & Hakkinen, (2013) reported a reduction in testosterone (at 24 and 48hrs recovery) during strength then endurance sequencing alongside lower levels of cortisol post training compared to the endurance – strength - endurance sequencing group. Utilising a sequence containing endurance training prior to strength training may also allow for the strength training stimulus to be the last stimulus of the day (evening session) where strength levels are at their highest (Souissi, et al., 2013) and training may result in an elevation in the mTOR signaling pathway and maximise post-session recovery time, facilitating more time for protein synthesis and a more favorable anabolic environment (Lundberg Fernandez-Gonzalo, Gustafsson & Tesch, 2012; Chtourou et al., 2014), including while sleeping. Equally, it has been reported that strength training in the morning produces a 'priming effect' resulting in improved physical performance 6-hours later (Cook, Kilduff, Crewther, Beaven, & West, 2014). Although this phenomenon has not be studied in regards to training session adaptations or to the adaptation and signaling interaction, it may be that there is still much more to learn.

Further studies have also measured performance related outcomes, such as Collins & Snow, (1993) and Chtara et al., (2008) who report training sequence has no significant effect on maximal strength or aerobic power adaptations in untrained men. Conversely, well-trained kayakers did not show improvement in a maximal strength mesocycle when strength training was performed prior to endurance training or with at least 6-hours rest (Garcia-Pallares et al., 2009). However, as discussed later, it is important to consider all training variables such as volume and intensity when comparing magnitude of change after training interventions.

This supports the requirement for a strong consideration of the training variables, not just the overall sequence when programming concurrent training, especially when endurance training is to be performed prior to strength training. Therefore, the mixed conclusions in the literature of the optimum exercise sequencing may be due to variation in other variables, such as the training duration, intensity and modality (Kraemer et al., 1995; Rønnestad, Hansen and Raastad, 2012; Bell et al., 2000). Supporting this, Wilson et al., (2012), reported that endurance training modality and volume (frequency and duration) are key determining factors of the interference effect. Therefore, sequencing studies may only be compared if these variables have been matched in the studies protocols.

Training Recovery

Insufficient recovery between training sessions may limit the desired adaptations from previous training, cumulatively contributing to overtraining syndrome. Residual fatigue from aerobic training may reduce the quality of strength training sessions by alterations in the neural recruitment patterns of skeletal muscle (Chromiak & Mulvaney, 1990; Gergley, 2009), limitations to adequate force generation (Rhea et al., 2008; Rønnestad, et al., 2012) and increased neuromuscular fatigue (Leveritt & Abernethy, 1999; Davis et al., 2008). For example, Schumann et al., (2013) reported that endurance - strength training sequencing resulted in longer lasting fatigue levels post training session (creatine kinase, testosterone cortisol ratio and maximal force production) compared to the strength endurance sequencing group. Moreover, Robineau, Babault, Piscione, Lacome, & Bigard, (2016) concluded that strength and power adaptations were inhibited 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 superior to 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 the reduced interference with increasing recovery between sessions is due to the lower likelihood of there being an interference effect in the muscle signaling pathways (Lundberg et al., 2012) and a maximised recovery time allowing for increased protein synthesis and management of fatigue before the following training sessions (Chtourou et al., 2014).

Further, this interference may also be increased when the same muscle groups are utilised for 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 both a sub maximal aerobic training protocol (36min cycling at 70% maximal power at VO_2) and a high intensity interval training (3min work and 3min rest at 95-100% of maximal power at VO_2) with no difference between groups at any recovery time point. Moreover, strength and endurance training performed on different days resulted in a greater effect size (although not significantly different) than those performed on the same day (1.06 vs 0.8) (Wilson et al., 2012). Where this is not possible, athletes who engage in multiple strength training units per week, may benefit from utilising a split training routine where upper body strength training can be completed on days that contain aerobic training sessions (given these predominately tax the legs), as upper body hypertrophy has shown to have less interference during periods of concurrent training compared to lower body hypertrophy (Wilson et al., 2012).

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. In addition, it may also be recommended that long duration aerobic exercise should be avoided as the depletion of glycogen stores negatively effects subsequent training sessions (Bergström, Hermansen, Hultman, & Saltin, 1967). However, Sporer & Wenger, (2003) concluded that endurance training intensity had no significant acute effect on strength after 8 hours rest. Furthermore, De Souza et al., (2007) compared the acute effect

(10min rest) of two endurance training protocols (one close to the second ventilatory threshold and the other of a higher intensity at maximal aerobic speed) on maximal strength. Results demonstrated that neither endurance protocol had a detrimental effect on maximal strength. Silva et al., (2012), supports this by reporting no difference in strength improvements after continuous low intensity or intermittent high intensity aerobic training when performed prior to strength training over an 11 week period. Interestingly, it has also been reported that high intensity aerobic training may minimise the interference effect due to the recruitment of high threshold motor units and muscle fibers 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% maximal aerobic speed and passive recovery). Importantly, 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 X.

Training Frequency and 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 et al., 1995). Jones, et al., (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 et al., (2013) reported that recreationally trained men taking part in a high frequency strength and muscular endurance training (both 3 x per week) resulted in lower strength and hypertrophy adaptation compared to a programme performing strength only (3 x per week) or low frequency strength and muscular endurance training (3 x strength and 1 x endurance per week). The low frequency strength and endurance training also resulted in greater strength and hypertrophy improvements than the high frequency training group. In contrast, McCarthy et al., (1995) found similar improvements in maximal strength and power when combined strength and endurance training was performed 3 days per week compared to strength training only. These differences may be due to the competing peripheral demands of the isokinetic knee extension endurance training performed in the study by Jones et al., (2013) compared to the central demands of a 50-min cycle at 70% heart rate reserve reported by McCarthy et al., (1995). Subsequently, it may be important to think about the peripheral demands, potential muscle damage and biomechanical similarity of the endurance training intervention when minimizing the interference effect. Wilson et al., (2012) support's this reporting smaller reductions in lower body hypertrophy, strength and power when endurance exercise was performed on a cycle ergometer compared to running.

It should be noted that methodological differences make comparing and contrasting frequency research problematic due to variations in training duration and intensity, thus producing erroneous results due to differences in total training volume. Supporting this, through a meta-analysis of concurrent training studies, Wilson et al., (2012) concluded that there is a significant relationship between endurance training frequency, duration and lower body adaptations 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). However, no correlation between endurance training intensity and effect sizes was reported due to insufficient data. The prescription of strength training should also be monitored, as when concurrent training is necessary, the overall training load is likely much higher due to needing to meet this minimum-dose response of two different fitness qualities. Therefore strength-training regimes of moderate volume may be a sufficient and a safe alternative to high volume training to failure (Garcia-Pallares et al., 2009; Izquierdo-Gabarren et al., 2010).

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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 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 hypertrophic adaptations) 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 may therefore be best limiting any long periods of concurrent training.

During the planning of training, overall periodisation including microcycles and mesocycles need to 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 outcome as possible. It may also be optimum to reduce the frequency of endurance training (and strongly consider total accumulated fatigue) when hypertrophy adaptations are required. During training cycles where concurrent training is unavoidable it would be prudent 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 for other physical qualities, such as speed and agility to be prioritised.

It may be concluded that best practice is to have strength and endurance training units split by at least 24 hours of rest, where this is not possible, 6-8 hours would be sufficient. In scenarios where training density must be much higher, strength training should follow endurance training to ensure optimal strength improvements but the overall accumulated fatigue being carried from from one session to another should be the main variable of interest. This may also be managed via a reduced endurance training frequency of less than 3 x sessions per week. In addition, aerobic training using different muscle groups should be considered. For example, where 24 hours rest cannot utilised, upper body strength development may best be performed on aerobic training days. Aerobic training may also be completed via a mode that does not interfere with areas of desired strength development or reduces the level of eccentric stress, for example, an arm or cycle ergometer compared to running. Also appropriate fueling, i..e, glycogen, prior to strength tarining

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