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REVIEW ARTICLE

Functional Overreaching in Endurance Athletes: A Necessity or Cause for Concern?

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Abstract

There are variable responses to short-term periods of increased training load in endurance athletes, whereby some athletes improve without deleterious effects on performance, while others show diminished exercise performance for a period of days to months. The time course of the decrement in performance and subsequent restoration, or super compensation, has been used to distinguish between the different stages of the fitness–fatigue adaptive continuum termed functional overreaching (FOR), non-functional overreaching (NFOR) or overtraining syndrome. The short-term transient training-induced decrements in performance elicited by increases in training load (i.e. FOR) are thought be a *sufficient* and *necessary* component of a training program and are often deliberately induced in training to promote meaningful physiological adaptations and performance super-compensation. Despite the supposition that deliberately inducing FOR in athletes may be *necessary* to achieve performance super-compensation, FOR has been associated with various negative cardiovascular, hormonal and metabolic consequences. Furthermore, recent studies have demonstrated dampened training and performance adaptations in FOR athletes compared to non-overreached athletes who completed the same training program or the same relative increase in training load. However, this is not always the case and a number of studies have also demonstrated substantial performance super-compensation in athletes who were classified as being FOR. It is possible that there are a number of contextual factors that may influence the metabolic consequences associated with FOR and classifying this training-induced state of fatigue based purely on a decrement in performance may be an oversimplification. Here, the most recent research on FOR in endurance athletes will be critically evaluated to determine (1) if there is sufficient evidence to indicate that inducing a state of FOR is *necessary* and *required* to induce a performance super-compensation; (2) the metabolic consequences that are associated with FOR; (3) strategies that may prevent the negative consequences of overreaching.

1 Introduction

Short-term periods of increased training intensity [1, 2], training volume [3–5], or a combination of both [6, 7] have been shown to improve performance in trained endurance athletes. However, these increases in training load may result in variable responses [3–5, 7–21], whereby some athletes improve without deleterious effects on performance, while others show diminished exercise performance. Indeed, the transient exercise-induced decrements in performance elicited by increases in training load are thought to be *necessary* to promote meaningful physiological adaptations and performance super-compensation following a taper period [14, 22–24]. The time course of the decrement in performance and subsequent restoration that is induced by increases in training load has been used to distinguish between the different stages of the fitness–fatigue adaptive continuum termed functional overreaching (FOR), non-functional overreaching (NFOR) or overtraining syndrome [14, 25]. FOR is thought to result from an accumulation of training and/or non-training stress leading to a short-term decrement in performance capacity, in which restoration [12, 26], and sometimes super-compensation [4, 6], may occur following an appropriate period of recovery (~ 1 to 3 week) [25, 27]. As such, FOR may be considered to be a *sufficient* and *necessary* component of a training program and is often deliberately induced in training to improve performance [14, 23]. This justification may be based on

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Key Points

While functional overreaching is considered a *necessary* and *normal* response to periods of overload training in trained endurance athletes, there is growing evidence to suggest that at least in some cases, functional overreaching is associated with negative metabolic consequences and maladaptation to training.

In the studies that do report a performance super-compensation effect following functional overreaching, the magnitude of performance enhancement is not greater when compared to non-overreached athletes who completed the same relative increase in training load without experiencing a performance decrement.

As a result of the large inter-individual variability in response to overload training, it is recommended that future research focuses more on the individual responses to overload training and the concomitant alterations in training stress responses, and the factors that contribute to these individual responses.

theoretical models [24] and field-based results [4, 28] of overload training and tapering suggesting that a period of overload training before the taper elicits greater performance gains in endurance athletes compared to normal training. Despite the supposition that deliberately inducing FOR in athletes may be *necessary* to achieve performance super-compensation [14, 22–24], recent research suggests that FOR has been associated with various negative cardiovascular [5, 29], hormonal [5, 30] and metabolic consequences [8, 9, 13] which may be associated with maladaptation to training. Indeed, in three recent studies, endurance athletes who were classified as being FOR had smaller performance improvements and dampened training adaptations compared to non-overreached athletes who completed the same relative increase in training load [3, 12, 17]. Furthermore, Hausswirth et al. [11] demonstrated that FOR athletes experienced disturbed sleep and had a higher incidence of illness compared with athletes who completed the same training but were only acutely fatigued (maintenance of performance but increased subjective fatigue). FOR also directly precedes the more severe and undesirable state of NFOR that can lead to a decrement in performance that may last for several weeks or months [14]. There is no doubt that trained endurance athletes are required to undergo a certain amount of training overload for physiological adaptations to manifest upon recovery [31]. However, whether inducing FOR is indeed *necessary* to induce the various physiological adaptations in response to training in trained endurance athletes is still a point of contention. While several excellent reviews and meta-analyses have been compiled that have assessed the responses to overload training [23, 32–34], none of these reviews have attempted to delineate specific responses in FOR athletes compared to non-overreached athletes who completed the same training program or the same relative increase in training load. The purpose of this review is to critically evaluate the most recent research on overreaching to determine if there is sufficient evidence to indicate that inducing a state of FOR is *necessary* and *required* to induce performance improvements in trained endurance athletes. Furthermore, this review will also highlight the metabolic consequences that are associated with FOR and identify strategies that may prevent the negative consequences of overreaching.

To do this, this review will focus on studies that have included an overload training period and compared the physiological and psychological responses between athletes who have a decrement in performance (i.e. FOR) and those that show no decrease in performance.

2 Classification of Overreaching

The term overreaching was first described as a period of short-term overtraining which sometimes results in a mild form of staleness [35]. The term was later defined as an accumulation of training and/or non-training stress resulting in a short-term decrement in performance capacity with or without related physiological and psychological signs and symptoms of overtraining in which restoration of performance capacity may take several days to several weeks [27]. In 2006, the European College of Sport Science position statement was published on the prevention, diagnosis and treatment of the overtraining syndrome which described two distinct stages of overreaching as FOR and NFOR [25]. FOR was described as the temporary decrement in performance that results from a short period of overload training that may lead to a super-compensation effect following a recovery period lasting days to week [25]. NFOR was described as a state of extreme overreaching that can result from the continuation of extended periods of overload training which leads to a stagnation or decrease in performance which will not resume for several weeks or months [25]. This overreaching classification system is based on the duration of time required for performance restoration, or super-compensation, and not the type or duration of training stress or degree of impairment in exercise performance. While NFOR is thought to exhibit the first signs and symptoms of prolonged maladaptation such as psychological disturbance (decreased vigour, increased fatigue) and hormonal disturbances, these symptoms may also be present in athletes that are classified as FOR [14]. As such, changes in performance and recovery time remain the only methods to segregate the two stages of overreaching. However, it is clear that these definitions do not clearly partition the recovery time course of FOR from NFOR given that the time required for performance restoration may take "weeks" in either state. In order to improve the distinction between the two states of overreaching given the crossover in the recovery time course, it has been suggested that a state of NFOR is classified when a performance super-compensation does not arise following an overload and subsequent taper period [14]. Furthermore, a complication that applies to the NFOR recovery time course is detraining. Detraining may reduce maximal exercise performance due to the loss of training adaptations that may occur after a short period (i.e. < 4 weeks) of rest or light training [36], which would make it difficult to differentiate between the persistence of NFOR and detraining.

The most common model employed in research studies attempting to identify the responses and subsequent recovery from overreaching is the employment of an overload training period that typically lasts up to 4 weeks [3–5, 7–21]. Exercise performance in a sport-specific task (i.e. time trial) or incremental exercise test and physiological and psychological variables are compared from before and after an overload training period, and also after a recovery period in most cases, within the same athlete or, between athletes who have a decrement in performance (i.e. overreached) and those that show no decrease in performance. In reference to the latter, athletes who complete the overload training period and maintain or increase their exercise performance despite having high perceived fatigue have been termed acutely fatigued (AF) in some studies [3, 5, 10–12, 16, 17, 37]. A number of well-designed studies [4, 5, 10–13] have also included a control group who continue their normal training as well as undertake a taper period alongside the experimental group who are exposed to the overload training period (Fig. 1). As such, these studies seek to compare the physiological and performance responses between a control group who would likely demonstrate no sign of FOR during a period of normal training (i.e. control group) with an experimental group either demonstrating no sign of FOR (i.e. no decrease in exercise performance) but high perceived fatigue (i.e. AF), or presenting with a decrease in exercise performance (i.e. FOR). While this overload training model may or may not reflect a typical training regimen of an endurance athlete, it does permit control of confounding variables that may be associated with monitoring athletes throughout different training phases and comparing athletes showing symptoms of overreaching and those without.

An additional consideration for the classification of overreaching is what constitutes a decrement in performance. Given that all tests of exercise performance have a magnitude of error associated with their measurement, the identification of the within-subject variation in the performance measure is a crucial aspect of overload training studies attempting to classify overreached subjects. Studies that have included a control group [4, 5, 10–13] typically obtain the performance repeatability from this group by conducting exercise performance assessments before and after a normal training period and taper. On the basis of this analysis, a decrement in maximal exercise performance greater than the test–retest magnitude is used as the criterion to discriminate the overreached subjects in the overload training group. An alternative design that is also effective includes exercise performance assessments before and after a control period that all subjects complete prior to the overload training intervention [3]. The coefficient of variation and smallest worthwhile change is computed from the variation in performance from before to after the control period and is used as an overreaching threshold. While there are some difficulties associated with using changes in performance and recovery time as the only methods to partition the two stages of overreaching, the various physiological and psychological disturbances resulting from overload training do not systematically discern between FOR and NFOR. As such, until a new categorisation method can be validated, the time course of the decrement in performance and subsequent restoration or super-compensation period is the only available method to distinguish between the different stages of overreaching. Furthermore, the difficulties associated with identifying an overreaching performance decrement threshold can be mitigated using established methods [38] to identify the smallest meaningful change in exercise performance to detect an overreaching threshold.

3 Consequences of Overreaching

There is no doubt that trained endurance athletes are required to undergo a certain amount of training overload to induce physiological adaptations and improve exercise performance [31]. Mathematical modelling simulations also suggest that increases in training load above habitual training levels (and inducing a state of FOR) prior to a taper elicits a greater performance super-compensation compared with a taper following the continuation of habitual training load [24]. As such, there is a supposition that inducing a state of FOR may be *necessary* to promote meaningful physiological adaptations and achieve a performance super-compensation [14, 22–24]. Interestingly, the simulations from Thomas et al. [24] did not provide a theoretical framework for an athlete who completes an overload training period without experiencing a decrement in performance (compared to baseline) prior to the taper. Experimental evidence from Aubry et al. [12] was the first to address this concept and showed that

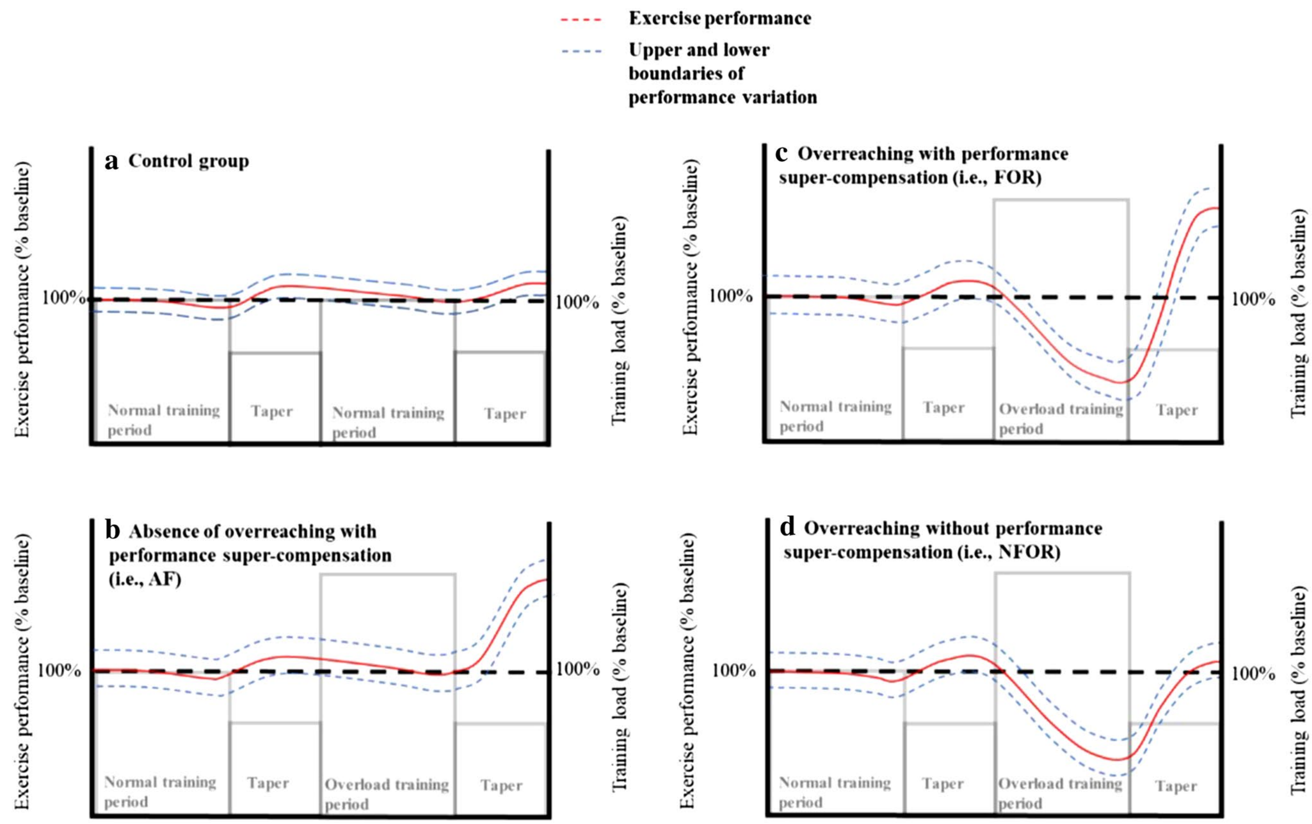

Fig. 1 Schematic representation of independent groups featured in study designs that aim to identify the responses and subsequent recovery from an overload training period. The most common model employed is an overload training period that typically lasts 3–4 weeks which is followed and preceded by a taper and a control period [3–5, 7–21]. A number of studies [4, 5, 10–13] have included a control group (**a**) who continue their normal training as well as undertake a taper period alongside the experimental group who are exposed to the overload training period. Exercise performance (blue trace; with the upper and lower limits representing the variation in performance) and physiological and psychological variables are compared during and/or from before and after an overload training period, and also after a recovery period in most cases, within the same athlete or, between athletes who have a decrement in performance (i.e. overreached; **c** and **d**) and those that show no decrease in performance (**b**). In reference to the latter (**b**), athletes who complete the overload training period and maintain or increase their exercise performance despite having high perceived fatigue have been termed acutely fatigued (AF) in some studies [3, 5, 10–12, 16, 17, 37]. Some studies [3, 12, 17] have shown that when compared to AF athletes, short-term overreaching can lead to suboptimal training and/or performance adaptations (**d**), but this is not always the case (**c**). By consensus statement definition [14], **d** is defined as non-functional overreaching (NFOR). *AF* acute fatigue, *FOR* functional overreaching, *NFOR* non-functional overreaching

greater gains in performance and VO_{2peak} can be achieved when an overload training period is prescribed before the taper, but only in athletes who did not present with FOR (Table 1). Furthermore, given that FOR is associated with various negative cardiovascular [5, 29, 39, 40], hormonal [5, 30], immunological [41–43] and metabolic consequences [8, 9, 13], as well as impaired exercise performance [3–5, 7–21], its necessity could be questioned. Indeed, the impairment in exercise performance, disturbed sleep [11, 14, 44, 45], increased muscle soreness [41] and higher incidence of illness [11, 43] in FOR endurance athletes could all contribute to impaired training intensity and lead to suboptimal training adaptations [3, 12, 17].

3.1 Cardiac Output

Recent evidence [5, 40] suggests that overload training resulting in FOR in endurance athletes is associated with reductions in stroke volume, heart rate and cardiac output during submaximal and maximal exercise, independent of alterations in blood volume [5]. It was postulated that these impaired cardiac responses resulted from reduced epinephrine excretion [5] and/or increased resting arterial stiffness [40]. A recent study by Bourdillon et al. [17] reported that an overload training period blunted the increase in baroreceptor sensitivity and parasympathetic activity in FOR athletes, while there were favourable increases in those athletes who completed the same relative increase in training load but

Table 1 Summary of characteristics of all studies that have assessed the response to an overload training period in endurance athletes and partitioned subjects as either functionally overreached (FOR, i.e. decrement in maximal exercise performance) or as acutely fatigued (AF, i.e. no decrement in maximal exercise performance)

Study	Participants	Overload period	Incidence of FOR	Taper period	Overload period outcomes (FOR vs AF)	Taper period outcomes (FOR vs AF)
Aubry et al. [12]	33 male triathletes. 10 CON and 23 OL	3 weeks (+ 30% volume increase)	11/23	4 weeks (− 40% stepwise reduction)	Greater increase in subjective fatigue, greater reduction in energy index and higher incidence of URTI in FOR compared to AF	Greater increases in incremental cycling peak power output and VO_{2max} in AF group compared to FOR group. No differences in restoration of perceived fatigue between groups
Le Meur et al. [5]	35 male triathletes. 11 CON and 24 OL	3 weeks (+ 30% volume increase)	12/24	2 weeks (− 50% stepwise reduction)	Greater increase in subjective fatigue and reductions in VO_{2max}, cardiac output, stroke volume, $(A\text{-}V)O_2$ diff and peak Bla in FOR compared to AF	Improvements in incremental cycling peak power output for AF but only restoration for FOR. Restoration in subjective fatigue, VO_{2max}, cardiac output, stroke volume, $(A\text{-}V)O_2$ diff and peak BLa for FOR
Hausswirth et al. [11]	27 male triathletes. 9 CON and 18 OL	3 weeks (+ 30% volume increase)	9/18	2 weeks (− 50% stepwise reduction)	Higher incidence of URTI, greater increase in subjective fatigue, reductions in VO_{2max} and had a decrease in the indices of sleep quality and quantity in FOR compared to AF	Improvements in incremental cycling peak power output for AF but only restoration for FOR. Restoration in subjective fatigue and sleep quality and quantity
Aubry et al. [10]	31 male triathletes. 10 CON and 21 OL	3 weeks (+ 30% volume increase)	10/22	2 weeks (− 40% stepwise reduction)	Greater increase subjective fatigue, reductions in peak HR, HRR, peak BLa and peak norepinephrine in FOR compared to AF	Improvements in incremental cycling peak power output for AF but only restoration for FOR. Restoration in other variables occurred in FOR but there was still a small decrease in peak HR
Bourdillon et al. [16, 17]	15 recreational athletes (7 female, 8 male)	3 weeks (+ 45% volume increase)	8/15	2 weeks (− 20% stepwise reduction)	Increase in BRS in AF, while there was no change in FOR. No group effect for any HRV parameter. Alterations in PPG variables that differed between FOR and AF	Improvement in 3-km running time trial performance was greater in AF compared to FOR. BRS was greater in AF compared to FOR. Not all PPG alterations restored in both groups

Table 1 (continued)

Study	Participants	Overload period	Incidence of FOR	Taper period	Overload period outcomes (FOR vs AF)	Taper period outcomes (FOR vs AF)
Bellinger et al. [3]	24 middle-distance runners (8 female, 16 male)	3 weeks (+ 10–30% volume increase)	12/24	1 week (− 55% exponential reduction)	Moderately higher subjective fatigue ratings after the first and second week in FOR compared to AF. The change in oxidative capacity was significantly greater in AF compared with FOR	Compared to FOR, AF had substantially larger improvements in TTE, whereas the improvements in VO_{2peak} were similar between groups

It should be noted that the studies from Aubry et al. [12] and Aubry et al. [10] are derived from the same project as well as Le Meur et al. [5] and Hausswirth et al. [11]

CO control, *OL* overload, *URTI* upper respiratory tract infection, *FOR* functionally overreached, *AF* acute fatigue (i.e., no decrement in maximal exercise performance), VO_{2max} maximal oxygen uptake, $(A\text{-}V)O_2$ *diff* arteriovenous oxygen difference, *BLa* blood lactate concentration, *HRR* heart rate recovery, *HRV* heart rate variability, *PPG* photoplethysmography, *BRS* baroreflex sensitivity, *TTE* time to exhaustion

achieved a performance enhancement. These findings are further supported by Coates et al. [39] who also demonstrated an absence of baroreceptor sensitivity increase following an overload training period in endurance athletes who became FOR following an overload training period compared to a control group who continued normal training. These studies [5, 17, 39, 40] suggest that a possible determinant of performance impairment experienced by athletes who are FOR may be related to cardiac impairments during both submaximal and maximal exercise.

3.2 Heart Rate Responses

Outcomes from a meta-analysis [46] demonstrated that both submaximal and peak heart rate is typically decreased in athletes that were classified as FOR. In agreement, Le Meur et al. [13] reported that variations in both submaximal and maximal heart rate (and blood lactate concentration) were the two most discriminating factors which identified 89.5% of the triathletes as overreached or not. Heart rate recovery has also been shown to discriminate between athletes being classified as FOR and those that did not have a performance decrement, whereby Aubry et al. [10] observed that the decrease in heart rate during the first minute after cessation of exhaustive exercise was faster in FOR athletes. Importantly, this change was reversed after a 2-week taper and a faster heart rate recovery has also been shown to occur following submaximal exercise in FOR athletes [47] increasing the practicality of this assessment on a more regular basis. However, it should also be noted that this is not always a universal finding whereby Bellenger et al. [19] suggested that heart rate recovery was only sensitive to changes in training status when assessed after maximal exercise. These authors [19] also suggested that the maximal rate of heart rate increase to submaximal cycling exercise provided the most sensitive measure for tracking performance changes compared with heart rate variability and heart rate recovery in response to an overload training period. However, despite substantial decreases in performance on a group level, the authors did not indicate how many of the twelve participants could be considered FOR, thus limiting the conclusions that can be drawn from a comparative group of athletes that did not develop FOR [19]. Furthermore, it remains to be determined whether alterations in the heart rate response to exercise and subsequent heart rate recovery during submaximal and/or maximal exercise precede or occur concomitantly with the reductions in maximal exercise performance.

3.3 Heart Rate Variability

Heart rate variability is a non-invasive measure of cardiovascular autonomic regulation [48] that has been employed in a number of studies to detect alterations in response to overload training that has induced FOR in endurance athletes [4, 49–51]. Hedelin et al. [49] exposed 9 elite canoeists to a 50% increase in training load, but found no group changes in high or low frequency heart rate variability at rest or following a tilt to a 70° upright position despite all athletes being classified as FOR. Similarly, Dupey et al. [50] found no alterations in heart rate variability in endurance athletes who all became FOR after a 100% increase in training load over a 2-week period. However, the authors of these studies [49, 50] only employed a single pre- and post-overload training period heart rate variability assessment and more recent research [52] has suggested that a minimum of three randomly selected valid measurements are required each week due to the high day-to-day variability of heart rate variability measurements. Le Meur et al. [4] subjected 13 triathletes to a 3-week overload training period and 1-week taper and compared morning resting heart rate variability responses to a control group who continued their normal training. All triathletes in the overload group were classified as FOR and the analysis of weekly average values of heart rate variability in this group indicated that there was a progressive increase in parasympathetic modulation of heart rate during the overload period, which was reversed during the subsequent taper. In contrast, there was no clear effect of FOR when considering the heart rate variability values obtained once per week. In support of these findings, Coates et al. [51] found that same-day resting heart rate variability measures were insufficient for predicting the subsequent alterations in exercise performance in FOR athletes following an overload training period. Similar to Le Meur et al. [4], two recent studies [18, 19] have reported that overload training induced an increase in vagal-related heart rate modulation indicating an increased parasympathetic modulation both prior to and during exercise. Interestingly, Bellenger et al. [18] also reported a further increase in vagally mediated heart rate variability following the taper period which coincided with a performance super-compensation indicating that additional measures of training stress and knowledge of the training phase should be considered when interpreting changes in heart rate variability measures.

3.4 Photoplethysmography

Another cardiac parameter that has recently been shown [16] to have promise in demonstrating the early detection of overreaching is the use of photoplethysmography, which can detect volumetric changes in blood in the microvascular bed of subcutaneous tissue. Bourdillon et al. [16] subjected 15 recreational runners to a 3-week overload period (+ 45% training load) and 2-week recovery (− 20%) and an overnight photoplethysmography measurement every third night on their non-dominant hand. When normalised to baseline, the diastolic time decreased, while the systolic slope was greater in the eight subjects who were classified as FOR compared to those that were not overreached. Although further experimental evidence is required, it could be suggested that the changes in the photoplethysmography variables may have preceded changes in exercise performance given that these changes occurred in the first week of the overload period. However, not all photoplethysmography variables returned to baseline values following 2 weeks of recovery, and the error of measurement can be dependent on the photosensitivity of the skin [53]. Future research should examine whether changes in photoplethysmography variables are systematically shown to be related to changes in exercise performance and the onset of FOR.

3.5 Resting Metabolic Rate

Two recent studies [8, 9] have reported a reduction in resting metabolic rate (RMR) in response to an increase in training load in well-trained endurance athletes. Woods et al. [9] reported a decrease in absolute (− 466 ± 488 kJ/day^{-1}) and relative RMR [− 8.0 ± 8.1 kJ kg fat free mass (FFM)$^{-1}$] in national-level rowers following a 4-week increase in training load which was also accompanied by reductions in body mass (− 1.6 ± 1.3 kg, $p = 0.003$) and fat mass (− 2.2 ± 1.2 kg, $p = 0.0001$). Furthermore, in trained male cyclists [8], relative RMR was reduced (~ 122 to 107 kJ kg FFM^{-1}), concomitant with reductions in body mass, fat mass and FFM in response to a 2-week increase in training load. The mechanism responsible for the reduction in RMR in these studies [8, 9] remains somewhat elusive. It is likely that the increased energetic demands of training, coupled with insufficient energy intake, are contributing factors to these findings. For example, despite the 21% increase in training load, the rowers failed to increase their total energy intake or individual macronutrients which lead to reductions in body mass (− 1.6 ± 1.3 kg, $p = 0.003$) and fat mass (− 2.2 ± 1.2 kg) [9], while the trained cyclists had a reduction in body mass, fat mass and FFM [8]. Given that there was no performance super-compensation effect after 2 weeks of recovery in the trained cyclists, it is likely that a reduction in RMR is an undesirable consequence associated with overreaching in this study [8]. Furthermore, both training intensity and volume were manipulated in both studies [8, 9] and the interplay between alterations in training intensity and/or volume on the subsequent metabolic consequences requires further examination.

3.6 Immunology and Illness

A recent study [11] has shown that endurance athletes presenting with symptoms of FOR during a period of overload training have an increased illness likelihood. The increased illness likelihood is in accordance with several previous studies reporting compromised innate and/or adaptive immunity during sustained periods of heavy training [42, 54–57]. However, few studies have compared alterations in markers of immune function in FOR athletes to those without a performance decrement in response to an overload period. With this point in consideration, Greenham et al. [32] performed a systematic review and meta-analysis aiming to identify biomarkers associated with the alteration in exercise performance following an overload training period. Of the 118 biomarkers that were evaluated, most were cellular communication and immunity markers ($n=54$). Importantly, the authors associated the directional change in biomarkers with the change in exercise performance which could provide insight into the association with FOR. The findings from this review [32] suggest that the markers of immunity that decrease when performance decreases, but remain unaltered when performance is maintained are $CD20^+$ and neutrophil cell count. Original research studies that have induced FOR in endurance athletes have reported modest immunological changes in response to overload training [42, 58]. Halson et al. [58] subjected endurance-trained cyclists to a 2-week, twofold increase in training volume and found no evidence for alterations in cytokines and other immune system parameters, despite a reduction in maximal exercise performance. Furthermore, Svendsen et al. [42] reported that an 8-day period of overload training in highly trained cyclists induced modest changes in immunological cell counts and exercise performance (− 13 to + 4%), but these subjects were not individually classified as FOR or otherwise. As such, the current weight of evidence suggests that overload training may result in modest changes in immunological cell counts, but there is no evidence to suggest that these changes are further influenced by the presence of overreaching.

3.7 Hormonal Changes

There are few studies that have identified training-state-specific (i.e. FOR) alterations in hormone levels following an overload training period. Indeed, hormonal alterations found in athletes with FOR, NFOR and/or overtraining syndrome athletes may result from overload training, regardless of the resultant performance state. For example, Hoogeveen et al. [59] showed that hormonal changes were similar between athletes with overtraining syndrome and healthy athletes, while Uusitalo et al. [60] reported marked individual differences during both normal training and overload training-induced changes in adrenaline, noradrenaline and cortisol. In cyclists and triathletes who were classified as being FOR, the concentrations of testosterone, cortisol, luteinizing hormone, follicle-stimulating hormone, adrenocorticotropic hormone, growth hormone, and insulin were comparable with those measured in a non-overreached state in the same athletes [61]. These studies [59–61] suggest that alterations in hormone levels may not always differentiate between training states, but rather represent the general responses to overload training. Furthermore, it should also be noted that changes in particular hormone levels are not necessarily detrimental (i.e. decreased testosterone:cortisol ratio) as Hoogeveen et al. [59] showed that decreased total testosterone and increased cortisol did not relate to the changes in incremental cycling performance in professional cyclists.

It is clear that increases in training load should be matched with increased energy intake to compensate for the increased energy expenditure [62]. Two studies have reported alterations in hormones relating to energy homeostasis and appetite regulation during periods of overload training [8, 63]. These studies have shown leptin to increase [8] or decrease [63], while ghrelin was not affected [63] by the overload training period, but both studies did not differentiate between athletes who developed FOR and those that did not have a performance decrement. Furthermore, a recent meta-analysis [32] identified that glutamine and the testosterone:cortisol ratio exhibited some consistent evidence of changes in response to overload training, while other research [64] suggests that changes in thyroid hormones may be related to changes in performance in endurance runners [64]. However, while changes in these biomarkers occur in response to periods of overload training, these changes have not been shown to differentiate between overreached and non-overreached athletes. A recent study by Poff et al. [63] suggested that growth differentiation factor 15 may be an adequate hormonal marker to assess the development of overreaching. In this study [63], 18 recreationally active males completed an overload training period with half of the subjects consuming a ketone ester drink, while the other half consuming an isocaloric placebo. The group which consumed the ketone ester drink displayed less severe symptoms of overreaching and experienced a blunted increase in growth differentiation factor 15. However, this study [63] did not individually classify the subjects as being overreached (either functional or non-functional) based on their change in cycling performance and resultant recovery timeline so further research is required to substantiate these conclusions.

3.8 Sleep

Sleep is considered to be one of the primary forms of recovery due to its physiological and psychological restorative effects [65]. However, sleep quality and quantity are impaired during periods of overload training [11, 14, 44, 45, 66]; poor sleep is a common complaint among overreached athletes [67] and normative data on endurance athletes suggest that their sleep quality is inferior to non-athlete control subjects [68]. Furthermore, it is unknown whether impaired sleep contributes to the onset of overreaching, or whether it is a direct consequence of the overload training period [44]. Killer et al. [45] showed that a 9-day overload training period (2.5-fold increase in training volume and intensity) had no effect on actual sleep time, despite reducing the percentage sleep time (87.9 ± 1.5 to 82.5 ± 2.3%; $p < 0.05$) due to the increase in time in bed. In comparison, Hausswirth et al. [11] showed that an overload training period (3-week, 30% increase in training volume) reduced actual sleep time, sleep efficiency and immobile time in FOR triathletes compared to non-overreached triathletes who were exposed to the same overload training period. As such, disruptions in sleep may manifest from FOR, rather than simply be a product of an overload training period. Importantly, impaired sleep during a period of overload training has been associated with an increase in upper respiratory tract infections [11] which is supported by several previous studies demonstrating impairments in both innate and adaptive immunity during sustained periods of overload training [54]. Of course, these findings are not evidence of causality—that is, that sleep disturbances directly result in impaired immune function during periods of overload training. The mechanism that may underpin the disturbance in sleep in FOR athletes has been postulated to be associated with the muscle fatigue and/or soreness resulting from the increase in training loads [11]. It is conceivable that the reduction in sleep efficiency reported in these studies [11, 45, 66] resulted from the difficulty in remaining immobile during sleep, or from the associated disturbances in mood [11, 45, 66]. Future research is required to identify the mechanistic underpinning of the disturbances in sleep of FOR athletes.

The method of quantifying sleep quality and quantity is also important to contextualise conclusions that are drawn from studies [66]. Lastella et al. [66] subjected twenty-one male cyclists to a simulated cycling grand tour (715.7–832.3 km week^{-1} for 3 weeks) and monitored sleep through subjective sleep diaries and wrist activity monitors. Interestingly, there were conflicting results between objective and subjective sleep assessments, whereby the quality of sleep as assessed via wrist activity monitors (i.e. sleep efficiency and mean activity score) declined during the simulated grand tour, while the cyclists concomitantly reported improved sleep quality throughout the same training phase. Previous research has also reported a disagreement between subjective and objective measures of sleep quality and quantity [69].

3.9 Mood and Perceptual Responses

Subjective measures of training stress have also been used to detect changes in mood resulting from periods of overload training in athletes. Questionnaires that are typically employed are the Daily Analysis of Life Demands for Athletes (DALDA) questionnaire [70], the Profile of Mood States (POMS) questionnaire [71], or the Recovery-stress questionnaire for athletes [72]. While studies have shown that these questionnaire responses are consistently altered during periods of overload training [6, 18, 19, 26, 50, 73, 74], a number of studies have also demonstrated that subjective questionnaire responses may be exacerbated in athletes who become FOR compared to those that do not follow an overload training period [5, 10–12]. For example, Aubry et al. [10] showed that all endurance athletes who completed an overload training period had an increase in subjective fatigue, but the increase from the preceding normal training period was likely larger in the FOR subjects (4 ± 4 vs 13 ± 5) compared to the subjects that did not have a performance decrement (4 ± 3 vs 9 ± 5). More recently, Twen Haaf [37] demonstrated that the combination of changes in subjective fatigue and readiness to train after only 3 days of a cycling tour correctly predicted 78% of the subjects as either FOR or not using simple visual analogue scales. However, this study [37] monitored recreational cyclists over an extreme training period consisting of an 8-day, 1300-km cycling event which may not translate to how endurance athletes may respond to more realistic alterations in training load. Furthermore, despite not being significantly different, there was still a large reduction in incremental exercise test peak power output in the FOR group approximately 1 month following the cycling event which may indicate that some subjects were NFOR or had a detraining effect which may have influenced the conclusions drawn from this study [37]. As such, while there is some evidence [5, 10–12] that subjective questionnaires can differentiate between athletes who are FOR and those that are not following an overload training period, more research is required to see if these responses manifest prior to a decrement in exercise performance.

3.10 Performance and Training Adaptations

Recent work [3] has shown that a period of overload training blunted the increase in muscle oxidative capacity in runners that were classified as FOR, while there were favourable increases in those runners that completed the same relative increase in training volume, but did not experience a performance decrement. Importantly, runners who did not develop FOR had substantially larger improvements in running capacity following a taper period. While there are limited studies that have assessed mitochondrial adaptations in athletes that develop FOR, a recent training study in rats [75] reported impaired training-induced alterations in citrate synthase activity and mitochondrial complex IV activity in overreached rats. One other study in humans (trained triathletes) has also reported greater performance improvements (peak incremental cycling test power output) and physiological adaptations (VO_{2peak}) following an overload period in athletes who did not develop FOR [12]. Aubry et al. [12]

prescribed a 3-week, 30% increase in training volume to triathletes and reported that lower taper induced improvements in VO_{2peak} and cycling capacity were associated with FOR subjects. These studies provide empirical evidence to suggest that FOR, in some cases [3, 12, 17], is associated with impaired training adaptations and attenuated performance super-compensation following an overload training period. However, it must also be noted that a number of other studies [6, 26, 28] have also demonstrated a substantial performance super-compensation following an overload and taper period in athletes who were classified as being FOR. It is possible that there are a number of contextual factors that may influence the metabolic consequences and associated training adaptations with FOR and classifying this training-induced state of fatigue based purely on a decrement in performance may be an oversimplification.

4 Preventing the Negative Consequences of Overreaching

It is clear that endurance athletes are required to undertake periodised increases in training load to provide an overload stimulus [31] and induce physiological adaptations to training [14, 22–24]. However, there is no evidence to suggest that inducing a state of FOR is *necessary* or *required* to promote these adaptations and improve exercise performance. FOR has been associated with negative cardiovascular [5, 29], hormonal [5, 30] and metabolic consequences [8, 9, 13], as well as suboptimal performance improvements [3, 12], compared to non-overreached athletes who completed the same relative increase in training load. However, this is not always the case and a number of studies have also demonstrated substantial performance super-compensation in athletes who were classified as being FOR [4, 6, 18, 76]. Nonetheless, strategies that can mitigate the negative consequences of overreaching may be beneficial in improving the training process for endurance athletes. Periods of increased training load should be matched with increased energy intake to compensate for the increased energy expenditure [62]. Carbohydrate (CHO) intake may play a role in the prevention of overreaching with some studies [76–78], but not all [42, 79], showing that various increases in CHO intake may alleviate overreaching symptoms. One study [78] demonstrated that a very high CHO diet [12 g kg(body mass) day^{-1}] during an overload training period attenuated cortisol release and increased salivary secretory immunoglobulin-A concentration compared to a lower CHO diet of 5.9 g kg day^{-1}. However, maximal exercise performance was not measured in this study so it can not be determined whether the subjects were FOR or not. In support, two other studies found that increasing CHO intake from 5.4 to 8.5 g kg day^{-1} [77] and 6.4 to 9.4 g CHO kg day^{-1} [76] attenuated the decrement in exercise performance, rise in cortisol [76] and mood state induced by an overload training period. Interestingly, in the study by Halson et al. [76], exercise performance had still not returned to baseline levels after a 2-week recovery period in the lower CHO condition (6.4 g kg day^{-1}), while the higher CHO condition (9.4 g g kg day^{-1}) achieved a performance super-compensation. These findings indicate that increasing CHO content may at least prevent, in part, the performance decrement and fatigue associated with a period of overload training and lead to a performance super-compensation. Svendsen et al. [42] reported that higher carbohydrate intake (7.2 ± 1.6 vs 9.7 ± 1.5 g kg day^{-1}) was not able to alleviate physiological and immunological disturbances associated with an overload training period. In this study, there was a high inter-individual variation in the magnitude of the performance change following the overload period (− 13 to + 4%) across both trials, but these subjects were not partitioned into FOR or otherwise. It should also be noted that while these studies were well designed [42, 76–79], none of these studies compared athletes that became FOR following the overload training period with those that did not demonstrate a reduction in maximal exercise performance. Nonetheless, it is clear that CHO may play an important role for attenuating the severity of FOR symptoms and potentially also prevent the progression of FOR to NFOR.

During periods of overload training, the likelihood of upper respiratory tract infection is increased [11] and this is likely to be linked to the alterations in immune function during these periods of training [42, 54–56]. In addition to CHO which may play a preventative role in mitigating immunological disturbances [76, 78], increasing protein (PRO) intake could also alleviate these alterations [43]. Witard et al. [43] reported that consuming a high-PRO diet (3 g kg day^{-1}) compared to an energy and CHO-matched control diet (1.5 g kg day^{-1}) during an overload training period restored leukocyte kinetics to similar levels observed during a control training period and resulted in fewer upper respiratory tract infection symptoms. Alterations in energy intake may also be important for alleviating other symptoms of overreaching relating to the depression of RMR that was reported in two recent studies [8, 9]. Woods et al. [8, 9] demonstrated reductions in RMR in rowers [9] who failed to increase their total energy intake and cyclists [8] who were unable to maintain FFM following an overload training period. Given that FFM [80] and energy availability [81] are major determinants of RMR, failure to increase energy intake and/or preserve FFM in response to overload training may be responsible for the reductions in RMR evident in these studies [8, 9]. As such, increasing energy intake through alterations in CHO and PRO intake during periods of overload training may be an effective strategy in attenuating the severity of FOR symptoms.

It is evident that sleep quality and quantity are impaired during periods of overload training [11, 14, 44, 45]. Paradoxically, improving sleep quality and quantity has also been proposed to be the primary psychological and physiological recovery strategy available to athletes [82, 83]. Regardless of whether reductions in sleep quality or quantity predispose athletes to becoming overreached, or impaired sleep is a consequence of FOR, strategies to improve sleep may be beneficial during periods of overload training and effectively reduce the negative consequences of FOR. One recent study suggested that a sleep hygiene education session is effective in improving sleep quantity in elite female athletes [84]. Other strategies that may improve sleep related to various nutritional interventions that may act on the neurotransmitters in the brain that are associated with the sleep–wake cycle [82]. Future research should investigate the importance of these and other novel interventions to enhance sleep. In addition to sleep, other forms of recovery, such as cold water immersion (CWI), may be beneficial in reducing the negative consequences of FOR, while also not impeding the long-term adaptations to endurance training [85]. Halson et al. [85] randomised 34 endurance-trained competitive cyclists to CWI (four times each week) or passive recovery (control group) for 1 week of baseline training, 3 weeks of overload training, and an 11-day taper. While the cyclists in this study were not individually classified as overreached, it was only the control group that experienced a decline in performance at the group level in the second 4-min cycling time trial during the overload training period. Furthermore, there were greater improvements in repeat high-intensity cycling time trial performance (2 × 4-min time trials), sprint performance (1-s maximum mean sprint power) and self-selected cycling intensity during training in the CWI group compared to the control group. As such, the results from this study [85] do suggest that CWI may be an effective strategy to prevent FOR and possibly enhance the training-induced performance improvements following an overload training period.

While nutritional and recovery strategies can be implemented during overload training to mitigate the negative metabolic consequences associated with overreaching, training load monitoring may assist in determining whether an athlete is adapting to a given training period or at risk of maladaptation to training [22]. While there are many different methods available that quantify the training load of endurance athletes [86], these are typically categorised as either external or internal training load [22, 86]. The integration of different measures of training load and/or training intensity may be used to quantify ratios that could assist in identifying the presence of training induced fatigue [87]. Sanders et al. [87] studied the training loads of twelve professional cyclists during a 2-week baseline training period and during the Giro d'Italia and Vuelta a España cycling grand tours which have extreme physiological demands [88, 89]. Compared to a normal training period, there were moderate to large increases in the ratios of different intensity measures such as the rating of perceived exertion (RPE):heart rate and RPE:power output as well as the ratio of the load measures of session RPE:training stress score ($d = 0.79–1.79$). Furthermore, there were small-to-moderate week-to-week changes ($d = 0.21–0.63$) in measures of intensity such as power output:heart rate, RPE:power output, RPE:heart rate as well as measures of load such as training stress score:individualised training impulse (iTRIMP), session RPE(sRPE):individualised TRIMP and sRPE:training stress score ratios during the grand tours. The findings from this study suggest that during cycling grand tours when elite cyclists are likely to be fatigued [90], increases in the ratios between subjective and objective methods of quantifying training intensity and/or load may reflect progressive fatigue that may not be readily detected by changes in solitary intensity/load measures. However, whether these ratios are able to delineate between athletes that are FOR or not overreached remains to be determined.

5 Limitations

One major issue pertaining to studies investigating the performance and training responses to periods of overload training lies in the difficulty of involving elite athletes in a scientific experiment. Given their already high physiological capacities and training loads, introducing overload training periods into the programs of elite endurance athletes may not be feasible nor well accepted by these athletes or their coaches. As such, one model that may be appropriate to study overreaching responses in elite endurance athletes is the assessment of exercise performance and training responses throughout a competitive season without direct control over the training program [64, 91, 92]. The natural variation in training load and other stressors may provide enough stress to induce a state of overreaching which could be captured through continuous monitoring. While this approach has its advantages as it allows for higher level athletes to be studied given that there is no direct manipulation of the training program, the limitations of this approach relate to the limited control over confounding variables such as illness, travel, dietary changes, competition stress and seasonal variability, as well as how frequently performance can be assessed. The other approach to studying overreaching responses is the employment of an overload training period that typically lasts up to 4 weeks [3–5, 7–21]. Exercise performance and training responses are compared from before and after an overload training period, and subsequent recovery period, either within the same participant or between athletes who have a decrement in performance (i.e. overreached) and those that show no decrease in performance. While this overload training model may or may not reflect a typical training regimen of an endurance athlete, it does permit control of confounding variables and the physiological responses of overreached and non-overreached athletes can be contrasted during the same overload period. The limitation of this method is that it may only permit the inclusion of recreational and well-trained athletes but not those of an elite standard.

The interplay between periods of increased training intensity and/or volume and the subsequent metabolic consequences that may arise have not been fully elucidated. Previous studies have typically increased training volume [3, 10–12, 47] or training volume and intensity [8, 9, 26] to overload training, while the exact nature of the increase in training load in other studies is not well described. As such, it is difficult to propose whether the nature of the increase in training load (i.e. volume, intensity or a combination of both) may influence the onset of overreaching or the subsequent metabolic consequences.

There is a large inter-individual variation in the development of overreaching in athletes in response to overload training (i.e. increases of 30–40% of training volume for 3–4 weeks) with studies reporting 69% [4], 50% [11], 33% [93] and 48% [12] of athletes being diagnosed as FOR following increases of this magnitude in training volume. There is currently no evidence that clearly demonstrates the reason why some athletes respond optimally to increases in training volume whilst others display signs and symptoms of fatigue and overreaching. Gaining a better understanding of the individual athlete characteristics that may predispose athletes to overreaching is required.

6 Conclusions

Recent research has shown that FOR may be associated with various negative cardiovascular, hormonal, and metabolic consequences and dampened training adaptations in FOR athletes compared to non-overreached athletes who completed the same training program or the same relative increase in training load. However, this is not always the case and a number of studies have demonstrated substantial performance super-compensation effects in athletes who were classified as being FOR. Importantly, in the studies that do report a performance super-compensation effect following FOR, the magnitude of performance enhancement is no greater than that of athletes who completed the same relative increase in training load without experiencing a performance decrement. As such, there does not seem to be evidence to suggest that FOR is *necessary* to induce performance improvements in trained endurance athletes. The various physiological and psychological disturbances resulting from overload training do not systematically discern between FOR and NFOR, but classifying these training-induced states of fatigue based purely on a decrement in performance may be an oversimplification. Increasing energy intake through the consumption of larger amounts of CHO and PRO, as well as incorporating recovery strategies and training monitoring systems seem to be important contextual factors that may influence the metabolic consequences associated with overreaching.

Compliance with Ethical Standards

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