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REVIEW ARTICLE

Training Considerations for Optimising Endurance Development: An Alternate Concurrent Training Perspective

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Abstract

Whilst the "acute hypothesis" was originally coined to describe the detrimental effects of concurrent training on strength development, similar physiological processes may occur when endurance training adaptations are compromised. There is a growing body of research indicating that typical resistance exercises impair neuromuscular function and endurance performance during periods of resistance training-induced muscle damage. Furthermore, recent evidence suggests that the attenuating effects of resistance training-induced muscle damage on endurance performance are influenced by exercise intensity, exercise mode, exercise sequence, recovery and contraction velocity of resistance training. By understanding the influence that training variables have on the level of resistance training-induced muscle damage and its subsequent attenuating effects on endurance performance, concurrent training programs could be prescribed in such a way that minimises fatigue between modes of training and optimises the quality of endurance training sessions. Therefore, this review will provide considerations for concurrent training prescription for endurance development based on scientific evidence. Furthermore, recommendations will be provided for future research by identifying training variables that may impact on endurance development as a result of concurrent training.

Key Points

The stress induced by a bout of resistance training may impair the quality of subsequent endurance training sessions for several days post-exercise.

Continually undertaking endurance training under resistance training-induced stress may impede chronic endurance development, also referred to as resistance training-induced suboptimisation on endurance performance (RT-SEP).

The RT-SEP phenomenon could be minimised by accounting for a recovery period between resistance and endurance training sessions, resistance training volume and intensity, endurance training intensity, mode of endurance exercise, exercise sequence and resistance training contraction velocity.

1 Introduction

Whilst the application of optimal physiological stress is essential to progressively adapt to increasing training loads, this process may be hindered by inadequate recovery, which may ultimately compromise training adaptation [1]. Thus, establishing a balance between physiological stress and recovery is critical, particularly when combining resistance and endurance training in the one training program, known as concurrent training. From an acute post-exercise standpoint, neuromuscular fatigue induced by a typical resistance training session may last for several days irrespective of training background [2–5], as opposed to recovery of neuromuscular properties within 60–90 min following a typical endurance training session [6, 7]. In addition, several studies have reported that determinants of endurance performance (e.g. movement economy, time to exhaustion and time-trial performance) are impaired 24–72 h following a single lower body resistance training bout for both resistance-untrained and resistance-trained individuals [8–14]. In a recent review [15], we referred to the concept of resistance training-induced sub-optimisation on endurance performance (RT-SEP). The underlying theory of this phenomenon suggested that residual neural and metabolic effects of previous resistance training sessions may compromise the ability to perform optimally

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during subsequent endurance training sessions and possibly limit training stimuli to maximise endurance adaptation. Several physiological processes were highlighted to explain potential causes of the compromise in the quality of endurance training sessions during a typical concurrent training program (Fig. 1). These included: (1) impaired neural recruitment patterns; (2) attenuated movement efficiency due to perturbation in kinematics of endurance exercises and increased energy expenditure; (3) delayed onset of muscle soreness; and (4) reduced muscle glycogen stores [15].

We further suggested that the level of acute interference in the quality of endurance training could depend on the intensity, volume, training order, frequency of training and recovery periods between resistance and endurance training sessions [15]. However, as our previous review [15] focused on describing the potential mechanisms of RT-SEP, the practical implications of RT-SEP were not thoroughly considered. Thus, the purpose of this review was to explore studies that have examined the acute effects of resistance training on endurance performance that have utilised various training methods. Findings from such studies will assist in determining the impact that training variables have on RT-SEP and in developing recommendations for coaches to minimise residual carry-over effects of fatigue from resistance to endurance training sessions during a typical concurrent training program.

2 Time Between Resistance and Endurance Training Sessions

Designing exercise programs comprising of both resistance and endurance training may appear to be a challenging task given that variation in recovery between the modes of exercise would influence recovery dynamics and impact on the severity of interference in chronic training adaptation [16]. The following section discusses the influence that between-session recovery periods may have on endurance development during concurrent training, and the implications of impaired quality of endurance training sessions as a result of inadequate recovery from resistance training.

2.1 Chronic and Acute Changes in Endurance Performance with Different Recovery Periods

Studies on the chronic effects of concurrent training thus far have incorporated various recovery periods between resistance and endurance training sessions. For example, concurrent training studies with durations of 10–15 min [17–19] to 5–6 h [20] between resistance and endurance training sessions have all shown sub-optimal endurance development. However, few studies have systematically compared the magnitude of interference in training adaptation when manipulating recovery periods between

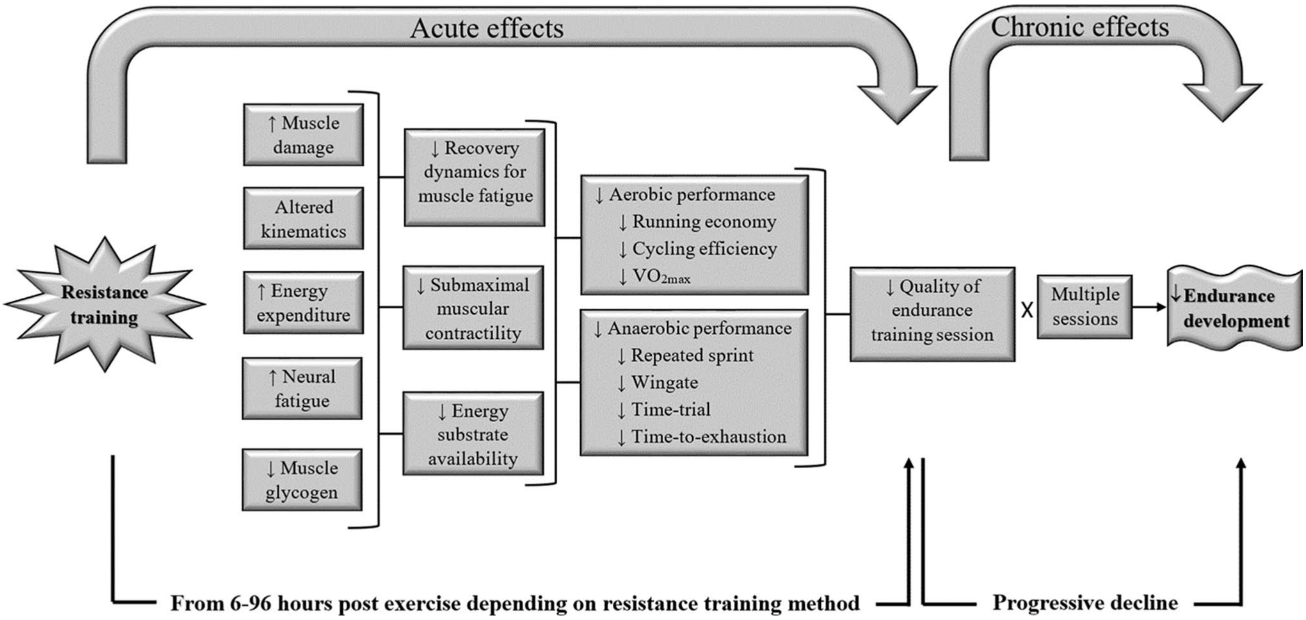

Fig. 1 Schematic representation of the detrimental effects of resistance training-induced muscular fatigue on the quality of endurance training sessions during concurrent training and its implications on chronic endurance development over weeks and months. VO_{2max} maximal oxygen consumption

individual resistance and endurance training sessions within the one study. Sale et al. [21] was one of the first research groups to experiment with this system by comparing resistance and endurance development for same-day versus alternate-day concurrent training methods. The results showed that cycling maximal oxygen consumption (VO_{2max}) was similar between the two groups, suggesting that variation in recovery periods between each mode of training did not affect endurance development.

A more recent study by Robineau and colleagues [22] compared groups that undertook resistance training followed by endurance training in the same session (R–E0 h), on the same day with 6 h0 of recovery (R–E6 h) and on alternate days with 24 h of recovery (R–E24 h). The results showed that the magnitude of increase in peak oxygen consumption (VO_{2peak}) was greater for R–E24 h than for both R–E0 h and R–E6 h, suggesting an interference effect on endurance development for groups that undertook resistance and endurance training on the same day.

The discrepancies in findings between Sale et al. [21] and Robineau et al. [22] may be attributed to a number of factors. Firstly, Sale and colleagues [21] altered the sequence of the mode of training for each training session whereas Robineau et al. [22] always had participants perform resistance before endurance training. Interestingly, Chtara et al. [23] reported that endurance development is sub-optimal following 12 weeks of concurrent training with the R–E sequence compared to the E–R sequence, and attributed these findings to accumulation of residual fatigue from resistance to endurance training sessions. We also confirmed this phenomenon from an acute standpoint [10], where the R–E sequence performed on the same day induced greater neuromuscular fatigue the following day, and therefore impaired running performance to a greater extent than the E–R sequence. Had Sale et al. [21] consistently incorporated resistance prior to endurance training, or if endurance training had been consistently prescribed during periods of resistance training-induced fatigue, concurrent training may have induced sub-optimal endurance adaptations, although further research is necessary to confirm this.

The second point explaining the disparity in findings between Sale et al. [21] and Robineau et al. [22] may be the intensity of endurance training sessions. Sale et al. [21] incorporated moderate-to-high intensity endurance training sessions (i.e. at or below the power output measures obtained at cycling VO_{2max}) whereas Robineau et al. [22] prescribed endurance training sessions at supra-maximal running intensities (i.e. 120% of maximal aerobic velocity). Indeed, resistance training has been reported to impair sub-maximal cycling and running performance several hours post-exercise (i.e. on the same day) [9, 10, 24, 25] without having the same effect the following day (i.e. alternate days) [8, 26] in previously resistance-trained participants. However, attenuation in running performance has been reported when measured at maximal effort 24 h post resistance training in resistance-trained individuals [8, 27]. Accordingly, the period of recovery required between resistance and endurance training sessions appears to be strongly dependent on a variety of variables. Therefore, the following sections discuss the impact that training training variables have on RT-SEP, with practical recommendations to optimise the quality of endurance training sessions.

3 Resistance and Endurance Training Intensities

3.1 Acute Effect of Resistance Training Intensity on Endurance Performance

Resistance and endurance training intensity and volume are continually manipulated during the course of a concurrent training program to optimise training adaptation [28]. During the course of a resistance training program, exercises prescribed at heavier loads and lower volumes typically result in augmented muscular strength whilst higher volumes and moderate loads are associated with muscular hypertrophy [29]. This phenomenon occurs as distinct physiological and neuromuscular stresses are induced when resistance training intensity and volume are altered [30]. Thus, it can be speculated that the magnitude and duration of fatigue induced by a bout of resistance exercises may be influenced by both training intensity and volume. In fact, several recent studies have shown that resistance training intensity and volume alter acute physiological and neuromuscular responses for several days post-exercise. For example, Abboud et al. [31] compared acute responses between greater volume (i.e. 20,000 kg) and lower volume (i.e. 10,000 kg) of resistance exercise bouts after adjusting for training loads in resistance-trained men. The results showed the higher volume resistance training bout induced greater creatine kinase (CK) and delayed-onset of muscle soreness (DOMS) levels than the lower volume resistance training bout for up to 48 h post-exercise with moderate effect size (ES = 0.61–0.79). It is important to note that Abboud et al. [31] still reported increased CK and DOMS levels for up to 24 h following the lower volume resistance exercise bout (i.e. 10,000 kg) with moderate effects (ES = 0.59–1.03). Interestingly, Morán-Navarro et al. [32] reported significantly greater CK levels 24 h following a resistance training bout performed to failure in each set (three sets of ten repetitions), compared to sets performed not to failure with equal load-volume (six sets of five repetitions). Using equivalent training volume, Weakley et al. [33] also reported that two separate resistance exercises performed in the one set (i.e. superset, e.g.

combining bench press and squat in the one set) resulted in higher CK levels than traditional sets where each set consisted of one type of resistance exercise for up to 24 h post-exercise. These findings collectively suggest that a bout of greater resistance training load-volume, a bout of resistance training with sets performed to failure or a bout of resistance training with multiple exercises performed in one set induce greater physiological strain for at least 24 h post-exercise. Thus, from a concurrent training standpoint, results from these acute studies may have implications for the amount of recovery required following a bout of resistance training prior to undertaking an endurance training session when manipulating resistance training load-volume. However, the practicality of these findings could be further improved by examining the acute effects of resistance training load-volume on endurance performance measures, rather than solely on indirect muscle damage markers.

In contrast to resistance training load-volume, studies have also examined the acute responses of varying resistance training intensities. For example, Hasenoehrl et al. [34] compared the acute responses of eccentric biceps curl exercises using heavy load (i.e. 1RM concentric contraction) and light load (i.e. 50% of 1RM concentric contraction) applications performed to failure. The results showed that the heavy-load condition increased CK, DOMS and upper arm circumference to a greater extent than the light-load condition for 96 h post-exercise. Interestingly, these findings were despite greater total work performed by the light load condition than the heavy load condition, demonstrating that resistance training load was the primary variable that induced changes in acute responses, rather than resistance training load-volume. In addition, the participants were introduced to a ‘wash out’ period, whereby they were exposed to the resistance exercise bout prior to trial commencement. These findings indicate that heavy-load resistance training bouts may induce greater stress than light-load conditions for those previously exposed to resistance training. Confirming these findings, Draganidis and colleagues [35] also showed that a heavy-load resistance exercise bout (85–90% of 1RM) induced greater CK and DOMS values whilst also impairing strength measures compared to a light-load resistance exercise bout (65–70%) for 48 h post-exercise in resistance trained athletes. Similar to the results from Hasenoehrl et al. [34], total volume of work was greater for the light-load resistance training bout compared to the heavy-load resistance training bout. Whilst the findings of both Hasenoehrl et al. [34] and Draganidis et al. [35] demonstrate that heavier resistance training bouts cause greater acute physiological stress for several days post-exercise than lighter load resistance training bouts, the outcome measures were limited to indirect muscle damage markers only and training volume was not adjusted for.

A number of studies have in fact examined the acute effects of altering resistance training loads whilst adjusting for volume of work on endurance performance measures [12, 24, 36]. For example, Deakin [24] investigated the effects of different intensities of resistance training on cycling performance in resistance-trained men. The participants in the study either performed a session consisting of heavy-load (6RM, or ~ 80% of 1RM) or light-load (20 repetitions with work equated to the heavy load session) resistance training exercises (i.e. leg press, bench press and lat-pull down) and a cycling efficiency test conducted 3 h after each resistance training session. The results showed a greater physiological cost during the cycling efficiency test following the heavy-load session compared to the lighter-load session. Similarly, we [12] reported attenuation in running time to exhaustion measures 6 h following a heavy resistance training session (i.e. 6RM, or ~ 80% of 1RM), although such results were not found following a resistance training session (i.e. leg press, leg extension and leg curls) with lighter loads (i.e. 20 repetitions with work equated to the heavy-load session) in resistance-trained men. Furthermore, Freitas and colleagues [36] reported impaired performance measures in repeated sprint ability and agility immediately following a heavy load of circuit training, although no differences were observed in these measures following a lighter load of circuit training when work was equated in resistance-trained men. Collectively, resistance training sessions undertaken with heavier loads (i.e. ≥ 80% of 1RM) may increase susceptibility to RT-SEP more than that with lighter loads with equated work volumes.

3.2 Acute Effect of Resistance Training on the Intensity of Endurance Performance

In the previous section, we presented results from our previous studies [12, 24], demonstrating how resistance training intensity may acutely impact on endurance performance. However, RT-SEP could also be augmented if an endurance training bout acutely following a resistance training bout is performed at higher intensities. For example, we [12] reported significant reductions in both running time to exhaustion at maximal effort [i.e. above anaerobic threshold (AT)] and knee extensor torque 6 h following a bout of moderate- to high-intensity resistance training (i.e. 6RM), although running economy (RE) measures (i.e. 70% and 90% of AT) were unaffected in resistance-trained men. In addition, we [8] showed a reduction in running time-to-exaustion (i.e. above AT) and knee extensor torque with a concomitant increase in DOMS 24 h following a resistance training session despite no differences observed in RE measures (i.e. 90% of AT) in men and women with previous resistance training exposure. Similar findings were also observed by us [37] in resistance-untrained men, in whom a bout of resistance exercises caused no changes in RE measures (i.e. 90% of AT), although running time to exhaustion (i.e. above AT) was reduced for up to 48 h post-exercise. These findings also confirm the work of others in untrained individuals with greater attenuation of running performance measures at higher running intensities in conjunction with impaired measures of muscular contractility (e.g. knee extensor isometric torque, vertical jump) and increased DOMS during periods of exercise-induced muscle damage (EIMD) [10, 11, 38, 39]. It has been speculated that the acute effects of resistance training may have greater deleterious effects on endurance performance measures at higher intensities since fast twitch muscle fibres have greater susceptibility to muscle damage and glycogen depletion [40] and are also predominantly recruited when exercising above the AT [41].

4 Different Modes of Endurance Training

4.1 Interference in Endurance Adaptation by Different Modes of Endurance Exercises

In addition to intensity and volume, the degree of endurance adaptation is highly dependent on the mode of endurance exercise. Indeed, physiological responses have been reported to vary at comparable intensities between different modes of endurance exercise (e.g. running, cycling, skiing and rowing) [42–45]. For example, Thomas and colleagues [45] reported greater oxygen cost during running and stationary skiing compared to stationary cycling and rowing during a 20 min exercise bout at equivalent rating of perceived exertion (RPE). The authors postulated that running and skiing induced greater physiological strain due to these modes of exercises being weight-bearing as opposed to the non-weight-bearing modes of exercise, such as cycling and rowing. Hill and colleagues [46] also reported greater anaerobic capacity, as measured by accumulated oxygen deficit, during running compared to cycling, suggesting that running may depend on a larger anaerobic component for performance than cycling. More recently, Casuso et al. [47] showed greater metabolic stress markers (i.e. interleukin-6 and cortisol) 2 h following sprint interval running compared to sprint interval swimming in athletes regularly involved in both endurance modes of exercise. According to Casuso et al. [47], running may have induced greater physiological stress due to higher eccentric loading involved with this mode of exercise compared to swimming.

In light of the above, there appears to be a trend whereby modes of endurance exercise with greater loading of the body mass and/or higher eccentric loading cause greater physiological stress (e.g. cycling and swimming with less loading vs. running with greater loading). Thus, the extent to which resistance training-induced fatigue impairs the quality of multiple, successive endurance training sessions during concurrent training may be dependent on the mode of endurance exercise. Gergley et al. [48] pioneered this approach, comparing training adaptations in a group that combined resistance training with cycling with those in a group that combined resistance training with inclined walking in healthy untrained individuals. The results showed greater strength gains with cycling than when inclined walking was combined with resistance training. The authors [48] postulated that walking may have generated a greater level of physiological stress due to the eccentric contractions that are not typically present during cycling, thereby compromising the quality of resistance training sessions. This is further supported by the evidence that eccentric contractions induce greater muscle damage and fatigue than concentric contractions [49]. Using a similar approach, Silva and colleagues [50] compared strength development in individuals who combined resistance training and running with that in individuals who participanted in cycling only. Interestingly, no differences in strength measures were found between groups. The authors speculated that the differences in their findings compared with those of Gergley et al. [48] may have been due to differences in training volume, given that resistance and endurance training sessions were undertaken twice a week in the study by Silva et al. [50], whereas Gergley et al. [48] incorporated each mode of training three times per week. Overall, research on the adaptation of concurrent training with various modes of aerobic exercise is limited and appears equivocal possibly due to different training protocols.

Whilst Gergley et al. [48] only compared cycling and walking, given that running produces greater mechanical stress and consequently higher eccentric loading than walking [51], the interference in training adaptation could be assumed to be more pronounced if running was incorporated instead of walking. In support of this hypothesis, Dolezal et al. [52] and Glowacki et al. [53] used running for the endurance training sessions, and, to date, these have been the only studies that have shown sub-optimal development in both strength and endurance adaptations. Furthermore, concurrent training studies that have reported sub-optimal endurance development have primarily incorporated running (e.g. running VO_{2max} [19, 52–55], RE [56, 57], 1–4 km running trial [23, 58, 59] and running time to exhaustion [59]) with fewer studies of cycling (e.g. cycling VO_{2max} [60] and 1 km cycling sprint [61]) and rowing (e.g. 2000 m rowing performance [18]). Subsequently, greater recovery may be required following resistance training if undertaking endurance training sessions that comprise eccentric contractions with greater loading of the body mass (e.g. running) than endurance training sessions that are primarily performed with concentric contractions with less loading (e.g. cycling, rowing and swimming). This phenomenon is particularly important for athletes involved in multiple aerobic events (e.g. triathletes), rather than single-mode endurance athletes who are highly familiarised and trained in a particular mode of aerobic exercise (e.g. cyclists, runners or swimmers). More research is needed to systematically compare different modes of endurance development (e.g. running, cycling, rowing, swimming) when combined with resistance training in a variety of endurance athletes, which will assist coaches to select exercises that minimise the interference effect on endurance development.

4.2 Acute Effects of Resistance Training on Different Modes of Endurance Performance

In addition to long-term endurance development, the influence that the mode of endurance exercises has on RT-SEP could be determined by systematically examining the acute effects of resistance training on the performance of different endurance modes (e.g. the physiological cost of running, cycling and rowing when equated for relative intensity and duration). To date, the majority of studies that have examined the acute effects of a bout of typical resistance training on endurance performance have been based on determinants of running performance. For example, a bout of resistance training consisting of lower body exercises (e.g. squats, leg press, leg extension and leg curls) has been reported to impair RE 8, 24 and 48 h post-exercise [25, 62, 63] and running time to exhaustion 6 and 24 h post-exercise [8, 10, 12, 13]. Some studies have reported attenuation in cycling efficiency 3 h following lower body resistance exercises [24], reduced cycling power output 48 h following lower body resistance exercises [64], lower power output during 2000 m rowing time-trial test 24 h following upper and lower body resistance exercises [14], and reduced time to exhaustion during arm crank ergometry test 48 h following upper body resistance exercise [65]. All of these studies have also shown increases in CK levels, DOMS and/or impaired muscle force generation capacity measures, suggesting that indirect markers of muscle damage and/or fatigue induced by typical resistance training may in part have contributed to attenuation of various modes of endurance performance.

Whilst research on the acute effects of a typical bout of resistance training has primarily been focused on running, several studies have shown that EIMD caused by other exercise protocols impairs various modes of endurance performance measures. For example, eccentric-emphasised exercises via isokinetic contractions have been reported to elevate the oxygen cost of cycling for up to 48 h post-exercise in untrained males [66] and cycling time to exhaustion for up to 48 h post-exercise in untrained females [67], with elevated levels of CK and DOMS and impaired neuromuscular performance measures. Plyometric-based exercises have also been reported to augment the oxygen cost of cycling for up to 48 h post-exercise in untrained men [62, 68, 69], also with increased levels of CK and DOMS. Given that symptoms of EIMD are observed following typical resistance exercises for up to 48 h post-exercise in both resistance-trained [70, 71] and -untrained [13, 62, 63] individuals, it is reasonable to assume that typical resistance exercises may impair various modes of endurance exercise for several days post-exercise. Taken together, these findings suggest that appropriate recovery should be prioritised following resistance training bouts to optimise the quality of the subsequent endurance training session, irrespective of the mode of endurance exercise. However, resistance training-induced stress may further compromise the quality of an endurance training session consisting of exercises that involve greater body mass loading and eccentric contractions (e.g. running) during periods of EIMD for athletes involved in multiple aerobic events (e.g. triathletes or those undertaking cross training).

5 Effect of Squence of Mode of Training on Endurance Performance

5.1 Chronic Effects of Training Sequence

The extent of adaptation induced by concurrent training is highly dependent on the interaction between resistance and endurance training sessions [72, 73]. Thus, the sequence of resistance and endurance training session may be critical for optimising endurance development given that the acute physiological responses are distinct between each mode of exercise [15]. The classical work that investigated endurance adaptations following different sequences of the mode of training was conducted by Collins and Snow [74]. The participants in this study were allocated to groups that performed resistance prior to endurance training (R–E) and groups that performed endurance prior to resistance training (E–R) on separate days. Seven weeks following the commencement of concurrent training, the participants' VO_{2max} significantly increased for both groups (R–E and E–R); however, there were no significant differences between the groups. Accordingly, Collins and Snow [74] concluded that training sequence had minimal impact on endurance adaptation.

More recently, Eddens and colleagues [75] reported no differences on measures of VO_{2max} between R–E and E–R sequences based on a meta-analysis of seven studies, which confirmed the findings of Collins and Snow [74]. However, whilst maximal aerobic capacity is typically used to report on chronic endurance adaptation, this variable is not an appropriate measure of endurance performance per se [76]. Testing protocols that measure the physiological cost of running, time to reach exhaustion at a given workload, or self-paced time-trial performance are endurance-performance measures that better replicate task constraints during a race [77, 78]. Interestingly, Psilander et al. [60] reported no additional benefits when incorporating resistance training following endurance training (i.e. E–R sequence), with greater adaptations for endurance performance based on cycling time to exhaustion for the group that undertook endurance training only. Whilst these findings suggest that the addition of resistance training to an endurance training program may induce sub-optimal endurance development when compared to endurance training alone, the authors neglected to include a group that undertook concurrent training using the reverse sequence (i.e. R–E sequence). Chtara et al. [23] examined the effect of a 12 week concurrent training program on 4 km running time-trial performance between R–E and E–R groups by combining both resistance and endurance exercises within the same session (i.e. intra-session) in trained men. The results showed significantly greater improvement in 4 km running time trial performance for the E–R group compared to the R–E group. Chtara and colleagues [23] speculated that the R–E sequence may induce sub-optimal endurance performance when compared to the E–R sequence, as carry-over effects of fatigue from each resistance training session may interfere with the quality of a subsequent endurance training session if appropriate recovery is not allowed. As mentioned previously (Sect. 1), this concept is consistent with RT-SEP, whereby compromise in the quality of successive endurance training sessions due to resistance training-induced fatigue during the course of concurrent training may limit optimal endurance development [15]. To confirm the potential mechanisms contributing to the effects of resistance and endurance training sequence on endurance development, an effective approach is to examine the acute effects of resistance and endurance training sequence on indices of endurance performance.

5.2 Acute Effects of Training Sequence

There is a growing body of evidence suggesting that resistance and endurance training sequence acutely affects determinants of endurance performance. For example, we [11] examined the acute effects of resistance and endurance training sequence on running performance and muscle force generation capacity (MFGC). The participants in this study either performed resistance prior to running (R–E) or running prior to resistance training (E–R) on the same day separated by 6 h in random order with running performance and MFGC examined the following day. The results showed that RE was impaired with a concomitant reduction in MFGC following the R–E sequence although the E–R sequence had no effect on these measures. Whilst RE was impaired as a result of the R–E sequence, running time to exhaustion was significantly reduced the day following both training sequences, suggesting that residual fatigue from resistance and endurance training sessions performed on the same day will impair running performance at maximum effort the following day irrespective of training sequence. Deakin [24] also investigated the acute effects of resistance and endurance training sequence on sub-maximal cycling performance. In this study, the participants undertook either resistance training prior to cycling (R–E) or cycling prior to resistance training (E–R). Results of the cycling efficiency test revealed greater metabolic cost following the R–E compared to the E–R sequence, suggesting that strength and endurance performance was impaired to a greater extent with the R–E compared to the E–R sequence.

The significant increase in the metabolic cost of running and cycling during the R–E sequence [10, 24] suggests that resistance training may be the primary mode of exercise contributing to the accumulation effect of fatigue responsible for impaired endurance performance. In practice, the increase in metabolic cost of aerobic exercise tends to suggest that athletes may have difficulty covering particular distances, maintaining optimal pacing or sustaining power output (e.g. interval training) to meet session goals, suggesting sub-optimal adaptation to race-specific training [79]. Subsequently, training intensity and/or volume may have to be reduced during periods of resistance training-induced fatigue to complete an endurance training session. The chronic effects of undertaking endurance training sessions consistently under fatigue are presently unknown and thus warrant further research to bridge the gap in our knowledge of acute and chronic effects of resistance training on endurance development.

6 Strength Training Contraction Velocity

The contraction velocity during a resistance training session is an important training variable to consider [29]. This is because alterations in contraction velocity have been associated with chronic changes in neural [80], hypertrophic [81] and metabolic [82] responses following several weeks of resistance training. The slow contraction velocities can be defined by two models during the performance of resistance exercises: (1) unintentional and (2) intentional slow contractions [29]. The unintentional slow contractions are executed due to an inability to perform fast contractions performed against heavy resistance (load). This notion follows the force/velocity curve characteristics (i.e. load and velocity are inversely related), thereby preventing muscles from contracting at high speeds during heavy-load resistance exercises, which necessitates greater muscular force production. Conversely, slow contraction velocities can be intentional by deliberately slowing the execution of a movement against an external load. The unintentional slow contractions occur as a consequence of heavy resistance loading and are typically used to increase muscular strength. Contrarily, intentional slow contractions are used to increase time-under-tension, particularly to induce adequate physiological stress for training adaptation with lighter loads [83, 84].

6.1 Effect of Contraction Velocities on Chronic Strength Development

Kraemer et al. [29] suggested that sub-maximal loads are used during the performance of resistance exercises with slow contractions in order to obtain greater control of body movement velocity. Indeed, a study has shown that concentric force production was significantly less during a bench press exercise performed with intentionally slow contractions when compared to contractions performed more explosively [85]. However, Keeler et al. [86] reported significantly less strength gains after 10 weeks of training following training with super-slow contractions (10 s concentric:5 s eccentric) compared to slow contractions (2 s concentric:4 s eccentric). The authors suggested that this may have been due to lower training stimuli, given that a 30% reduction in training load was required during the super slow compared with the slow training method. Thus, whilst resistance training sessions with slow concentric and eccentric contractions may limit residual effects of fatigue on subsequent endurance training sessions during concurrent training, optimum strength gains may not occur due to insufficient resistance training stimuli.

6.2 Acute Effects of Fast Concentric and Slow Eccentric Contractions on Neuromuscular and Endurance Performance Measures

Performing resistance exercises with fast concentric (e.g. 1 s) and slow eccentric contractions (e.g. 4 s) compared to slow concentric and eccentric contractions may provide greater training stimuli for strength development whilst limiting its attenuating effect on the quality of subsequent endurance training sessions. The morphological properties of the muscle have greater susceptibility to neuromuscular fatigue and muscle damage during eccentric compared to concentric contractions [87, 88]. It has been suggested that the lengthening of muscle contractile properties causes damage to sarcomeres and components of excitation–contraction coupling [89, 90]. In light of this hypothesis, Chapman et al. [91, 92] showed that DOMS and CK levels were significantly greater whilst maximal voluntary contraction (MVC) was significantly lower following fast compared to slow eccentric contractions for up to 7 days after. Accordingly, slow eccentric contractions appear to limit factors that impair muscle function to a greater extent than fast eccentric contractions. However, exercises evaluated by Chapman et al. [91, 92] did not consist of concentric contractions and were performed using isokinetic devices, which are not typical methods of traditional resistance training.

Dolezal et al. [93] were one of the first groups of researchers to examine the acute effects of fast concentric (i.e. 1 s) and slow eccentric (i.e. 4 s) contractions on indirect muscle damage markers in resistance-trained and -untrained individuals, using traditional resistance exercises (i.e. leg press). The results showed that CK and DOMS levels were significantly elevated for up to 48 h post-exercise for both groups, although these values were greater for the untrained individuals. Similarly, Hackney et al. [94] reported elevated levels of CK and DOMS in both resistance-trained and -untrained individuals for up to 48 h following both upper and lower body resistance exercises performed with fast concentric (i.e. 1 s) and slow eccentric (i.e. 3 s) contraction using exercise machines. Thus, these findings suggest that physiological stress is induced following traditional resistance exercises with fast concentric and slower eccentric contractions, possibly due to the increased time under tension during the eccentric phase. However, the measures reported by both Dolezal et al. [93] and Hackney et al. [94] were limited to indirect muscle damage markers.

Adapting the method used by previous studies [93, 94], we [12] examined the impact of traditional resistance training at 6RM with fast concentric (i.e. 1 s) and slow eccentric (i.e. 4 s) contractions on RE, running time to exhaustion and knee extensor torque in trained and moderately trained runners. Interestingly, the findings showed that the resistance training bout did not affect RE and knee extensor torque 6 h post-exercise although running time to exhaustion was impaired. We [10] conducted a further study to examine the acute effects of a resistance training bout at 6RM on RE, running time to exhaustion and knee extensor torque performed with 1 s concentric and 1 s eccentric contractions. The authors reported significant increases in the physiological cost of submaximal running 6 h after with a concomitant reduction in running time to exhaustion and knee extensor torque. According to the discrepancies in findings between these two studies [10, 12], traditional resistance exercises performed with faster eccentric contractions may induce greater neuromuscular fatigue and consequently impair submaximal and maximal running performance several hours post-exercise. Conversely, several hours of recovery following traditional resistance exercises performed with slow eccentric contractions does not seem to perturb sub-maximal running performance post-exercise, although maximal effort running performance is impaired.

7 Accumulation Effect of Resistance and Endurance Training

Whilst research examining the impact of concurrent training has found that the level and type of adaptation may vary depending on the mode of exercise and training variables employed [18, 19, 53, 95], the acute responses during a typical concurrent training program have not been extensively explored. Given that training adaptation is ultimately dependent on the accumulation of responses generated over successive training sessions [96], the mechanisms associated with the type and extent of training adaptation cannot be determined simply by monitoring training responses prior to, mid and following a concurrent training program. One approach to gaining a better understanding of physiological processes that impact upon adaptations to concurrent training would be to systematically examine the acute responses across a number of individual resistance and endurance training sessions using various performance and physiological outcome measures.

In one study, Drummond et al. [97] compared excess post-exercise oxygen consumption (EPOC) following a combined session consisting of resistance (70% of 1RM of upper and lower body exercises) and endurance (running for 25 min at 70% of VO_{2max}) exercises to resistance and endurance exercises performed in isolation. The results showed that EPOC was greater following the combination of resistance and endurance exercises. Drummond and colleagues [97] suggested that the combination of resistance and endurance exercises may have generated a greater physiological burden due to a large volume of work compared to either modes of exercise performed in isolation. However, EPOC is measured at rest and hence is a basal metabolic indicator. Examining acute responses of combining resistance and endurance training sessions on performance (e.g. endurance and/or strength performance measures) would better replicate conditions experienced during concurrent training and allow exercise prescription that minimises cumulative effects of fatigue across different modes of training sessions.

We used this approach [8] to examine the cumulative effect of alternate-day resistance training combined with consecutive-day endurance training on RE, running time to exhaustion, MFGC and muscle soreness over 6 days (i.e. a typical microcycling of concurrent training). Specifically, moderately endurance-trained individuals with prior exposure to resistance training were randomly separated into a concurrent training group, a resistance training group and an endurance training group. The concurrent training group undertook high-intensity lower body resistance training (i.e. 6RM) on alternate days in conjunction with moderate- to high-intensity running (i.e. below and above AT) on consecutive days for 6 days. On days when resistance and running sessions were combined for the concurrent training group, a 9 h recovery period was incorporated between each mode of training session to replicate a typical concurrent training schedule (i.e. resistance training in the morning and endurance training in the afternoon, or vice versa). The resistance training group undertook three resistance training sessions on alternate days without running sessions whilst the endurance training group undertook running sessions across three consecutive days.

For the concurrent training group, no differences were found in RE although running time to exhaustion and MFGC were significantly reduced with a concomitant increase in muscle soreness over the 6-day period. No differences in MFGC and muscle soreness were found for the resistance training group and endurance training group. These findings exemplify the cumulative fatiguing effects of successive training sessions that could be observed during a microcycle of a concurrent training program if resistance exercises for the same muscle groups were performed on alternate days (i.e. 48 h of recovery between each resistance training session) and running sessions on consecutive days (i.e. 24 h of recovery between each running session).

8 Conclusion

According to the findings from the studies investigating outcomes of chronic and acute concurrent training thus far, the level of interference in endurance performance, and possibly on subsequent chronic endurance adaptation, appears to be dependent on the mode of exercise, training intensity, sequence of the mode of training, contraction velocity and recovery periods employed between each mode of training session. Flowcharts providing practical applications to improve concurrent training prescription and optimise endurance development have been provided when undertaking resistance and endurance training on the same day (Fig. 2), endurance training the day after a bout of resistance training (Fig. 3), and endurance training the day after resistance and endurance training sessions performed on the same day (Fig. 4). In summary, the general practical applications include the following:

- The level of fatigue should be monitored between resistance and endurance training using physical performance measures (e.g. heart rate and RPE at predetermined training intensities, changes in completion times of endurance exercises, sprint times etc.) particularly when combining resistance training sessions at moderate-to-high intensity (i.e. 1–6RM or $\geq 80\%$ of 1RM) with high-intensity endurance training (i.e. above AT) in the same training week.
- If performance decrements are observed during a moderate- to high-intensity endurance training session (i.e. at or above AT) caused by residual fatigue from a bout of resistance exercises, modifications should be made by reducing the intensity and/or volume of endurance exercises.
- Greater recovery periods may be required following resistance training when undertaking subsequent

running sessions compared to other modes of endurance training that are primarily concentric-based (e.g. cycling, rowing, swimming), particularly for endurance athletes in triathlons or duathlons (e.g. running vs. cycling and swimming).

- When undertaking moderate intensity endurance training (i.e. below AT) after resistance exercises with fast concentric and eccentric contractions, at least 1 day of recovery is required, although greater recovery periods may be required if undertaking high intensity endurance training (i.e. above AT).
- More than 1 day (> 24 h) may be necessary when undertaking an endurance training session after a resistance training session with a greater volume load (> 10,000 kg), resistance exercises undertaken as super-sets or to failure in each set.
- Several hours of recovery are required when undertaking moderate-intensity endurance training (i.e. below AT) after resistance exercises with slow eccentric contractions and fast concentric contractions, and at least 1 day of recovery is required with high intensity endurance training (i.e. above AT).
- If the combination of resistance and endurance training sessions on the same day is unavoidable, endurance training sessions should be prescribed prior to resistance training irrespective of the type of resistance and

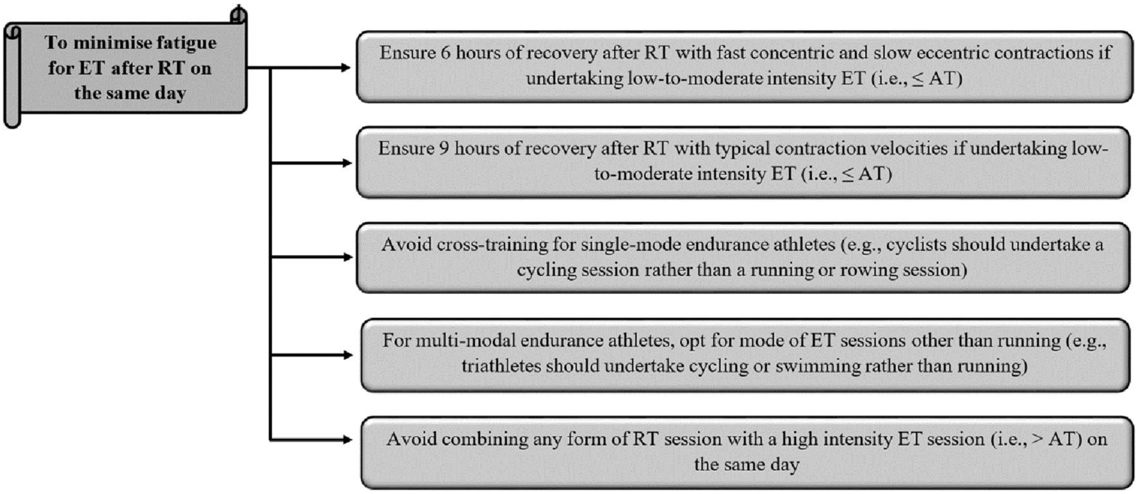

Fig. 2 Flow chart with recommendations to minimise fatigue and optimise quality of endurance training sessions, either above or below anaerobic threshold (AT), when undertaking endurance training (ET) sessions on the same day as resistance training (RT)

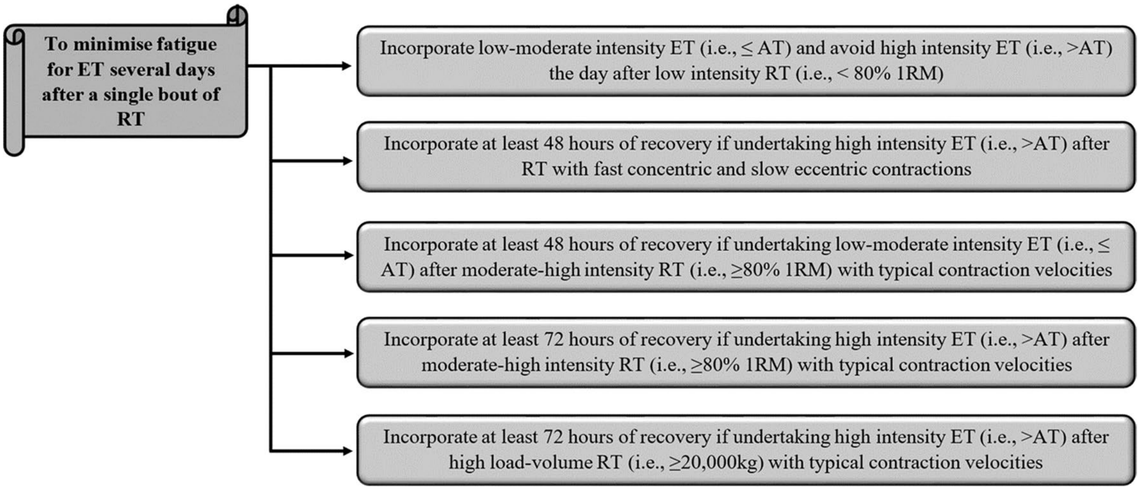

Fig. 3 Flow chart with recommendations to minimise fatigue and optimise quality of endurance training sessions, either above or below anaerobic threshold (AT), when undertaking endurance training (ET) sessions several days after a single bout of resistance training (RT). *RM* repetition maximum

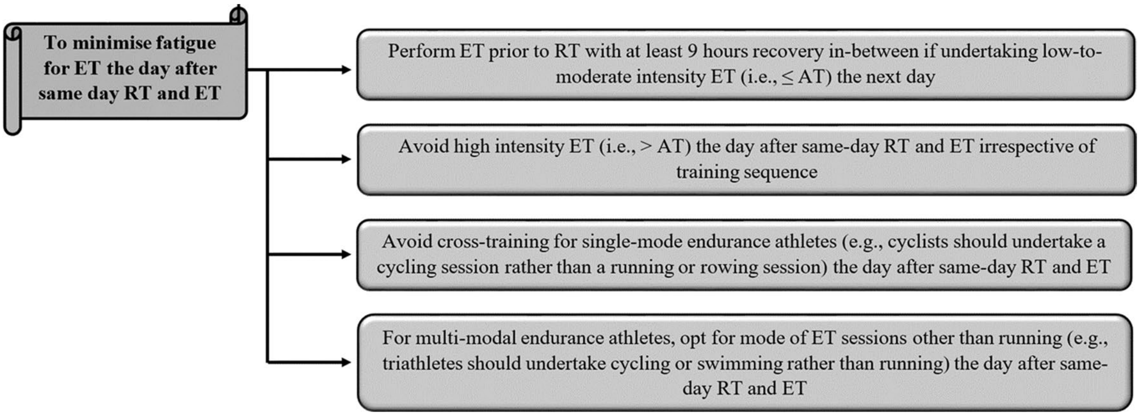

Fig. 4 Flow chart with recommendations to minimise fatigue and optimise quality of endurance training sessions, either above or below anaerobic threshold (AT), when undertaking endurance training (ET) and resistance training (RT) sessions several days after a single bout of resistance training (RT)

endurance training variables with at least half a day of recovery in-between training sessions.

- When undertaking moderate- to high-intensity resistance training sessions (i.e. 1–6RM or ≥ 80% of 1RM) on alternate days and moderate to high-intensity endurance training sessions (i.e. ≥ AT) on consecutive days, sequencing the mode of training by performing endurance training sessions half a day prior to resistance training sessions will limit cumulative effects of fatigue during a typical micro-cycle of concurrent training.
- Muscle strength and endurance development attained in a preceding prepatory concurrent training period has been shown to be preserved for 12 weeks with as little as one resistance training session per week in endurance athletes [98]. Thus, concurrent training should primarily be periodised to minimise resistance training-induced stress using the recommendatons mentioned above, so that endurance training load could be maximised whilst previously developed gains in muscle strength are maintained. However, resistance training adaptation is also an essential component for endurance development. Therefore, certain aspects of concurrent training cycles may also require increased resistance training load, or frequency, for further muscle strength development at the expense of more extensive endurance training.

Although these recommendations are aimed at minimising RT-SEP to optimise the benefit of resistance training for endurance athletes, it is important to note that there are some limitations inherent in the practicality of current evidence, and more research is necessary to further improve the recommendations provided in this paper. Firstly, the majority of studies that have examined the acute effects of a bout of resistance training have focused on determinants of running performance (e.g. RE, running time-trial or running time to exhaustion). Secondly, whilst there is evidence to suggest that manipulation of resistance training-load volume alters acute physiological responses for several days post-exercise, these measures have been limited to indirect muscle damage markers (i.e. CK, DOMS and vertical jump performance). However, it is important to note that indirect muscle damage markers are strong determinants of impaired endurance performance, and coaches should therefore be cautious about incorporating high-intensity endurance training sessions during periods of EIMD. Third, the majority of studies that have reported on the acute effects of resistance exercises on endurance performance have only incorporated one resistance training bout, despite growing evidence indicating an accumulation effect of fatigue induced by multiple bouts of resistance and endurance training. Thus, further research examining the effects of multiple bouts of resistance training, whilst manipulating resistance training-load volume, on various modes of endurance performance measures is warranted.

Compliance with Ethical Standards

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Conflict of Interest Kenji Doma, Glen Deakin, Mortiz Schumann and David Bentley declare that they have no conflicts of interest relevant to the content of this review.

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