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The Fitness-Fatigue Model Revisited: Implications for Planning Short- and Long-Term Training

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ELITE ATHLETIC PERFORMANCE is dependent on a systemized training program. The general adaptation syndrome (GAS) was the original model from which periodization was designed (67). The GAS describes the physiological response of an organism to stress. A more comprehensive model of the physiological responses to training stimuli is the fitness-fatigue theory (1). In light of recent research examining resistance exercise overreaching and overtraining, it is prudent to review the fitness-fatigue theory and determine how it can be applied to strength and conditioning.

General Adaptation Syndrome

Initially described by Selye in 1956 (60), the GAS proposes that all stressors result in similar responses. The initial response, the alarm stage, is negative, with the physiological state of the organism decreasing following the imposition of stress. Secondary to the alarm stage is the resistance stage, where positive adaptations occur, returning the organism to homeostasis and possibly into a higher state, known as supercompensation. The exhaustion stage occurs when the imposed stress is greater than the adaptive reserves of the organism. This can happen when the magnitude of stress is too large or additional stressors occur. As the response is supposedly similar for all stressors, the magnitude and duration of training determine the magnitude and duration of adaptation.

In traditional periodization models, there are multiple bouts of training, resulting in multiple flights of alarm and resistance stages (63, 67). Periodically reducing volume load may prevent the exhaustion stage (63, 67). If the individual reaches the exhaustion stage, overtraining occurs.

Fitness-Fatigue Model

Proposed in 1982 by Bannister (1), the fitness-fatigue model argues that different training stresses result in different physiological responses. The state of the organism without training is the baseline level, which represents the individual's general fitness. Training results in 2 after-effects, which can positively or negatively influence performance: fitness and fatigue (Figure 1). For strength and power athletes, factors that affect general fitness include muscle cross-sectional area, muscle contractile protein composition, and muscle metabolic enzyme concentrations (23, 24, 44, 62). For endurance athletes, both cardio-respiratory factors and muscular factors affect general fitness (53). Examples of these are maximal oxygen consumption, mitochondrial density, and muscle capillarization. General fitness increases with training age; thus elite athletes have higher general fitness than novices do.

The fitness after-effect is a positive physiological response, whereas the fatigue after-effect is a negative physiological response. The interaction between these 2 after-effects results in the change in performance following the stimulus (1, 67). It is important to note here that the fitness-fatigue model is not necessarily an alternative to the GAS, but rather a better representation of stimulus and response. Indeed, the resultant change in performance as described in this model is identical to the GAS. The distinction of fitness and fatigue after-effects, however, is important for the development of training paradigms.

Fitness after-effects, whether acute or chronic, appear to be primarily neural in nature. Facilitation of the peripheral nervous system occurs via optimal magnitude and rate of activation of the neuromuscular complex, coactivation of intrafusal fibers, and decreased autogenic inhibition (20–22, 27–34, 38–41, 51, 52). Central nervous system activity increases through up-regulation of the alpha- and beta-receptors and greater catecholamine release (12).

Fatigue after-effects are both neural and metabolic in nature. Down-regulation of the alpha- and beta-receptors or decreasing the release of catecholamines can decrease nervous system function (12, 25, 28, 35). Metabolic fatigue is primarily due to decreased storage and availability of energy substrates (10, 25, 45, 64, 67).

The magnitude and duration of the after-effects is dependent on the stimulus, where Bannister (1) initially proposed that training impulse, an indicator of physiological work, was the sole variable. In general, the fatigue after-effect is large in magnitude with a brief duration. This results in the initial decrease in performance (similar to Selye's alarm stage). The fitness after-effect has a dull magnitude, but a long duration. This manifests as a long-term improvement in performance (similar to Selye's resistance stage).

Evidence of After-Effects

Evidence of the existence of 2 after-effects, as opposed to a single unified response, exists in the physiological literature. Similarly, there is an absence of evidence supporting the single unified response proposed by Selye (60). The initial bases for the GAS are the endocrine responses to stress (60, 67). These endocrine responses, however, are not the same for all exercise regimes. Higher-volume training results in an acute decrease in circulating testosterone, whereas higher-intensity training results in an acute increase in circulating testosterone (46, 47, 49). High-volume, moderate-intensity exercise increases growth hormone, but low-volume, very high-intensity training has no growth hormone response (47, 49). Correspondingly, a brief decrease in performance can occur regardless of the increase or decrease in circulating hormones (35–38, 40, 41). The original propositions of the GAS are thus far too simplistic to accurately describe the physiological response to stimuli.

Perhaps the best evidence of fitness and fatigue after-effects is the physiological phenomenon posttetanic potentiation. Posttetanic potentiation is the increase in muscle twitch force following voluntary or involuntary maximal contractions (9). Brown and von Euler (3) reported that successive contractions in isolated muscle preparations resulted in greater force production. Further research in animals and humans corroborated these findings, indicating that maximal voluntary contractions resulted in an increase in performance (9, 11, 19, 42, 57). Interestingly, individuals competing in sports respond favorably, whereas recreationally trained individuals fatigued after the maximal voluntary contractions (9). Chiu et al. (9) speculated that the athletic individuals had a greater potentiation response (fit-

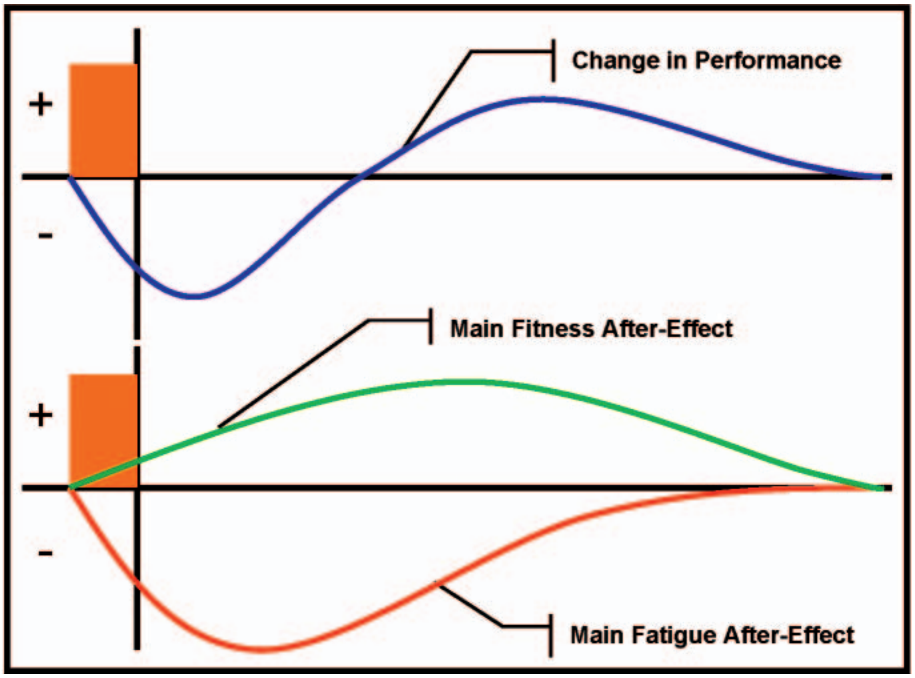

Figure 1. Fitness-fatigue theory.

ness after-effect) and less fatigue compared with the recreationally trained individuals.

Physiologically, maximal contractions cause a depletion of creatine phosphate, an accumulation of extracellular potassium, and an increase in intramuscular calcium and hydrogen (53). These changes contribute to decreased muscle force production. Alternatively, maximal contractions result in phosphorylation of the regulatory myosin light chain and the H-reflex (9, 19, 42, 57). The regulatory myosin light chain is a protein that regulates the rate of muscle contraction. Phosphorylation of this protein increases the rate of binding of actin and myosin, resulting in faster muscle contraction (57). The H-reflex is a reflexive neural signal, which when superimposed on voluntary muscle activation, increases the strength of the electrical impulse, thus activating more motor units (19).

In addition to these acute responses, short-term training adaptations support the fitness-fatigue model. Fry et al. (16) found that following 3 weeks of high relative intensity resistance exercise, strength did not change, whereas speed decreased. Subjects performed near maximal lifts 3 days per week using the free-weight barbell squat. Sprint performance decreased following training, with a 10% increase in 9.1-m run time. This differential response between strength and speed occurs repeatedly in resistance exercise overtraining studies and is supportive of different responses to stress (12, 13, 15, 16, 45, 58).

Stimulus and Response

Bannister (1) suggested that training impulse—the product of heart rate (or exercise intensity) and exercise duration—was the appropriate measure for the training stimulus. Training impulse is a measure of total work performed, and a similar measure exists for resistance exercise, called volume load (64). Volume load refers to the total kilograms of weight lifted. Whether training impulse (for endurance activities) or volume load (for resistance exercise), this notion that total work is the stimulus responsible for short- and long-term adaptation is intellectually appealing. However, the research by Fry et al. (12, 13, 15, 16) shows that exercise with high load or high intensity in absence of high volume loads results in both positive and negative adaptations (45, 58). Thus for a single bout of exercise, absolute load, training intensity, and total work are responsible for the magnitude and duration of the fitness and fatigue after-effects (4–7, 20–22, 29–32, 34, 40, 51, 52, 56).

This important revelation illustrates the differing impacts of the GAS and fitness-fatigue theory. The GAS theory states that total work alone, regardless of the magnitude of stress, is responsible for the responses. In the fitness-fatigue model, both the amount and magnitude of the stimulus contributes to the post-exercise response. Indeed, this distinction may demonstrate the complexity of the fitness-fatigue model. Absolute load, training intensity, and total work appear to have their own fitness and fatigue after-effects. Therefore, the original model—having 1 fitness after-effect and 1 fatigue after-effect—may be misleading. There may actually be multiple fitness after-effects and multiple fatigue after-effects (Figure 2).

Although each specific fitness and fatigue after-effect is independent of each other, they have a cumulative effect. Of primary concern is the summation of fatigue after-effects. Individual fatigue after-effects are specific responses to stimuli; however, these responses can have a systemic ef-

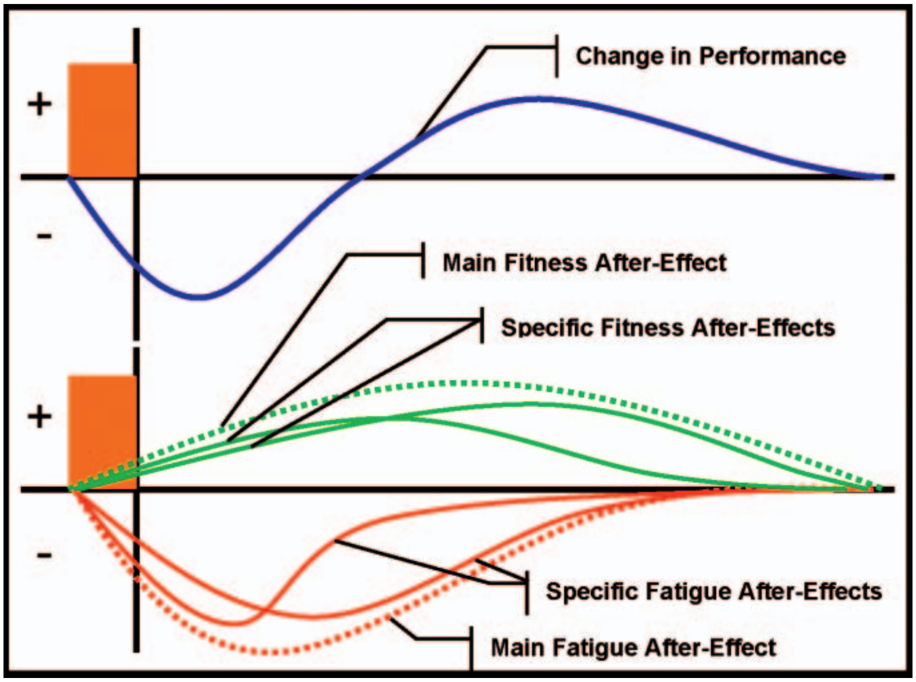

Figure 2. Revised fitness-fatigue theory

fect, in particular affecting the immune system. When fatigue after-effects are small and brief, the systemic effect is small. However, stressful periods of training without sufficient recovery result in an accumulation of fatigue and an increase in the systemic or main fatigue after-effect.

The existence of multiple fitness and fatigue after-effects may explain why individual physical qualities respond differently to variations in training. For example, empirical evidence in weightlifters finds that in periods of maximal strength training, explosive strength and muscular endurance suffer. Similarly, strength is impaired when the emphasis is on explosive strength (2). If different fitness after-effects exist for absolute strength, explosive strength, and muscular endurance, they should be specific to the mode of training best suited for that physical quality. Thus when the emphasis of training is on one and not the other physical qualities, the other specific fitness after-effects diminish and that specific aspect of performance increases.

Implications for Training

For novice athletes, the emphasis of training is on improving the general fitness level. The general fitness aspect of the fitness-fatigue theory explains why beginners tend to respond to any type of training program. When beginners train, general fitness adaptations occur without substantial fitness and fatigue after-effects. Novices cannot train with sufficient absolute load, intensity, or volume to elicit large fitness and fatigue after-effects. Thus beginners adapt so that they can tolerate greater absolute loads, exercise intensities, and training volumes.

Regardless of the training parameters, adaptations in beginners performing resistance exercise include muscle hypertrophy and shift of myosin heavy chain IIb to IIa (8, 53, 55, 62). Maximal oxygen consumption, increased mitochondrial density, and increased capillarization result from most types of endurance training (53). An explanation for the divergence in performance adaptations between different programs is the rate and magnitude of adaptations, rather than the type of adaptations (55). These adaptations are stable and do not tend to regress unless a prolonged period of detraining occurs (43, 44, 48).

Elite athletes have developed a high general fitness level; thus the training emphasis shifts to specific fitness adaptations. The highest level of performance occurs when fatigue after-effects are minimal and fitness after-effects are maximal. Mathematical functions can represent the fitness and fatigue after-effects (1, 4–7). As the after-effects decay, they follow an asymptotic function where the after-effect approaches but does not reach zero. Thus it is impossible for fitness or fatigue to exist independently. Bannister (1) proposes that it is better to have high fitness with moderate fatigue, rather than moderate fitness and low fatigue. Manipulating training parameters can alter the magnitude and durations of these after-effects, producing the optimal level of performance. From the temporal pattern of the fatigue after-effect, it is important to note that maximal performance does not occur immediately after the training phase.

Delayed Training Effect

The delayed training effect is a direct consequence of the fitness-fatigue model. Following a period of stressful training, the magnitude of specific fitness and fatigue after-effects is high. A period of training involving reduced total work and relative intensity is required to remove the fatigue after-effects (1, 67). When applied before a major competition, this phase is a taper (14, 18, 27, 54, 61, 65). Although widely applied in coaching circles, the acknowledgment of the delayed training effect has been missing in scientific research. Without a taper period, it is difficult to interpret the true impact of a training program. Preliminary evidence suggests 96 hours of rest may be necessary in recreationally trained individuals for optimal strength performance (65).

The period of rest required for maximal strength and velocity adaptations to manifest may depend on the nature of the training (59). Training involving concentric-only or eccentric-only movements requires 10–14 days of rest for optimal strength and velocity adaptations. For typical eccentric-concentric exercise, strength and velocity were greatest 21 days following termination of training. Whether the concentric-only, eccentric-only, or eccentric-concentric exercise modes were directly responsible for the different taper times is disputable, as eccentric-concentric training would involve roughly twice the volume load as the other modalities. Regardless, the major finding is in support of a delayed training effect.

It is rare, however, for elite athletes to completely abstain from training the last weeks before competition. Although a drastic reduction in volume load occurs during these few weeks, empirically, intensity remains high. This is especially true in elite weightlifters. The brief, infrequent imposition of high-intensity training may maintain or increase the specific fitness after-effects without substantially affecting fatigue after-effects (16, 43, 64). Therefore, this period is more than simply removing the fatigue after-effect; this period also maximizes the magnitude of the fitness after-effect. Thus, rather than taper, a more appropriate term for this phase of training may be ramping.

■ Short-Term Overreaching

The fitness-fatigue theory and delayed training effect are important to consider in planning the training of elite athletes. Elite athletes can tolerate greater volume load and training intensity than novices and require more stress to stimulate adaptations. The frequent imposition of these stresses, however, makes the athlete more susceptible to overtraining. The need for variation in volume load and intensity are the rationale behind short-term overreaching (12, 64, 67).

Short-term overreaching is the deliberate imposition of stressful training for brief periods interspersed with periods of recovery (12, 64). These stressful periods result in large fitness and fatigue after-effects. As the duration of the fitness after-effect is longer than the fatigue after-effect, a period of rest allows fatigue to diminish while fitness remains high. Stone and Fry (64) and Fry (12) have proposed that this frequent cycling of training and recovery phases is necessary to improve performance in elite athletes.

■ Overtraining

It is important to consider that the fitness and fatigue after-effects are dynamic and not static entities. If training occurs while fatigue after-effects persist, additional after-effects will superimpose on existing ones, exacerbating the maladaptations (1). However, performance decrements may not occur due to the positive effect of the fitness after-effects. Over time, the persistent addition of fatigue after-effects results in a depletion in the athlete's adaptive abilities, resulting in overtraining. It is here that the GAS falls short in explaining why performance drops sharply when overtraining occurs. Following the GAS model, performance should decrease progressively with additional stressors, which empirically is not the case. With the fitness-fatigue model, fatigue accumulates, and at the point when fatigue after-effects greatly exceed fitness after-effects, overtraining occurs.

We must be careful in labeling overtraining, as it typically requires a prolonged period of stressful training to reach (12, 64). Coaches and sport scientists should not underestimate the adaptive abilities of the human body (14). Most individuals will never reach a true overtraining state. Prior research in elite athletes has found an ability to tolerate twofold or threefold increases in training volume for periods of 1–3 weeks (14, 64).

With resistance exercise, recreationally trained individuals are able to maintain or increase strength with 3–5 d/wk of training with near maximal loads (>90% 1 repetition maximum [1RM]; 13, 16). Velocity-related performances, such as sprinting, decrease at this frequency and intensity of training. A training frequency of 7 d/wk for 2 consecutive weeks results in large strength decrements (15, 58). Thus training with excessive loads results in overtraining faster than training with excessive volume.

Similarly, overtraining resulting from load and intensity manipulations appears to resolve faster than overtraining resulting from excess training volume. Lehmann et al. (50) found performance impairments in overtrained endurance athletes as much as 1 year following reduction in training stress. Overtraining from increased loads or training intensity should resolve within a few weeks of rest (16, 45, 64).

■ Long-Term Planning

Although it has fallen out of favor among many strength and conditioning professionals, the traditional periodization model holds concepts that are still important for planning training programs. Perhaps the most important is the inverse relationship between volume and intensity (63). If we remember that longer durations are required to overtrain and recover from overtraining, with training volume it would be prudent to only use higher training volumes early in the training plan.

Higher frequency of training, and therefore higher training volume, increases the duration of the fatigue effect associated with a single training session (4). This may be tolerable early in the training year when fatigue has not accumulated; however, if training frequency remains high throughout the training year, the ability to recover is impaired (4). Reducing training volume toward the midpoint of the training year will allow sufficient time for fatigue to diminish. The use of higher training volume early in the training plan also results in increased adaptive abilities, which would be useful later in the training year (14).

Intensity manipulations result in more predictable responses than volume manipulation, whether positive or negative (9, 20, 21, 25, 29, 32, 35–38, 40, 51, 52, 56). Thus as the competition period nears, it is wise to reduce training volume to avoid prolonged fatigue after-effects while addressing training intensity to maximize the fitness after-effects.

Typically, sequencing of long-term training is in a multidirectional fashion. With multidirectional training, athletes train multiple physical qualities in the same period. For elite athletes, it may be necessary to train in a unidirectional fashion, where emphasis is on only 1 physical quality during a given training period. For example, an athlete may perform a 4-week block of training focusing on strength only (67). The unidirectional method usually results in short-term overreaching of the trained quality.

Some coaches and scientists suggest that consecutive overreaching phases are possible, so long as each phase is unidirectional and emphasizes a different physical quality (67). This concurs with the proposed revised fitness-fatigue model involving multiple fitness and fatigue after-effects. The fatigue after-effect specific to 1 physical quality should not hamper the performance of another physical quality. This applies so long as systemic maladaptations, such as impaired immune system function, do not occur. Thus even with unidirectional sequencing, the training plan should include brief periods for recovery.

Dynamics of the Training Day

A single training session can influence subsequent training sessions, both positively and negatively (2, 26, 40, 66). The effect depends on the type of training performed. From the research literature, there are 3 distinctive types of strength training, which have differing physiological effects on the organism: maximal strength, maximal intensity, and maximal work (67). Maximal strength training involves near-maximal loads lifted for multiple sets of few repetitions. Maximal intensity training uses submaximal loads lifted with maximal acceleration for multiple sets of low to moderate repetitions. Maximal work training involves a high volume of lifts with submaximal loads.

Maximal intensity training has the largest fitness after-effect, which is of short duration (9, 19, 34, 51, 52). Maximal work training has the smallest fitness after-effect, yet the duration is longest (25). Maximal strength training has a smaller fitness after-effect than maximal intensity training (9, 19, 34, 51, 52). The fatigue after-effects are similar, with maximal intensity resulting in large fatigue for a brief period and maximal work resulting in low-levels of fatigue for a prolonged period (5–7, 9, 17, 19, 25, 34, 51, 52, 56, 66).

In planning a single training session, maximal intensity and maximal strength training always precede maximal work. The onset of fatigue with maximal work training is nearly immediate, as opposed to maximal intensity and strength, where the fitness after-effect offsets fatigue (17, 25). Elite athletes can perform maximal strength training before maximal intensity. This sequencing takes advantage of the posttetanic potentiation phenomenon (9). Lesser-trained athletes, however, should always perform maximal intensity training before maximal strength training. Elite athletes may also use this sequencing. In lesser-trained individuals, fatigue follows maximal strength training, impairing maximal intensity performance (9, 11).

Rather than training multiple strength qualities in a single training session, dividing training into multiple sessions per day may be appropriate. Even when total training volume was equal, athletes who trained twice per day improved strength more than individuals who trained only once per day (26). Only athletes who have a high level of general fitness should perform multiple daily training sessions. From preliminary research, maximal strength training sessions precede maximal intensity sessions. The large fatigue after-effect from maximal intensity training appears to manifest during the session or in the intersession interval (2, 66). This fatigue after-effect negatively affects maximal strength, but not explosive strength (2). A single maximal intensity training session results in decreased force production during a second training session 4–6 hours later. The earlier training session does not affect explosive strength or training velocity. Again, when training multiple times per day, maximal work training occurs last.

Short-Term Training

When concurrently training multiple strength qualities, early in the week the emphasis should be on maximal intensity. As the fatigue after-effect is shortest for maximal intensity training, this arrangement has the smallest negative effect on subsequent days of training. Additionally, the large fitness after-effect may positively influence subsequent training days. A day emphasizing maximal strength occurs after days of maximal intensity training, so it does not negatively affect the maximal intensity training sessions. Similarly, maximal work occurs toward the end of the week, closer to days of rest, which will allow fatigue to recover.

In general, training sessions resulting in a large fitness after-effect and a brief fatigue after-effect should occur early in the training week. The positive change in performance from the fitness after-effect allows the athlete to train harder in subsequent days. Training sessions resulting in a longer fatigue after-effect occur later in the training week, immediately before rest days. The rest days allow fatigue to subside. Even 1 day per week of rest can be sufficient for recovery (12, 13).

■ Summary

High-level human performance requires years of diligent training. Coaches and athletes should not leave performance adaptations to chance. Proper planning and organization of training results in the desired performance outcomes, and empirical and scientific evidence is in support of modeling training after the fitness-fatigue theory. From the design of the yearly training structure to each individual training session, an athlete's training plan should account for fitness and fatigue after-effects in an effort to maximize the effects of training. ▲

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