The Application of Repeated-Sprint Training

Fraser Thurlow,[1,2,3] Shaun J. McLaren,[4,5] Andrew Townshend,[1,2] and Jonathon Weakley[1,2,6]
[1]School of Behavioural and Health Sciences, Faculty of Health Sciences, Australian Catholic University, Brisbane, Australia; [2]Sports Performance, Recovery, Injury and New Technologies (SPRINT) Research Centre, Australian Catholic University, Brisbane, Australia; [3]School of Sport, Exercise and Rehabilitation, Faculty of Health, University of Technology Sydney, Sydney, Australia; [4]Newcastle Falcons Rugby Club, Newcastle upon Tyne, United Kingdom; [5]Department of Sport and Exercise Sciences, Manchester Metropolitan University, Institute of Sport, Manchester, United Kingdom; and [6]Carnegie Applied Rugby Research (CARR) Centre, Carnegie School of Sport, Leeds, United Kingdom

ABSTRACT

Repeated-sprint training (RST) involves maximal-effort, short-duration sprints (≤10 seconds) interspersed with brief (≤60 seconds) recovery periods. It can enhance a range of physical qualities to help prepare intermittent sport athletes for the high-intensity demands of competition. This review provides a scientific basis for applying running-based RST with intermittent sport athletes. The acute and chronic responses to RST are reviewed, as well as the manipulation of programming variables to target specific training outcomes (i.e., sprint modality, number of repetitions and sets, repetition distance, rest time, rest modality, volume, training frequency, and program duration). Furthermore, practical considerations for an individualized approach to RST and an applied framework for how and when it can be best integrated into the annual training program are presented.

INTRODUCTION

The physical preparation of athletes requires the effective application of different training methods. These training methods should enhance athletic performance and often need to be efficiently implemented to meet the time constraints of sporting environments, where there is a need to balance technical, tactical, and physical training, as well as recovery (46). The manipulation of programming variables (e.g., frequency, volume) forms the foundation of training design and, when applied effectively, can optimize the acute and chronic response to training (119,122). Therefore, just as athletes are required to select the appropriate skill for a given match scenario, coaches must select the most appropriate training content to optimize performance for teams and individuals. High-intensity interval training (HIIT) is commonly used by coaches to elicit specific metabolic and neuromuscular responses (22). It includes long-bout HIIT (i.e., 1−4 minutes submaximal efforts), short-bout HIIT (i.e., 10−60 seconds submaximal efforts), repeated-sprint training (RST), sprint interval training (i.e., 20−30 seconds maximal sprints), and small-sided games (74). While all these HIIT methods are useful in their own context, this review focuses on the science and application of RST, which are discussed with relevance to running-based intermittent sport athletes.

Address correspondence to Fraser Thurlow, fraser.thurlow1@gmail.com.

WHAT IS REPEATED-SPRINT TRAINING

RST is an effective and time-efficient HIIT method that involves maximal-effort, short-duration sprints (≤10 seconds) interspersed with brief (≤60 seconds) recovery periods (51). It can be implemented with various different exercise modalities (e.g., running, cycling) and causes physiological, neuromuscular, and morphological changes that help prepare intermittent sport athletes for the rigorous demands of competition (119,121). Eleven primary programming variables are commonly manipulated to alter the acute training demands and chronic adaptations of RST (Table 1) (119,122). The manipulation of programming variables allows coaches to strategically design training sessions and training programs that elicit targeted responses. To emphasize different movement demands, RST can be prescribed as a straight-line, shuttle, or multidirectional format across a range of short distances (e.g., 10−40 m). Sets can be structured to incorporate long-series of repetitions that cause the accumulation of fatigue or prescribed as small groups of repetitions that allow the maintenance of maximal sprint performance. Passive or active rest periods can be implemented between sets and repetitions, including the addition of sport-specific actions, such as jumps and grappling, or the execution of skills (e.g., shooting, passing). These

KEY WORDS:
high-intensity interval training; periodization; team sport; injury rehabilitation; sports performance; physiology

Table 1
Programming variables applied in the design of repeated-sprint training

Programming variable	Definition	Common prescription
Sprint modality	The type of running-based RST (i.e., straight-line, shuttle or multidirectional sprints*)	Straight-line sprints
Number of repetitions	The number of sprints performed per set	6 repetitions
Number of sets	The number of sprints performed per session	3 sets
Repetition distance	The distance of each sprint	30 m
Inter-repetition rest time	The rest time between each sprint	20 s
Inter-set rest time	The rest time between each set	4 min
Inter-repetition rest modality	The type of rest between repetitions (i.e., passive or active)	Passive
Inter-set rest modality	The type of rest between sets	Passive
Session volume	The total number of repetitions performed per session multiplied by the repetition distance	600 m
Session frequency	The number of RST sessions per week	2 per week
Program duration	The number of weeks an RST program is implemented	6 wk

m = meters; min = minutes; RST = repeated-sprint training; s = seconds.

manipulations make RST a versatile training method, but they also influence the adaptative response and raise questions for coaches in relation with its optimal prescription.

WHY REPEATED-SPRINT TRAINING

Training methods that can be used to concurrently develop several physical qualities efficiently may be valuable within the time-pressed environment of sports. RST is a mixed training method that targets both neuromuscular and metabolic systems simultaneously (18,22), resulting in substantial improvements across a range of physical qualities that are important to sports performance, including speed, aerobic capacity, intermittent running performance, repeated-sprint ability (RSA), change of direction (COD) ability, and jump height (119). In addition, RST can expose athletes to maximal sprinting, acceleration, deceleration, and COD, all common during competition (15,108,116). Physical adaptations and improvements in performance can be achieved in as little as 2 weeks with 6 × 10−20 minutes sessions (117). Furthermore, RST is easily implemented, requiring limited equipment and simply involves maximal effort sprints. While a range of training methods and intensities are required to optimally prepare athletes for competition, the ability of RST to enhance performance within real-world training environments makes its application highly beneficial for athletes and practical for coaches.

BUILD THE CAR

The automotive manufacturing process follows a series of logical steps and requires a range of tools to ensure safety, quality, and performance are maximized. Just like manufacturing a car, the physical development of an athlete should follow a progressive application of different training methods integrated at the correct time and with precise detail (Figure 1). The beginning of preseason (the general preparation period) is when production starts to upgrade an athlete's performance. To build the frame (i.e., develop the athlete's energy systems), coaches should optimize the function and capacity of the adenosine triphosphate-phosphocreatine (ATP-Pcr), glycolytic, and aerobic systems with training methods that are general to the sport, but specific to physiological adaptation (60). Steady-state continuous training and long-bout HIIT are the best methods to increase mitochondrial content and enhance aerobic capacity (61). In addition, traditional sprint training will improve the function of the ATP-Pcr system and fine-tune the neuromuscular system while allowing for gradual increases in sprint volume (103). Longer training durations and a greater focus on physical development are typically afforded during the general preparation period, which provides the time to implement these isolated training methods. This process should not be rushed as it is crucial to an athlete's overall physical development, but once the frame has been constructed, the engine can be installed.

Short-bout HIIT is often applied as athletes progress from the general to specific stages of preseason (74). It provides general energy system development for both the aerobic and anaerobic systems, increasing mitochondrial capacity and function while

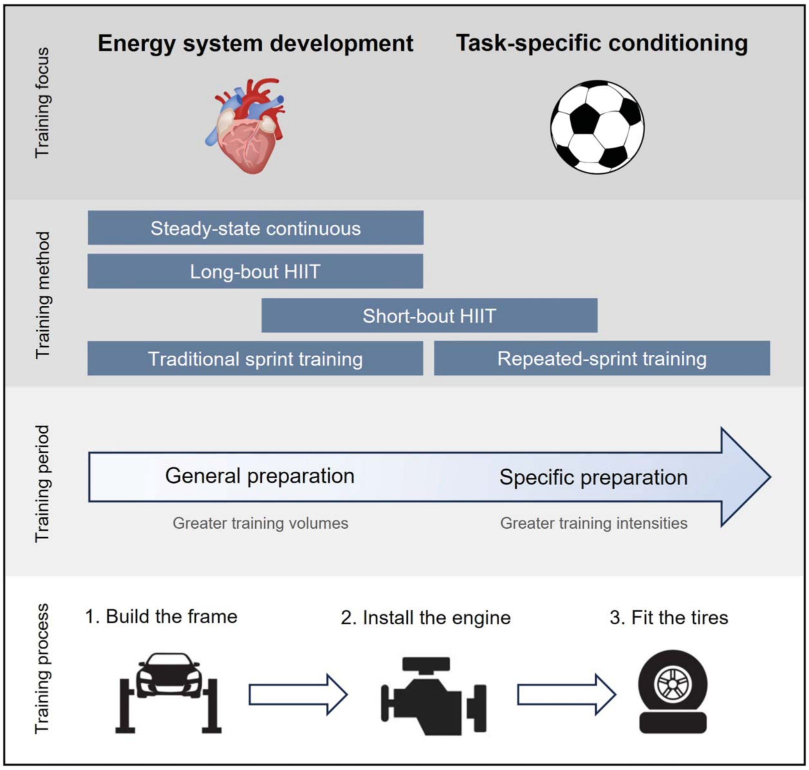


Figure 1. A visual representation of an integrated approach to the preseason conditioning of an intermittent sport athlete. *Note*, the length of the training periods may not be equal and will depend on each given situation.

improving an athlete's maximal aerobic speed (30,60). Short-bout HIIT can also be made more task-specific through manipulating programming variables such as sprint modality (e.g., shuttle sprints) and rest modality (e.g., active rest periods with sport-specific actions). To add the tires and complete the build (i.e., condition athletes for the demands of the sport), RST can be applied during the specific preparation period, which often incurs a small reduction in volume and an increase in training intensity (67). Because RST is a mixed training method that emphasizes movement demands directly relevant to intermittent sport competition, it can be considered a training method specific to the task but general to physiological adaptation (60). Its application may, therefore, improve an individual's physical capabilities in task-specific scenarios and may aid transfer to competition.

THE ACUTE DEMANDS OF REPEATED-SPRINT TRAINING

The internal and external training loads experienced by athletes (i.e., the acute demands) induce physiological responses (i.e., training effects) that lead to chronic adaptations when the training stimulus is repeated over weeks, months, and years (65). The acute physiological, neuromuscular, perceptual, and performance demands incurred during RST are similar across many protocols, sports, and athlete characteristics (Table 2) (122). Coaches can expect an average oxygen consumption ($\dot{V}O_2$) and heart rate of around 70–80% and 80–90% of maximum, respectively (119). There is an abrupt increase in $\dot{V}O_2$ and heart rate during the first 3–4 repetitions of a set, but due to the extended rest times of RST compared with its work durations, the cardiorespiratory demands plateau (Figure 2) (120). Time above 90% of maximal oxygen consumption ($\dot{V}O_2$max) is therefore limited (≤1 minute) (22,120), which may explain why the improvement in aerobic capacity following RST is often less than other HIIT methods (i.e., short and long HIIT) (11,30,121).

Anaerobic systems provide the majority of energy during a single sprint, which results in the depletion of muscle phosphocreatine stores by 35–55% (Figure 3) (35,44,51). As sprints are repeated, the intensive demand placed on the glycolytic system is demonstrated by a high blood lactate concentration, which is regularly above 10 $mmol \cdot L^{-1}$, and this value can be reached after just 5 repetitions (50,122). A high rate of anaerobic energy production may be an important stimulus to elicit positive adaptations in enzymes central to anaerobic glycolysis (7,83). However, the maximal intensity of RST causes the accumulation of metabolic by-products (e.g., hydrogen ions, inorganic phosphate), which lead to an inhibition of excitation-contraction coupling and impairment of sarcolemma excitability (54,94). Together with the rapid depletion of PCr, these peripheral mechanisms contribute extensively to a reduction in force and power output (62,94). Consequently, there is a decline in sprint times across a set of repeated sprints, which, when represented by the percentage sprint decrement formula, equates to 5.0 ± 0.3% (122).

RST is a conditioning method perceived as "very hard" (i.e., 6.5 on a CR10 rating of perceived exertion scale), fluctuating between "moderate" to "extremely hard" (120,122). However, given its short duration, the internal training load (session ratings of perceived exertion × training duration) is a fraction of that observed during team sport practice (33,56,79), ranging between 20 and 135 au (deciMax units) (120,122). The perceptual demand on an athlete's leg muscles and central respiratory system is similar (120). When programming variables such as volume, sprint distance, and the number of repetitions per set are manipulated, athletes report little difference

Table 2
Summary of the acute demands of repeated-sprint training. Adapted from Thurlow et al. (122).

Avg VO_2	Avg HR	$T > 90\%\ VO_{2max}$	B[La]	Sdec	sRPE
70% of max	90% of max	≤1 min	10.8 mmol L^{-1}	−5.0%	6.5 au

au = arbitrary units; B [La] = blood lactate; HR = heart rate; S_{dec} = percentage sprint decrement; sRPE = session ratings of perceived exertion (Borg CR10 Scale); T = time; $\dot{V}O_2$ = oxygen consumption.

between perceived leg-muscle exertion and breathlessness (120). A sensation of exercise-induced hyperventilation is common during RST (120), which may be the body's attempt to compensate for lactic acidosis during such intense anaerobic work, and this would have a large influence on the perception of breathlessness and leg-muscle exertion (59,84).

The effects of RST on acute fatigue are diverse. Within practical sport settings, neuromuscular fatigue (i.e., impairment in the muscle's ability to produce force) is often quantified by performance in jumping tasks such as the countermovement jump (CMJ) (55,126,128). Depending on the design of the RST session, the fatigue response can be drastically different. Typically, coaches can expect an acute decline in jump height of around ~4−5%, although this can range from +8 to −27% (120,122). Alterations in the mechanical effectiveness of sprinting may also occur during RST with reductions in maximal velocity and power (66). In addition, leg-spring behavior is impaired during RST, as evidenced by a progressively lower vertical stiffness and an increased center of mass vertical displacement over 6 sprints (14,52). This is accompanied by altered stride parameters (e.g., increased contact time and stride duration, reduced stride frequency and length) and, ultimately, slower sprint times (14,52). While fatigue can be important for adaptation (27), adopting programming strategies to help maintain mechanical efficiency during RST could enhance sprint performance.

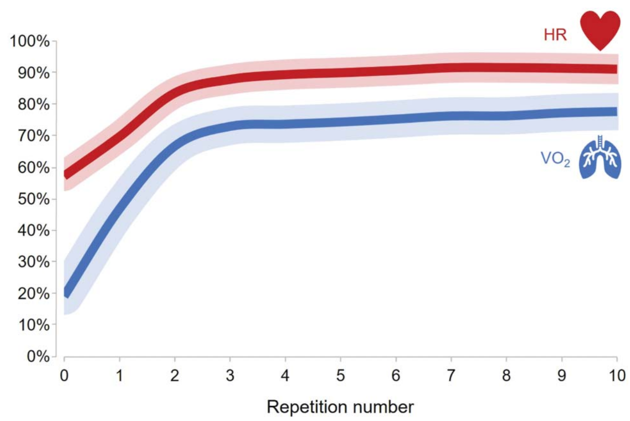


Figure 2. The percent change in average heart rate (HR) and oxygen consumption ($\dot{V}O_2$) across a set of 10 × 40 m straight-line repeated-sprints, performed with 30-second inter-repetition rest. *Note*, thick lines indicate the mean and the shaded zones indicate the standard deviation. Reproduced from Thurlow F. The acute demands and physical adaptations of repeated-sprint training [Doctoral Thesis]. Australian Catholic University, 2024 by permission of the Australian Catholic University.

THE CHRONIC ADAPTATIONS TO REPEATED-SPRINT TRAINING

RST can enhance a range of physical qualities important to athletic performance (115,119,121). Sprints often occur at decisive moments of competition (40,81), so speed is crucial to intermittent sport athletes. Recent work has indicated that RST consistently improves 10, 20, and 30 m sprint times by 2–3% (115,119). This improvement is substantial, considering that the smallest worthwhile change in short sprint performance is said to be 1−2% (57). RST is yet to be compared with traditional sprint training methods (e.g., free or resisted sprint training), which typically enhance sprint times by 3–5% (102). However, greater improvements in linear sprint times and sprint force-velocity-power characteristics were achieved with 6 weeks of RST compared with short-bout HIIT (121). Compared with small-sided games, long-bout HIIT, plyometric training, and agility training, greater improvements in linear sprint times have also been observed with RST (11,23,28,78). Exposure to high-speed running and sprinting during small-sided games is highly variable (36); thus, RST appears to be a more effective HIIT method to improve sprint performance and provide more controlled doses of near-to-maximal speed running (120).

RST can enhance CMJ height and COD test time by small magnitudes (Table 3) (115,119). Increases in CMJ height are less with RST compared with plyometric training (23), similar to short-bout HIIT (24,121), and greater than small-sided games (13). Given the multidirectional nature of small-sided games and agility training, coaches may expect these training methods to have a larger beneficial effect on COD test time, yet similar improvements with RST have been demonstrated, which may be related to the rapid accelerations and decelerations that athletes complete during RST (13,24,28,78). Therefore, coaches can use RST in addition or as a replacement for agility training to

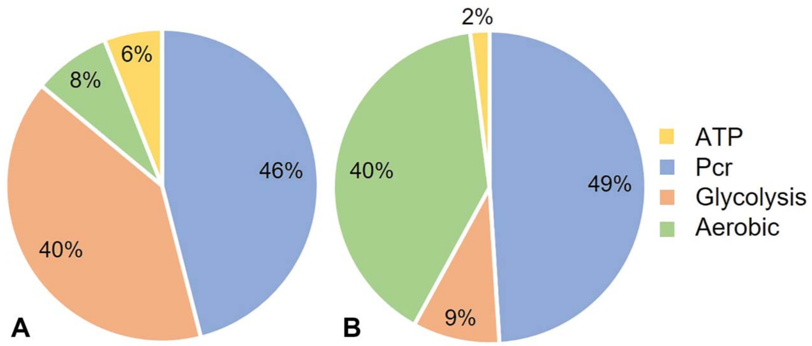


Figure 3. Changes in metabolism during (A) the first and (b) the last repetition of 10 × 6 seconds repeated-sprints. *Note*, ATP = adenosine triphosphate; PCr = phosphocreatine. Adapted from Girard O et al. (50).

improve COD ability, with the incorporation of shuttles or turns recommended.

Given the high-speed muscular contractions that occur during RST, morphological adaptations are attained, which may enhance the force-generating capacity of the leg extensor muscles. Moderate increases in biceps femoris fascicle length and small increases in muscle thickness were recently observed following a 6-week RST intervention with rugby league players, despite an absence of eccentric hamstring strength training during an otherwise normal preseason program (121). While further evidence is needed to support this finding, it may have implications for hamstring injury prevention and rehabilitation, whereby increases in fascicle length have been associated with reduced risk of hamstring strain injury (123). Furthermore, compared with a short-bout HIIT, there were greater increases in eccentric hamstring strength (121), which is also important to hamstring injury prevention and rehabilitation (123).

For an optimal physiological stimulus during HIIT, several minutes above 90% of $\dot{V}O_2max$ per session have been recommended (6,75,85,86). Yet, substantial improvements in aerobic capacity can still be attained through RST (122). From baseline, coaches can expect an increase in $\dot{V}O_2max$ of $2.2\ mL \cdot kg^{-1} \cdot min^{-1}$, which equates to an improvement of ~4% (122). While considerable, this improvement is less than long-bout HIIT (11) and small-sided games (78), which typically elicit greater time at or near $\dot{V}O_2max$ (22). There is a lack of evidence regarding the specific physiological mechanisms underlying the increase in $\dot{V}O_2max$ achieved through RST, but there are several theories derived from investigation into sprint interval training, which refer to the role of exercise intensity being a key driver of aerobic training adaptations (77,99,125). The "all out" intensity of sprint training causes the rapid depletion of PCr and glycogen after just a few repetitions while also resulting in the accumulation of metabolic by-products (e.g., hydrogen ions, inorganic phosphate) (51,113). Repeated exposure to these acute demands ultimately results in chronic adaptations, including mitochondrial biogenesis, improved mitochondrial respiratory function, and metabolic adaptations of all 3 energy systems (26,53,99,101,105,107). Although the brief duration of RST may be insufficient to induce significant increases in cardiac output, which tends to respond best to prolonged bouts of submaximal exercise (10,29,77). Therefore, improvements in $\dot{V}O_2max$ with RST may predominantly arise from an enhanced ability to extract and use oxygen due to increased muscle oxidative handling capacity (i.e., a greater arteriovenous oxygen difference) (77,111).

The ability to perform repeated intermittent bouts of high-intensity running is enhanced through RST, demonstrated by moderate improvements in RSA and the Yo-Yo Intermittent Recovery Test level 1 (YYIR1) (115,122). Performance during these field-based fitness tests is associated with physical (e.g., high-speed running distance, total distance) (8,70–72,95,112,124) and game-related (e.g., number of tackles, number of assists) (32,41,96) performance during team sport competition. A recent meta-analysis (122) demonstrated that across 21 RST groups, athletes achieved a mean improvement of 252 m in the YYIR1, which is the equivalent of 6 shuttles. When directly compared with long-bout HIIT and small-sided games, YYIR1 improvement is considerably greater following RST (11,12,39,78). Furthermore, RSA is also enhanced to a greater extent with RST when compared with long-bout HIIT (11), plyometric training, and agility training (28), with similar improvements compared with short-bout HIIT (24). The YYIR1 and RSA tests heavily tax both the aerobic and anaerobic systems (51,69,71); thus, the substantial improvement in these tests reflects the ability of RST to concurrently enhance both energy pathways.

Table 3
Summary of the physical improvements to repeated-sprint training. Adapted from Thurlow et al. (119).

VO_{2max}	YYIR1	20 m time	RSA avg	CMJ height	COD time
4.0%	16.0%	2.2%	1.6%	3.3%	2.0%

CMJ = counter-movement jump; COD = change of direction; RSA = repeated-sprint ability; $\dot{V}O_2max$ = maximal oxygen consumption; YYIR1 = Yo-Yo Intermittent Recovery Test Level 1.

THE EFFECT OF PROGRAMMING VARIABLES ON THE ACUTE AND CHRONIC RESPONSES TO REPEATED-SPRINT TRAINING

While the acute and chronic responses to RST are consistent across many protocols, they can also be altered by manipulating programming variables. The following subsections detail the acute and chronic effects of manipulating RST volume, frequency, program duration, the number of repetitions per set, the number of sets per session, sprint repetition distance, rest time, rest modality, and sprint modality. A summary of the effects of programming variables on the acute and chronic responses to RST are presented in Figure 4 and Table 4, respectively.

VOLUME

RST volumes usually range from 200 to 800 m per session and 400−2000 m per week (119). Improvements in physical performance can be achieved with low weekly volumes (400−1,000 m) (1,5,23,24,28,45,47–49,63,89,97,121), which, when prescribed as individual sessions, are typically perceived as moderate to hard and incur minimal neuromuscular fatigue (120). This makes the application of low training volumes more useful during the in-season when small improvements in physical performance are desired, but fatigue needs to be mitigated. In addition, low volumes should be applied at the beginning of a training program to gradually expose athletes to the intensity of RST. Conversely, higher volumes increase the acute physiological, neuromuscular, and perceptual demands of RST (Figure 5); thus, their application is more suited to the preseason period when a greater training load is desired. For example, average $\dot{V}O_2$ and heart rate were 8% higher when sessions with 800-m volume were prescribed, compared with 200 m (120). Higher weekly volumes of around 1,200−1,400 m per week appear to maximize physical adaptation (119), but this is also dependent on the prescription of programming variables that influence weekly volume (i.e., frequency, sets, repetitions, and sprint distance).

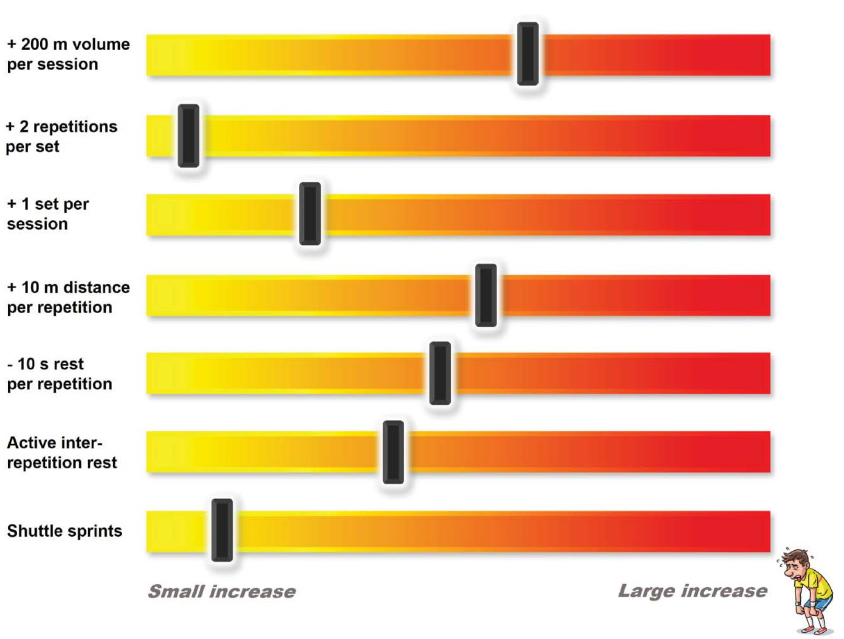


Figure 4. A summary of the effects of programming variables on acute physiological, perceptual, and neuromuscular demands during repeated-sprint training. *Note*, effects are compared with a reference session, consisting of 1 set of 6 × 30 m straight-line sprints, with 20-second inter-repetition rest. Adapted from Thurlow et al. (122).

TRAINING FREQUENCY

One RST session per week can enhance physical performance and physiological adaptation (23,88,97) or, at the least, maintain fitness attributes (5,58). However, 2 RST sessions per week are more effective, particularly during preseason periods when greater sprint volumes are accumulated (119). Three sessions per week can be beneficial during short mesocycles, with Taylor et al. (117) demonstrating that just 6 RST sessions in 2 weeks can improve speed and high-intensity running performance in soccer players. Other than this application, 3 sessions per week are not advised and have been shown to cause a small impairment in the development of COD ability (119).

PROGRAM DURATION

Changes in enzyme activity related to aerobic and anaerobic metabolism can arise within 2 weeks of high-intensity training (98). In addition, Rosenblatt et al. (100) demonstrated that 2 weeks is the optimal duration of a SIT program to improve time trial performance. Similarly, performance improvements have been observed after just 2 weeks of RST (117), but these may be augmented by slightly longer program durations. Compared with 6-week programs, there are no meaningful benefits of an additional week of RST (i.e., 7 weeks) on physical fitness and physiological adaptation (119). Therefore, 2−6 weeks is an efficient program duration for applying RST.

NUMBER OF REPETITIONS

The prescription of 2 additional repetitions per set (8 versus 6) has demonstrated trivial effects on the acute physiological demands (i.e., heart rate, $\dot{V}O_2$, blood lactate) of RST and can attenuate physical adaptations (119,122). High-repetition sets reduce the magnitude of improvement in speed and endurance attained with RST (Figure 6) because they tend to result in pacing strategies and/or an excessive sprint decrement. Provided that RST volume is maintained through an increased number of sets or sprint distance, low-repetition

Table 4
A summary of the effects of programming variables on the physical adaptations to repeated-sprint training. Adapted from Thurlow et al. (119).

Programming variable	Endurance	Speed	CMJ	RSA	COD
+ 1-week program duration	o	o	o	o	o
+ 1 session per week	o	o	o	o	-
+ 200-m volume per week	o	o	o	o	o
+ 2 repetitions per set	o	o	o	o	o
+ 1 set per session	+	o	o	o	o
+ 10-m distance per repetition	o	o	o	o	o
+ 10-s rest per repetition	o	+	NA	o	NA
Shuttle sprints	+	o	o	o	+

Effects compared with a reference program, consisting of 3 sets of 6 × 30 m straight-line sprints, with 20-s inter-repetition rest, performed twice per week for 6 weeks (1,200 m volume per week). There was insufficient evidence to summarize the effects of rest modality.

COD = change of direction ability; CMJ = counter-movement jump; RSA = repeated-sprint ability.

+ = small improvement; - = small impairment; o = no substantial change; NA = not applicable due to insufficient evidence.

sets (e.g., 4–6 reps) are recommended for most athletes. This is because they support the maintenance of maximal running velocity across a set while still inducing a substantial metabolic and cardiorespiratory response (50,122,127). However, there may be an exception for endurance-based athletes, who can often sustain consistent sprint performance for 8–12 repetitions and, thus, may benefit from the higher repetition sets in this vicinity.

Figure 5. The approximate relationship between session volume and ratings of perceived exertion during repeated-sprint training. Adapted from Thurlow F. The acute demands and physical adaptations of repeated-sprint training [Doctoral Thesis]. Australian Catholic University, 2024 by permission of the Australian Catholic University.

NUMBER OF SETS

With an increasing number of sets during a RST session, there is a greater systemic physiological demand (37,93,120). Most notable is the increase in time above 90% of the maximal heart rate, which rises by an additional minute when a second set is performed (116). Current evidence suggests that 1 set per session is insufficient to attain meaningful improvements in performance (58,118). Therefore, to augment the acute physiological demands of RST and maximize physical adaptation, 2–3 sets per session is generally recommended. Although 4 sets are beneficial when low numbers of repetitions are prescribed (e.g., 4–6 reps) or used to increase session volume during the preparation period. To maintain the time-efficient nature of RST when a higher number of sets are implemented, shorter interset rest times (e.g., 2 minutes) can be applied, which allows for similar recovery of cardiorespiratory function compared with 3-minute sets (120).

SPRINT DISTANCE

The distance of each sprint repetition ranges from 10–to 40 m (119,122). Short distances (e.g., 20 m) incur greater acceleration loads and allow for consistent sprint times across each set, while increased volumes of near-to-maximal velocity sprinting are attained with longer distances (e.g., 40 m) (116). The manipulation of sprint distance also has a considerable influence on the acute physiological demands of RST (122). For example, sprinting 10 m further per repetition (i.e., 40 versus 30 m) increases peak heart rate by 2.5 ± 2.7 $b \cdot min^{-1}$ and blood lactate by 2.7 ± 1.2 $mmol \cdot L^{-1}$ (120,122). However, longer sprints are also associated with increased perceived exertion, sprint decrement, and

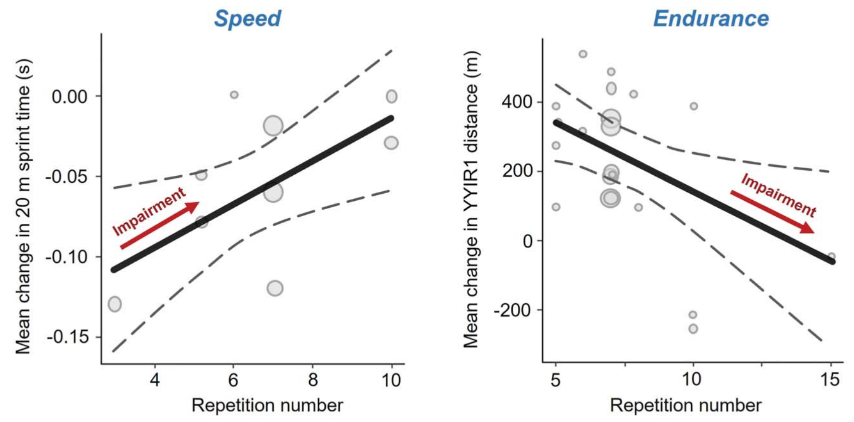


Figure 6. The effects of manipulating the number of repetitions per set within a repeated-sprint training program on change in 20-m sprint time (left) and distance achieved in the Yo-Yo Intermittent Recovery Test level 1 (right). *Note*, thick black lines indicate the mean change, dashed lines indicate 90% confidence intervals, and circles indicate each study's mean change with thicker circles indicating a greater sample size. Adapted from Thurlow et al. (119).

neuromuscular fatigue (120,122). While sprint distance has substantial effects on the acute demands of RST, current evidence indicates that it has a minor influence on physical adaptation (119). This is perhaps cause for a pragmatic interpretation of its role. Shorter sprints (10−20 m) may be more applicable to the in-season period and for court-based athletes, where confined spaces mean that quick linear and multidirectional movement is essential. Conversely, longer sprint distances (30−40 m) are highly suitable during the preseason and offseason periods, and for team sport athletes who require exposure to faster absolute speeds.

REST TIME

The prescription of both short (≤20 seconds) and long (≥30 seconds) inter-repetition rest times is effective during RST, but coaches can increase or reduce rest time to elicit specific acute responses and prioritize the development of certain physical qualities. Short rest times cause a higher blood lactate and greater sprint decrement (122), and when implemented over the duration of a training program, lead to greater improvements in intermittent running performance and 200-m sprint time compared with long rest times (63). Longer rest times enhance the clearance of metabolic by-products and allow for increased PCr resynthesis, which assists power output (51,76). Consequently, faster and more consistent within-session sprint times are achieved when long rest times are implemented (Figure 7), while neuromuscular fatigue is mitigated (91,122). Despite the addition of a 10-second longer inter-repetition rest (i.e., 30 versus 20 seconds), there is no substantial change in peak heart rate (−0.7 ± 90% confidence interval: 1.8 b·min^{-1}) (122). Therefore, providing athletes with a 30-second rest between repetitions maintains the physiological demands of RST while permitting faster acute sprint performance. In the long term, this may translate into greater improvements in explosive physical qualities, with greater improvements in 20-m sprint times and RSA achieved when 30-second recovery was compared against 15-second recovery in soccer players (63).

REST MODALITY

The chronic effects of passive versus active rest on physical adaptation are yet to be directly compared within the literature. However, passive rest periods reduce perceived exertion during an RST session and are associated with enhanced PCr resynthesis between sprints, which allows for faster sprint times across the set (20,38). The acute demands of RST with active recovery are dependent on the intensity of the auxiliary activity, and thus, their effects are broad. However, in general, active recovery can be used to amplify the physiological and muscular demands without increasing sprint volume (17,20,92,122). Coaches should also be aware that higher ratings of perceived exertion and greater sprint decrement will be induced with active rest modalities.

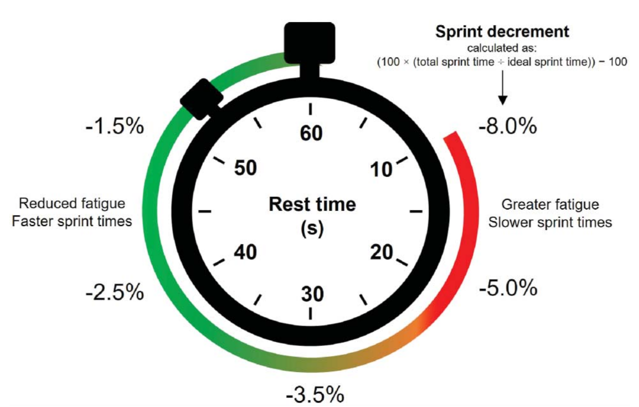


Figure 7. The acute effects of inter-repetition rest time on within-session performance fatigue (i.e., percentage sprint decrement) during repeated-sprint training. *Note*, ideal sprint time is the number of sprints × fastest sprint time.

SPRINT MODALITY

Coaches can expect the acute demands and chronic adaptations of the different sprint modalities to be similar, and each respective modality can enhance physical performance (119,122). Therefore, all 3 sprint modalities (i.e., straight-line, shuttle, and multidirectional) can be applied with similar results, but minor differences may be observed (119,122). For instance, shuttle sprints can elicit a slightly greater systemic physiological, metabolic, and neuromuscular load (Figure 4) (122), which may maximize improvement in aerobic capacity (119). However, these responses are conditional to the number and angle of direction changes, the distance between each direction change, and the duration of each repetition (2,19,21,90,130), which affects the absolute speeds that are attained and the muscular work performed during acceleration and deceleration.

THE INTEGRATION OF REPEATED-SPRINT TRAINING

There are several situations where blocks of RST are useful and feasible within the training program. The following sections describe these situations in detail and are applied in Tables 5–8.

Table 5
Example of a 1-week repeated-sprint training program during the offseason

Training content	Session 1	Session 2
Aim	Improve physical qualities + maintain exposure to various movement demands	Improve physical qualities + maintain exposure to various movement demands
Sets × repetitions	3 × 6	3 × 6
RST modality	Set 1: straight-line	Set 1: straight-line
	Set 2: shuttle (1 × COD)	Set 2: shuttle (2 × COD)
	Set 3: multi-directional	Set 3: multidirectional
Repetition distance	30 m	30 m
Inter-repetition rest	On 30 s, passive	On 30 s, active
Interset rest	3 min, passive	3 min, passive
Session duration	15 min	15 min
Prescribed volume	540 m	540 m
Est. volume >90% MSS	150 m	0 m
Physiological demand	Moderate	High
Neuromuscular demand	Moderate	Moderate
Perceptual demand	Moderate	High
Progression	+10 m distance	+10 m distance

COD = change of direction; m = meter; min = minutes; MSS = maximal sprint speed; RST = repeated-sprint training; s = second.

OFFSEASON

The offseason is a time for athletes to rest, recover, and regenerate from the physical and psychological demands of the previous season (87). However, it is important that athletes maintain fitness levels during this time to be prepared for the elevated training demands of preseason (87). To mitigate loss in physical capacity during the offseason, Silva et al. (109) suggested the prescription of simple training tools to facilitate compliance with offseason programs and recommended a "minimum effective training dose" to maintain or at least attenuate the loss of physiological and neuromuscular qualities. While evidence is needed to determine the effectiveness of RST during the offseason, it could be used to maintain exposure to maximal velocity, acceleration, deceleration, and COD. Furthermore, given that RST requires minimal equipment, time, and space, it is ideal when athletes are away from their usual training environments.

To maintain exposure to various movement patterns during the offseason, coaches can prescribe different repeated-sprint modalities across the same session, week, or program (39,73). For example, straight-line sprints could be assigned to set 1, shuttle sprints assigned to set 2, and multidirectional sprints assigned to set 3 (Table 5). Multidirectional sprints can incorporate a range of different sequences (i.e., various angles and courses), with coaches encouraged to increase the complexity of movement as athletes progress (e.g., administer course D before course E; Figure 8). As athletes often train unsupervised during the offseason period, prescribing recovery on time cycles will allow athletes to easily manage their sessions (e.g., sprints starting every 30 seconds).

PREPARATION PERIOD

The preparation period, or "preseason," is crucial for athletes to

Table 6
Example of a 1-week repeated-sprint training program during the preseason

Training content	Session 1	Session 2
Aim	Maximize physical qualities + expose athletes to maximal velocity	Maximize physical qualities + expose athletes to maximal COD
Sets × repetitions	4 × 5	4 × 5
RST modality	Straight line	Shuttle (2 × COD)
Repetition distance	40 m	30 m (10 + 10 + 10)
Inter-repetition rest	30 s, passive	30 s, passive
Inter-set rest	2 min, passive	2 min, passive
Session duration	18 min	18 min
Prescribed volume	800 m	600 m
Est. volume >90% MSS	200 m	0 m
Physiological demand	High	High
Neuromuscular demand	High	High
Perceptual demand	Moderate	Moderate
Progression	Active recovery with sport-specific actions	Active recovery with sport-specific actions

COD = change of direction; m = meter; min = minutes; MSS = maximal sprint speed; RST = repeated-sprint training; s = second.

improve their fitness and physical preparation for the upcoming season. Following a general preparation block (Figure 1), RST can be administered during the specific preparation phase with sessions demanding on the metabolic and neuromuscular systems to maximize adaptation (Table 6). This may include longer sprints (30−40 m), active recovery, and a greater weekly RST volume (1,200−1,600 m). Coaches may wish to implement sets between technical and tactical drills or include additional modifications during or after sprint efforts (Figure 9). The objective of administering additional modifications is to provide a further physiological stimulus and/or execute movement patterns transferable to sport-specific actions.

COMPETITION PERIOD

Consistent performance across a season is crucial to success, and as such, recovery between games is paramount (87). In addition, technical and tactical practice is prioritized to fine-tune elements of match-play (46). The time assigned for isolated physical training is subsequently reduced during the competitive season, which makes the need for efficient and effective training methods even more important (46). While a reduction in training load is necessary to help manage the in-season stress on athletes, intensity should be maintained to avoid a slump in performance (31,110). Given that RST is time-efficient, low volume, high-intensity, and quickly recovered from (121), its application during the competition period is highly suitable. Low volume (<820 m), in-season RST interventions have been shown to significantly improve a range of physical qualities (23,28,63,88,97). Furthermore, when training and competition schedules are particularly congested, just 1 low-volume RST session per week, administered for 6−-8 weeks, maintained (5) and improved (97) 10-m and 20-m sprint times, RSA, intermittent running performance, and COD ability in young soccer players. Therefore, coaches may wish to implement RST at the beginning of in-season training sessions when athletes are least fatigued (e.g., as part of an extended warm-up), with just 2 sets of 4–6 repetitions of 20–30 m sprints providing a sufficient stimulus for adaptation (Table 7).

For players not selected for the weekly team or those playing limited minutes, "top-up" conditioning sessions are required to maintain a state of preparedness. In these instances, RST could be 1 strategy used within a multifactorial session consisting of several training methods (e.g., RST, small-sided games, short-bout and long-bout HIIT). Its application will provide adequate exposure to the intensity of competition and a considerable volume of high-speed running. Within a single 10-minute RST session consisting of 2 sets of 5 × 40 m straight-line sprints with 30-second rest, it was demonstrated that athletes attain 105 ± SD 54 m of sprinting (>90% of maximal speed) (120). Additional modifications to RST for top-up conditioning sessions could be easily implemented by coaches to provide a further physiological stimulus, permit the practice of movement skills under accumulating fatigue, and incorporate physical contact into the session.

RETURN TO COMPETITION FROM INJURY

The return to sport following injury is a multifactorial process requiring a player to meet a number of individually tailored criteria before they can safely and effectively resume

Table 7
Example of a 1-week repeated-sprint training program during the in-season

Training content	Session 1	Session 2
Aim	Maintain physical qualities + exposure to maximal acceleration	Maintain physical qualities + exposure to maximal COD
Sets × repetitions	2 × 5	2 × 5
RST modality	Straight line	Shuttle (1 × COD)
Repetition distance	20 m	20 m (10 + 10)
Inter-repetition rest	On 30 s, passive	On 30 s, passive
Inter-set rest	2 min, passive	2 min, passive
Session duration	7 min	7 min
Prescribed volume	200 m	200 m
Est. volume >90% MSS	40 m	0 m
Physiological demand	Low	Low
Neuromuscular demand	Low	Low
Perceptual demand	Low	Low
Progression	+ 1 set, +10-m distance	+ 1 set, +10-m distance

COD = change of direction; m = meter; min = minutes; MSS = maximal sprint speed; RST = repeated-sprint training; s = second.

competition (9,68). An important component of this process is the return to competition phase, where the player must successfully progress through a period of training involving sport-specific loading, including volumes of high-speed running and sprinting, which could be expected during matches (9,42,43,129). RST is 1 training method that can be administered during this phase to help prepare a player for the intensity of competition and may transfer to the performance of repeated high-intensity efforts, which appear frequently at critical times during a game (3,82,106). Shorter sprint distances (e.g., 20 m) and longer rest times (≥30 seconds) are initially advised to limit the physiological stress and musculoskeletal strain on the athlete. Sessions can progressively increase in volume and complexity by incorporating longer sprint distances, changes of direction, physical contact, and sport-specific actions (Table 8). Coaches should also consider that high-intensity efforts usually occur in small clusters within a game (3,4,16,34,106,114), which, along with current evidence (119,122), suggests that it is more beneficial to administer multiple sets of low repetitions (e.g., 3−4 sets of 4–6 reps), rather than a long series of exhaustive sprints that are more likely to exacerbate fatigue (119,122).

PRACTICAL CONSIDERATIONS FOR IMPLEMENTATION

RST is a highly practical conditioning method to implement with an entire sports team. In team sport athletes, sessions are traditionally completed as 1 large group that performs the same protocol. However, across a team of players, individual differences in athlete physiology (e.g., muscle fiber typology, energy substrate utilization) will exist, leading to each athlete having a propensity for speed versus endurance (104). Athletes with a large anaerobic speed reserve (i.e., speed profile: high sprint speed but relatively low maximal aerobic speed) record a fast initial sprint time but quickly fatigue during RST. Conversely, athletes with a small anaerobic speed reserve (i.e., endurance profile: relatively low sprint speed but high maximal aerobic speed) record a slower initial sprint time but can potentially sustain near-to-maximal speeds for approximately 10 repetitions. Hybrid athletes, who possess relatively equal potential for speed and endurance performance, lie in the middle, maintaining consistent sprint times for around 6 repetitions. These individual differences should be considered by coaches looking to optimize RST outcomes for each athlete. Therefore, rather than administering RST as 1 large group, a squad of athletes can be split into 3 groups: speed, hybrid, and endurance dominance. The speed group may benefit most from performing slightly less volume (104), divided across fewer successive repetitions and over additional sets with longer inter-repetition rest times (e.g., 4 sets of 4 reps with 30-second rest). The hybrid group can be prescribed a more traditional protocol (e.g., 3 sets of 6 reps with 20-second rest), while the endurance group would favor a higher volume (104) and higher repetition session with short inter-repetition rest (e.g., 3 sets of 8 reps with 15-second rest).

When training individual athletes, applying velocity-loss thresholds is a feasible method of prescription that accounts for diverse physical profiles and reductions in sprint performance (127). If the decrement of performance beyond a certain point is untenable (e.g., sprint performance declines more than 5% of initial sprint time), coaches can apply a threshold

Table 8
Example of a 1-week repeated-sprint training program for a player returning to competition from injury

Training content	Session 1	Session 2
Aim	Introduce repeated maximal linear sprints and sport skills under fatigue	Introduce repeated maximal COD and sport skills under fatigue
Sets × repetitions	3 × 4	3 × 4
RST modality	Straight-line	Multi-directional (see Figure 10, D)
Repetition distance	30 m	20 m (5 + 5 + 5 + 5)
Inter-repetition rest	30 s, passive	30 s, passive
Inter-set rest	4 min, active (sport-specific skills)	4 min, active (sport-specific skills)
Session duration	15 min	15 min
Prescribed volume	360 m	240 m
Est. volume >90% MSS	100 m	0 m
Physiological demand	Moderate	Moderate
Neuromuscular demand	Moderate	Moderate
Perceptual demand	Moderate	Moderate
Progression	+10 m distance, + 1 set, + contact	+ 10 m distance, + 1 set, + contact

COD = change of direction; m = meter; min = minutes; MSS = maximal sprint speed; RST = repeated-sprint training; s = second.

that terminates the set, allowing for a consistent sprint performance across the session for each individual athlete (127). Alternatively, rest redistribution protocols reallocate recovery time to introduce small intraset recovery periods during RST (127). For example, a set of 12 repetitions may be split into 4 sets of 3 repetitions with a small rest period between reps and sets. This strategy can allow for greater maintenance of sprint velocity and heart rate compared with traditional prescription without altering perceived effort (127).

Finally, an athlete's acute and chronic training loads are an important consideration when administering a training stimulus (64,80). Under the umbrella of training load, a player's exposure to high-speed running and maximal velocity sprinting is included. Underexposure and over-exposure to maximal velocity sprinting can increase the risk of injury, but an adequate or "optimal" range of sprinting is a relevant strategy to decrease the incidence of injury and prepare players for critical moments of match-play (25,80). While sprint exposure is specific to each population and context (25), RST provides considerable doses of both high-speed running and sprinting (120). Coaches should consider the individual athlete's chronic and recent exposure to these training loads within their decision-making framework. An applied example of a decision-making framework for the individualized application of RST for a speed-dominant athlete is provided in Figure 10. A similar framework can be applied with hybrid and endurance-dominant athletes but with altered RST prescriptions based on the strategies mentioned above.

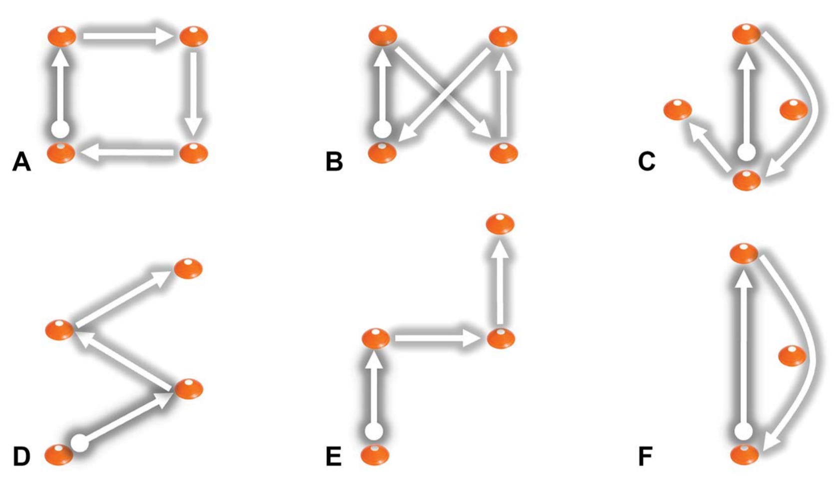


Figure 8. Some programming options for the application of multidirectional repeated-sprint training.

CONCLUSIONS

RST is an effective and time-efficient conditioning method that can be used to prepare intermittent sport athletes for the high-intensity demands of

Figure 9. Additional modifications to repeated-sprint training that may alter the training stimulus.

competition. To summarize the main findings from this review:

- RST is a mixed training method that emphasizes movement demands directly relevant to competition; thus, it is specific to the task but general to physiological adaptation.
- The substantial acute physiological demands of RST are demonstrated by an end-set blood lactate of ~10 $mmol \cdot L^{-1}$, an average heart rate of ~90% of max, and an average $\dot{V}O_2$ of ~70% of max. Sessions are perceived to be hard, but given they are short in duration, sRPE-TL is low, between 25 and 135 au.
- Shorter inter-repetition rest periods (≤20 seconds) and longer repetition distances (>30 m) increase physiological demands and cause greater reductions in acute sprint performance. Conversely, longer inter-repetition rest periods (≥30 seconds) and shorter repetition distances (≤20 m) enhance acute sprint performance and reduce physiological demands.
- RST concurrently improves a range of physiological, neuromuscular, morphological, and performance outcomes. It is associated with an improvement in linear and multidirectional sprint times by 2–3%, CMJ height and eccentric hamstring strength by 3%, aerobic capacity by 4%, biceps-femoris fascicle length by 10%, and YYIR1 distance by 16%.
- The prescription of 3 sets of 6 × 30 m sprints, twice per week for 6 weeks is an effective training program to achieve the established benefits of RST.

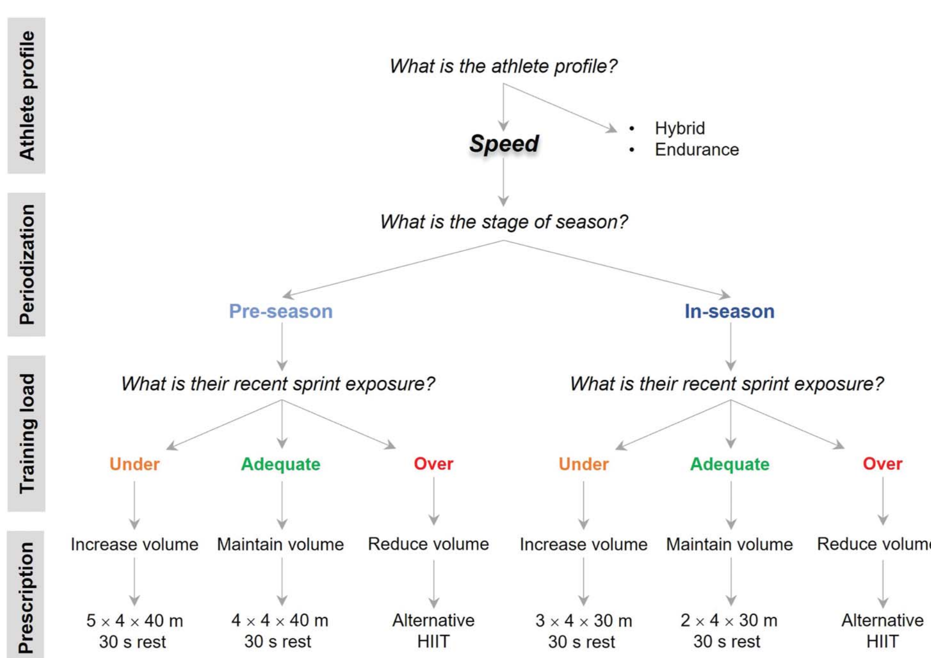


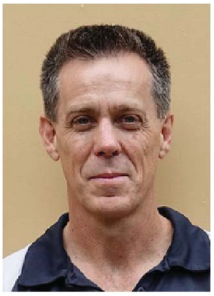
Figure 10. A decision chart demonstrating an individualized approach to repeated-sprint training for a speed-dominant athlete. *Note*, HIIT = high-intensity interval training; applying velocity-loss threshold may enable further individualization of the training prescription; alternative HIIT methods that would exclude players from sprint exposure include short-bout and long-bout high-intensity intervals.

- Higher repetition sets (e.g., 8–12 reps) are not associated with any beneficial effects on acute demands or chronic adaptations and may impair some outcomes. Training sessions incorporating small groups of repetitions performed over multiple sets (e.g., 3–4 sets of 4–6 repetitions) appear to be a more effective programming strategy.
- RST can be effectively applied during the offseason, preparation period, competition period, and return to competition from injury by manipulating programming variables to achieve desired outcomes.
- To individualize the prescription of RST, coaches should consider the specific demands of the sport, the athlete profile, the stage of the season, and the athlete's recent training load. Alternative methods of prescription, such as velocity loss thresholds and rest-redistribution, may also enhance the acute training stimulus.

Conflicts of Interest and Source of Funding: The authors report no conflicts of interest and no source of funding.

Fraser Thurlow, PhD *is a Lecturer in the School of Sport, Exercise and Rehabilitation at the University of Technology Sydney.*

Shaun J. McLaren, PhD *is a strength and conditioning coach at Newcastle Falcons Rugby Club and a research fellow at Manchester Metropolitan University.*



Andrew D. Townshend, PhD *is an Associate Professor at Australian Catholic University and the Sports Performance, Recovery, Injury and New Technologies (SPRINT) Research Centre.*

Jonathan Weakley, PhD *is an Associate Professor at Australian Catholic University and Research Associate at Leeds Beckett University.*

REFERENCES

1. Arede J, Fernandes JF, Schöllhorn WI, Leite N. Differential repeated sprinting training in youth basketball players: An analysis of effects according to maturity status. *Int J Environ Res Public Health* 19: 12265, 2022.
2. Attene G, Nikolaidis PT, Bragazzi NL, et al. Repeated sprint ability in young basketball players (Part 2): The chronic effects of multidirection and of one change of direction are comparable in terms of physiological and performance responses. *Front Physiol* 7: 262, 2016.
3. Austin DJ, Gabbett TJ, Jenkins DJ. Repeated high-intensity exercise in a professional rugby league. *J Strength Cond Res* 25: 1898–1904, 2011.
4. Atkins S, Barron DJ, Edmundson C, Fewtrell D. Repeated acceleration activity in competitive youth soccer. *Cent Eur J Sport Sci Med* 14: 55–61, 2016.
5. Beato M, Bianchi M, Coratella G, Merlini M, Drust B. A single session of straight line and change-of-direction sprinting per week does not lead to different fitness improvements in elite young soccer players. *J Strength Cond Res* 36: 518–524, 2022.
6. Billat LV. Interval training for performance: A scientific and empirical practice: Special recommendations for middle-and long-distance running. Part I: Aerobic interval training. *Sports Med* 31: 13–31, 2001.
7. Bishop D, Girard O, Mendez-Villanueva A. Repeated-sprint ability–part II: Recommendations for training. *Sports Med* 41: 741–756, 2011.
8. Black GM, Gabbett TJ, Johnston RD, Cole MH, Naughton G, Dawson B. The influence of physical qualities on activity profiles of female Australian football match play. *Int J Sports Physiol Perform* 13: 524–529, 2018.
9. Blanch P, Gabbett TJ. Has the athlete trained enough to return to play safely? The acute: Chronic workload ratio permits clinicians to quantify a player's risk of subsequent injury. *Br J Sports Med* 50: 471–475, 2016.
10. Blomqvist CG, Saltin B. Adaptations to physical training. *Ann Rev Physiol* 4: 169–189, 1983.
11. Bravo DF, Impellizzeri FM, Rampinini E, Castagna C, Bishop D, Wisloff U. Sprint vs. interval training in football. *Int J Sports Med* 29: 668–674, 2008.
12. Brini S, Marzouki H, Castagna C, Bouassida A. Effects of a four-week small-sided game and repeated sprint ability training during and after Ramadan on aerobic and anaerobic capacities in senior basketball players. *Ann Appl Sport Sci* 6: 7–13, 2018.
13. Brini S, Ouerghi N, Bouassida A. Small sided games vs repeated sprint training effects on agility in fasting basketball players. *Rev Bras Med Esporte* 26: 248–252, 2020.
14. Brocherie F, Millet GP, Girard O. Neuro-mechanical and metabolic adjustments to the repeated anaerobic sprint test in professional football players. *Eur J Appl Physiol* 115: 891–903, 2015.
15. Brughelli M, Cronin J, Levin G, Chaouachi A. Understanding change of direction ability in sport: A review of resistance training studies. *Sports Med* 38: 1045–1063, 2008.
16. Buchheit M-v, Mendez-Villanueva A, Simpson B, Bourdon P. Repeated-sprint sequences during youth soccer matches. *Int J Sports Med* 31: 709–716, 2010.
17. Buchheit M. Performance and physiological responses to repeated-sprint and jump sequences. *Eur J Appl Physiol* 110: 1007–1018, 2010.
18. Buchheit M. Should we be recommending repeated sprints to improve repeated-sprint performance? *Sports Med* 42: 169–173, 2012.
19. Buchheit M, Bishop D, Haydar B, Nakamura FY, Ahmaidi S. Physiological responses to shuttle repeated-sprint running. *Int J Sports Med* 31: 402–409, 2010.
20. Buchheit M, Cormie P, Abbiss C, Ahmaidi S, Nosaka KK, Laursen P. Muscle deoxygenation during repeated sprint running: Effect of active vs. passive recovery. *Int J Sports Med* 30: 418–425, 2009.
21. Buchheit M, Haydar B, Ahmaidi S. Repeated sprints with directional changes: Do angles matter? *J Sports Sci* 30: 555–562, 2012.
22. Buchheit M, Laursen PB. High-intensity interval training, solutions to the programming puzzle. Part II: Anaerobic energy, neuromuscular load and practical applications. *Sports Med* 43: 927–954, 2013.
23. Buchheit M, Mendez-Villanueva A, Delhomel G, Brughelli M, Ahmaidi S. Improving repeated sprint ability in young elite soccer players: Repeated shuttle sprints vs. explosive strength training. *J Strength Cond Res* 24: 2715–2722, 2010.
24. Buchheit M, Millet GP, Parisy A, Pourchez S, Laursen PB, Ahmaidi S. Supramaximal training and postexercise parasympathetic reactivation in adolescents. *Med Sci Sports Exerc* 40: 362–371, 2008.
25. Buchheit M, Settembre M, Hader K, McHugh D. Exposures to near-to-maximal speed running bouts during different turnarounds in elite football: Association with match hamstring injuries. *Biol Sport* 40: 1057–1067, 2023.
26. Burgomaster KA, Howarth KR, Phillips SM, et al. Similar metabolic adaptations during exercise after low volume sprint interval and traditional

endurance training in humans. *J Physiol* 586: 151–160, 2008.

27. Chiu LZ, Barnes JL. The fitness-fatigue model revisited: Implications for planning short-and long-term training. *Strength Cond J* 25: 42–51, 2003.
28. Chtara M, Rouissi M, Haddad M, et al. Specific physical trainability in elite young soccer players: Efficiency over 6 weeks' in-season training. *Biol Sport* 34: 137–148, 2017.
29. Clausen JP. Effect of physical training on cardiovascular adjustments to exercise in man. *Physiol Rev* 57: 779–815, 1977.
30. Connolly F, White P. *Game Changer*. Las Vegas, NV: Victory Belt Publishing; 2017.
31. Cunningham DJ, Shearer DA, Drawer S, et al. Relationships between physical qualities and key performance indicators during match-play in senior international rugby union players. *PLoS ONE* 13: e0202811, 2018.
32. Dalton-Barron NE, McLaren SJ, Black CJ, Gray M, Jones B, Roe G. Identifying contextual influences on training load: An example in professional rugby union. *J Strength Cond Res* 35: 503–511, 2021.
33. Dawson B. Repeated-sprint ability: Where are we? *Int J Sports Physiol Perform* 7: 285–289, 2012.
34. Dawson B, Goodman C, Lawrence S, et al. Muscle phosphocreatine repletion following single and repeated short sprint efforts. *Scand J Med Sci Sports* 7: 206–213, 1997.
35. Dello Iacono A, McLaren SJ, Macpherson TW, et al. Quantifying exposure and intra-individual reliability of high-speed and sprint running during sided-games training in soccer players: A systematic review and meta-analysis. *Sports Med* 53: 371–413, 2023.
36. Dent JR, Edge JA, Hawke E, McMahon C, Mündel T. Sex differences in acute translational repressor 4E-BP1 activity and sprint performance in response to repeated-sprint exercise in team sport athletes. *J Sci Med Sport* 18: 730–736, 2015.
37. Dupont G, Moalla W, Guinhouya C, Ahmaidi S, Berthoin S. Passive versus active recovery during high-intensity intermittent exercises. *Med Sci Sports Exerc* 36: 302–308, 2004.
38. Eniseler N, Şahan Ç, Özcan I, Dinler K. High-intensity small-sided games versus repeated sprint training in junior soccer players. *J Hum Kinet* 60: 101–111, 2017.
39. Faude O, Koch T, Meyer T. Straight sprinting is the most frequent action in goal situations in professional football. *J Sports Sci* 30: 625–631, 2012.
40. Fort-Vanmeerhaeghe A, Montalvo A, Latinjak A, Unnithan V. Physical characteristics of elite adolescent female basketball players and their relationship to match performance. *J Hum Kinet* 53: 167–178, 2016.
41. Gabbett T, Sancho I, Dingenen B, Willy RW. When progressing training loads, what are the considerations for healthy and injured athletes? *Br J Sports Med* 55: 947–948, 2021.
42. Gabbett TJ. Debunking the myths about training load, injury and performance: Empirical evidence, hot topics and recommendations for practitioners. *Br J Sports Med* 54: 58–66, 2020.
43. Gaitanos GC, Williams C, Boobis LH, Brooks S. Human muscle metabolism during intermittent maximal exercise. *J Appl Physiol* 75: 712–719, 1993.
44. Galvin HM, Cooke K, Sumners DP, Mileva KN, Bowtell JL. Repeated sprint training in normobaric hypoxia. *Br J Sports Med* 47: i74–i79, 2013.
45. Gamble P. Periodization of training for team sports athletes. *Strength Cond J* 28: 56–66, 2006.
46. Gantois P, Batista GR, Aidar FJ, et al. Repeated sprint training improves both anaerobic and aerobic fitness in basketball players. *Isokinetics Exerc Sci* 27: 97–105, 2019.
47. Gantois P, Batista GR, Dantas M, et al. Short-term effects of repeated-sprint training on vertical jump ability and aerobic fitness in collegiate volleyball players during pre-season. *Int J Exerc Sci* 15: 1040–1051, 2022.
48. Gatterer H, Philippe M, Menz V, Mosbach F, Faulhaber M, Burtscher M. Shuttle-run sprint training in hypoxia for youth elite soccer players: A pilot study. *J Sports Sci Med* 13: 731–735, 2014.
49. Gharbi Z, Dardouri W, Haj-Sassi R, Castagna C, Chamari K, Souissi N. Effect of the number of sprint repetitions on the variation of blood lactate concentration in repeated sprint sessions. *Biol Sport* 31: 151–156, 2014.
50. Girard O, Mendez-Villanueva A, Bishop D. Repeated-sprint ability–part I: Factors contributing to fatigue. *Sports Med* 41: 673–694, 2011.
51. Girard O, Racinais S, Kelly L, Millet GP, Brocherie F. Repeated sprinting on natural grass impairs vertical stiffness but does not alter plantar loading in soccer players. *Eur J Appl Physiol* 111: 2547–2555, 2011.
52. Granata C, Oliveira RS, Little JP, Renner K, Bishop DJ. Training intensity modulates changes in PGC-1α and p53 protein content and mitochondrial respiration, but not markers of mitochondrial content in human skeletal muscle. *FASEB J* 30: 959–970, 2016.
53. Haff GG, Triplett NT. *Essentials of Strength Training and Conditioning*. 4th ed. Champaign, IL: Human Kinetics; 2015.
54. Halson SL. Monitoring training load to understand fatigue in athletes. *Sports Med* 44: 139–147, 2014.
55. Harrison PW, Johnston RD. Relationship between training load, fitness, and injury over an Australian rules football preseason. *J Strength Cond Res* 31: 2686–2693, 2017.
56. Haugen T, Buchheit M. Sprint running performance monitoring: Methodological and practical considerations. *Sports Med* 46: 641–656, 2016.
57. Haugen T, Tønnessen E, Øksenholt Ø, et al. Sprint conditioning of junior soccer players: Effects of training intensity and technique supervision. *PLoS ONE* 10: e0121827, 2015.
58. Houtmeyers KC, Robberechts P, Jaspers A, et al. Differential ratings of perceived exertion: Relationships with external intensity and load in elite men's football. *Int J Sports Physiol Perform* 17: 1415–1424, 2022.
59. Howells D. Energy system development in high intensity repeat effort sports. In: *Presented at Australian Strength and Conditioning Association*. Australia: International Conferance Gold Coast, 2023.
60. Hughes DC, Ellefsen S, Baar K. Adaptations to endurance and strength training. *Cold Spring Harb Perspect Med* 8: a029769, 2018.
61. Hureau TJ, Ducrocq GP, Blain GM. Peripheral and central fatigue development during all-out repeated cycling sprints. *Med Sci Sports Exerc* 48: 391–401, 2016.
62. Iaia FM, Fiorenza M, Larghi L, Alberti G, Millet GP, Girard O. Short-or long-rest intervals during repeated-sprint training in soccer? *PLoS ONE* 12: e0171462, 2017.
63. Impellizzeri FM, Marcora SM, Coutts AJ. Internal and external training load: 15 years on. *Int J Sports Physiol Perform* 14: 270–273, 2019.
64. Jeffries AC, Marcora SM, Coutts AJ, Wallace L, McCall A, Impellizzeri FM. Development of a revised conceptual framework of physical training for use in research and practice. *Sports Med* 52: 709–724, 2021.
65. Jiménez-Reyes P, Cross M, Ross A, et al. Changes in mechanical properties of sprinting during repeated sprint in elite rugby sevens athletes. *Eur J Sport Sci* 19: 585–594, 2019.
66. Joyce D, Lewindon D. *High-performance Training for Sports*. Champaign, IL: Human Kinetics; 2014.
67. Joyce D, Lewindon D. *Sports Injury Prevention and Rehabilitation*. Abingdon, Oxfordshire: Routledge; 2016.
68. Kaufmann S, Hoos O, Kuehl T, et al. Energetic profiles of the Yo-Yo intermittent recovery tests 1 and 2. *Int J Sports Physiol Perform* 15: 1400–1405, 2020.
69. Krustrup P, Bangsbo J. Physiological demands of top-class soccer refereeing in relation to physical capacity: Effect of intense intermittent exercise training. *J Sports Sci* 19: 881–891, 2001.
70. Krustrup P, Mohr M, Amstrup T, et al. The yo-yo intermittent recovery test: Physiological response, reliability, and validity. *Med Sci Sports Exerc* 35: 697–705, 2003.
71. Krustrup P, Mohr M, Ellingsgaard H, Bangsbo J. Physical demands during an elite female soccer game: Importance of training status. *Med Sci Sports Exerc* 37: 1242–1248, 2005.
72. Lapointe J, Paradis-Deschênes P, Woorons X, Lemaître F, Billaut F. Impact of hypoventilation training on muscle oxygenation, myoelectrical changes, systemic [K+], and repeated-sprint ability in basketball players. *Front Sports active Living* 2; 29, 2020.
73. Laursen P, Buchheit M. *Science and Application of High-Intensity Interval Training*. Champaign, IL: Human Kinetics; 2019.
74. Laursen PB, Jenkins DG. The scientific basis for high-intensity interval training: Optimising training programmes and maximising performance in highly trained endurance athletes. *Sports Med* 32: 53–73, 2002.
75. Little T, Williams AG. Effects of sprint duration and exercise: Rest ratio on repeated sprint performance and physiological responses in professional soccer players. *J Strength Cond Res* 21: 646–648, 2007.
76. Macpherson RE, Hazell TJ, Olver TD, Paterson DH, Lemon PW. Run sprint interval training improves aerobic performance but not maximal cardiac output. *Med Sci Sports Exerc* 43: 115–122, 2011.
77. Maggioni MA, Bonato M, Stahn A, et al. Effects of ball drills and repeated-sprint-ability training in basketball players. *Int J Sports Physiol Perform* 14: 757–764–764, 2019.
78. Malone JJ, Di Michele R, Morgans R, Burgess D, Morton JP, Drust B. Seasonal training-load quantification in elite English Premier League soccer players. *Int J Sports Physiol Perform* 10: 489–497, 2015.
79. Malone S, Roe M, Doran DA, Gabbett TJ, Collins K. High chronic training loads and exposure to bouts of maximal velocity running reduce injury risk in elite Gaelic football. *J Sci Med Sport* 20: 250–254, 2017.
80. Manuel Clemente F, Ramirez-Campillo R, Nakamura FY, Sarmento H. Effects of high-intensity interval training in men soccer player's physical fitness: A systematic review with meta-analysis of randomized-controlled and non-controlled trials. *J Sports Sci* 39: 1202–1222, 2021.
81. Martínez-Hernández D, Quinn M, Jones P. Linear advancing actions followed by deceleration and turn are the most common movements preceding goals in male professional soccer. *Sci Med Footb* 7: 25–33, 2022.
82. McLaren SJ, Weston M, Smith A, Cramb R, Portas MD. Variability of physical performance and player match loads in professional rugby union. *J Sci Med Sport* 19: 493–497, 2016.

83. Medbø J, Burgers S. Effect of training on the anaerobic capacity. *Med Sci Sports Exerc* 22: 501–507, 1990.
84. Meyer T, Faude O, Scharhag J, Urhausen A, Kindermann W. Is lactic acidosis a cause of exercise induced hyperventilation at the respiratory compensation point? *Br J Sports Med* 38: 622–625, 2004.
85. Midgley AW, McNaughton LR, Jones AM. Training to enhance the physiological determinants of long-distance running performance: Can valid recommendations be given to runners and coaches based on current scientific knowledge? *Sports Med* 37: 857–880, 2007.
86. Midgley AW, McNaughton LR, Wilkinson M. Is there an optimal training intensity for enhancing the maximal oxygen uptake of distance runners? Empirical research findings, current opinions, physiological rationale and practical recommendations. *Sports Med* 36: 117–132, 2006.
87. Mujika I, Halson S, Burke LM, Balagué G, Farrow D. An integrated, multifactorial approach to periodization for optimal performance in individual and team sports. *Int J Sports Physiol Perform* 13: 538–561, 2018.
88. Nedrehagen ES, Saeterbakken AH. The effects of in-season repeated sprint training compared to regular soccer training. *J Hum Kinet* 49: 237–244, 2015.
89. Negra Y, Sammoud S, Ramirez-Campillo R, Bouguezzi R, Moran J, Chaabene H. The effects of repeated sprint training with versus without change of direction on measures of physical fitness in youth male soccer players. *The J Sports Med Phys fitness* 63: 8–15, 2023.
90. Padulo J, Laffaye G, Haddad M, et al. Repeated sprint ability in young basketball players: One vs. two changes of direction (Part 1). *J Sports Sci* 33: 1480–1492, 2015.
91. Padulo J, Tabben M, Ardigò L, et al. Repeated sprint ability related to recovery time in young soccer players. *Res Sports Med* 23: 412–423, 2015.
92. Padulo J, Tabben M, Attene G, Ardigò L, Dhahbi W, Chamari K. The impact of jumping during recovery on repeated sprint ability in young soccer players. *Res Sports Med* 23: 240–252, 2015.
93. Paulauskas R, Kamarauskas P, Nekriošius R, Bigwood NM. Physical and physiological response to different modes of repeated sprint exercises in basketball players. *J Hum Kinet* 72: 91–99, 2020.
94. Perrey S, Racinais S, Saimouaa K, Girard O. Neural and muscular adjustments following repeated running sprints. *Eur J Appl Physiol* 109: 1027–1036, 2010.
95. Rampinini E, Bishop D, Marcora S, Ferrari Bravo D, Sassi R, Impellizzeri F. Validity of simple field tests as indicators of match-related physical performance in top-level professional soccer players. *Int J Sports Med* 28: 228–235, 2007.
96. Rampinini E, Impellizzeri FM, Castagna C, Azzalin A, Ferrari Bravo D, Wisløff U. Effect of match-related fatigue on short-passing ability in young soccer players. *Med Sci Sports Exerc* 40: 934–942, 2008.
97. Rey E, Padrón-Cabo A, Costa PB, Lago-Fuentes C. Effects of different repeated sprint-training frequencies in youth soccer players. *Biol Sport* 36: 257–264, 2019.
98. Rodas G, Ventura JL, Cadefau JA, Cussó R, Parra J. A short training programme for the rapid improvement of both aerobic and anaerobic metabolism. *Eur J Appl Physiol* 82: 480–486, 2000.
99. Rosenblat MA, Granata C, Thomas SG. Effect of interval training on the factors influencing maximal oxygen consumption: A systematic review and meta-analysis. *Sports Med* 52: 1329–1352, 2022.
100. Rosenblat MA, Lin E, da Costa BR, Thomas SG. Programming interval training to optimize time-trial performance: A systematic review and meta-analysis. *Sports Med* 51: 1687–1714, 2021.
101. Ross A, Leveritt M. Long-term metabolic and skeletal muscle adaptations to short-sprint training: Implications for sprint training and tapering. *Sports Med* 31: 1063–1082, 2001.
102. Rumpf MC, Lockie RG, Cronin JB, Jalilvand F. Effect of different sprint training methods on sprint performance over various distances: A brief review. *J Strength Cond Res* 30: 1767–1785, 2016.
103. Sahlin K. Muscle energetics during explosive activities and potential effects of nutrition and training. *Sports Med* 44: 167–173, 2014.
104. Sandford GN, Laursen PB, Buchheit M. Anaerobic speed/power reserve and sport performance: Scientific basis, current applications and future directions. *Sports Med* 51: 2017–2028, 2021.
105. Scalzo RL, Peltonen GL, Binns SE, et al. Greater muscle protein synthesis and mitochondrial biogenesis in males compared with females during sprint interval training. *FASEB J* 28: 2705–2714, 2014.
106. Serpiello FR, Duthie GM, Moran C, Kovacevic D, Selimi E, Varley MC. The occurrence of repeated high acceleration ability (RHAA) in elite youth football. *Int J Sports Med* 39: 502–507, 2018.
107. Serpiello FR, McKenna MJ, Bishop DJ, et al. Repeated sprints alter signaling related to mitochondrial biogenesis in humans. *Med Sci Sports Exerc* 44: 827–834, 2012.
108. Sheppard JM, Young WB. Agility literature review: Classifications, training and testing. *J Sports Sci* 24: 919–932, 2006.
109. Silva JR, Brito J, Akenhead R, Nassis GP. The transition period in soccer: A window of opportunity. *Sports Med* 46: 305–313, 2016.
110. Slattery KM, Wallace LK, Bentley DJ, Coutts AJ. Effect of training load on simulated team sport match performance. *Appl Physiol Nutr Metab* 37: 315–322, 2012.
111. Sloth M, Sloth D, Overgaard K, Dalgas U. Effects of sprint interval training on VO 2max and aerobic exercise performance: A systematic review and meta-analysis. *Scand J Med Sci Sports* 23: e341–e352, 2013.
112. Souhail H, Castagna C, Mohamed HY, Younes H, Chamari K. Direct validity of the yo-yo intermittent recovery test in young team handball players. *J Strength Cond Res* 24: 465–470, 2010.
113. Spencer M, Bishop D, Dawson B, Goodman C. Physiological and metabolic responses of repeated-sprint activities:specific to field-based team sports. *Sports Med* 35: 1025–1044, 2005.
114. Spencer M, Lawrence S, Rechichi C, Bishop D, Dawson B, Goodman C. Time–motion analysis of elite field hockey, with special reference to repeated-sprint activity. *J Sports Sci* 22: 843–850, 2004.
115. Taylor J, Macpherson T, Spears I, Weston M. The effects of repeated-sprint training on field-based fitness measures: A meta-analysis of controlled and non-controlled trials. *Sports Med* 45: 881–891, 2015.
116. Taylor JB, Wright AA, Dischiavi SL, Townsend MA, Marmon AR. Activity demands during multi-directional team sports: A systematic review. *Sports Med* 47: 2533–2551, 2017.
117. Taylor JM, Macpherson TW, McLaren SJ, Spears I, Weston M. Two weeks of repeated-sprint training in soccer: To turn or not to turn? *Int J Sports Physiol Perform* 11: 998–1004, 2016.
118. Taylor L, Jakeman JR. The Impact of a Repeated sprint training program on performance measures in male field hockey players. *J Strength Cond Res* 36: 1984–1988, 2022.
119. Thurlow F, Huynh M, Townshend A, et al. The effects of repeated-sprint training on physical fitness and physiological adaptation in athletes: A systematic review and meta-analysis. *Sports Med* 54: 953–974, 2023.
120. Thurlow F, McLaren SJ, Townshend A, Morrison M, Cowley N, Weakley J. Repeated-sprint training: The effects of session volume on acute physiolgical, neuromuscular, perceptual and performance outcomes in athletes. *Euro J Sport Sci*. 2024.
121. Thurlow F, Timmins RG, McLaren SJ, et al. The effects of repeated-sprint training vs short-bout high-intensity interval training on hamstring architecture and physical fitness. *J Strength Cond Res*. 2024. In press.
122. Thurlow F, Weakley J, Townshend AD, Timmins RG, Morrison M, McLaren SJ. The acute demands of repeated-sprint training on physiological, neuromuscular, perceptual and performance outcomes in team sport athletes: A systematic review and meta-analysis. *Sports Med*. 2023;53:1609–1640.
123. Timmins RG, Bourne MN, Shield AJ, Williams MD, Lorenzen C, Opar DA. Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): A prospective cohort study. *Br J Sports Med* 50: 1524–1535, 2016.
124. Veale JP, Pearce AJ, Carlson JS. The Yo-Yo intermittent recovery test (level 1) to discriminate elite junior Australian football players. *J Sci Med Sport* 13: 329–331, 2010.
125. Vollaard N, Metcalfe R, Williams S. Effect of number of sprints in an SIT session on change in VO2max: A meta-analysis. *Med Sci Sports Exerc* 49: 1147–1156, 2017.
126. Weakley J, Black G, McLaren S, et al. Testing and profiling athletes: Recommendations for test selection, implementation, and maximizing information. *Strength Cond J* 10: 1519, 2022.
127. Weakley J, Castilla AP, Ramos AG, et al. Effect of traditional, rest redistribution, and velocity-based prescription on repeated sprint training performance and responses in semiprofessional athletes. *J Strength Cond Res* 10: 1519, 2022.
128. Weakley J, McLaren S, Ramirez-Lopez C, et al. Application of velocity loss thresholds during free-weight resistance training: Responses and reproducibility of perceptual, metabolic, and neuromuscular outcomes. *J Sports Sci* 38: 477–485, 2020.
129. Whiteley R, Massey A, Gabbett T, et al. Match high-speed running distances are often suppressed after return from hamstring strain injury in professional footballers. *Sports Health* 13: 290–295, 2021.
130. Zagatto AM, Ardigò LP, Barbieri FA, et al. Performance and metabolic demand of a new repeated-sprint ability test in basketball players: Does the number of changes of direction matter? *J Strength Cond Res* 31: 2438–2446, 2017.