Sports Med (2013) 43:313–338
DOI 10.1007/s40279-013-0029-x

REVIEW ARTICLE

High-Intensity Interval Training, Solutions to the Programming Puzzle

Part I: Cardiopulmonary Emphasis

Martin Buchheit · Paul B. Laursen

Published online: 29 March 2013
© Springer International Publishing Switzerland 2013

Abstract High-intensity interval training (HIT), in a variety of forms, is today one of the most effective means of improving cardiorespiratory and metabolic function and, in turn, the physical performance of athletes. HIT involves repeated short-to-long bouts of rather high-intensity exercise interspersed with recovery periods. For team and racquet sport players, the inclusion of sprints and all-out efforts into HIT programmes has also been shown to be an effective practice. It is believed that an optimal stimulus to elicit both maximal cardiovascular and peripheral adaptations is one where athletes spend at least several minutes per session in their 'red zone,' which generally means reaching at least 90 % of their maximal oxygen uptake ($\dot{V}O_{2max}$). While use of HIT is not the only approach to improve physiological parameters and performance, there has been a growth in interest by the sport science community for characterizing training protocols that allow athletes to maintain long periods of time above 90 % of $\dot{V}O_{2max}$ (T@$\dot{V}O_{2max}$). In addition to T@$\dot{V}O_{2max}$, other physiological variables should also be considered to fully characterize the training stimulus when programming HIT, including cardiovascular work, anaerobic glycolytic energy contribution and acute neuromuscular load and musculoskeletal strain. Prescription for HIT consists of the manipulation of up to nine variables, which include the work interval intensity and duration, relief interval intensity and duration, exercise modality, number of repetitions, number of series, as well as the between-series recovery duration and intensity. The manipulation of any of these variables can affect the acute physiological responses to HIT. This article is Part I of a subsequent II-part review and will discuss the different aspects of HIT programming, from work/relief interval manipulation to the selection of exercise mode, using different examples of training cycles from different sports, with continued reference to T@$\dot{V}O_{2max}$ and cardiovascular responses. Additional programming and periodization considerations will also be discussed with respect to other variables such as anaerobic glycolytic system contribution (as inferred from blood lactate accumulation), neuromuscular load and musculoskeletal strain (Part II).

M. Buchheit
ASPIRE, Football Performance & Science Department, Academy for Sports Excellence, Doha, Qatar

M. Buchheit (✉)
Physiology Unit, Sport Science Department, ASPIRE, Academy for Sports Excellence, P.O. Box 22287, Doha, Qatar
e-mail: martin.buchheit@aspire.qa; mb@martin-buchheit.net

P. B. Laursen
High Performance Sport New Zealand, Auckland, New Zealand

P. B. Laursen
Sport Performance Research Institute New Zealand (SPRINZ), Auckland University of Technology, Auckland, New Zealand

1 Introduction

With respect to prescribing training that improves performance, coaches know that ''there's more than one way to skin the cat.''[1] Recent reviews [1, 2] have highlighted the potential of varying quantities of both high-intensity interval training (HIT) and continuous high-volume, low-intensity training on performance in highly trained athletes. While there is no doubt that both types of training can effectively improve cardiac and skeletal muscle metabolic function, and that a dose of both types of training are important constitutes of an athlete's training programme,

this review will focus solely on the topic of HIT. Indeed, a number of studies in this area have emerged over the last decade, and it is perhaps not surprising that running- or cycling-based HIT is today considered one of the most effective forms of exercise for improving physical performance in athletes [3–6]. "HIT involves repeated short-to-long bouts of rather high-intensity exercise interspersed with recovery periods" [3], and has been used by athletes for almost a century now. For example, in 1920, Paavo Nurmi, one of the best middle- and long-distance runners in the world at that time, was already using some form of HIT in his training routines. Emil Zatopek contributed later in the 1950s to the popularization of this specific training format (see Billat [3] for a detailed history of HIT). The progressive emergence of this training method amongst elite athletes is the first evidence of its effectiveness (i.e. 'best practice' theory [2]). More recently, the use of sprints and all-out efforts has also emerged, both from the applied (team sport) field and the laboratory [7–9]. These particularly intense forms of HIT include repeated-sprint training (RST; sprints lasting from 3 to 7 s, interspersed with recovery periods lasting generally less than 60 s) or sprint interval training (SIT; 30 s all-out efforts interspersed with 2–4 min passive recovery periods).

Following pioneering experiments by Hill in the 1920s (Hill included intermittent exercises in his first studies [2]), Astrand and co-workers published several classical papers in the 1960s on the acute physiological responses to HIT, which created the first scientific basis for long [10] and short [11, 12] duration intervals. Studies by Balsom et al. followed in the 1990s, emphasizing all-out efforts [13]. As will be detailed in the review, most of the scientific work that followed these studies over the past 20–50 years has been an extension of these findings using new technology in the field (i.e. more accurate and portable devices). However, the important responses and mechanisms of HIT had already been demonstrated [10–12].

It has been suggested that HIT protocols that elicit maximal oxygen uptake ($\dot{V}O_{2max}$), or at least a very high percentage of $\dot{V}O_{2max}$, maximally stress the oxygen transport and utilization systems and may therefore provide the most effective stimulus for enhancing $\dot{V}O_{2max}$ [5, 14, 15]. While evidence to justify the need to exercise at such an intensity remains unclear, it can be argued that only exercise intensities near $\dot{V}O_{2max}$ allow for both large motor unit recruitment (i.e. type II muscle fibres) [16, 17] and attainment of near-to-maximal cardiac output (see Sect. 3.2), which, in turn, jointly signals for oxidative muscle fibre adaptation and myocardium enlargement (and hence, $\dot{V}O_{2max}$). For an optimal stimulus (and forthcoming cardiovascular and peripheral adaptations), it is believed that athletes should spend at least several minutes per HIT session in their 'red zone,' which generally means attaining an intensity greater than 90 % of $\dot{V}O_{2max}$ [3, 5, 15, 18]. Consequently, despite our limited understanding of the dose-response relationship between the training load and training-induced changes in physical capacities and performance (which generally shows large inter-individual responses [19, 20]), there has been a growing interest by the sport science community for characterizing training protocols that allow athletes to maintain the longest time >90 % $\dot{V}O_{2max}$ (T@$\dot{V}O_{2max}$; see Midgley and McNaughton [14] for review). In addition to T@$\dot{V}O_{2max}$, however, other physiological variables should also be considered to fully characterize the training stimulus when programming HIT [21–23]. Any exercise training session will challenge, at different respective levels relative to the training content, both the metabolic and the neuromuscular/musculoskeletal systems [21, 22]. The metabolic system refer to three distinct yet closely related integrated processes, including (1) the splitting of the stored phosphagens (adenosine triphosphate [ATP] and phosphocreatine [PCr]); (2) the nonaerobic breakdown of carbohydrate (anaerobic glycolytic energy production); and (3) the combustion of carbohydrates and fats in the presence of oxygen (oxidative metabolism, or aerobic system) [184]. It is therefore possible to precisely characterize the acute physiological responses of any HIT session, based on (a) the respective contribution of these three metabolic processes; (b) the neuromuscular load; and (c) the musculoskeletal strain (Fig. 1, Part I). Under these assumptions, we consider the cardiorespiratory (i.e. oxygen uptake; $\dot{V}O_2$) data, but also cardiovascular work [24–27]), stored energy [28, 29] and cardiac autonomic stress [30–33] responses as the primary variables of interest when programming HIT sessions (review Part I). By logic, anaerobic glycolytic energy contribution and neuromuscular load/musculoskeletal strain are therefore likely the more important secondary variables to consider when designing a given HIT session (Part II).

Several factors determine the desired acute physiological response to an HIT session (and the likely forthcoming adaptations) [Fig. 1]. The sport that the athlete is involved in (i.e. training specificity) and the athlete's profile or sport specialty (e.g. an 800 m runner will likely favour a greater proportion of 'anaerobic-based' HIT compared with a marathon runner [6]) should first be considered in relation to the desired long-term training adaptations. Second, and more importantly on a short-term basis, training periodization has probably the greatest impact on the HIT prescription. Many of the desired training adaptations are likely training cycle dependent (e.g. generic aerobic power development in the initial phase of the preseason vs. sport-specific and more anaerobic-like HIT sessions towards the

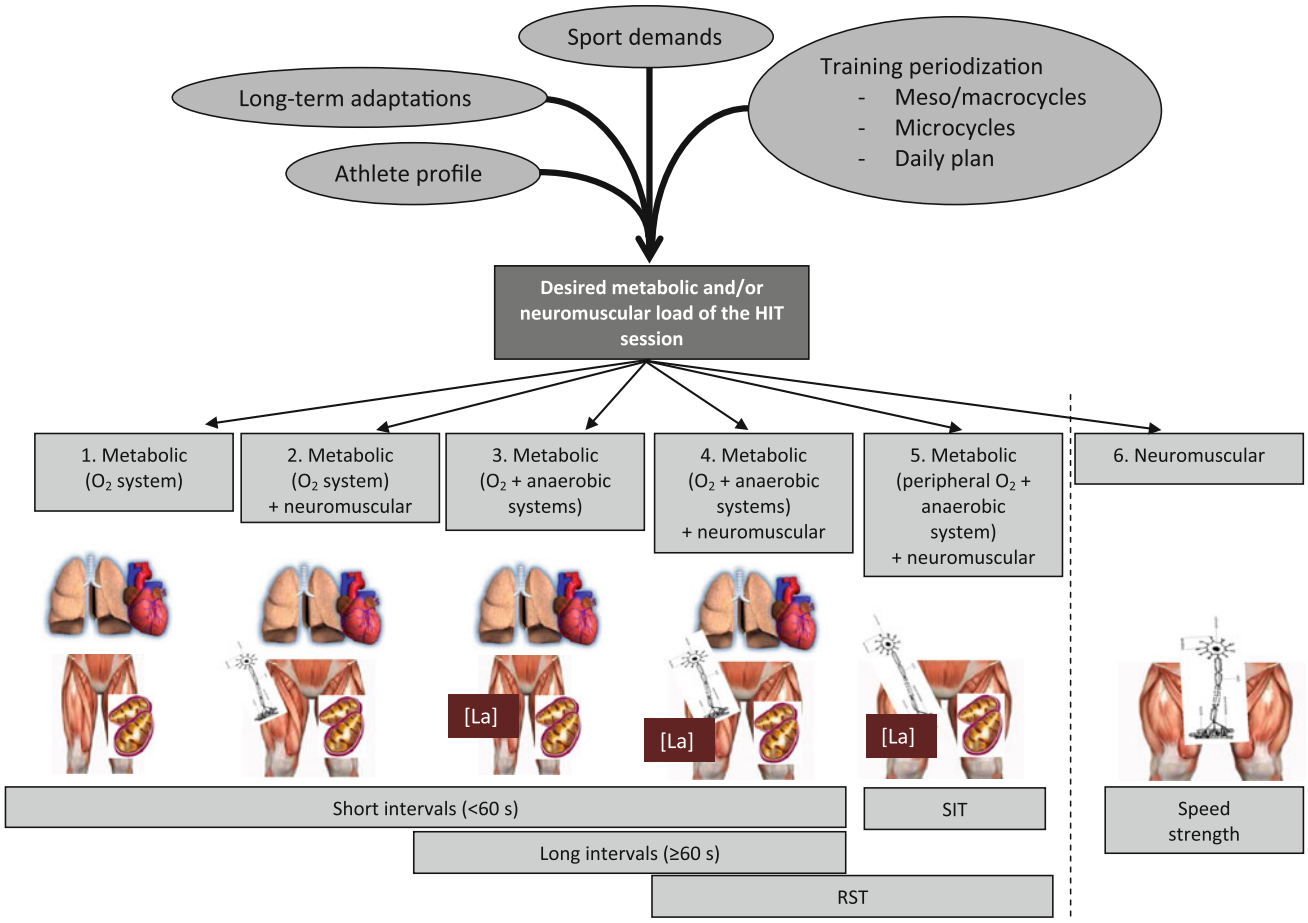

Fig. 1 Decision process for selecting an HIT format based on the expected acute physiological response/strain. The six different types of acute responses are categorized as (*1*) metabolic, but eliciting essentially large requirements from the O_2 transport and utilization systems, i.e. cardiopulmonary system and oxidative muscle fibres; (*2*) metabolic as for (1) but with a certain degree of neuromuscular strain; (*3*) metabolic as for (1) but with a large anaerobic glycolytic energy contribution; (*4*) metabolic as for (3) plus a certain degree of neuromuscular load; (*5*) metabolic with essentially an important anaerobic glycolytic energy contribution and a large neuromuscular load; and (*6*) eliciting a high predominant neuromuscular strain. While some HIT formats can be used to match different response categories (e.g. short intervals when properly manipulated can match into categories 1–4), SIT for example can only match category 5. Category 6 is not detailed in the present review since it does not fit into any particular type of HIT. *HIT* high-intensity interval training, *[La]* blood lactate accumulation; surrogate of anaerobic glycolytic energy release *RST* repeated-sprint training, *SIT* spring interval training

start of the competitive season in team sports). Additionally, for athletes training twice a day, and/or in team sport players training a myriad of metabolic and neuromuscular systems simultaneously [34], the physiological strain associated with a given HIT session needs to be considered in relation to the demands of other physical and technical/tactical sessions to avoid overload and enable appropriate adaptation (i.e. maximize a given training stimulus and minimize musculoskeletal injury risk). There are likely several approaches (i.e. HIT format) that, considered in isolation, will achieve a similar metabolic and/or neuromuscular training adaptation outcome. However, the ability of the coach to understand the isolated acute responses to various HIT formats may assist with selection of the most appropriate HIT session to apply, at the right place and time.

At least nine variables can be manipulated to prescribe different HIT sessions (Fig. 2 [35]). The intensity and duration of work and relief intervals are the key influencing factors [10, 12]. Then, the number of intervals, the number of series and between-series recovery durations and intensities determine the total work performed. Exercise modality (i.e. running vs. cycling or rowing, or straight line vs. uphill or change of direction running) has to date received limited scientific interest, but it is clear that it represents a key variable to consider when programming HIT, especially for team and racquet sport athletes. The manipulation of each variable in isolation likely has a direct impact on metabolic, cardiopulmonary and/or neuromuscular responses. When more than one variable is manipulated simultaneously, responses are more difficult to

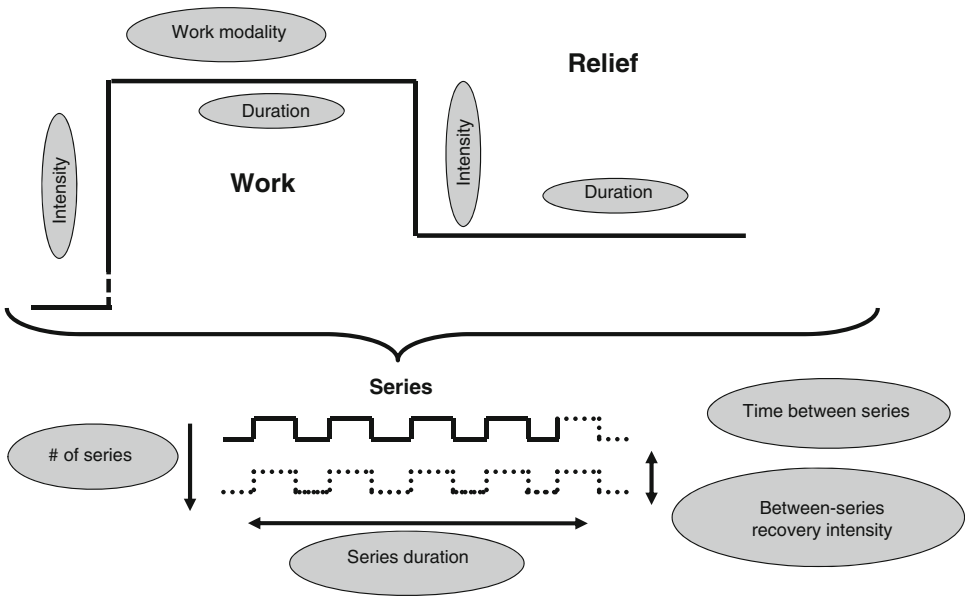

Fig. 2 Schematic illustration of the nine variables defining a HIT session adapted from Buchheit [35]. *HIT* high-intensity interval training

predict, since the factors are inter-related. While our understanding of how to manipulate these variables is progressing with respect to T@$\dot{V}O_{2max}$ [14], it remains unclear which combination of work-interval duration and intensity, if any, is most effective at allowing an individual to spend prolonged T@$\dot{V}O_{2max}$ while 'controlling' for the level of anaerobic engagement [3] and/or neuromuscular load (review Part II).

Considering that long-term physiological and performance adaptations to HIT are highly variable and likely population-dependent (age, gender, training status and background) [19, 20], providing general recommendations for the more efficient HIT format is difficult. We provide, however, in Part I of this review, the different aspects of HIT programming, from work/relief interval manipulation to the selection of exercise modality, with continued reference to T@$\dot{V}O_{2max}$ (i.e. time spent ≥90 % $\dot{V}O_{2max}$, otherwise stated), which may assist to individualize HIT prescription for different types of athletes. Additional programming considerations will also be discussed with respect to other variables, such as cardiovascular responses. Different examples of training cycles from different sports will be provided in Part II of the present review. As this was a narrative, and not a systematic review, our methods included a selection of the papers we believed to be most relevant in the area. Since the main goal of HIT sessions is to improve the determinants of $\dot{V}O_{2max}$, only HIT sessions performed in the severe intensity domain (i.e. greater than the second ventilatory threshold or maximal lactate steady state) were considered. Acute responses to running-based HIT were given priority focus, since the largest quantity of literature has used this exercise mode. It is likely, however, that the manipulation of these same HIT variables has comparable effects in other sports (or exercise modes, e.g. cycling, rowing, etc.), with the exception of under-water activities that may require a specific programming approach [36]. Finally, we believe that the present recommendations are essentially appropriate for moderately trained to elite athletes. For special populations (e.g. sedentary or cardiac patients), the reader is referred to recent reviews [37] and original investigations [38–40]. Standardized differences (or effect sizes; ES [41]) have been calculated where possible to examine the respective effects of the manipulation of each HIT variable, and interpreted using Hopkins' categorization criteria, where 0.2, 0.6, 1.2 and >2 are considered 'small', 'medium', 'large' and 'very large' effects, respectively [42].

2 Prescribing Interval Training for Athletes in the Field

To prescribe HIT and ensure that athletes reach the required intensity, several approaches exist to control and individualize exercise speed/power accordingly. We will discuss these points and illustrate why, in our opinion, using incremental test parameters is far more objective, practical, and likely more accurate and effective at achieving desired performance outcomes.

2.1 The Track-and-Field Approach

To programme HIT for endurance runners, coaches have traditionally used specific running speeds based on set times for distances ranging from 800 m to 5000 m, but without using physiological markers such as the speeds

associated with $\dot{V}O_{2max}$, lactate or ventilatory thresholds [3]. It is worth mentioning, however, that coaches and athletes have been, and still are, highly successful using this approach; an observation that should humble the exercise physiologist. The attraction of this method is that the entire locomotor profile (i.e. both maximal sprinting and aerobic speeds, Fig. 3) of the athlete can be used to 'shape' the HIT session, so that each run can be performed in accordance with the athlete's (maximal) potential. While for short intervals (i.e. 10–60 s) the reference running time will be a percentage of the time measured over a maximal 100–400 m sprint, the speed maintained over 800–1,500 m to 2,000–3,000 m can be used to calibrate longer intervals (e.g. 2–4 to 6–8 min). The disadvantage of this approach, however, is that it does not allow the coach to consciously manipulate the acute physiological load of the HIT session, and precisely target a specific adaptation (i.e. Fig. 1, when there is a need to improve a physiological quality and not just to prepare for a race). Additionally, this approach tends to be reserved for highly experienced coaches and well trained athletes, for whom best running times on several set distances are known. The translation and application of the track-and-field method to other sports is, however, difficult. For example, how might a coach determine the expected 800-m run time for a 2.10-m tall basketball player that has never run more that 40 s continuously on a court before? Thus, using the track-and-field approach for non-track-and-field athletes is unlikely to be appropriate, practical or effective.

2.2 The Team Sport Approach

Due to the technical/tactical requirements of team sports, and following the important principle of training specificity, game- (i.e. so-called small sided games, SSG) [43–46] or skill-based [47, 48] conditioning has received an exponential growth in interest [49]. While understanding of the $\dot{V}O_2$ responses to SSG is limited [44, 50, 51], T@$\dot{V}O_{2max}$ during an SSG in national-level handball players was achieved for 70 % of the session (i.e. 5 min 30 s of the 8-min game) [50]. Although the effectiveness of such an approach has been shown [43, 46, 52, 53], SSGs have limitations that support the use of less specific (i.e. run based) but more controlled HIT formats at certain times of the season or for specific player needs. The acute physiological load of an SSG session can be manipulated by changing the technical rules [54], the number of players and pitch size [55], but the overall load cannot, by default, be precisely standardized. Within-player responses to SSG are highly variable (poor reproducibility for blood lactate [coefficient of variation (CV): 15–30 %] and high-intensity running responses [CV: 30–50 %] [56, 57]), and the between-player variability in the (cardiovascular) responses is higher than more specific run-based HIT [49]. During an SSG in handball, average $\dot{V}O_2$ was shown to be inversely related to $\dot{V}O_{2max}$ [50], suggesting a possible ceiling effect for $\dot{V}O_{2max}$ development in fitter players. Additionally, reaching and maintaining an elevated cardiac filling is believed to be necessary to improve maximal cardiac

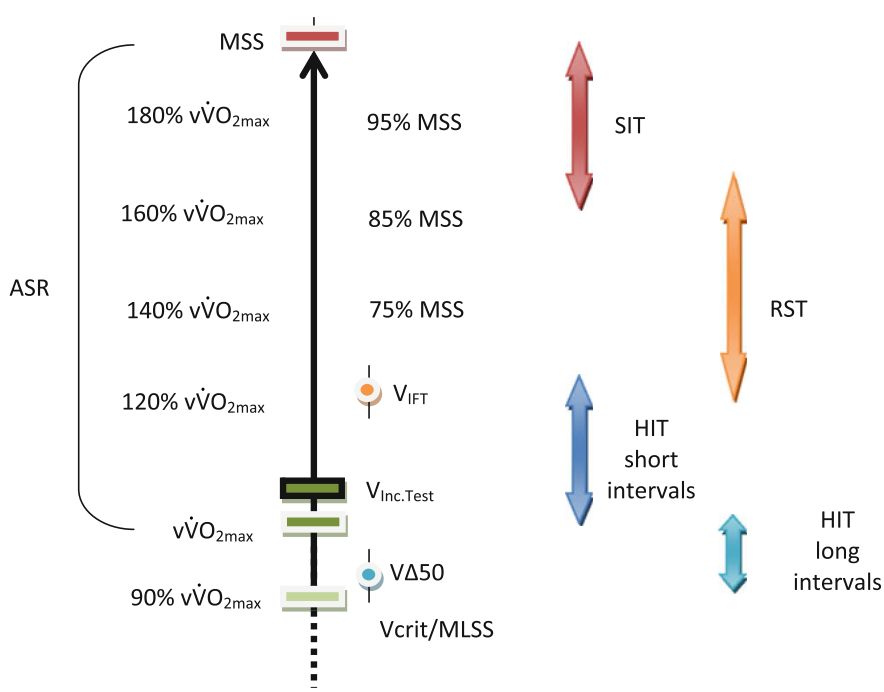

Fig. 3 Intensity range used for the various run-based HIT formats. *ASR* anaerobic speed reserve, *MLSS* maximal lactate steady state, *MSS* maximal sprinting speed, *RST* repeated-sprint training, *SIT* sprint interval training, $\dot{V}O_{2max}$ maximal oxygen uptake, $v\dot{V}O_{2max}$ minimal running speed required to elicit $\dot{V}O_{2max}$, $V\Delta 50$ speed half way between $v\dot{V}O_{2max}$ and MLSS, V_{crit} critical velocity, V_{IFT} peak speed reached at the end of the 30–15 Intermittent Fitness Test, $V_{Inc.Test}$ peak incremental test speed

function [58, 59]. The repeated changes in movement patterns and the alternating work and rest periods during an SSG might therefore induce variations in muscular venous pump action, which can, in turn, limit the maintenance of a high stroke volume (SV) throughout the exercise and compromise long term adaptations [60] (see Sect. 3.2). Compared with generic run-based exercises, the $\dot{V}O_2$/heart rate (HR) ratio (which can be used with caution as a surrogate of changes in SV during constant exercise when the arteriovenous O_2 difference is deemed constant [61]) is also likely lower during an SSG [44, 50, 51]. While this ratio is generally close to 1 during run-based long intervals (i.e. $\dot{V}O_2$ at 95 % $\dot{V}O_{2max}$ for HR at 95 % of maximal HR (HR_{max}) [21, 62]), authors have reported values at 79 % $\dot{V}O_{2max}$ and 92 % HR_{max} during basketball drills [44] and at 52 % $\dot{V}O_{2max}$ and 72 % HR_{max} during a five-a-side indoor soccer game [51]. This confirms the aforementioned possible limitations with respect to SV enlargement, and suggests that assessment of cardiopulmonary responses during an SSG (and competitive games) using HR may be misleading [63]. Finally, the $\dot{V}O_2$/speed [50] (and HR/speed [63]) relationship also tends to be higher during an SSG compared with generic running, possibly due to higher muscle mass involvement. While this method of training is often considered to be highly specific, this is not always the case, since during competitive games players have often more space to run and reach higher running speeds (up to 85–90 % of maximal sprinting speed [64–66]) for likely similar metabolic demands.

2.3 Heart Rate-Based Prescription

Heart rate has become the most commonly measured physiological marker for controlling exercise intensity in the field [67]. Setting exercise intensity using HR zones is well suited to prolonged and submaximal exercise bouts; however, its effectiveness for controlling or adjusting the intensity of an HIT session may be limited. HR cannot inform the intensity of physical work performed above the speed/power associated with $\dot{V}O_{2max}$, which represents a large proportion of HIT prescriptions [3–5]. Additionally, while HR is expected to reach maximal values (>90–95 % HR_{max}) for exercise at or below the speed/power associated with $\dot{V}O_{2max}$, this is not always the case, especially for very short (<30 s) [68] and medium-long (i.e. 1–2 min) [69] intervals. This is related to the well-known HR lag at exercise onset, which is much slower to respond compared with the $\dot{V}O_2$ response [70]. Further, HR inertia at exercise cessation (i.e. HR recovery) can also be problematic in this context, since this can create an overestimation of the actual work/physiological load that occurs during recovery periods [69]. It has also been shown that substantially different exercise sessions (as assessed by accumulated blood lactate levels during run-based HIT [71] and by running speed during an SSG [63]) can have a relatively similar mean HR response. Thus, the temporal dissociation between HR, $\dot{V}O_2$, blood lactate levels and work output during HIT limits our ability to accurately estimate intensity during HIT sessions using HR alone. Further, it is difficult to imagine how an athlete would practically control or adjust exercise intensity during an interval, especially for athletes running at high speed, where viewing HR from a watch is difficult.

2.4 Rating of Perceived Exertion-Based Prescription

Prescribing the intensity of HIT bouts using the rating of perceived exertion (RPE) method [72] is highly attractive because of its simplicity (no need to monitor HR) and versatility. Using this approach, coaches generally prescribe independent variables such as the duration or distance of work and relief intervals [71]. In return, the athlete can self-regulate their exercise intensity. The intensity selected is typically the maximal intensity of exercise perceived as sustainable ('hard' to 'very hard', i.e. ≥6 on a CR-10 Borg scale and ≥15 on a 6–20 scale) and is based on the athlete's experience, the session goal and external considerations related to training periodization. While the specific roles (or contributions) played by varying biological afferents and other neurocognitive processes involved with the selection of exercise pace based on effort are still debated (see viewpoint/counterpoint [73]), RPE responses may reflect "a conscious sensation of how hard, heavy, and strenuous exercise is" [74], relative to the combined physiological [75], biomechanical and psychological [76] stress/fatigue imposed on the body during exercise [77]. RPE responses are gender-independent [78] and comparable during free versus constant pace exercise [79]. In practice, the first benefit of RPE-guided HIT sessions [69, 71] is that they do not require any knowledge of the athletes' fitness level (no test results needed). Finally, RPE is a universal 'exercise regulator', irrespective of locomotor mode and variations in terrain and environmental conditions. While more research in trained athletes is needed to confirm the efficacy of RPE-guided training sessions, it has been shown to promote the same physiological adaptations as an HR-based programme over 6 weeks in young women [80]. The RPE method does have limitations, however, since it does not allow for the precise manipulation of the physiological response to a given HIT session. This could limit the ability to target a specific adaptation (i.e. Fig. 1), and might also be problematic in a team sport setting (as discussed in the three preceding sections). There is also some evidence to suggest that the ability to adjust/evaluate

exercise intensity based on RPE may be age- [81], fitness- [82, 83], exercise-intensity- and pleasure-[84] dependent.

2.5 Velocity/Power Associated with Maximal Oxygen Uptake ($\dot{V}O_{2max}$)

Following early works in the 1970s and 1980s [85–88], the physiologists V.L. Billat and D.W. Hill popularized the speed (or power) associated with $\dot{V}O_{2max}$ (so-called v/p$\dot{V}O_{2max}$ or maximal aerobic speed/power [MAS/MAP] [89, 90]) as a useful reference intensity to programme HIT [3–5]. The attractiveness of the v/p$\dot{V}O_{2max}$ method is that it represents an integrated measure of both $\dot{V}O_{2max}$ and the energetic cost of running/cycling into a single factor; hence, being directly representative of an athletes' locomotor ability [89]. Since v/p$\dot{V}O_{2max}$ is theoretically the lowest speed/power needed to elicit $\dot{V}O_{2max}$, it makes intuitive sense for this marker to represent an ideal reference for training [5, 15, 89].

v/p$\dot{V}O_{2max}$ can be determined, or estimated, a number of different ways. Methods include using the following:

1) The linear relationship between $\dot{V}O_2$ and running speed established at submaximal speeds [88].
2) The individual cost of running to calculate a theoretical running speed for a given $\dot{V}O_{2max}$, either with [91] or without [92] resting $\dot{V}O_2$ values.
3) Direct measurement (i.e. pulmonary gas exchange [93]) during ramp-like incremental running/cycling tests to exhaustion, either on the track, on a treadmill or using an ergometer. On the track, the University of Montreal Track Test (UM-TT [87]) is the protocol most commonly used with athletes [94, 95], although the Vam-Eval [96], which only differs from the UM-TT due to its smoother speed increments and shorter intercones distances, has also received growing interest since it is easier to administer in young populations and/or non-distance running specialists [97, 98]. Since the 'true' v/p$\dot{V}O_{2max}$ during incremental tests requires $\dot{V}O_2$ measures to determine the lowest speed/power that elicits $\dot{V}O_{2max}$ (generally defined as a plateau in $\dot{V}O_2$ or an increase less than 2.1 mL/min/kg despite an increase in running speed of 1 km/h [93]), the final (peak) incremental test speed/power reached at the end of these tests (V/$p_{Inc.Test}$) is only an approximation of v/p$\dot{V}O_{2max}$. These two distinct speeds/powers are strongly correlated ($r > 0.90$ [87]), but V/$p_{Inc.Test}$ can be 5–10 % greater than v/p$\dot{V}O_{2max}$, with individuals possessing greater anaerobic reserves presenting generally a greater v/p$\dot{V}O_{2max}$ − V/$p_{Inc.Test}$ difference. Measurement of $V_{Inc.Test}$ is, however, very practical in the field since it is largely correlated with distance running performance [99] and match running capacity in team sports (but for some positions only) [98, 100].
4) A 5-min exhaustive run [101], since the average time to exhaustion at v$\dot{V}O_{2max}$ has been reported to range from 4 to 8 min [89, 102]. The v$\dot{V}O_{2max}$ calculated from this test has been shown to be largely correlated with the $V_{Inc.Test}$ reached in the UM-TT ($r = 0.94$) and on a ramp treadmill test ($r = 0.97$) [101], while being slightly (i.e. 1 km/h range) slower and faster than these velocities, respectively. The v$\dot{V}O_{2max}$ estimated via the 5-min test is, however, likely influenced by pacing strategies, and may only be valid for trained runners able to run at v$\dot{V}O_{2max}$ for ≈5 min.

v$\dot{V}O_{2max}$ is also method-[90] and protocol-dependent [103]. A mathematically estimated v$\dot{V}O_{2max}$ [88, 91] is likely to be lower than a measured v$\dot{V}O_{2max}$ [93] that is also lower than $V_{Inc.Test}$ [89, 104]. Additionally, irrespective of the method used to determine v$\dot{V}O_{2max}$, protocols with longer-stage durations tend to elicit lower speed/power values [103], while larger speed/power increments result in higher-speed/power values. Similarly, v$\dot{V}O_{2max}$ also appears to be inversely related to the terrain or treadmill slope [105]. Endurance-trained athletes are likely able to tolerate longer stages and therefore, less likely to present impairments in v$\dot{V}O_{2max}$ with variations in protocol. These differences must be acknowledged since small differences in the prescribed work intensity have substantial effects on acute HIT responses.

The reliability of v$\dot{V}O_{2max}$ and $V_{Inc.Test}$ (as examined using CVs) has been shown to be good: 3 % for v$\dot{V}O_{2max}$ in moderately trained middle- and long-distance runners [68], 3.5 % for UM-TT $V_{Inc.Test}$ in moderately trained athletes [87], 3.5 % (90 % confidence limits: 3.0, 4.1 [Buchheit M, unpublished results]) for Vam-Eval $V_{Inc.Test}$ in 65 highly trained young football players, 2.5 % and 3 % for treadmill $V_{Inc.Test}$ in well trained male distance runners [106] and recreational runners [104], respectively, and finally, 1–2 % for the 5-min test in a heterogeneous sporting population [107].

For training prescription, $V_{Inc.Test}$, as determined in the field with the UM-TT [87] or the Vam-Eval [96], is probably the preferred method, since, in addition to not requiring sophisticated apparatus, the tests account for the anaerobic contribution necessary to elicit $\dot{V}O_{2max}$ [108]. It is, however, worth noting that using v$\dot{V}O_{2max}$ or $V_{Inc.Test}$ as the reference running speed is essentially suitable for long (2–6 min) intervals ran around v$\dot{V}O_{2max}$ (90–105 %). For sub- and supramaximal training intensities, however, the importance of other physiological attributes should be

considered. For instance, endurance capacity (or the capacity to sustain a given percentage of $v\dot{V}O_{2max}$ over time [109]) and anaerobic power/capacity [110] are likely to influence time to exhaustion and, in turn, the physiological responses. The following section highlights the different options available for the prescription of supramaximal training (i.e. training at intensities > $v\dot{V}O_{2max}$).

2.6 Anaerobic Speed Reserve

Consideration for an individual's anaerobic speed reserve (ASR; the difference between maximal sprinting speed (MSS) and $v\dot{V}O_{2max}$, Fig. 3) is often not fully taken into account by coaches and scientists in their training prescription. While track-and-field (running) coaches have indirectly used this concept for years to set the work interval intensity (as discussed in Sect. 2.1), its scientific basis and interest was only brought forth merely a decade ago, when Billat and co-workers [110] showed that time to exhaustion at intensities above $v\dot{V}O_{2max}$ were better related to the ASR and/or MSS, than to $v\dot{V}O_{2max}$. Bundle et al. [111–113] demonstrated, using an empirical prediction model, that the proportion of ASR used could determine performance during all-out efforts lasting between a few seconds and several minutes. While these studies have used continuous exercise, ASR has only recently been considered in relation to repeated-sprint performance [114, 115]. In practice, two athletes can present with clearly different MSS ability, despite a similar $v\dot{V}O_{2max}$ (Fig. 4 [116]). If during an HIT session they exercise at a similar percentage of $v\dot{V}O_{2max}$, as is generally implemented in the field (e.g. see [117]), the exercise will actually involve a different proportion of their ASR, which results in a different physiological demand, and in turn, a different exercise tolerance [116]. Therefore, it appears that, in addition to $v\dot{V}O_{2max}$, the measurement of MSS (and ASR) should be considered for individualizing training intensity during supramaximal HIT [110, 116].

2.7 Peak Speed in the 30–15 Intermittent Fitness Test

While using the ASR to individualize exercise intensity for supramaximal runs might represent an improved alternative over that of $v\dot{V}O_{2max}$ or $V_{Inc.Test}$, it still does not capture an overall picture of the different physiological variables of importance during team- or racquet-based specific HIT sessions. In many sports, HIT is performed indoors and includes repeated very short work intervals (<45 s). This implies that, in addition to the proportion of the ASR used, the responses to these forms of HIT appear related to an individual's (1) metabolic inertia (e.g. $\dot{V}O_2$ kinetics) at the onset of each short interval; (2)

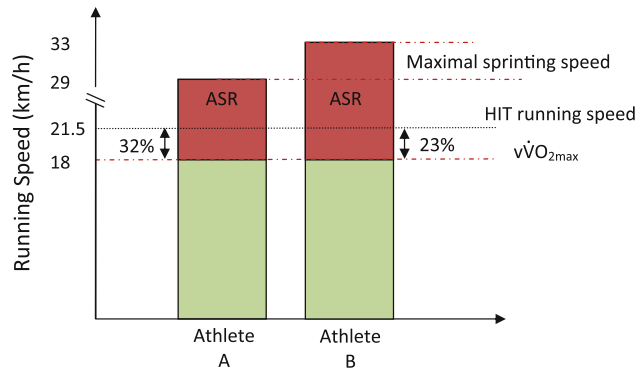

Fig. 4 Illustration of the importance of ASR for two athletes possessing similar running speeds associated with $v\dot{V}O_{2max}$, but different maximal sprinting speeds. During an HIT session, Athlete B with a greater ASR will work at a lower percentage of his ASR, and will therefore achieve a lower exercise load compared with Athlete A [116]. *ASR* anaerobic speed reserve, *HIT* high-intensity interval training, $v\dot{V}O_{2max}$ minimal running speeds associated with maximal oxygen uptake

physiological recovery capacities during each relief interval; and (3) change of direction ability (since indoor HIT is often performed in shuttles) [94, 116]. Programming HIT without taking these variables into consideration may result in sessions with different aerobic and anaerobic energy demands, which prevents the standardization of training load, and likely limits the ability to target specific physiological adaptations [94]. To overcome the aforementioned limitations inherent with the measurement of $v\dot{V}O_{2max}$ and ASR, the 30–15 Intermittent Fitness Test ($30–15_{IFT}$) was developed for intermittent exercise and change of direction (COD)-based HIT prescription [35, 94, 116]. The $30–15_{IFT}$ was designed to elicit maximal HR and $\dot{V}O_2$, but additionally provide measures of ASR, repeated effort ability, acceleration, deceleration, and COD abilities [94, 118, 119]. The final speed reached during the $30–15_{IFT}$, V_{IFT}, is therefore a product of those above-mentioned abilities. In other words, the $30–15_{IFT}$ is highly specific, not to a specific sport, but to the training sessions commonly performed in intermittent sports [116]. While the peak speeds reached in the different Yo-Yo tests [120] (e.g. vYo-YoIR1 for the Yo-Yo Intermittent Recovery Level 1) and V_{IFT} have likely similar physiological requirements [221], only the V_{IFT} can be used accurately for training prescription. For instance, vYo-YoIR1 cannot be directly used for training prescription since, in contrast to V_{IFT} [35], its relationship with $V_{Inc.Test}$ (and $v\dot{V}O_{2max}$) is speed-dependent [121], Fig. 5). When running at vYo-YoIR1, slow and unfit athletes use a greater proportion of their ASR, while fitter athletes run below their $v\dot{V}O_{2max}$ (Fig. 5). Finally, V_{IFT} has been shown to be more accurate than $V_{Inc.Test}$ for individualizing HIT with COD in well trained team sport players [94], and its reliability is good, with the typical

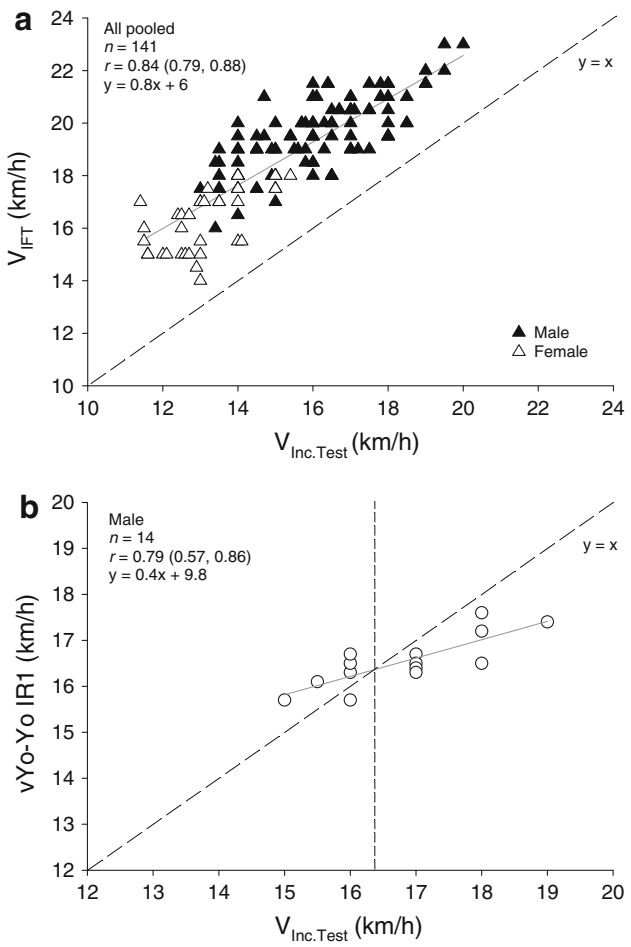

Fig. 5 Relationships (90 % confidence limits) between the V_{IFT}, upper panel (Buchheit M, personal data [35]), vYo-YoIR1, lower panel [121] and $V_{Inc.Test}$. *V_{IFT}* speed reached at the end of the 30–15 Intermittent Fitness Test, *$V_{Inc.Test}$* peak incremental test speed, *vYo-YoIR1* peak running speed reached at the end of the Yo-Yo intermittent recovery level 1 test

error of measurement (expressed as CV) shown to be 1.6 % (95 % CL 1.4, 1.8) [122]. Also of note, since V_{IFT} is 2–5 km/h (15–25 %) faster than v$\dot{V}O_{2max}$ and/or $V_{Inc.Test}$ [35, 116, 119], it is necessary to 'adjust' the percentage of V_{IFT} used when programming. While HIT is generally performed around v$\dot{V}O_{2max}$ (i.e. 100–120 % [3, 4], Fig. 3), V_{IFT} constitutes the upper limit for these exercises (except for very short intervals and all-out repeated-sprint training). Thus, the 30–15_{IFT} permits improved precision of programming by individualizing the intensity of the prescribed interval bouts around intensities ranging from 85 % to 105 % of V_{IFT} [43, 50, 123–125].

2.8 All-Out Sprint Training

Repeated all-out sprinting efforts have received a marked growth in research interest lately [9, 126]. In practical terms, these sessions can be divided into either short (3–10 s, RST) or long (30–45 s sprints, SIT) duration sprints. Since such exercise is consistently performed 'all-out', they can be prescribed without the need to pre-test the individual (i.e. v/p$\dot{V}O_{2max}$ is not specifically needed to calibrate the intensity).

3 Acute Responses to Variations of Interval Training

3.1 Maximizing the Time Spent at or Near $\dot{V}O_{2max}$

We lead off this review with data related to T@$\dot{V}O_{2max}$ (reviewed previously [14]), since pulmonary $\dot{V}O_2$ responses may actually integrate both cardiovascular and muscle metabolic (oxidative) responses to HIT sessions. In the present review, we integrate recently published work and provide a comprehensive analysis of the $\dot{V}O_2$ responses to different forms of HIT, from long intervals to SIT sessions, through short intervals and repeated-sprint sequences (RSS, Fig. 3). Figure 6 illustrates the $\dot{V}O_2$ responses of four distinct HIT sessions, including long intervals, and highlights how changes in HIT variables can impact the T@$\dot{V}O_{2max}$ [21, 50, 127, 128]. There are, however, numerous methodological limitations that need to be considered to interpret the findings shown from the different studies [68, 103, 129]. In addition to methodological considerations between studies (treadmill vs. overground running, determination criteria for both $\dot{V}O_{2max}$ and v$\dot{V}O_{2max}$, data analysis [averaging, smoothing technique], threshold for minimal $\dot{V}O_2$ values considered as maximal [90 %, 95 %, $\dot{V}O_{2max}$ minus 2.1 ml/min/kg, 100 %]), differences in the reliability level of analysers and intra-day subject variation in $\dot{V}O_{2max}$, $\dot{V}O_2$ kinetics and times to exhaustion, make comparison between studies difficult. The within-study effects of HIT variable manipulation on the observed T@$\dot{V}O_{2max}$ can, however, provide insight towards understanding how best to manipulate HIT variables.

3.1.1 Oxygen Uptake ($\dot{V}O_2$) Responses to Long Intervals

3.1.1.1 Exercise Intensity during Long Intervals During a single constant-speed or power exercise, work intensity close to v/p$\dot{V}O_{2max}$ is required to elicit maximal $\dot{V}O_2$ responses. In an attempt to determine the velocity associated with the longest T@$\dot{V}O_{2max}$ during a run to exhaustion, six physical-education students performed four separate runs at 90 %, 100 %, 120 % and 140 % of their v$\dot{V}O_{2max}$ (17 km/h) [130]. Not surprisingly, time to exhaustion was inversely related to running intensity. T@$\dot{V}O_{2max}$ during the 90 % and 140 % conditions was trivial (i.e. <20 s on average), but reached substantially

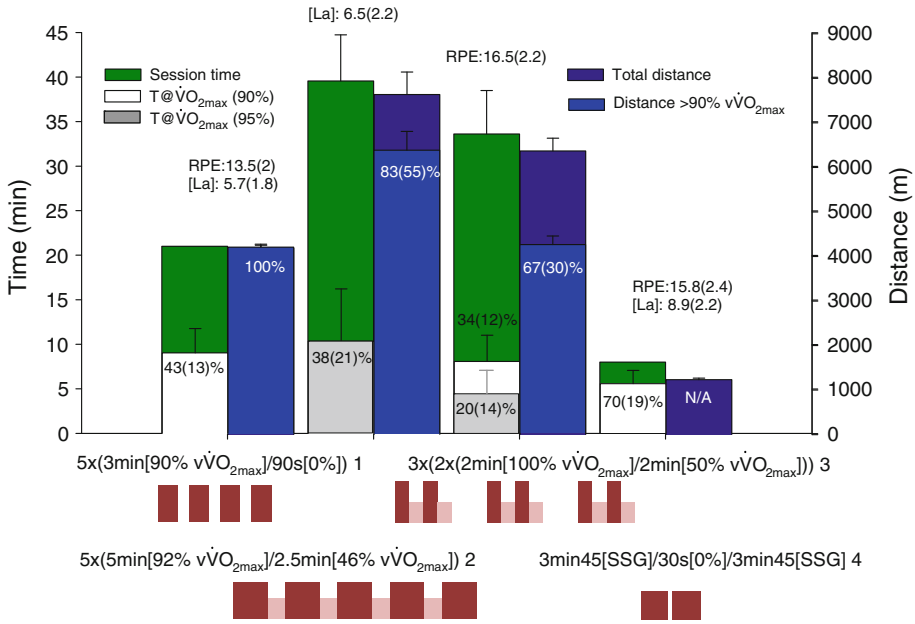

Fig. 6 Mean ± SD of total session time, T@$\dot{V}O_{2max}$, total distance and distance ran above 90 % of v$\dot{V}O_{max}$ during four different HIT sessions including long intervals. Percentages (mean ± SD) refer to T@$\dot{V}O_{2max}$ relative to the total session time, and distance ran above 90 % of v$\dot{V}O_{2max}$ relative to the total distance ran. RPE and [La], mmol/L) are provided as mean ± SD when available. References: 1 [21]; 2 [127]; 3 [128] and 4 [50]. *HIT* high-intensity interval training, *[La]* blood lactate concentration, *N/A* not available, *RPE* rating of perceived exertion, *SSG* small-sided games (handball), $\dot{V}O_{2max}$ maximal oxygen uptake, *T@*$\dot{V}O_{2max}$ time spent above 90 % or 95 % of $\dot{V}O_{2max}$, *v*$\dot{V}O_{2max}$ minimal running speed associated with $\dot{V}O_{2max}$

'larger' values at 100 % and 120 %: mean ± standard deviation 190 ± 87 (57 % of time to exhaustion, ES > +2.8) and 73 ± 29 s (59 %, ES > +1.7). In another study, middle-distance runners did not manage to reach $\dot{V}O_{2max}$ while running at 92 % of v$\dot{V}O_{2max}$ [131]. The ability to reach $\dot{V}O_{2max}$ during a single run at the velocity between the maximal lactate steady state and v$\dot{V}O_{2max}$ (i.e. vΔ50, ≈92–93 % of v$\dot{V}O_{2max}$ [130]) via the development of a $\dot{V}O_2$ slow component [10] is likely fitness-dependent [132] (with highly trained runners unlikely to reach $\dot{V}O_{2max}$). In addition, as the determination of vΔ50 is impractical in the field, work intensities of ≥95 % v/p$\dot{V}O_{2max}$ are therefore recommended for maximizing T@$\dot{V}O_{2max}$ during single isolated runs. However, in practice, athletes do not exercise to exhaustion, but use intervals or sets. Slightly lower intensities (≥90 % v/p$\dot{V}O_{2max}$) can also be used when considering repeated exercise bouts (as during HIT sessions), since interval $\dot{V}O_2$ is likely to increase with repetitions with the development of a $\dot{V}O_2$ slow component [10]. As suggested by Astrand in the 1960s [10], exercise intensity does not need to be maximal during an HIT session to elicit $\dot{V}O_{2max}$.

3.1.1.2 Time-to-Reach $\dot{V}O_{2max}$ and Maximizing Long-Interval Duration If $\dot{V}O_{2max}$ is to be reached during the first interval of a sequence, its interval duration must at least be equal to the time needed to reach $\dot{V}O_{2max}$. Thus, with short intervals, as during typical HIT sessions (work interval duration < time needed to reach $\dot{V}O_{2max}$), $\dot{V}O_{2max}$ is usually not reached on the first interval. $\dot{V}O_{2max}$ values can, however, be reached during consecutive intervals, through the priming effect of an adequate warm-up and/or the first intervals (that accelerates $\dot{V}O_2$ kinetics [133, 134]) and the development of a $\dot{V}O_2$ slow component [10]. The time needed to reach $\dot{V}O_{2max}$ during constant-speed exercise to exhaustion has received considerable debate in the past [104, 131, 135–138]. The variable has been shown to range from 97 s [138] to 299 s [131] and has a high intersubject variability (20–30 % [131, 135, 137] to 40 % [104]). While methodological differences could explain some of these dissimilarities (whether 95 % or 100 % of $\dot{V}O_{2max}$ is considered, the presence and type of pretrial warm-up), the variability is consistent with those shown in $\dot{V}O_2$ kinetics at exercise onset. $\dot{V}O_2$ kinetics are generally affected by exercise intensity [139], accelerated during running compared with cycling exercise [140] and faster in trained individuals [141]. The relationship between $\dot{V}O_2$ kinetics at exercise onset and $\dot{V}O_{2max}$, however, is less clear, with some studies reporting relationships [141–143], and others showing no correlation [144–146], suggesting that the $\dot{V}O_2$ kinetics at exercise onset is more related to training status [141, 147] than $\dot{V}O_{2max}$ *per se*.

As an alternative to using fixed long-interval durations, using 50–70 % of time to exhaustion at v$\dot{V}O_{2max}$ has been suggested by the scientific community as an alternative to individualizing interval training [3, 5, 137, 148–150]. However, to our knowledge, prescribing training based on time to exhaustion is very rare compared with how endurance athletes actually train. Additionally, while the rationale of this approach is sound (50–70 % is the average proportion of time to exhaustion needed to reach $\dot{V}O_{2max}$), this is not a practical method to apply in the field. First, in addition to v$\dot{V}O_{2max}$, time to exhaustion at v$\dot{V}O_{2max}$ must be determined, which is only a moderately reliable measure (CV = 12 % [68] to 25 % [93]), is exhaustive by nature and highly dependent on the accuracy of the v$\dot{V}O_{2max}$ determination [103]. Second, the time required to reach $\dot{V}O_{2max}$ has frequently been reported to be longer than 75 % of time to exhaustion in some participants [131, 135, 136]. Intervals lasting 70 % of time to exhaustion have also been reported as very difficult to perform, likely due to the high anaerobic energy contribution this requires [150]. For athletes presenting with exceptionally long time to exhaustion, repeating sets of 60 % of time to exhaustion is typically not attainable [137]. Finally, there is no link between the time needed to reach $\dot{V}O_{2max}$ and time to exhaustion [135, 137]. Therefore, since a given percentage of time to exhaustion results in very different amounts of T@$\dot{V}O_{2max}$, it appears more logical to use the time needed to reach $\dot{V}O_{2max}$ to individualize interval length [135] (e.g. time needed to reach $\dot{V}O_{2max}$ + 1 or 2 min). If the time needed to reach $\dot{V}O_{2max}$ cannot be determined (as is often the case in the field), we would therefore recommend using fixed intervals durations ≥2–3 min that could be further adjusted in accordance with the athlete's training status (with the less trained performing lower training loads, but longer intervals) and the exercise mode. Indeed, if we consider that the time constant of the primary phase of the $\dot{V}O_2$ kinetics at exercise onset (τ) in the severe intensity domain is generally in the range of 20 s to 35 s [131, 140, 146], and that a steady-state (≥95 % $\dot{V}O_{2max}$) is reached after exercise onset within ≈4 τ, $\dot{V}O_{2max}$ should then be reached from within 1 min 20 s to 2 min 20 s (at least when intervals are repeated), irrespective of training status and exercise mode. This is consistent with the data shown by Vuorimaa et al. in national level runners (v$\dot{V}O_{2max}$ = mean ± SD 19.1 ± 1 km/h), where $\dot{V}O_{2max}$ values were reached during 2-min work/2-min rest intervals, but not during 1 min/1 min [22]. Similarly, in the study by Seiler and Sjursen [71] in well trained runners (v$\dot{V}O_{2max}$ = 19.7 ± 1 km/h), peak $\dot{V}O_2$ was only 82 ± 5 % of $\dot{V}O_{2max}$ during 1-min intervals, while it reached 92 ± 4 during 2-min intervals; extending the work duration did not modify these peak values (93 ± 5 and 92 ± 3 % for 4- and 6-min intervals, respectively). Although performed on an inclined treadmill (5 %), these latter sessions were performed at submaximal self-selected velocities (i.e. 91 %, 83 %, 76 % and 70 % v$\dot{V}O_{2max}$ for 1-, 2-, 4- and 6-min intervals, respectively [71]), which probably explains why $\dot{V}O_{2max}$ was not reached [130] (see Sect. 3.1.1.4 below with respect to uphill running).

3.1.1.3 Relief Interval Characteristics during Long-Interval High-Intensity Interval Training (HIT) When programming HIT, both the duration and intensity of the relief interval are important [152]. These two variables must be considered in light of (1) maximizing work capacity during subsequent intervals (by increasing blood flow to accelerate muscle metabolic recovery, e.g. PCr resynthesis, H^+ ion buffering, regulation of inorganic phosphate (Pi) concentration and K^+ transport, muscle lactate oxidation) and; (2) maintaining a minimal level of $\dot{V}O_2$ to reduce the time needed to reach $\dot{V}O_{2max}$ during subsequent intervals (i.e. starting from an elevated 'baseline') [3, 14]. While performing active recovery between interval bouts is appealing to accelerate the time needed to reach $\dot{V}O_{2max}$ and in turn, induce a higher fractional contribution of aerobic metabolism to total energy turnover [134], its effects on performance capacity (time to exhaustion), and hence, T@$\dot{V}O_{2max}$ are not straightforward. The benefit of active recovery has often been assessed via changes in blood lactate concentration [153, 154], which has little to do with muscle lactate concentration [155]. Additionally, neither blood [156, 157] nor muscle [155] lactate has a direct (nor linear) relationship with performance capacity. The current understanding is that active recovery can lower muscle oxygenation [158, 159], impair PCr resynthesis (O_2 competition) and trigger anaerobic system engagement during the following effort [160]. Additionally, while a beneficial performance effect on subsequent intervals can be expected with long recovery periods (≥3 min [134, 161, 162], when the possible 'wash out' effects overcome that of the likely reduced PCr resynthesis), active recovery performed during this period may negate subsequent interval performance using both long periods at high intensities (>45 % v/p$\dot{V}O_{2max}$) [153] and short periods of varying intensity [159, 163]. In the context of long interval HIT, passive recovery is therefore recommended when the relief interval is less than 2–3 min in duration. If an active recovery is chosen for the above-mentioned reasons (i.e. [3, 14, 134].), relief intervals should last at least 3–4 min at a submaximal intensity [153] to allow the maintenance of high-exercise intensity during the following interval.

In practice, active recovery is psychologically difficult to apply for the majority of athletes, especially for non-

endurance athletes. When moderately trained runners ($v\dot{V}O_{2max}$ = 17.6 km/h) were asked to self-select the nature of their relief intervals during an HIT session (6 × 4 min running at 85 % $v\dot{V}O_{2max}$ on a treadmill with 5 % incline), they chose a walking recovery mode of about 2 min [69]. Compared with 1-min recovery intervals, the 2-min recovery duration enabled runners to maintain higher running speeds; extending passive recovery to 4 min did not provide further benefits with respect to running speeds. The low T@$\dot{V}O_{2max}$/total exercise time ratio shown by Millet et al. [128] (34 % when considering time >90 % $\dot{V}O_{2max}$; Fig. 6) in well trained triathletes ($v\dot{V}O_{2max}$ = 19.9 ± 0.9 km/h) was likely related to the introduction of 5-min passive pauses every second interval. With intervals performed successively (no passive pauses, no blocks but active recoveries < 50 % $v\dot{V}O_{2max}$ between runs), Demarie et al. [127] reported a longer T@$\dot{V}O_{2max}$ in senior long-distance runners ($v\dot{V}O_{2max}$ = 16.6 ± 1.1 km/h). More recently, Buchheit et al. showed, in highly trained young runners ($v\dot{V}O_{2max}$ = 18.6 ± 0.3 km/h), that even shorter recovery periods (i.e. 90 s), despite a passive recovery intensity (walk), enabled athletes to spend a relatively high proportion of the session at >90 % of $\dot{V}O_{2max}$ (43 %) [21]. This particular high 'efficiency' was also likely related to both the young age [222] and the training status [141] of the runners (since both are generally associated with accelerated $\dot{V}O_2$ kinetics).

Finally, in an attempt to individualize between-run recovery duration, the return of HR to a fixed value or percentage of HR_{max} is sometime used in the field and in the scientific literature [165, 166]. The present understanding of the determinants of HR recovery suggest, nevertheless, that this practice is not very relevant [69]. During recovery, HR is neither related to systemic O_2 demand nor muscular energy turnover [142, 167], but rather to the magnitude of the central command and metaboreflex stimulations [168].

3.1.1.4 Uphill Running during HIT with Long Intervals Despite its common practice [169], the cardiorespiratory responses to field-based HIT sessions involving uphill or staircase running has received little attention. Laboratory studies in trained runners ($V_{Inc.Test}$ ≥ 20 km/h) [170, 171] have shown that, for a given running speed, $\dot{V}O_2$ is higher during uphill compared with level running after a couple of minutes, probably due to the increased forces needed to move against gravity, the subsequently larger motor units recruited and the greater reliance on concentric contractions; all of which are believed initiators of the $\dot{V}O_2$ slow component [172]. However, in practice, athletes generally run slower on hills versus the track [173]. Gajer et al. [174] found in elite French middle-distance runners ($v\dot{V}O_{2max}$ = mean ± SD 21.2 ± 0.6 km/h, $\dot{V}O_{2max}$ = 78 ± 4 ml/min/kg) that T@$\dot{V}O_{2max}$ observed during a hill HIT session (6 × 500 m [1 min 40 s] 4–5 % slope [85 % $v\dot{V}O_{2max}$]/1 min 40 s [0 %]) was lower compared with a 'reference' track session (6–600 m [1 min 40 s] {102 % $v\dot{V}O_{2max}$}/1 min 40 s [0 %]). While $\dot{V}O_2$ reached 99 % and 105 % $\dot{V}O_{2max}$ during the hill and track sessions, respectively, the T@$\dot{V}O_{2max}$/exercise time ratio was 'moderately' lower during the hill HIT (27 % vs. 44 %, ES ≈ − 1.0). The reason for the lower T@$\dot{V}O_{2max}$ during the hill HIT is unclear. Despite the expected higher muscle force requirement during hill running [173], this is unlikely enough to compensate for the reduction in absolute running speed. If we consider that running uphill at 85 % $v\dot{V}O_{2max}$ with a grade of 5 % has likely the same (theoretical) energy requirement as level running (or treadmill running with a 1 % grade to compensate for wind resistance [105]) at ≈ 105 %; [175] the differences observed by Gajer et al. could have been even greater if the flat condition was ran at a faster (and possibly better matched) speed (105 % vs. 102 % [174]). As well, intervals in these sessions might not have been long enough to observe the additional slow component generally witnessed with uphill running (≈ 2 min [172]). More research is required, however, to clarify the cardiorespiratory responses to uphill running at higher gradients (> 10 %) or to staircase running that may require very high $\dot{V}O_2$ values due to participation of upper body limbs (back muscles and arms when pushing down or grabbing handrails).

3.1.1.5 Volume of HIT with Long Intervals Another variable that can be used to maximize T@$\dot{V}O_{2max}$ is the number of long-interval repetitions. It is worth noting, however, that very few authors have examined HIT sessions/programmes that are consistent with the sessions that athletes actually perform, and that research on the optimal T@$\dot{V}O_{2max}$ per session is limited. Cumulated high-intensity (>90 % v/p$\dot{V}O_{2max}$) exercise time during typical sessions in well trained athletes has been reported to be 12 min (6 × 2 min or 6 × ≈600 m [128]), 15 min (5 × 3 min or 5 × ≈800–1,000 m [21]), 16 min (4 × 4 min or 4 × ≈1,000–1,250 m [46]), 24 min (6 × 4 min or 6 × ≈1,000–1,250 m [69]; 4 × 6 min or 4 × ≈ 1,500 m [71]) and 30 min (6 × 5 min or 5 × ≈1,300–1,700 m [127]), which enabled athletes to accumulate, depending on the HIT format, from 10 min >90 % [21, 128] to 4–10 min >95 % [127, 128] at $\dot{V}O_{2max}$. Anecdotal evidences suggest that elite athletes tend to accumulate greater T@$\dot{V}O_{2max}$ per session at some point of the season. In recreationally trained cyclists ($\dot{V}O_{2max}$: ~52 ml/min/kg),

Seiler et al. showed that larger volumes of HIT performed at a lower intensity (i.e. 4 × 8 min = 32 min at 90 % HR_{max}) may be more effective than more traditional HIT sessions (e.g. 4 × 4 min) [176]. Further research examining the influence of these particular sessions in more highly trained athletes are, however, required to confirm these findings.

3.1.2 $\dot{V}O_2$ Responses to HIT with Short Intervals

For short interval HIT runs to exhaustion, T@$\dot{V}O_{2max}$ is largely correlated with total exercise time (i.e. time to exhaustion) [14]. Hence, the first approach to maximizing T@$\dot{V}O_{2max}$ during such sessions should be to focus on the most effective adjustments to work/relief intervals (intensity and duration) that increase time to exhaustion. In practice, however, coaches do not prescribe HIT sessions to exhaustion; they prescribe a series or set of HIT [50, 128, 177, 178]. In this context, it is important to consider the strategies needed to maximize T@$\dot{V}O_{2max}$ within a given time period, or to define 'time-efficient' HIT formats with respect to the T@$\dot{V}O_{2max}$/exercise time ratio (i.e. T@$\dot{V}O_{2max}$ in relation to the total duration of the HIT session, warm-up excluded).

3.1.2.1 Effect of Work Interval Intensity on T@$\dot{V}O_{2max}$ Billat et al. [23] were the first to show the effect of exercise intensity on T@$\dot{V}O_{2max}$ during HIT with short intervals (15 s/15 s) in a group of senior (average age: 52 years) distance runners (v$\dot{V}O_{2max}$ = 15.9 ± 1.8 km/h). While the concurrent manipulation of the relief interval intensity (60–80 % of v$\dot{V}O_{2max}$, to maintain an average HIT intensity of 85 %) might partially have influenced the $\dot{V}O_2$ responses, the authors did show that increasing work interval intensity from 90 % to 100 % of v$\dot{V}O_{2max}$ was associated with a 'small' improvement in the T@$\dot{V}O_{2max}$/exercise time ratio (81 % vs. 68 %, ES = + 0.5). However, the T@$\dot{V}O_{2max}$/exercise time ratio (85 %) was not substantially greater using a work interval fixed at 110 compared with 100 % of v$\dot{V}O_{2max}$ (ES = +0.2). Using a fixed relief interval intensity (Fig. 7a, [117, 177, 179]), increasing work intensity from 100 % to 110 % of v$\dot{V}O_{2max}$ during a 30 s/30 s format in trained young runners (v$\dot{V}O_{2max}$ = 17.7 ± 0.9 km/h) induced a 'moderate' increase in the T@$\dot{V}O_{2max}$/exercise time ratio (ES = + 0.6), despite 'very large' and 'moderate' reductions in time to exhaustion (ES = −4.4) and T@$\dot{V}O_{2max}$ (ES = −0.7), respectively [179]. A slight increase in work intensity from 100 % to 105 % of v$\dot{V}O_{2max}$ during a 30 s/30 s HIT format in well trained triathletes (v$\dot{V}O_{2max}$ = 19.8 ± 0.93 km/h) was associated with a 'large' improvement in the T@$\dot{V}O_{2max}$/exercise time ratio (ES = +1.2) [177]. The twofold magnitude difference in Millet et al. [177] compared with Thevenet et al's. study [179] (ES: +1.2 vs. +0.6) is likely due to the fact that Millet et al's. runs were not performed to exhaustion, but implemented with pre-determined sets. It is therefore possible that if the runs at 100 % had been performed to exhaustion [177], this would have compensated for the lower efficiency of the protocol and decreased the difference in T@$\dot{V}O_{2max}$ observed. Similarly, increasing the work intensity from 110 % to 120 % of v$\dot{V}O_{2max}$ during a 15 s/15 s format in physical education students (v$\dot{V}O_{2max}$ = 16.7 ± 1.3 km/h) lead to a 'large' improvement in the T@$\dot{V}O_{2max}$/exercise time ratio (ES = +1.8) [117]. Interestingly, in the study by Millet et al. [177], individual improvements in T@$\dot{V}O_2$ with the increase in work intensity were inversely correlated with the athletes' primary time constant for $\dot{V}O_2$ kinetics at exercise onset (r = 0.91; 90 % CI 0.61, 0.98), suggesting that the time constant could be an important variable to consider when selecting HIT variables [116, 177]. Practically speaking, this data implies that coaches should programme HIT at slightly greater exercise intensities for athletes presenting with slow $\dot{V}O_2$ kinetics (i.e. older/less trained [141]), or for athletes exercising on a bike [140]. However, since increasing exercise intensity has other implications (e.g. greater anaerobic energy contribution, higher neuromuscular load, see Part II), such programming manipulations need to use a cost/benefit approach.

With respect to the use of very-high-exercise intensities (>102/120 % V_{IFT}/v$\dot{V}O_{2max}$) for HIT, while the T@$\dot{V}O_{2max}$/exercise time ratio is high (81 % and 77 % at 130 % and 140 % of v$\dot{V}O_{2max}$, respectively), exercise capacity is typically impaired and, hence, total T@$\dot{V}O_{2max}$ for a given HIT series is usually low [117] (i.e. 5 min 47 s at 120 % v$\dot{V}O_{2max}$ [117]). Nevertheless, the use of repeated sets of such training can allow the accumulation of a sufficient T@$\dot{V}O_{2max}$. Additionally, well trained athletes are generally able to perform HIT at this intensity for longer periods (i.e. >8 min [43, 50, 95, 180], especially when V_{IFT}, instead of v$\dot{V}O_{2max}$, is used [94]). To conclude, it appears that during HIT that involves short work intervals, selection of a work bout intensity that ranges between 100 % and 120 % of v$\dot{V}O_{2max}$ (>89 % and 105 % of V_{IFT}) may be optimal.

3.1.2.2 Effect of Work Interval Duration on T@$\dot{V}O_{2max}$ The effect of work interval duration on systemic $\dot{V}O_2$ responses during HIT involving repeated short intervals was one of the first parameters examined in the HIT literature [11, 12]. Surprisingly, there is little data available on repeated efforts lasting less than 15 s, despite the

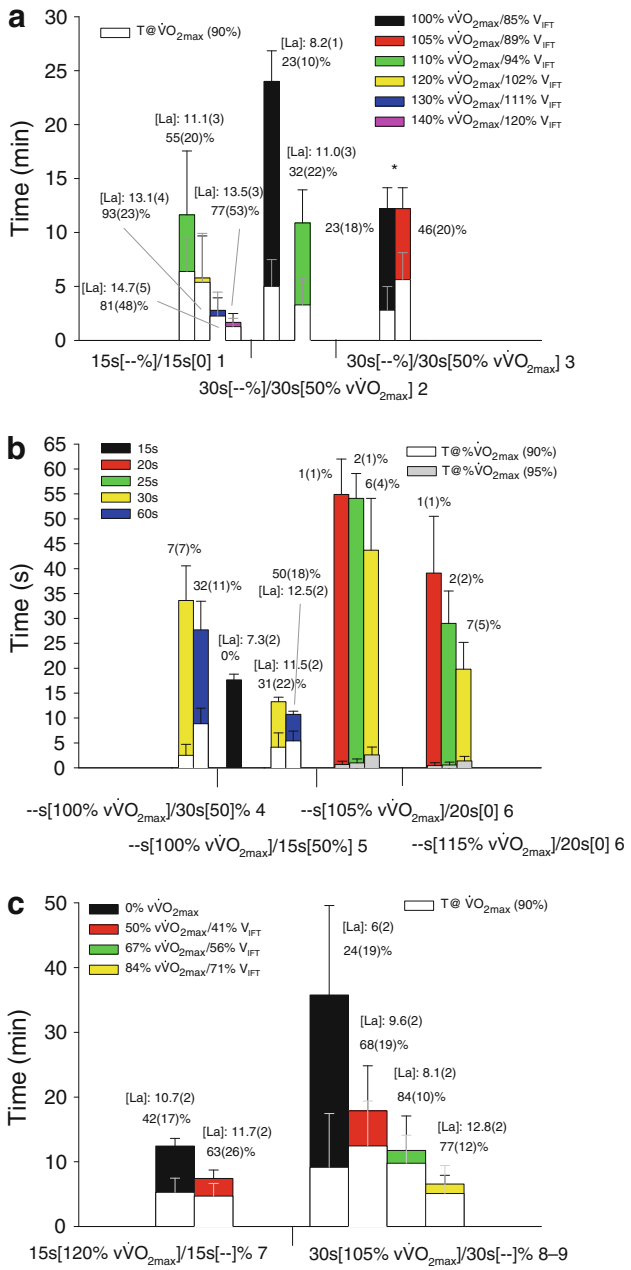

Fig. 7 Mean ± SD total time and T@$\dot{V}O_{2max}$ during different forms of HIT, including short intervals, as a function of changes in work interval intensity (**a:** references 1 [117]; 2 [179] and 3 [177]), work interval duration (**b**: references 4 [128], 5 [185] and 6 [186]) and relief interval intensity (**c**: references: 7 [190]; 8 [188] and 9 [164]). -- indicates the variable that was manipulated. Percentages refer to the mean ± SD T@$\dot{V}O_{2max}$ relative to total session time. Mean ± SD [La] mmol/L is provided when available (values for study 6 [186] were all < 6 mmol/L and are therefore not provided). *HIT* high-intensity interval training, $\dot{V}O_{2max}$ maximal oxygen uptake, *T@$\dot{V}O_{2max}$* time spent at 90 % or 95 % of $\dot{V}O_{2max}$, V_{IFT} running speed reached at the end of the 30–15 Intermittent Fitness Test, *v$\dot{V}O_{2max}$* minimal running speed associated with $\dot{V}O_{2max}$, * indicates HIT not performed to exhaustion

common approach used by coaches (e.g. 10 s/10 s, 10 s/20 s) [181, 182]. During very short runs (<10 s), ATP requirements in working muscle are met predominantly by oxidative phosphorylation, with more than 50 % of the O_2 used derived from oxymyoglobin stores [11]. During the recovery periods, oxymyoglobin stores are rapidly restored and then available for the following interval [11]. As a result, the cardiopulmonary responses of such efforts are relatively low [183], unless exercise intensity is set at a very high level (as detailed in Sect. 3.1.4) and/or relief intervals are short/intense enough so that they limit complete myoglobin resaturation. Therefore, in the context of HIT involving short intervals (100–120 % v$\dot{V}O_{2max}$ or 89/105 % V_{IFT}), work intervals ≥10 s appears to be required to elicit high $\dot{V}O_2$ responses. Surprisingly, the specific effect of work interval duration, using a fixed work/rest ratio in the same group of subjects, has not been investigated thus far; whether, for example, a 15 s/15 s HIT session enables a greater T@$\dot{V}O_{2max}$/exercise time ratio than a 30 s/30 s session is unknown.

What is known of course is that prolonging exercise duration increases the relative aerobic energy requirements [184]. Increasing the work interval duration, while keeping work relief intervals constant, also increases T@$\dot{V}O_{2max}$ (Fig. 7b, [128, 185, 186]). For example, extending work interval duration from 30 s to 60 s using a fixed-relief duration of 30 s in well trained triathletes (v$\dot{V}O_{2max}$ = 19.9 ± 0.9 km/h) induced 'very large' increases in T@$\dot{V}O_{2max}$ (9 vs. 1.5 min, ES = + 2.4), despite a shorter total session time (28 vs. 34 min, ES = −0.9; change in the T@$\dot{V}O_{2max}$/exercise ratio, ES = +2.8) [128]. Similarly, in wrestlers (v$\dot{V}O_{2max}$ = 16.3 ± 1.1 km/h), increasing running work interval duration from 15 s to 30 s lead to 'very large' increase in T@$\dot{V}O_{2max}$ (4 vs. 0 min, ES = 2.9); [185] a further increase in the interval duration to 60 s extended T@$\dot{V}O_{2max}$ to 5.5 min (ES = 0.5 vs. the 30-s condition). Considering the importance of $\dot{V}O_2$ kinetics for extending T@$\dot{V}O_{2max}$ [177], these data suggest that longer work intervals (e.g. 30 s/30 s vs. 15 s/15 s) are preferred for individuals with slow $\dot{V}O_2$ kinetics (i.e. older/less trained [141]), or for exercising on a bike [140].

3.1.2.3 Characteristics of the Relief Interval and T@$\dot{V}O_{2max}$ The intensity of the relief interval also plays a major role in the $\dot{V}O_2$ response during HIT involving short intervals, since it affects both the actual $\dot{V}O_2$ during the sets and exercise capacity (and, hence, indirectly time to exhaustion and T@$\dot{V}O_{2max}$; Fig. 7c, [164, 187, 188]). Compared with passive recovery, runs to exhaustion

involving active recovery are consistently reported to be 40–80 % shorter [164, 187–190]. Therefore, when considering runs to exhaustion during 15 s/15 s exercises, the absolute T@$\dot{V}O_{2max}$ might not differ between active and passive recovery conditions [190] (ES = −0.3), but the T@$\dot{V}O_{2max}$/exercise time ratio is substantially greater when active recovery is implemented (ES = +0.9); a factor of obvious importance when implementing predetermined sets of HIT [50, 128, 178]. During a 30 s/30 s exercise model, compared with passive recovery, recovery intensities of 50 % and 67 % of v$\dot{V}O_{2max}$ were associated with 'small' and 'very large' improvements in T@$\dot{V}O_{2max}$ (ES = +0.4 and +0.1, respectively) and the T@$\dot{V}O_{2max}$/exercise time ratio (ES = +2.3 and +4.1, respectively) [164, 188]. Increasing the recovery intensity to 84 % reduced 'moderately' T@$\dot{V}O_{2max}$ (ES = −0.6), but increased 'very largely' the T@$\dot{V}O_{2max}$/exercise time ratio (ES = +3.4). Taken together, these studies suggest that, for the short HIT formats examined thus far, relief interval intensities around ≈70 % v$\dot{V}O_{2max}$ should be recommended to increase both T@$\dot{V}O_{2max}$ and the T@$\dot{V}O_{2max}$/exercise time ratio [23]. The fact that active recovery had a likely greater impact on T@$\dot{V}O_{2max}$ during the 30 s/30 s [164, 188] compared with the 15 s/15 s [190] exercise model is related to the fact that $\dot{V}O_2$ reaches lower values during 30 s of passive rest, which directly affects $\dot{V}O_2$ levels during the following effort. For this reason, we recommend programming passive recovery ≤15–20 s for non-endurance sport athletes not familiar with performing active recovery, and/or performing active recovery during longer-relief interval durations (≥20 s). In general, the characteristic of the relief interval intensity can be adjusted in alignment with the work intensity, with higher-relief interval intensities used for lower-work interval intensities [23], and lower-relief exercise intensities used for higher-work interval intensities and durations [117, 177, 179].

3.1.2.4 Series Duration, Sets and T@$\dot{V}O_{2max}$ Dividing HIT sessions into sets has consistently been shown to reduce the total T@$\dot{V}O_{2max}$ [50, 128, 178]. For example, in endurance-trained young runners (v$\dot{V}O_{2max}$ = 17.7 ± 0.3 km/h), performing 4-min recoveries (30 s rest, 3 min at 50 % v$\dot{V}O_{2max}$, 30 s rest) every 6 repetitions (30 s/30 s) was associated with a 'moderately' lower T@$\dot{V}O_{2max}$ (ES = −0.8) despite 'very large' increases in time to exhaustion (ES = +4.3); the T@$\dot{V}O_{2max}$/exercise time ratio was therefore 'very largely' reduced (ES = −2.3) [178]. This is likely related to the time athletes needed to return to high $\dot{V}O_2$ levels after each recovery period, irrespective of the active recovery used. While it could be advised to consistently recommend HIT runs to exhaustion to optimize T@$\dot{V}O_{2max}$, this would likely be challenging, psychologically speaking, for both coaches and athletes alike; this is likely why HIT sessions to exhaustion are not often practiced by athletes.

In practice, the number of intervals programmed should be related to the goals of the session (total 'load' or total T@$\dot{V}O_{2max}$ expected), as well as to the time needed to reach $\dot{V}O_{2max}$ and the estimated T@$\dot{V}O_{2max}$/exercise time ratio of the session. The time needed to reach $\dot{V}O_{2max}$ during different work- and relief-interval intensities involving short HIT (30 s/30 s) was recently examined in young endurance-trained athletes [164, 179, 188]. Not surprisingly, these studies showed shorter time needed to reach $\dot{V}O_{2max}$ values for work intensities ≥105 % v$\dot{V}O_{2max}$ and relief intensities ≥60 % v$\dot{V}O_{2max}$. Conversely, using slightly lower work- and/or relief-interval intensities (i.e. work: 100 % and relief: 50 % v$\dot{V}O_{2max}$) the runners needed more than 7 min to reach $\dot{V}O_{2max}$. Despite a lack of statistical differences [164, 179, 188], all ES between the different work/relief ratios examined were 'small' to 'very large'. In the field then, time needed to reach $\dot{V}O_{2max}$ might be accelerated by manipulating HIT variables during the first repetitions of the session, i.e. using more intense work- and/or relief-interval intensities during the first two to three intervals, or using longer work intervals and/or shorter relief intervals.

If we consider that a goal T@$\dot{V}O_{2max}$ of ≈10 min per session is appropriate to elicit important cardiopulmonary adaptations (Sect. 3.1.1.5), athletes should expect to exercise for a total of 30 min using a 30 s [110 % v$\dot{V}O_{2max}$]/30 s [50 % v$\dot{V}O_{2max}$] format, since the T@$\dot{V}O_{2max}$/total exercise time ratio is approximately 30 % (Fig. 7a). Since it is unrealistic to perform a single 30-min session, it is possible for it to be broken into three sets of 10–12 min (adding 1–2 min per set to compensate for the time needed to regain $\dot{V}O_{2max}$ during the second and third set). Such a session is typical to that used regularly by elite distance runners in the field. A lower volume (shorter series or less sets) may be used for other sports (i.e. in team sports, a T@$\dot{V}O_{2max}$ of 5–7 min is likely sufficient [116]) and/or for maintenance during unloading or recovery periods in an endurance athlete's programme. In elite handball, for example, 2 × (20 × 10 s [110 % V_{IFT}]/20 s [0]) is common practice, and might enable players to spend ≈7 min at $\dot{V}O_{2max}$ (considering a T@$\dot{V}O_{2max}$/exercise time ratio of 35 %; Buchheit M, unpublished data). In football (soccer), HIT sessions such as 2 × (12–15 × 15 s [120 % $V_{Inc.Test}$]/15 s [0]) are often implemented [95], which corresponds to ≈6 min at $\dot{V}O_{2max}$ (14 min with a T@$\dot{V}O_{2max}$/exercise time ratio of ≈45 % [190]).

3.1.3 Short versus Long Intervals and T@$\dot{V}O_{2max}$

A direct comparison between long and short HIT sessions, with respect to T@$\dot{V}O_{2max}$, has only been reported twice in highly-trained athletes. Gajer et al. [174] compared T@$\dot{V}O_{2max}$ between 6 × 600 m (track session, 102 % v$\dot{V}O_{2max}$, ran in ≈1 min 40 s) and 10 repetitions of a 30 s/30 s HIT session (work/relief intensity: 105/50 % v$\dot{V}O_{2max}$) in elite middle-distance runners (v$\dot{V}O_{2max}$ = 21.2 ± 0.6 km/h). While $\dot{V}O_2$ reached 105 % $\dot{V}O_{2max}$ during the track session, $\dot{V}O_{2max}$ was not actually attained during the 30 s/30 s session. If the track session is considered as the 'reference' session (T@$\dot{V}O_{2max}$/exercise time ratio: 44 %), T@$\dot{V}O_{2max}$ was 'very largely' lower during the 30 s/30 s intervals (10 %, ES ≈ −2.6). Similarly, Millet et al. [128] showed that performing 2 min/2 min intervals enabled triathletes to attain a 'very largely' longer T@$\dot{V}O_{2max}$ compared with a 30 s/30 s session (ES = +2.2, T@$\dot{V}O_{2max}$/exercise time ratio = +2.2). Long intervals were however 'moderately' less 'efficient' than a 60 s/30 s effort model (T@$\dot{V}O_{2max}$/exercise time ratio, ES = −0.8) [128]. Taken together, these data suggest that long intervals and/or short intervals with a work/relief ratio >1 should be preferred due to the greater T@$\dot{V}O_{2max}$/exercise time ratio.

3.1.4 $\dot{V}O_2$ Responses to Repeated-Sprint Sequences

Compared with the extensive data available on cardiorespiratory responses to long and short HIT, relatively little has been presented on the acute responses to RSS. An RSS is generally defined as the repetition of >two short (≤10 s) all-out sprints interspersed with a short recovery period (<60 s) [191]. Early in the 1990s, Balsom et al. [13] demonstrated that RSS were aerobically demanding (i.e. >65 % $\dot{V}O_{2max}$). In addition, Dupont et al. have shown that footballers can reach $\dot{V}O_{2max}$ during repeated sprinting [192]. To our knowledge, however, T@$\dot{V}O_{2max}$ during RSS has not been reported. For the purpose of the present review, we have reanalysed data from previous studies [30, 158, 193, 194] to provide T@$\dot{V}O_{2max}$ values for several forms of RSS (Fig. 8, upper panel [13, 30, 158, 192–195]). When manipulating key variables already described (Fig. 2 [35]), $\dot{V}O_{2max}$ is often reached and sustained for 10–40 % of the entire RSS duration (i.e. 10–60 s; Fig. 8 a). If RSS are repeated two to three times per session, as is often done in practice [180, 196, 197], the majority of athletes may spend up to 2–3 min at $\dot{V}O_{2max}$ during the repeated sprints. To increase T@$\dot{V}O_{2max}$ during an RSS, it appears that sprints/efforts should last at least 4 s, and that the recovery should be active and less than 20 s (Fig. 8, lower panel [13, 30, 158, 192–195]). The introduction of jumps following the sprints [193], and/or changes in direction [194], are also of interest, since these may increase systemic O_2 demand without the need for increasing sprint distance, which could increase muscular load and/or injury risk (see review Part II). Nevertheless, with very short passive recovery periods (i.e. 17 s), some athletes can reach $\dot{V}O_{2max}$ by repeating 3 s sprints only (15 m). It is worth noting, however, that during all RSS examined here (Fig. 8, except for Dupont et al's. study [192]), a number of players did not reach $\dot{V}O_{2max}$, and T@$\dot{V}O_{2max}$ showed high interindividual variations (CV = 30–100 %). More precisely, when considering the four different forms of RSS performed by the same group of 13 athletes [193, 194], it was observed that six (45 %) of them reached $\dot{V}O_{2max}$ on four occasions, one (8 %) on three, four (31 %) on two, with two (15 %) never reaching $\dot{V}O_{2max}$ during any of the RSS. When the data from the four RSS were pooled, the number of times that $\dot{V}O_{2max}$ was reached was inversely related to $\dot{V}O_{2max}$ (r = −0.61, 90 % CL −0.84, −0.19). Similarly, the total T@$\dot{V}O_{2max}$ over the four different RSS was inversely correlated with $\dot{V}O_{2max}$ (r = −0.55; 90 % CL −0.85, 0.00). There was, however, no relationship between the number of times that $\dot{V}O_{2max}$ was reached or the T@$\dot{V}O_{2max}$ and $\dot{V}O_2$ kinetics at exercise onset, as measured during submaximal exercise [144]. These data show that, with respect to T@$\dot{V}O_{2max}$, using RSS may be questionable to apply in some athletes, especially those of high fitness.

3.1.5 $\dot{V}O_2$ Responses to Sprint Interval Sessions

The important research showing the benefits of SIT [126], notwithstanding, there is, to date, few data available showing the acute physiological responses to typical SIT sessions that might be implemented in practice. Tabata et al. [198] showed that $\dot{V}O_{2max}$ was not reached (peak of 87 % $\dot{V}O_{2max}$) during repeated 30 s cycling efforts (200 % of p$\dot{V}O_{2max}$ and therefore not actually 'all-out') interspersed by 2-min passive recovery. In contrast, we recently showed [142] that during a 'true' all-out SIT session, most subjects reached values close to (or above) 90 % of their $\dot{V}O_{2max}$ and HR. Nevertheless, T@$\dot{V}O_{2max}$ was only 22 s on average (range 0–60 s, with two subjects showing no values >90 % $\dot{V}O_{2max}$) [142], and $\dot{V}O_{2max}$ was reached by five (50 %) subjects only. These important individual $\dot{V}O_2$ responses to SIT sessions were partly explained by variations in cardiorespiratory fitness (i.e. there was a negative correlation between T@$\dot{V}O_{2max}$ and both $\dot{V}O_{2max}$ (r = −0.68; 90 % CL −0.90, −0.20) and $\dot{V}O_2$ kinetics at

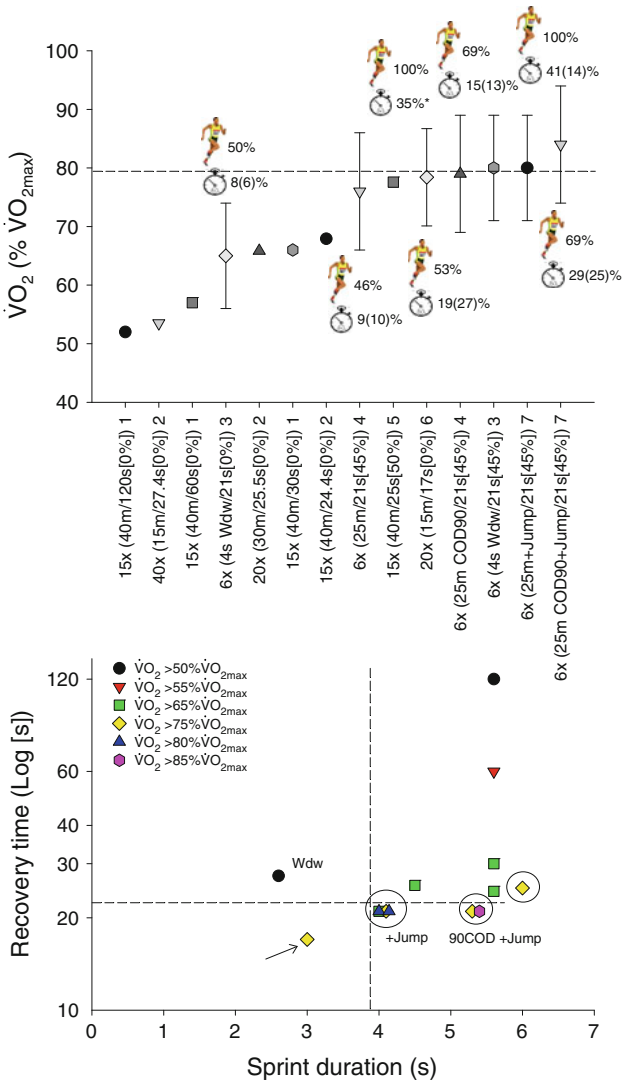

Fig. 8 **a** Mean ± SD $\dot{V}O_2$ responses during selected repeated-sprint sequences. The intensity of the relief interval (i.e. [percentage]) is expressed as a fraction of the v$\dot{V}O_{2max}$. When available, both the percentage of participants that reached $\dot{V}O_{2max}$ (runner) and the mean ± SD time spent above 90 % of $\dot{V}O_{2max}$ (clock) are provided. **b** The mean $\dot{V}O_2$ responses during the repeated-sprint sequences presented in section **a** are categorized into six colour-coded families (based in the % of $\dot{V}O_{2max}$ elicited) and then plotted as a function of sprint and recovery duration. The dashed lines represent the shorter sprint and recovery durations likely needed to achieve at least 80 % of $\dot{V}O_{2max}$. Circles indicate active recovery. Note (see arrow) that 75 % of $\dot{V}O_{2max}$ can be achieved with very short sprints (i.e. 15 m) with passive recovery when sprints are interspersed with very short pauses (i.e. 17 s). References: 1 [13]; 2 [195];3 [158]; 4 [194]; 5 [192]; 6 [30] and 7 [193]. *COD* changes of direction, $\dot{V}O_2$ oxygen uptake, $\dot{V}O_{2max}$ maximal $\dot{V}O_2$, v$\dot{V}O_{2max}$ minimal running speed required to elicit maximal $\dot{V}O_2$, *Wdw* refers to sprints performed on a non-motorized treadmill

(submaximal) exercise cessation ($r = 0.68$; 90 % CL 0.20, 0.90). As with RSS, there was no link between T@$\dot{V}O_{2max}$ and $\dot{V}O_2$ kinetics at exercise onset. Finally, it is worth noting that although pulmonary $\dot{V}O_2$ is not high during SIT, muscle O_2 demand likely is, especially as the number of sprint repetitions increase. It has been shown that there is a progressive shift in energy metabolism during a SIT session, with a greater reliance on oxidative metabolism when sprints are repeated [199, 200]. Along these same lines, muscle deoxygenation levels and post-sprint reoxygenation rates have been shown to become lower and slower, respectively, with increasing sprint repetition number. This response implies a greater O_2 demand in the muscle with increasing sprint repetition (since O_2 delivery is likely improved with exercise-induced hyperaemia) [142].

3.1.6 Summary

In this section of the review, we have highlighted the $\dot{V}O_2$ responses to various forms of HIT. It appears that most HIT formats, when properly manipulated, can enable athletes to reach $\dot{V}O_{2max}$. However, important between-athlete and between-HIT format differences exist with respect to T@$\dot{V}O_{2max}$. RSS and SIT sessions allow for a limited T@$\dot{V}O_{2max}$ compared with HIT that involve long and short intervals. Combined, data from high-level athletes [128, 174] suggest that long intervals and/or short intervals with a work/relief ratio >1 should enable a greater T@$\dot{V}O_{2max}$/exercise time ratio during HIT sessions. The methods of maximizing long-term $\dot{V}O_{2max}$ development and performance adaptations using different forms of HIT sessions that involve varying quantities of T@$\dot{V}O_{2max}$, as well as the most efficient way of accumulating a given T@$\dot{V}O_{2max}$ in an HIT session (i.e. intermittently vs. continuously), is still to be determined.

3.2 Cardiac Response with HIT and Repeated-Sprint Efforts

Due to the varying temporal aspects [70] and possible dissociation between $\dot{V}O_2$ and cardiac output (Qc) during intense exercise [201, 202], T@$\dot{V}O_{2max}$ might not be the sole criteria of importance for examining when assessing the cardiopulmonary response of a given HIT session. Since reaching and maintaining an elevated cardiac filling is believed to be necessary for improving maximal cardiac function [58, 59, 203], training at the intensity associated with maximal SV may be important [201]. Defining this key intensity, however, remains difficult, since this requires the continuous monitoring of SV during exercise (e.g [25–27, 201, 204]). Interestingly, whether SV is maximal at v/p$\dot{V}O_{2max}$, or prior to their occurrences, is still debated [205–207]. SV behaviour during an incremental test is

likely protocol-dependent [202] and affected by training status (e.g. ventricular filling partly depends on blood volume, which tends to be higher in trained athletes) [206], although this is not always the case [207]. In addition, the nature of exercise, i.e. constant power vs. incremental vs. intermittent, as well as body position (more supine during rowing or swimming vs. more upright during running and cycling), might also affect the SV reached and maintained throughout the exercise bout. In fact, there is limited data on cardiac function during exercises resembling those prescribed during field-based HIT sessions, i.e. constant-power bouts at high intensity. In these studies, SV reached maximal values within ≈1 min [26],] ≈2 min [24, 25, 204] and ≈4 min [27], and then decreased [24, 26, 204] or remained stable [25, 27] prior to fatigue. Inconsistencies in exercise intensities, individual training background and particular haemodynamic behaviours (e.g. presence of a HR deflection at high intensities [208]), as well as methodological considerations in the measurement of SV may explain these differences [205–207]. As discussed in Sect. 2.2, alternating work and rest periods during HIT with short intervals might also induce variations in the action of the venous muscle pump, which can, in turn, limit the maintenance of a high SV [60].

Following the beliefs of German coach, Woldemar Gerschler, in the 1930s, Cumming reported, in 1972, that maximal SV values were reached during the exercise recovery period, and not during exercise, irrespective of the exercise intensity [209]. Although these results were obtained during supine exercise in untrained patients, and despite contradictory claims [210], they contributed to the widespread belief that the repeated recovery periods and their associated high SV accounted for the effectiveness of HIT on cardiocirculatory function [211]. In partial support of this, Takahashi et al. [212] also reported in untrained males that during the first 80 s of an active recovery (20 % $\dot{V}O_{2max}$), SV values were 10 % greater than during a preceding submaximal cycling exercise (60 % $\dot{V}O_{2max}$). Surprisingly, these particular and still hypothetical changes in SV during recovery had never before been examined during typical HIT sessions in athletes. We recently collected haemodynamic data in well trained cyclists that partly confirmed Cumming's findings (Buchheit M, et al., unpublished data, Fig. 9). Irrespective of the exercise, i.e. incremental test, 3 min at p$\dot{V}O_{2max}$ or repeated 15-s sprints (30 % of the anaerobic power reserve, APR), the SV of a well trained cyclist (peak power output = 450 W, $\dot{V}O_{2max}$ = 69 ml/min/kg, training volume = 10 h/week) showed its highest values consistently during the recovery periods (upright position on the bike). While we acknowledge the limitations inherent to the impedance method used (PhysioFlow, Manaetec, France [213, 214]), and while further analysis on a greater number of subjects is needed, these preliminary data lend support to the belief that despite its supramaximal nature, HIT sessions might trigger cardiocirculatory adaptation via cardiovascular adjustments occurring specifically during the recovery periods. Take for example an HIT session involving three sets of eight repetitions of a 15 s sprint (30 % APR) interspersed with 45 s of passive recovery (long enough for peak SV to be reached). Such a format would allow such athletes to maintain their peak SV for 24 × 20 s = 480 s, which is similar to what can be sustained during a constant-power exercise performed to exhaustion [25]. Interestingly, Fontana et al. [215] also observed, using a rebreathing method in untrained men, 'largely' greater SV values at the end of a 30 s all-out sprint compared with an incremental test to exhaustion (127 ± 37 vs. 94 ± 15 ml, ES = + 1.3). HR_{max} was nevertheless 'very largely' lower (149 ± 26 vs. 190 ± 12 beats/min, ES = −2.2), so there was no substantial difference in maximal cardiac output (Qc_{max}) [18.2 ± 3.3 vs. 17.9 ± 2.6 L/min, ES = −0.1].

To conclude, the optimal nature and intensity of exercise needed to produce the greatest SV adaptations is not known. In acquiring the answer to this question, one needs to take into account individual characteristics, such as fitness level, training status and various individual haemodynamic behaviours to different exercise modes. In a practical way, on the basis of the limited data available, it might be recommended to prescribe a variety of different training methods to gain the adaptation advantages of each exercise format. HIT sessions, including near-to-maximal long intervals with long recovery durations (e.g. >3–4 min/ >2 min) might allow athletes to reach a high SV during the work (and possibly the relief intervals). Along these same lines, 4-min intervals ≈90–95 % v/p$\dot{V}O_{2max}$ appear to be receiving the greatest interest to improve cardiopulmonary function (e.g [46, 59, 216]). Alternatively, repeated short supramaximal work intervals (e.g. 15–30 s) with long recovery periods (>45 s) might also be effective at reaching high values both during exercise [215] and possibly, in recovery (Fig. 9). However, whether Qc_{max} adaptations are comparable following long- and short-interval sessions (i.e. continuous vs. intermittent), or whether achieving a certain quantity of time at Qc_{max} (T@Qc_{max}) is needed to maximize its adaptation, is still unknown. In the only longitudinal study to date comparing the effect of short versus long HIT on maximal cardiovascular function in university students ($\dot{V}O_{2max}$: 55–60 ml/min/kg) [59], there was a 'small' trend for greater improvement in Qc_{max} for the long interval protocol (ES = +1 vs. +0.7 for 4 × 4 min vs. 15/15, respectively). It is worth noting that Seiler et al. [176] showed, in recreational cyclists ($\dot{V}O_{2max}$: ~52 ml/min/kg), that accumulating 32 min of work at 90 % HR_{max} may

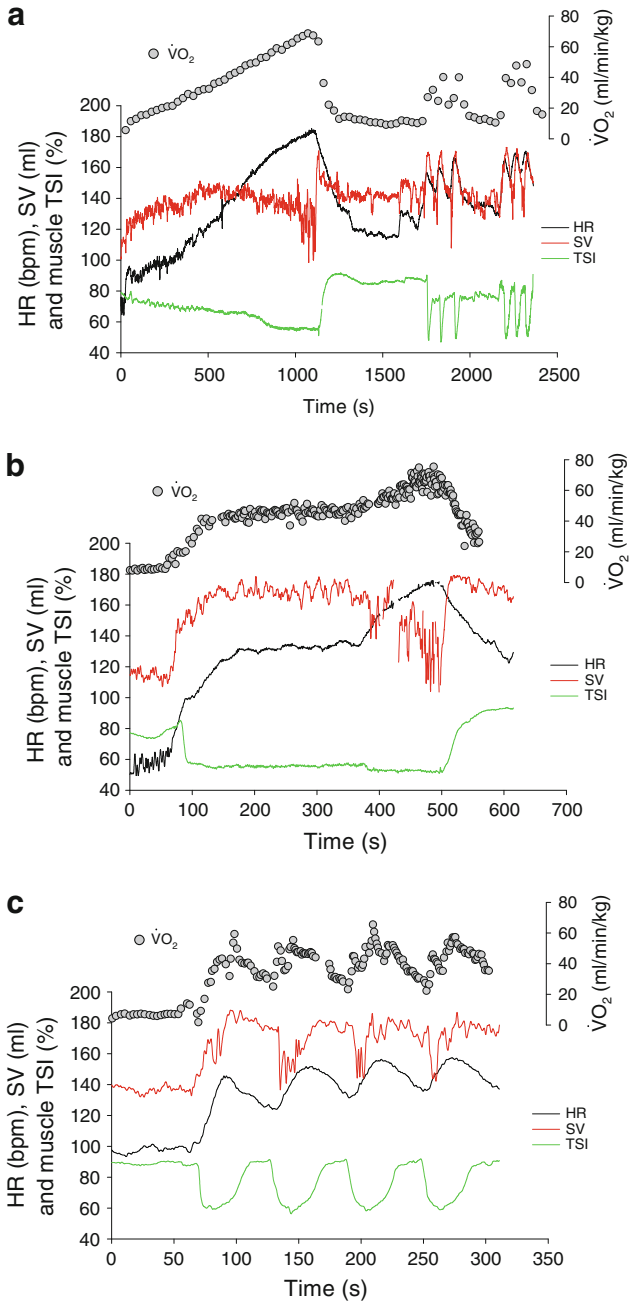

Fig. 9 **a** $\dot{V}O_2$, HR, SV and muscle oxygenation (TSI) during an incremental test followed by two sets of three supramaximal 15-s sprints (35 % APR); **b** 5-min bout at 50 % of p$\dot{V}O_{2max}$ immediately followed by 3 min at p$\dot{V}O_{2max}$; and (**c**) the early phase of an HIT session (i.e. first four exercise bouts (15-s [35 % APR]/45 s [passive]; in a well trained cyclist. Note the reductions in SV for intensities above >50 % of $\dot{V}O_{2max}$ during both the incremental and constant power tests, which is associated with a greater muscle deoxygenation during the incremental test. In contrast, maximal SV values are consistently observed during the post-exercise periods, either following incremental, maximal or supramaximal exercises. *APR* anaerobic power reserve, *HIT* high-intensity interval training, *HR* heart rate, $\dot{V}O_{2max}$ maximal oxygen uptake, *p* $\dot{V}O_{2max}$ minimal power associated with $\dot{V}O_{2max}$, *SV* stroke volume, *TSI* tissue saturation index

actually induce greater adaptive gains than 16 min of work at ~95 % HR_{max} [176]. While SV was not measured, these results contrast with the idea that exercise intensity directly determines the training responses [59]. Rather, they show that both exercise intensity and accumulated duration of interval training may act in an integrated way to stimulate physiological adaptations in this population [176]. In this latter case [176], the decrease in exercise intensity may have allowed for a greater T@Qc_{max} (or near Qc_{max}), and, in turn, a greater adaptation. Whether similar results would be observed in highly trained athletes who are more likely to require greater levels of exercise stress for further adaptations, is still unknown. Finally, since T@Qc_{max} has been shown to be largely correlated with time to exhaustion during severe exercise (*r* ranging from 0.79; 90 % CL 0.45, 0.93 to *r* 0.98; 90 % CL 0.94, 0.99) [25], pacing strategies that can increase time to exhaustion but that sustain a high cardiorespiratory demand may also be of interest. For instance, adjusting work intensity based on $\dot{V}O_2$ responses (constant-$\dot{V}O_2$ exercise at 77 % $\dot{V}O_{2max}$ on average) instead of power (constant-power exercise at 87 % p$\dot{V}O_{2max}$) led to 'moderate' increases in time to exhaustion (20 min ± 10 min vs. 15 min ± 5 min, ES = +1.0) and, in turn, T@Qc_{max} (16 min ± 8 min vs. 14 min ± 4 min, ES = +0.9) [25].

4 Conclusions

In Part I of this review, the different aspects of HIT programming have been discussed with respect to T@$\dot{V}O_{2max}$ and cardiopulmonary function. Important between-athlete and between-HIT format differences exist, so that precise recommendations are difficult to offer. Most HIT formats, if properly manipulated, can enable athletes to reach $\dot{V}O_{2max}$, but RSS and SIT sessions allow limited T@$\dot{V}O_{2max}$ compared with HIT sessions involving long and short intervals. The $\dot{V}O_2$ responses during RSS and SIT appear to be fitness-dependent, with the fitter athletes less able to reach $\dot{V}O_{2max}$ during such training. Based on the current review, the following general recommendations can be made:

1. To individualize exercise intensity and target specific acute physiological responses (Fig. 1), v/p$\dot{V}O_{2max}$ and ASR/APR or V_{IFT} are likely the more accurate references needed to design HIT with long (≥1–2 min) and short (≤45 s) intervals, respectively. For run-based HIT sessions, compared with the ASR, V_{IFT} integrates between-effort recovery abilities and COD capacities that make V_{IFT} especially relevant for programming short, supramaximal intermittent runs

performed with COD, as implemented in the majority of team and racket sports.

2. Especially in well trained athletes that perform exercises involving large muscle groups, and assuming the accumulation of T@$\dot{V}O_{2max}$ may maximize the training stimulus to improving performance, we recommend long- and short-bout HIT with a work/relief ratio >1 (see Part II, Table 1 for practical programming suggestions). Additionally:
   a. There should be little delay between the warm-up and the start of the HIT session so that the time needed to reach $\dot{V}O_{2max}$ is accelerated. Warm-up intensity can be ≤60–70 % v/p$\dot{V}O_{2max}$, or game based (moderate intensity) for team and racket sport athletes.
   b. Total session volume should enable athletes to spend between ≈5 (team and racket sports) and ≈10 (endurance sports) min at $\dot{V}O_{2max}$.
3. Until new evidence is provided, the importance of continuous versus repeated ventricular filling at high rates for developing cardiovascular adaptations is not known. Near-to-maximal and prolonged work intervals currently appear to be the preferred HIT option (i.e. >4 min at 90–95 % v/p$\dot{V}O_{2max}$, with likely decreasing external load with increasing fatigue to prolong T@Qc_{max}).

5 Perspective

Further research is required to specify the acute cardiopulmonary responses to HIT/RST/SIT in particular populations such as youth and female athletes, as well as the influence that training status and cardiorespiratory fitness have on these responses. Further research is also needed to improve our understanding of how to optimally manipulate HIT variables, in particular, environmental conditions (e.g. altitude [21], heat [217]), where 'typical' HIT sessions, as suggested for programming in the present review, cannot be performed. The impact of time of day, timing within a session, and external training contents should also be examined, as typically most studies are conducted with 'fresh' participants in controlled environments, while in practice, HIT sessions are often performed in a state of accumulated fatigue (end of a team-sport session or in the afternoon following an exhaustive morning training session). Understanding the physiological responses to technical/tactical training sessions is also likely an important aspect of successful training in team sport athletes, so that the optimal HIT sessions can be programmed as supplemental sessions (i.e. how does one "best solve the programming puzzle", while adding what is 'missed' during the technical/tactical sessions [151], since physiological and performance adaptations have been shown to occur in relation to the accumulated training load completed at high intensities [218]). Finally, since in team sports improvements in physical fitness might not have a similar impact on match running performance for all players (influence of playing positions, systems of play, individual playing styles) [63, 98, 219, 220], the implementation of HIT sessions should be individualized and considered using a cost-benefit approach. As will be discussed in Part II, consideration for other important aspects of HIT programming, such as glycolytic anaerobic energy contribution, neuromuscular load and musculoskeletal strain, should also be considered. Further studies are also needed to examine the long-term adaptations to all forms of HIT/repeated all-out efforts presented in the present review with respect to gender, age and training status/background.

Acknowledgments No sources of funding were used to assist in the preparation of this review. The authors have no conflicts of interest that are directly relevant to the content of this review.

References

1. Laursen PB. Training for intense exercise performance: high-intensity or high-volume training? Scand J Med Sci Sports. 2010;20(Suppl 2):1–10.
2. Seiler S, Tønnessen E. Intervals, thresholds, and long slow distance: the role of intensity and duration in endurance training. Sportscience. 2009;13:32–53.
3. 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. 2001;1:13–31.
4. Billat LV. Interval training for performance: a scientific and empirical practice: special recommendations for middle- and long-distance running. Part II: anaerobic interval training. Sports Med. 2001;31:75–90.
5. 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. 2002;32:53–73.
6. Laursen PB. Interval training for endurance. In: Mujika I, editor. Endurance training: science and practice (pp. 41–50). Vitoria-Gasteiz: Iñigo Mujika; 2012. ISBN 978-84-939970-0-7.
7. Bishop D, Girard O, Mendez-Villanueva A. Repeated-sprint ability—Part II: recommendations for training. Sports Med. 2011;41:741–56.
8. Gibala MJ, Little JP, van Essen M, et al. Short-term sprint interval versus traditional endurance training: similar initial adaptations in human skeletal muscle and exercise performance. J Physiol. 2006;575:901–11.
9. Iaia FM, Bangsbo J. Speed endurance training is a powerful stimulus for physiological adaptations and performance improvements of athletes. Scand J Med Sci Sports. 2010;20(Suppl. 2): 11–23.

10. Astrand I, Astrand PO, Christensen EH, et al. Intermittent muscular work. Acta Physiol Scand. 1960;48:448–53.
11. Astrand I, Astrand PO, Christensen EH, et al. Myohemoglobin as an oxygen-store in man. Acta Physiol Scand. 1960;48: 454–60.
12. Christensen EH, Hedman R, Saltin B. Intermittent and continuous running. (A further contribution to the physiology of intermittent work.). Acta Physiol Scand. 1960;50:269–86.
13. Balsom PD, Seger JY, Sjodin B, et al. Maximal-intensity intermittent exercise: effect of recovery duration. Int J Sports Med. 1992;13:528–33.
14. Midgley AW, McNaughton LR. Time at or near VO_{2max} during continuous and intermittent running: a review with special reference to considerations for the optimisation of training protocols to elicit the longest time at or near VO_{2max}. J Sports Med Phys Fitness. 2006;46:1–14.
15. 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. 2006;36:117–32.
16. Altenburg TM, Degens H, van Mechelen W, et al. Recruitment of single muscle fibers during submaximal cycling exercise. J Appl Physiol. 2007;103:1752–6.
17. Gollnick PD, Piehl K, Saltin B. Selective glycogen depletion pattern in human muscle fibres after exercise of varying intensity and at varying pedalling rates. J Physiol. 1974;241:45–57.
18. 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. 2007;37:857–80.
19. Vollaard NB, Constantin-Teodosiu D, Fredriksson K, et al. Systematic analysis of adaptations in aerobic capacity and submaximal energy metabolism provides a unique insight into determinants of human aerobic performance. J Appl Physiol. 2009;106:1479–86.
20. Bouchard C, Rankinen T. Individual differences in response to regular physical activity. Med Sci Sports Exerc. 2001;33: S446–51.
21. Buchheit M, Kuitunen S, Voss SC, et al. Physiological strain associated with high-intensity hypoxic intervals in highly trained young runners. J Strength Cond Res. 2012;26:94–105.
22. Vuorimaa T, Vasankari T, Rusko H. Comparison of physiological strain and muscular performance of athletes during two intermittent running exercises at the velocity associated with VO_{2max}. Int J Sports Med. 2000;21:96–101.
23. Billat LV, Slawinksi J, Bocquet V, et al. Very short (15 s–15 s) interval-training around the critical velocity allows middle-aged runners to maintain VO_2 max for 14 minutes. Int J Sports Med. 2001;22:201–8.
24. Faisal A, Beavers KR, Robertson AD, et al. Prior moderate and heavy exercise accelerate oxygen uptake and cardiac output kinetics in endurance athletes. J Appl Physiol. 2009;106: 1553–63.
25. Lepretre PM, Lopes P, Koralsztein JP, et al. Fatigue responses in exercise under control of VO_2. Int J Sports Med. 2008;29: 199–205.
26. Mortensen SP, Damsgaard R, Dawson EA, et al. Restrictions in systemic and locomotor skeletal muscle perfusion, oxygen supply and VO_2 during high-intensity whole-body exercise in humans. J Physiol. 2008;586:2621–35.
27. Richard R, Lonsdorfer-Wolf E, Dufour S, et al. Cardiac output and oxygen release during very high-intensity exercise performed until exhaustion. Eur J Appl Physiol. 2004;93:9–18.
28. Christmass MA, Dawson B, Arthur PG. Effect of work and recovery duration on skeletal muscle oxygenation and fuel use during sustained intermittent exercise. Eur J Appl Physiol Occup Physiol. 1999;80:436–47.
29. Christmass MA, Dawson B, Passeretto P, et al. A comparison of skeletal muscle oxygenation and fuel use in sustained continuous and intermittent exercise. Eur J Appl Physiol. 1999;80: 423–35.
30. Buchheit M, Laursen PB, Ahmaidi S. Parasympathetic reactivation after repeated sprint exercise. Am J Physiol Heart Circ Physiol. 2007;293:H133–41.
31. James DV, Barnes AJ, Lopes P, et al. Heart rate variability: response following a single bout of interval training. Int J Sports Med. 2002;23:247–51.
32. Mourot L, Bouhaddi M, Tordi N, et al. Short- and long-term effects of a single bout of exercise on heart rate variability: comparison between constant and interval training exercises. Eur J Appl Physiol 2004; 92:508–17.
33. Al Haddad H, Laursen PB, Ahmaidi S, et al. Nocturnal heart rate variability following supramaximal intermittent exercise. Int J Sports Physiol Perform. 2009;4:435–47.
34. Hoff J, Helgerud J. Endurance and strength training for soccer players: physiological considerations. Sports Med. 2004;3:165–80.
35. Buchheit M. The 30–15 Intermittent Fitness Test: a new intermittent running field test for intermittent sport players—part 1. Approches du Handball. 2005;87:27–34.
36. Buchheit M, Al Haddad H, Chivot A, et al. Effect of in- versus out-of-water recovery on repeated swimming sprint performance. Eur J Appl Physiol 2010;108:321–7.
37. Guiraud T, Nigam A, Gremeaux V, et al. High-intensity interval training in cardiac rehabilitation. Sports Med. 2012;42:587–605.
38. Metcalfe RS, Babraj JA, Fawkner SG, et al. Towards the minimal amount of exercise for improving metabolic health: beneficial effects of reduced-exertion high-intensity interval training. Eur J Appl Physiol. 2012;112:2767–75.
39. Hood MS, Little JP, Tarnopolsky MA, et al. Low-volume interval training improves muscle oxidative capacity in sedentary adults. Med Sci Sports Exerc. 2011;43:1849–56.
40. Trilk JL, Singhal A, Bigelman KA, et al. Effect of sprint interval training on circulatory function during exercise in sedentary, overweight/obese women. Eur J Appl Physiol. 2011;111:1591–7.
41. Cohen J. Statistical power analysis for the behavioral sciences. Hillsdale: Lawrence Erlbaum Assoc, Inc.; 1988. p. 599.
42. Hopkins WG, Marshall SW, Batterham AM, et al. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009;41:3–13.
43. Buchheit M, Laursen PB, Kuhnle J, et al. Game-based training in young elite handball players. Int J Sports Med. 2009;30: 251–8.
44. Castagna C, Impellizzeri FM, Chaouachi A, et al. Physiological responses to ball-drills in regional level male basketball players. J Sports Sci. 2011;29:1329–36.
45. Fernandez-Fernandez J, Sanz-Rivas D, Sanchez-Muñoz C, et al. Physiological responses to on-court vs running interval training in competitive tennis players. J Sports Sci Med. 2011;10:540–5.
46. Impellizzeri FM, Marcora SM, Castagna C, et al. Physiological and performance effects of generic versus specific aerobic training in soccer players. Int J Sports Med. 2006;27:483–92.
47. Sheppard JM, Borgeaud R. Skill based conditioning: a perspective from elite volleyball. NSCA hot topic series. 2009; December [online]. Available from URL: http://www.nsca-lift.org. [Accessed 12 Dec 2011].
48. Gabbett TJ. Skill-based conditioning games as an alternative to traditional conditioning for rugby league players. J Strength Cond Res. 2006;20:309–15.

49. Hill-Haas SV, Dawson B, Impellizzeri FM, et al. Physiology of small-sided games training in football: a systematic review. Sports Med. 2011;41:199–220.
50. Buchheit M, Lepretre PM, Behaegel AL, et al. Cardiorespiratory responses during running and sport-specific exercises in handball players. J Sci Med Sport. 2009;12:399–405.
51. Castagna C, Belardinelli R, Impellizzeri FM, et al. Cardiovascular responses during recreational 5-a-side indoor-soccer. J Sci Med Sport 2007;10:89–95.
52. Owen AL, Wong del P, Paul D, Dellal A. Effects of a periodized small-sided game training intervention on physical performance in elite professional soccer. J Strength Cond Res. 2012;26:2748–54.
53. Hill-Haas SV, Coutts AJ, Rowsell GJ, et al. Generic versus small-sided game training in soccer. Int J Sports Med. 2009;30:636–42.
54. Dellal A, Lago-Penas C, Wong del P, et al. Effect of the number of ball contacts within bouts of 4 vs. 4 small-sided soccer games. Int J Sports Physiol Perform 2011;6:322–33.
55. Rampinini E, Impellizzeri F, Castagna C, et al. Factors influencing physiological responses to small-sided soccer games. J Sports Sci. 2007;6:659–66.
56. Hill-Haas S, Coutts A, Rowsell G, et al. Variability of acute physiological responses and performance profiles of youth soccer players in small-sided games. J Sci Med Sport. 2008;11:487–90.
57. Hill-Haas S, Rowsell G, Coutts A, et al. The reproducibility of physiological responses and performance profiles of youth soccer players in small-sided games. Int J Sports Physiol Perform. 2008;3:393–6.
58. Daussin FN, Ponsot E, Dufour SP, et al. Improvement of Da-vO_2 by cardiac output and oxygen extraction adaptation during intermittent versus continuous endurance training. Eur J Appl Physiol. 2007;101:377–83.
59. Helgerud J, Hoydal K, Wang E, et al. Aerobic high-intensity intervals improve VO_{2max} more than moderate training. Med Sci Sports Exerc. 2007;39:665–71.
60. Hoff J, Wisloff U, Engen LC, et al. Soccer specific aerobic endurance training. Br J Sports Med. 2002;36:218–21.
61. Whipp BJ, Higgenbotham MB, Cobb FC. Estimating exercise stroke volume from asymptotic oxygen pulse in humans. J Appl Physiol. 1996;81:2674–9.
62. Saltin B, Blomqvist G, Mitchell JH, et al. Response to exercise after bed rest and after training. Circulation 1968;38:VII1–78.
63. Mendez-Villanueva A, Buchheit M, Simpson BM, et al. Match play intensity distribution in youth soccer. Int J Sport Med 2013;34:101–10.
64. Mendez-Villanueva A, Buchheit M, Simpson B, et al. Does on-field sprinting performance in young soccer players depend on how fast they can run or how fast they do run? J Strength Cond Res. 2011;25:2634–8.
65. Di Salvo V, Baron R, Gonzalez-Haro C, et al. Sprinting analysis of elite soccer players during European Champions League and UEFA Cup matches. J Sports Sci. 2010;28:1489–94.
66. Casamichana D, Castellano J, Castagna C. Comparing the physical demands of friendly matches and small-sided games in semiprofessional soccer players. J Strength Cond Res. 2012;26:837–43.
67. Achten J, Jeukendrup AE. Heart rate monitoring: applications and limitations. Sports Med. 2003;33:517–38.
68. Midgley AW, McNaughton LR, Carroll S. Reproducibility of time at or near VO_{2max} during intermittent treadmill running. Int J Sports Med. 2007;28:40–7.
69. Seiler S, Hetlelid KJ. The impact of rest duration on work intensity and RPE during interval training. Med Sci Sports Exerc. 2005;37:1601–7.
70. Cerretelli P, Di Prampero PE. Kinetics of respiratory gas exchange and cardiac output at the onset of exercise. Scand J Respir Dis 1971;Suppl.:35a–g.
71. Seiler S, Sjursen JE. Effect of work duration on physiological and rating scale of perceived exertion responses during self-paced interval training. Scand J Med Sci Sports. 2004;14:318–25.
72. Dishman RK, Patton RW, Smith J, et al. Using perceived exertion to prescribe and monitor exercise training heart rate. Int J Sports Med. 1987;8:208–13.
73. Marcora S. Perception of effort during exercise is independent of afferent feedback from skeletal muscles, heart, and lungs. J Appl Physiol. 2009;106:2060–2.
74. Marcora SM. Role of feedback from Group III and IV muscle afferents in perception of effort, muscle pain, and discomfort. J Appl Physiol 2011;110:1499 (author reply 500).
75. Coutts AJ, Rampinini E, Marcora SM, et al. Heart rate and blood lactate correlates of perceived exertion during small-sided soccer games. J Sci Med Sport. 2009;12:79–84.
76. Marcora SM, Staiano W, Manning V. Mental fatigue impairs physical performance in humans. J Appl Physiol. 2009;106:857–64.
77. Ulmer HV. Concept of an extracellular regulation of muscular metabolic rate during heavy exercise in humans by psychophysiological feedback. Experientia. 1996;52:416–20.
78. Garcin M, Fleury A, Mille-Hamard L, et al. Sex-related differences in ratings of perceived exertion and estimated time limit. Int J Sports Med. 2005;26:675–81.
79. Garcin M, Danel M, Billat V. Perceptual responses in free vs. constant pace exercise. Int J Sports Med. 2008;29:453–9.
80. Celine CG, Monnier-Benoit P, Groslambert A, et al. The perceived exertion to regulate a training program in young women. J Strength Cond Res. 2011;25:220–4.
81. Groslambert A, Mahon AD. Perceived exertion: influence of age and cognitive development. Sports Med. 2006;36:911–28.
82. Garcin M, Coquart JB, Robin S, et al. Prediction of time to exhaustion in competitive cyclists from a perceptually based scale. J Strength Cond Res. 2011;25:1393–9.
83. Garcin M, Mille-Hamard L, Billat V. Influence of aerobic fitness level on measured and estimated perceived exertion during exhausting runs. Int J Sports Med. 2004;25:270–7.
84. Cabanac ME. Exertion and pleasure from an evolutionary perspective. In: Acevedo EO, Ekkekakis P, editors. Psychobiology of physical activity. Champaign: Human Kinetics; 2006. p. 79–89.
85. Volkov NI, Shirkovets EA, Borilkevich VE. Assessment of aerobic and anaerobic capacity of athletes in treadmill running tests. Eur J Appl Physiol Occup Physiol. 1975;34:121–30.
86. Conley DL, Krahenbuhl GS. Running economy and distance running performance of highly trained athletes. Med Sci Sports Exerc. 1980;12:357–60.
87. Leger LA, Boucher R. An indirect continuous running multistage field test: the Universite de Montreal track test. Can J Appl Sport Sci. 1980;5:77–84.
88. Daniels J, Scardina N, Hayes J, et al. Elite and subelite female middle- and long-distance runners. In: Landers DM, editor. Sport and elite performers: the 1984 Olympic scientific congress proceedings, vol. 3. Champaign: Human Kinetics; 1984. p. 57–72.
89. Billat LV, Koralsztein JP. Significance of the velocity at VO_{2max} and time to exhaustion at this velocity. Sports Med. 1996;22:90–108.
90. Hill DW, Rowell AL. Running velocity at VO_{2max}. Med Sci Sports Exerc. 1996;28:114–9.
91. di Prampero PE, Atchou G, Bruckner JC, et al. The energetics of endurance running. Eur J Appl Physiol Occup Physiol. 1986;55:259–66.

92. Lacour JR, Padilla-Magunacelaya S, Barthelemy JC, et al. The energetics of middle-distance running. Eur J Appl Physiol Occup Physiol. 1990;60:38–43.
93. Billat V, Renoux JC, Pinoteau J, et al. Reproducibility of running time to exhaustion at VO_{2max} in subelite runners. Med Sci Sports Exerc. 1994;26:254–7.
94. Buchheit M. The 30–15 Intermittent fitness test: accuracy for individualizing interval training of young intermittent sport players. J Strength Cond Res. 2008;22:365–74.
95. Dupont G, Akakpo K, Berthoin S. The effect of in-season, high-intensity interval training in soccer players. J Strength Cond Res. 2004;18:584–9.
96. Cazorla G, Benezzedine-Boussaidi L. Carré, F. Aptitude aérobie sur le terrain. Pourquoi et comment l'évaluer? Médecins du Sport 2005;73:13–23.
97. Mendez-Villanueva A, Buchheit M, Kuitunen S, et al. Is the relationship between sprinting and maximal aerobic speeds in young soccer players affected by maturation? Ped Exerc Sci. 2010;4:497–510.
98. Buchheit M, Mendez-Villanueva A, Simpson BM, et al. Match running performance and fitness in youth soccer. Int J Sports Med. 2010;31:818–25.
99. Noakes TD. Implications of exercise testing for prediction of athletic performance: a contemporary perspective. Med Sci Sports Exerc. 1988;20:319–30.
100. Rampinini E, Bishop D, Marcora SM, et al. Validity of simple field tests as indicators of match-related physical performance in top-level professional soccer players. Int J Sports Med. 2007;28:228–35.
101. Berthon P, Fellmann N, Bedu M, et al. A 5-min running field test as a measurement of maximal aerobic velocity. Eur J Appl Physiol Occup Physiol. 1997;3:233–8.
102. Hill DW, Rowell AL. Significance of time to exhaustion during exercise at the velocity associated with VO_{2max}. Eur J Appl Physiol Occup Physiol. 1996;72:383–6.
103. Midgley AW, McNaughton LR, Carroll S. Time at VO_{2max} during intermittent treadmill running: test protocol dependent or methodological artefact? Int J Sports Med. 2007;28:934–9.
104. Harling SA, Tong RJ, Mickleborough TD. The oxygen uptake response running to exhaustion at peak treadmill speed. Med Sci Sports Exerc. 2003;35:663–8.
105. Pugh LG. The influence of wind resistance in running and walking and the mechanical efficiency of work against horizontal or vertical forces. J Physiol. 1971;213:255–76.
106. Saunders PU, Cox AJ, Hopkins WG, et al. Physiological measures tracking seasonal changes in peak running speed. Int J Sports Physiol Perform. 2010;5:230–8.
107. Dabonneville M, Berthon P, Vaslin P, et al. The 5 min running field test: test and retest reliability on trained men and women. Eur J Appl Physiol. 2003;88:353–60.
108. Berthon P, Fellmann N. General review of maximal aerobic velocity measurement at laboratory. Proposition of a new simplified protocol for maximal aerobic velocity assessment. J Sports Med Phys Fitness. 2002;42:257–66.
109. Bosquet L, Leger L, Legros P. Methods to determine aerobic endurance. Sports Med. 2002;32:675–700.
110. Blondel N, Berthoin S, Billat V, et al. Relationship between run times to exhaustion at 90, 100, 120, and 140% of vVO_{2max} and velocity expressed relatively to critical velocity and maximal velocity. Int J Sports Med. 2001;22:27–33.
111. Bundle MW, Hoyt RW, Weyand PG. High-speed running performance: a new approach to assessment and prediction. J Appl Physiol. 2003;95:1955–62.
112. Weyand PG, Bundle MW. Energetics of high-speed running: integrating classical theory and contemporary observations. Am J Physiol Regul Integr Comp Physiol. 2005;288:R956–65.
113. Weyand PG, Lin JE, Bundle MW. Sprint performance-duration relationships are set by the fractional duration of external force application. Am J Physiol Regul Integr Comp Physiol. 2006;290:R758–65.
114. Buchheit M. Repeated-sprint performance in team sport players: associations with measures of aerobic fitness, metabolic control and locomotor function. Int J Sport Med. 2012;33:230–9.
115. Mendez-Villanueva A, Hamer P, Bishop D. Fatigue in repeated-sprint exercise is related to muscle power factors and reduced neuromuscular activity. Eur J Appl Physiol. 2008;103:411–9.
116. Buchheit M. The 30–15 intermittent fitness test: 10 year review. Myorobie J 2010; 1 [online]. Available from URL: http://www.martin-buchheit.net. [Accessed 17 Feb 2013].
117. Dupont G, Blondel N, Lensel G, et al. Critical velocity and time spent at a high level of VO_2 for short intermittent runs at supramaximal velocities. Can J Appl Physiol. 2002;27:103–15.
118. Buchheit M. 30–15 Intermittent fitness test and repeated sprint ability. Sci Sports. 2008;23:26–8.
119. Buchheit M, Al Haddad H, Leprêtre PM, et al. Cardiorespiratory and cardiac autonomic responses to 30–15 intermittent fitness test. J Strength Cond Res. 2009;23:93–100.
120. Bangsbo J, Iaia FM, Krustrup P. The Yo-Yo intermittent recovery test: a useful tool for evaluation of physical performance in intermittent sports. Sports Med. 2008;38:37–51.
121. Dupont G, Defontaine M, Bosquet L, et al. Yo-Yo intermittent recovery test versus the Universite de Montreal Track Test: relation with a high-intensity intermittent exercise. J Sci Med Sport. 2010;13:146–50.
122. Buchheit M. The 30–15 intermittent fitness test: reliability and implication for interval training of intermittent sport players [abstract no. 1231]. 10th European Congress of Sport Science. 2005 Jul 13–16; Belgrade.
123. Buchheit M, Laursen PB, Millet GP, et al. Predicting intermittent running performance: critical velocity versus endurance index. Int J Sports Med. 2007;29:307–15.
124. Dellal A, Varliette C, Owen A, et al. Small-sided games vs. interval training in amateur soccer players: effects on the aerobic capacity and the ability to perform intermittent exercises with changes of direction. J Strength Cond Res. 2012;26:2712–20.
125. Mosey T. High intensity interval training in youth soccer players: using fitness testing results practically. J Aust Strength Cond. 2009;17:49–51.
126. Rakobowchuk M, Tanguay S, Burgomaster KA, et al. Sprint interval and traditional endurance training induce similar improvements in peripheral arterial stiffness and flow-mediated dilation in healthy humans. Am J Physiol Regul Integr Comp Physiol. 2008;295:R236–42.
127. Demarie S, Koralsztein JP, Billat V. Time limit and time at VO_{2max}, during a continuous and an intermittent run. J Sports Med Phys Fitness. 2000;40:96–102.
128. Millet GP, Candau R, Fattori P, et al. VO_2 responses to different intermittent runs at velocity associated with VO_{2max}. Can J Appl Physiol. 2003;28:410–23.
129. Dupont G, Blondel N, Berthoin S. Time spent at VO_{2max}: a methodological issue. Int J Sports Med. 2003;24:291–7.
130. Billat VL, Blondel N, Berthoin S. Determination of the velocity associated with the longest time to exhaustion at maximal oxygen uptake. Eur J Appl Physiol Occup Physiol. 1999;80:159–61.
131. Hill DW, Williams CS, Burt SE. Responses to exercise at 92% and 100% of the velocity associated with VO_{2max}. Int J Sports Med. 1997;18:325–9.
132. Billat V, Binsse V, Petit B, et al. High level runners are able to maintain a VO_2 steady-state below VO_{2max} in an all-out run over their critical velocity. Arch Physiol Biochem. 1998;106:38–45.

133. Gerbino A, Ward SA, Whipp BJ. Effects of prior exercise on pulmonary gas-exchange kinetics during high-intensity exercise in humans. J Appl Physiol. 1996;80:99–107.
134. Dorado C, Sanchis-Moysi J, Calbet JA. Effects of recovery mode on performance, O_2 uptake, and O_2 deficit during high-intensity intermittent exercise. Can J Appl Physiol. 2004;29:227–44.
135. Hill DW, Rowell AL. Responses to exercise at the velocity associated with VO_{2max}. Med Sci Sports Exerc. 1997;29:113–6.
136. Hill DW, Stevens EC. VO_2 response profiles in severe intensity exercise. J Sports Med Phys Fitness. 2005;45:239–47.
137. Laursen PB, Shing CM, Jenkins DG. Temporal aspects of the VO_2 response at the power output associated with VO_2peak in well trained cyclists: implications for interval training prescription. Res Q Exerc Sport. 2004;75:423–8.
138. Billat LV, Renoux J, Pinoteau J, et al. Validation d'une épreuve maximale de temps limiteà VMA (vitesse maximale aérobie) et à VO_{2max}. Sci Sports. 1994;9:3–12.
139. Hughson RL, O'Leary DD, Betik AC, et al. Kinetics of oxygen uptake at the onset of exercise near or above peak oxygen uptake. J Appl Physiol. 2000;88:1812–9.
140. Hill DW, Halcomb JN, Stevens EC. Oxygen uptake kinetics during severe intensity running and cycling. Eur J Appl Physiol. 2003;89:612–8.
141. Norris SR, Petersen SR. Effects of endurance training on transient oxygen uptake responses in cyclists. J Sports Sci. 1998;16:733–8.
142. Buchheit M, Abbiss C, Peiffer JJ, et al. Performance and physiological responses during a sprint interval training session: relationships with muscle oxygenation and pulmonary oxygen uptake kinetics. Eur J Appl Physiol. 2012;112(2):767–79.
143. Powers SK, Dodd S, Beadle RE. Oxygen uptake kinetics in trained athletes differing in VO_{2max}. Eur J Appl Physiol Occup Physiol. 1985;54:306–8.
144. Buchheit M, Laursen PB, Ahmaidi S. Effect of prior exercise on pulmonary O_2 uptake and estimated muscle capillary blood flow kinetics during moderate-intensity field running in men. J Appl Physiol. 2009;107:460–70.
145. Barstow TJ, Jones AM, Nguyen PH, et al. Influence of muscle fiber type and pedal frequency on oxygen uptake kinetics of heavy exercise. J Appl Physiol. 1996;81:1642–50.
146. Pringle JS, Doust JH, Carter H, et al. Oxygen uptake kinetics during moderate, heavy and severe intensity "submaximal" exercise in humans: the influence of muscle fibre type and capillarisation. Eur J Appl Physiol. 2003;89:289–300.
147. Kilding AE, Winter EM, Fysh M. A comparison of pulmonary oxygen uptake kinetics in middle- and long-distance runners. Int J Sports Med. 2006;27:419–26.
148. Billat V, Petit B, Koralsztein J. Calibration de la durée des répétition d'une séance d'interval training à la vitesse associée à VO_{2max} en référence au temps limite continu: effet sur les réponses physiologiques et la distance parcourue. Sci Mot. 1996;28:13–20.
149. Smith TP, McNaughton LR, Marshall KJ. Effects of 4-wk training using Vmax/Tmax on VO_{2max} and performance in athletes. Med Sci Sports Exerc. 1999;31:892–6.
150. Smith TP, Coombes JS, Geraghty DP. Optimising high-intensity treadmill training using the running speed at maximal O(2) uptake and the time for which this can be maintained. Eur J Appl Physiol. 2003;89:337–43.
151. Buchheit M. High-intensity interval training: how to best shape the puzzle piece. International congress of the Australian Strength and conditioning Association, November 9–11th 2012, Brisbane, QS, Australia.
152. Muller EA. The physiological basis of rest pauses in heavy work. Q J Exp Physiol Cogn Med Sci. 1953;38:205–15.
153. Belcastro AN, Bonen A. Lactic acid removal rates during controlled and uncontrolled recovery exercise. J Appl Physiol. 1975;39:932–6.
154. Ahmaidi S, Granier P, Taoutaou Z, et al. Effects of active recovery on plasma lactate and anaerobic power following repeated intensive exercise. Med Sci Sports Exerc. 1996;28:450–6.
155. Krustrup P, Mohr M, Steensberg A, et al. Muscle and blood metabolites during a soccer game: implications for sprint performance. Med Sci Sports Exerc. 2006;38:1165–74.
156. Gorostiaga EM, Asiain X, Izquierdo M, et al. Vertical jump performance and blood ammonia and lactate levels during typical training sessions in elite 400-m runners. J Strength Cond Res. 2010;24:1138–49.
157. Weltman A, Stamford BA, Fulco C. Recovery from maximal effort exercise: lactate disappearance and subsequent performance. J Appl Physiol. 1979;47:677–82.
158. Buchheit M, Cormie P, Abbiss CR, et al. Muscle deoxygenation during repeated sprint running: effect of active vs. passive recovery. Int J Sports Med. 2009;30:418–25.
159. Dupont G, Moalla W, Matran R, et al. Effect of short recovery intensities on the performance during two Wingate tests. Med Sci Sports Exerc. 2007;39:1170–6.
160. Spencer M, Bishop D, Dawson B, et al. Metabolism and performance in repeated cycle sprints: active versus passive recovery. Med Sci Sports Exerc. 2006;38:1492–9.
161. Bogdanis GC, Nevill ME, Lakomy HK, et al. Effects of active recovery on power output during repeated maximal sprint cycling. Eur J Appl Physiol Occup Physiol. 1996;74:461–9.
162. Connolly DAJ, Brennan KM, Lauzon CD. Effects of active versus passive recovery on power output during repeated bouts of short term, high intensity exercise. J Sports Sci Med 2003:47–51.
163. Spencer M, Dawson B, Goodman C, et al. Performance and metabolism in repeated sprint exercise: effect of recovery intensity. Eur J Appl Physiol. 2008;103:545–52.
164. Thevenet D, Leclair E, Tardieu-Berger M, et al. Influence of recovery intensity on time spent at maximal oxygen uptake during an intermittent session in young, endurance-trained athletes. J Sports Sci. 2008;26:1313–21.
165. Acevedo EO, Goldfarb AH. Increased training intensity effects on plasma lactate, ventilatory threshold, and endurance. Med Sci Sports Exerc. 1989;21:563–8.
166. Simoneau JA, Lortie G, Boulay MR, et al. Effects of two high-intensity intermittent training programs interspaced by detraining on human skeletal muscle and performance. Eur J Appl Physiol Occup Physiol. 1987;56:516–21.
167. Wu HC, Hsu WH, Chen T. Complete recovery time after exhaustion in high-intensity work. Ergonomics. 2005;48:668–79.
168. Rowell LB, O'Leary DS. Reflex control of the circulation during exercise: chemoreflexes and mechanoreflexes. J Appl Physiol. 1990;69:407–18.
169. Billat V. L'entraînement en pleine nature: conseils de préparation aux sports outdoor. Paris: De Boeck; 2005.
170. Paavolainen L, Nummela A, Rusko H. Muscle power factors and VO_{2max} as determinants of horizontal and uphill running performance. Scand J Med Sci Sports. 2000;10:286–91.
171. Staab JS, Agnew JW, Siconolfi SF. Metabolic and performance responses to uphill and downhill running in distance runners. Med Sci Sports Exerc. 1992;24:124–7.
172. Pringle JS, Carter H, Doust JH, et al. Oxygen uptake kinetics during horizontal and uphill treadmill running in humans. Eur J Appl Physiol. 2002;88:163–9.
173. Slawinski J, Dorel S, Hug F, et al. Elite long sprint running: a comparison between incline and level training sessions. Med Sci Sports Exerc. 2008;40:1155–62.

174. Gajer B, Hanon C, Lehenaff D, et al. Analyse comparée de différentes séances de développement de VO_{2max}. In: Expertise et sport de haut niveau: actes des Entretiens de l'INSEP Novembre 2002. Paris: Insep, 2003.
175. Minetti AE, Moia C, Roi GS, et al. Energy cost of walking and running at extreme uphill and downhill slopes. J Appl Physiol. 2002;93:1039–46.
176. Seiler S, Jøranson K, Olesen BV, et al. Adaptations to aerobic interval training: interactive effects of exercise intensity and total work duration. Scand J Med Sci Sports. 2013;23(1):74–83.
177. Millet GP, Libicz S, Borrani F, et al. Effects of increased intensity of intermittent training in runners with differing VO_2 kinetics. Eur J Appl Physiol. 2003;90:50–7.
178. Tardieu-Berger M, Thevenet D, Zouhal H, et al. Effects of active recovery between series on performance during an intermittent exercise model in young endurance athletes. Eur J Appl Physiol. 2004;93:145–52.
179. Thevenet D, Tardieu M, Zouhal H, et al. Influence of exercise intensity on time spent at high percentage of maximal oxygen uptake during an intermittent session in young endurance-trained athletes. Eur J Appl Physiol. 2007;102:19–26.
180. Buchheit M, Millet GP, Parisy A, et al. Supramaximal training and post-exercise parasympathetic reactivation in adolescents. Med Sci Sports Exerc. 2008;40:362–71.
181. Bisciotti GN. L'incidenza fisiologica dei parametri di durata, intensità e recupero nell'ambito dell'allenamento intermittente. Sienza di Sport 2004: 90-6 [online]. Available from URL: http://www.scienzaesport.com/SdS/050322074/074.htm. [Accessed 17 Feb 2013].
182. Dellal A, Keller D, Carling C, et al. Physiologic effects of directional changes in intermittent exercise in soccer players. J Strength Cond Res. 2010;24:3219–26.
183. Belfry GR, Paterson DH, Murias JM, et al. The effects of short recovery duration on VO(2) and muscle deoxygenation during intermittent exercise. Eur J Appl Physiol. 2012;112(5):1907–15.
184. Gastin PB. Energy system interaction and relative contribution during maximal exercise. Sports Med. 2001;31:725–41.
185. Rozenek R, Funato K, Kubo J, et al. Physiological responses to interval training sessions at velocities associated with VO_{2max}. J Strength Cond Res. 2007;21:188–92.
186. Wakefield BR, Glaister M. Influence of work-interval intensity and duration on time spent at a high percentage of VO_{2max} during intermittent supramaximal exercise. J Strength Cond Res. 2009;23:2548–54.
187. Dupont G, Moalla W, Guinhouya C, et al. Passive versus active recovery during high-intensity intermittent exercises. Med Sci Sports Exerc. 2004;36:302–8.
188. Thevenet D, Tardieu-Berger M, Berthoin S, et al. Influence of recovery mode (passive vs. active) on time spent at maximal oxygen uptake during an intermittent session in young and endurance-trained athletes. Eur J Appl Physiol. 2007;99:133–42.
189. Dupont G, Blondel N, Berthoin S. Performance for short intermittent runs: active recovery vs. passive recovery. Eur J Appl Physiol. 2003;89:548–54.
190. Dupont G, Berthoin S. Time spent at a high percentage of VO_{2max} for short intermittent runs: active versus passive recovery. Can J Appl Physiol. 2004;29(Suppl):S3–16.
191. Girard O, Mendez-Villanueva A, Bishop D. Repeated-sprint ability—part I: factors contributing to fatigue. Sports Med. 2011;41:673–94.
192. Dupont G, Millet GP, Guinhouya C, et al. Relationship between oxygen uptake kinetics and performance in repeated running sprints. Eur J Appl Physiol. 2005;95:27–34.
193. Buchheit M. Performance and physiological responses to repeated-sprint and jump sequences. Eur J Appl Physiol. 2010;101:1007–18.
194. Buchheit M, Bishop D, Haydar B, et al. Physiological responses to shuttle repeated-sprint running. Int J Sport Med. 2010; 31:402–9.
195. Balsom PD, Seger JY, Sjodin B, et al. Physiological responses to maximal intensity intermittent exercise. Eur J Appl Physiol Occup Physiol. 1992;65:144–9.
196. Bravo DF, Impellizzeri FM, Rampinini E, et al. Sprint vs. interval training in football. Int J Sports Med. 2008;29:668–74.
197. Buchheit M, Mendez-Villanueva A, Delhomel G, et al. Improving repeated sprint ability in young elite soccer players: repeated sprints vs. explosive strength training. J Strength Cond Res. 2010;24:2715–22.
198. Tabata I, Irisawa K, Kouzaki M, et al. Metabolic profile of high intensity intermittent exercises. Med Sci Sports Exerc. 1997;29:390–5.
199. Bogdanis GC, Nevill ME, Boobis LH, et al. Contribution of phosphocreatine and aerobic metabolism to energy supply during repeated sprint exercise. J Appl Physiol. 1996;80:876–84.
200. Parolin ML, Chesley A, Matsos MP, et al. Regulation of skeletal muscle glycogen phosphorylase and PDH during maximal intermittent exercise. Am J Physiol. 1999;277:E890–900.
201. Lepretre PM, Koralsztein JP, Billat VL. Effect of exercise intensity on relationship between VO_{2max} and cardiac output. Med Sci Sports Exerc. 2004;36:1357–63.
202. McCole SD, Davis AM, Fueger PT. Is there a disassociation of maximal oxygen consumption and maximal cardiac output? Med Sci Sports Exerc. 2001;33:1265–9.
203. Gt Cooper. Basic determinants of myocardial hypertrophy: a review of molecular mechanisms. Annu Rev Med. 1997;48: 13–23.
204. Gonzalez-Alonso J, Calbet JA. Reductions in systemic and skeletal muscle blood flow and oxygen delivery limit maximal aerobic capacity in humans. Circulation. 2003;107:824–30.
205. Gonzalez-Alonso J. Point: stroke volume does/does not decline during exercise at maximal effort in healthy individuals. J Appl Physiol 2008;104:275–6; discussion 9–80.
206. Warburton DE, Gledhill N. Counterpoint: Stroke volume does not decline during exercise at maximal effort in healthy individuals. J Appl Physiol 2008;104:276–8; discussion 8–9.
207. Coyle EF, Trinity JD. The stroke volume response during or throughout 4-8 min of constant-power exercise that elicits VO_{2max}. J Appl Physiol 2008;104:282–3; author reply 4–5.
208. Lepretre PM, Foster C, Koralsztein JP, et al. Heart rate deflection point as a strategy to defend stroke volume during incremental exercise. J Appl Physiol. 2005;98:1660–5.
209. Cumming GR. Stroke volume during recovery from supine bicycle exercise. J Appl Physiol. 1972;32:575–8.
210. Astrand PO, Rodhal K, editors. Textbook of work physiology: physiological bases of exercise. Series in Health Education, Physical Education, and Recreation. Lower Mitcham (SA). Human Kinetics. New York: MacGraw-Hill, 2003. p. 649.
211. Fox EL, Mathews DK. Interval training: conditioning for sports and general fitness. Orlando (FL): Saunders College Publishing; 1974.
212. Takahashi T, Okada A, Saitoh T, et al. Difference in human cardiovascular response between upright and supine recovery from upright cycle exercise. Eur J Appl Physiol. 2000;81: 233–9.
213. Charloux A, Lonsdorfer-Wolf E, Richard R, et al. A new impedance cardiograph device for the non-invasive evaluation of cardiac output at rest and during exercise: comparison with the "direct" Fick method. Eur J Appl Physiol. 2000;82:313–20.
214. Richard R, Lonsdorfer-Wolf E, Charloux A, et al. Non-invasive cardiac output evaluation during a maximal progressive exercise test, using a new impedance cardiograph device. Eur J Appl Physiol. 2001;85:202–7.

215. Fontana P, Betschon K, Boutellier U, et al. Cardiac output but not stroke volume is similar in a Wingate and VO_2peak test in young men. Eur J Appl Physiol. 2011;111:155–8.
216. Helgerud J, Engen LC, Wisloff U, et al. Aerobic endurance training improves soccer performance. Med Sci Sports Exerc. 2001;33:1925–31.
217. Sunderland C, Morris JG, Nevill ME. A heat acclimation protocol for team sports. Br J Sports Med. 2008;42:327–33.
218. Castagna C, Impellizzeri FM, Chaouachi A, et al. Effect of training intensity distribution on aerobic fitness variables in elite soccer players: a case study. J Strength Cond Res. 2011;25:66–71.
219. Mooney M, O'Brien B, Cormack S, et al. The relationship between physical capacity and match performance in elite Australian football: a mediation approach. J Sci Med Sport. 2011;14:447–52.
220. Buchheit M, Simpson BM, Mendez-Villaneuva A. Repeated high-speed activities during youth soccer games in relation to changes in maximal sprinting and aerobic speeds. Int J Sport Med. 2012;34:40–8.
221. Buchheit M, Rabbani A. 30–15 Intermittent Fitness Test vs. Yo-Yo Intermittent Recovery Test Level 1: relationship and sensitivity to training. Int J Sports Physiol Perform; In press.
222. Armstrong N, Barker AR. Oxygen uptake kinetics in children and adolescents: a review. Pediatr Exerc Sci. 2009;21:130–47.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.