Chapter 34

High Intensity Interval Training

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Introduction

High-intensity interval training (HIIT) describes exercise ‘characterised by brief, intermittent bursts of vigorous activity, interspersed by periods of rest or low-intensity exercise’ (p.1047)[1]. The popularity of this type of training has increased recently as a time-efficient and potent alternative to ‘traditional’ moderate-intensity continuous training (MCT). With a global crisis in chronic, non-communicable diseases[2] providing an alarming backdrop, much of this attention has centred on the potential of HIIT to assist in the fight against lifestyle-related disease (e.g., cardiovascular disease and type 2 diabetes mellitus).

The popular discourse surrounding HIIT has been fuelled by renewed academic interest in this form of exercise[3,4,5,6] and emerging evidence supporting the notion that HIIT may induce physiological adaptations comparable to those from higher volume MCT[5]. Perhaps the most alluring feature of HIIT is the priority afforded to intensity over duration, and thus, the purported time-efficiency[7]. The remarkably low-volume of exercise performed typically during HIIT is also likely to be appealing to a modern society, which frequently cites a ‘lack of time’ as a major barrier to regular exercise participation[8].

Although HIIT has only been aligned recently to public health promotion, the origins of this training method may be traced back to, at least, the early twentieth century[9]. The history of modern sport is littered with accounts of elite athletes and coaches using, and honing through anecdotal inquiry, various forms of HIIT to optimise sport performance. High intensity interval training is by no means a new phenomenon, but instead a training concept long-appreciated by athletes. This training technique has, however, evolved recently, from rudimentary origins, into a contemporary exercise tool utilised by sport- and health-professionals alike. This chapter will examine the scientific evidence supporting the efficacy of HIIT to confer benefit to both sports performance and health in children and adolescents (young people).

The use of HIIT by young people is particularly relevant because: first, it seems that high-intensity exercise may be completed by children without substantial fatigue compared with adults[10]. Second, it has been suggested that HIIT may resemble the spontaneous, intermittent nature of habitual physical activity in young people[11]. Third, it is possible that HIIT is less susceptible to the monotony that young people often associate with MCT[12] and is, consequently, more conducive to longer-term exercise adherence. However, considering most young people fail to meet international physical activity guidelines[13], perhaps the most compelling rationale for HIIT is that it could offer them a viable alternative to more "traditional" forms of exercise and encourage greater engagement during these formative years[14]. Of course, HIIT is not a panacea; indeed, numerous caveats come with HIIT training in young people and will be addressed throughout the proceeding discussion.

When critically appraising any research findings, the contextual framework is very important. Training is defined as methods used to enhance or develop skills and/or knowledge with the intention of improving one or more predetermined outcomes. In this chapter, training refers specifically to physical activity or exercise, which is completed repeatedly over time, to enhance a physical, physiological or sports performance outcome that can be quantified using recognised measurement techniques. Moreover, because training implies sustainable improvements are sought, we will make every effort to differentiate chronic training adaptations from acute exercise responses. We define "high intensity" as exercise that can be sustained for up to 4 min (240-s) before a rest interval is required. It is also critical to determine whether the emphasis on exercise training is for gains in sports performance or physical health. The literature includes some outcome measures that relate explicitly to one of these two paradigms and others apply to both (e.g., peak $\dot{V}O_2$; a measure of cardiorespiratory fitness). We will review the literature from both perspectives and there may be some overlap. Finally, there are many detailed reviews on the scientific basis and prescription of high intensity training,[9,15,16,17,18,19] which are based on a multitude of laboratory and field studies with adults. Buchheit and Laursen[9] indicated recently that further research is required with "youth"; therefore, it is not our intention to indicate how HIIT should be prescribed for young people, but to critically appraise the current scientific literature to evaluate the efficacy of this form of exercise training with young people. Finally, whilst most researchers use traditional null-hypothesis significance testing (NHST) methods to compare outcome measures over time and between groups or training conditions, we have used their published means and standard deviations to estimate pairwise effect sizes to determine whether the findings might be meaningful from a sport performance or health perspective. Thus, the following descriptors suggested by Cohen[20] were used to describe the range of effect sizes: trivial <0.2, small 0.2 to <0.5, moderate 0.5 to <0.8 and large ≥0.8.

High-intensity Interval Training and the Young Performance Athlete

Participation in organised youth sport is progressing constantly to new heights of competitiveness and sophistication. Indeed, optimising the performance of young athletes has emerged as a burgeoning area of interest for sport scientists and coaches alike. The provision of highly-structured training now pervades the broad spectrum of youth sport. Although not comparable in number to those conducted with adults, various studies have examined the efficacy of HIIT to improve sport performance outcomes in young people. The following section will highlight the key findings, with specific focus on the physiological parameters associated with sporting success. At this point, it is important that the reader recognises some of the difficulties faced when attempting to evaluate the effect of a training intervention on sporting performance *per se*. The complex nature of sports performance - dependent on a number of intricately linked physiological, biomechanical, psychological, technical and tactical factors - renders the laboratory-based assessment of sporting capability inherently difficult. Consequently, many researchers rely on the assessment of the components of fitness (e.g., speed, aerobic endurance and strength) associated with successful sport performance. Whilst tightly-controlled laboratory measures can provide reliable, valid and comparable data, it is much more challenging to interpret these data and establish whether training-induced changes in such parameters translate to meaningful improvements in sport performance under free-living, competitive conditions. There has, however, been some endeavour to bridge this gap in knowledge and an emerging body of research provides valuable insight into the role that HIIT might play in enhancing athletic performance.

An array of studies have examined the effect of HIIT on a wide range of performance outcomes in male and female athletes aged 8 to 18 years (Table 34.1). The characteristics of the training protocols varied considerably with the interventions spanning 11 days to 10 weeks and 2 or 3 training sessions per week. The repetitions ranged from 3 to 40 and lasted between 10-s and 4 min (240-s). In most studies, exercise intensity was fixed at 90 to 95% predicted HR_{max}. Alternatively, high-intensity exercise was defined as all-out (maximum) intensities; >95% maximal aerobic speed (MAS); and/or >90% of personal best time.

Cardiorespiratory fitness

Cardiorespiratory fitness (CRF) is recognised as an important determinant of athletic performance in sports requiring a high aerobic energy provision. Hence, its response to HIIT in the context of sports performance will be examined here; whereas a latter sub-section will approach it from a health perspective. Peak oxygen consumption ($\dot{V}O_2$), measured during exhaustive exercise, is the criterion measure of CRF. Although a high level of CRF alone does not guarantee sporting success, it is often exhibited by elite athletes. It has been reported consistently that the performance of 14 to 30 HIIT sessions, over a period ranging from 11 days to 10 weeks, leads to significant increases in CRF in both trained and untrained young people (Table 34.1). These studies have demonstrated that HIIT is efficacious in increasing peak $\dot{V}O_2$ by 6 to 12%, typically. A number of studies have employed laboratory-based measures of gas exchange (e.g., indirect calorimetry) to quantify HIIT-induced changes in peak $\dot{V}O_2$, whilst others have used field-based fitness tests to estimate it; the former will be prioritised for discussion in this section.

Baseline CRF is an important factor when assessing training-induced changes. As young athletes regularly engage in structured aerobic exercise training programmes, they will have an enhanced capacity for oxidative metabolism at baseline, compared with their untrained counterparts. Hence, gains may be more difficult through increased sub-maximal training load alone[21,22,23]. Consequently, it has been suggested that HIIT may be a particularly useful training tool to use with youth athletes. Impressive baseline fitness ≥63 $mL \cdot kg^{-1} \cdot min^{-1}$ was seen in two studies[24,25], though the former was scaled using lean body mass. The 8.3% increase found by Chamari et al.[24] was in 14 y old male footballers who completed 8 weeks of HIIT, comprised of 4 min (240-s) intervals at 90 to 95% individual HR_{max}. Similarly, it was reported that an 8-week HIIT programme resulted in a 10.1% increase in peak $\dot{V}O_2$ in late adolescent male footballers[25]. Collectively, these studies support the efficacy of HIIT in already well-trained youth athletes, but the omission of a control group in both studies precludes direct causality. Furthermore, as HIIT was performed alongside their regular technical and tactical sessions, it is not possible to attribute the change in CRF to HIIT exclusively.

<< INSERT TABLE 34.1 HERE >>

Athletes and coaches may question how HIIT-induced changes in CRF compare to those conferred by high-volume, MCT; some studies have compared the different regimes directly (Table 34.1). In a randomised, crossover study conducted in 9 to 11 year old competitive swimmers, Sperlich and colleagues[31] compared changes in peak $\dot{V}O_2$ after 5 weeks of HIIT and, what was called, high-volume training (HVT). The within measures research design eliminates between group variance common to all mixed design studies and the 8.5 week wash-out period should have countered a possible period effect. Significant, moderate and small (d=0.57 & 0.46) increases were observed after HIIT (10.2%) and HVT (8.5%), respectively. It was concluded that desirable, short-term changes in CRF could be achieved through HIIT despite a comparatively reduced training time (2 hours less each week) and volume (5.5 vs. 11.9 $km \cdot week^{-1}$). Importantly, the authors recognised the limitation of a cycle ergometer-based test in swimmers. Indeed, this was reflected in the modest baseline peak $\dot{V}O_2$ values (~40 $mL \cdot kg^{-1} \cdot min^{-1}$), which were considerably lower than might be expected in children accustomed to training at least four times a week. However, the difficulties associated with the in-pool measurement of gaseous exchange with young children were highlighted and provided justification for the surrogate use of cycle-ergometry.

In a later study, conducted with 14 year old footballers using a between-measures experimental design, it was reported that peak $\dot{V}O_2$ increased significantly by ~7% following 5 weeks of HIIT yet was unchanged (non-significant, ~2% increase) following 5 weeks of high-volume training[32]. Although the boys continued to participate in regular football-specific training during the intervention period, this additional training load was similar in both groups. Other studies suggest that similar changes in CRF are induced by both HIIT and continuous cycle ergometer training in untrained prepubertal girls and boys[34,35]. Interestingly, in the latter of these studies, the interval training group exhibited pre- to post-increases in a number of physiological parameters, including ventilatory threshold, that were not observed in the continuous training group[35]. This limited body of research, provides preliminary evidence that HIIT appears to be at least as efficacious as MCT at enhancing CRF in young athletes.

The timeframe over which CRF may be enhanced through HIIT represents an interesting point for discussion. Whilst the majority of studies with young athletes (Table 34.1) have examined the effect of 4 to 10 weeks of HIIT on peak $\dot{V}O_2$, mixed findings emerged from two studies that assessed the efficacy of a shorter "shock microcycle"[28,40]. It was demonstrated, in a well-controlled study conducted in the off-season preparatory period, that 15 HIIT sessions performed over 11 days resulted in a 6% increase in peak $\dot{V}O_2$ in late adolescent alpine skiers[28]. In contrast, a control group exhibited no change in cardiorespiratory fitness following maintenance of their habitual training patterns. The magnitude of change was relatively modest in comparison to those reported following HIIT regimes spanning a longer period of time with young athletes (Table 34.1). The authors suggested that the high frequency of HIIT may have compromised the efficiency of the training with regard to the maximal capacity for improvement in aerobic capacity. However, it is reasonable to conclude that a moderate 6% (d=0.58) increase in peak $\dot{V}O_2$ represents a generous return from 11 days of training for skiers with good baseline fitness (53 $mL \cdot kg^{-1} \cdot min^{-1}$).

In contrast to these findings, Wahl and colleagues[40] reported no meaningful change (d=0.02) in peak $\dot{V}O_2$ in 16 young triathletes following a similar microcycle of HIIT consisting of 15 sessions performed over 14 days. The authors speculated that a slight decrease in post-HIIT [haemoglobin], possibly the result of a loss of red blood cells due to the high impact of the HIIT regime, might explain the failure of the training microcycle to induce meaningful improvements. It is possible that these losses could not be fully compensated in the 7 day recovery period post-intervention. A particularly pertinent finding of this latter study was that significant decreases were observed in some dimensions of the Persons Perceived Physical State Scale (PEPS), including perceived physical energy, perceived physical flexibility and readiness to train, highlighting the exhausting nature of this training intervention. This, of course, raises important questions surrounding the extent to which this form of high-frequency HIIT may be tolerated as well as the possibility that such training, if not carefully managed, might lead to the manifestation of overtraining symptoms and the impairment of performance often associated with this condition. Future research is undoubtedly warranted to further elucidate the optimal combination of HIIT frequency, intensity and recovery time for use with young athletes.

Similar increases in aerobic performance – estimated using field-based fitness tests – have also been reported[27,29,31,32,36]. Typically, such studies have employed incremental fitness tests, the assessment of intermittent exercise performance (e.g., shuttle run test, intermittent fitness test), and/or physiological parameters such as individual anaerobic threshold as surrogate measures of aerobic capacity. Of course, field-based estimates of endurance performance do not provide the quality of data associated with the sophisticated laboratory assessment of gas exchange. However, such field-based tests represent a convenient and inexpensive method of estimating endurance performance and represent a valuable tool to track changes over a period of training, especially with large groups of athletes. Ultimately, the emerging findings from these studies provide further, albeit weaker, evidence supporting the efficacy of HIIT to induce desirable improvements in endurance performance, which is likely to be underpinned by cardiorespiratory fitness in young people.

Explosive strength

The effect of HIIT on explosive strength (power), the ability to exert maximal muscular contraction in the shortest possible time, has been examined in several studies (Table 34.1) using a battery of jump tests. Typically, a selection of the following jump tests have been used to assess training-induced changes in the explosive strength of the lower limbs: counter movement jump (CMJ); drop jump (DJ); standing broad (long) jump (SBJ); squat jump (SJ) and vertical jump (VJ). Explosive strength is a component of physical fitness that may be particularly important to sports in which sprinting and/or jumping (vertical and/or horizontal) are integral to successful performance, with the obvious examples being the 100 m sprint and long jump. There are, however, many other sports in which explosive strength represents an essential, yet more subtle, determinant of sports performance and/or skill execution. Of course, sports performance outcomes are normally very complex and it is likely that the changes in the ability to produce explosive strength, as measured by the performance of simple jump tasks in isolation to other sport-related skills, represents an ill-defined fraction of these outcomes. Nonetheless, jumping ability remains a useful performance assessment tool and a number of noteworthy findings have emerged from HIIT studies in which explosive strength has been assessed by this method.

Changes in power are more heterogeneous than CRF following HIIT; untrained, prepubertal children, completing 7 weeks of high-intensity interval running (10 or 20s at 100 to 130%

MAS) experienced a significant, but moderate increase (d=0.62; 9.6%) in SBJ distance[27]. The authors concluded that HIIT performed at velocities greater than MAS enhanced lower limb explosive strength and speculated that this likely resulted from a combination of both neurological adaptations and/or alterations in muscle fibre type characteristics; although, it was suggested that the former was likely to be the primary mechanism of the observed improvement. It should be reiterated that this study was conducted in untrained boys and girls, which could magnify the increase. This is supported by trained, late adolescent professional footballers who experienced only small gains in CMJ (d=0.35; 2.7%) and SJ (d=0.42; 6.9%) performance after 10 weeks of HIIT involving football-specific interval running at a fixed intensity of 90 to 95% of HR_{max}[25]. As expected, these "statistically significant", but small effects, in jump performance did not translate into a concomitant improvement in 10 m sprint time, which illustrates that jump-specific measures of explosive strength may not always translate to a holistic enhancement of power-related performance.

A number of studies have reported no meaningful improvement in explosive jump performance following HIIT. Buchheit and colleagues[29] demonstrated that 10 weeks of HIIT resulted in trivial changes in CMJ (d=0.13) and 10 m sprint time (d=0.13) in well-trained male and female handball players. Similarly, trivial and small increases in SBJ were exhibited amongst youth football players following a 7 week HIIT programme consisting of either all-out short-sprint repetitions (50 m; d=0.19) or long-sprint repetitions (200 m; d=0.32) performed at 85% of maximal 100 m time[36]. These findings were contrary to the authors' hypothesis that the short-sprint programme would yield improvements in jump ability and led to the conclusion that the technical aspects of jump performance may need to be practised during HIIT if meaningful improvements in performance are to be conferred. Finally, in a well-designed, but somewhat underpowered study, 5 weeks of HIIT resulted in only small increases in CMJ or SJ performance in adolescent football players[39]. Although these studies reported no meaningful improvement in jump performance following HIIT, it is equally noteworthy that the weekly performance of two to three sessions of high intensity exercise over a period of 5 to 10 weeks resulted in no impairment of power-related performance. This is particularly encouraging given concern about potential incompatibility of endurance training and maintenance of power-related performance. The evidence that has emerged from studies conducted with young people may reassure athletes and coaches that HIIT, if designed and supervised appropriately, can be utilised to enhance important components of fitness (e.g., cardiorespiratory fitness) without compromising explosive strength and power-related performance.

The importance of design and management of HIIT is, however, highlighted further by the findings of Breil *et al.*[28]; following an 11-day shock micro-cycle of HIIT consisting of 15 sessions, participants experienced a moderate reduction (d=-0.54; 4.8%) in CMJ performance. This performance decrement was observed despite an improvement in cardiorespiratory fitness. The authors speculated that the high-frequency training microcycle could have contributed to persistent muscle fatigue and subsequent impairment of performance. The authors[28] concluded that participants may have needed more than 7 days post-HIIT recovery to fully restore explosive strength capacity.

Overall, the weight of the available evidence suggests that HIIT, if carefully managed, is unlikely to result in an impairment of explosive strength and, in some cases, might lead to performance enhancement. It is, however, important for young athletes and their coaches to consider the frequency of HIIT sessions carefully as well as the recovery time provided between exercise bouts. Furthermore, particular attention should be paid to the recovery period following the completion of an intensive block of HIIT, especially in the lead-up to competition.

Sport-specific performance outcomes

A small number of studies have attempted to assess the effect of HIIT on competitive sporting performance and/or sport-specific capacities directly. Impellizzeri *et al.*[33] used a matched, randomised, parallel-group experimental model with young footballers. Employing increases in total running distance, number of sprints performed, and time spent performing at higher exercise intensities, they concluded that competitive match performance had improved after HIIT. These improvements in sport-specific parameters were accompanied by an increase in peak $\dot{V}O_2$. Another interesting finding from this study was the observed improvement in performance during the football-specific Ekblom aerobic endurance field test, which comprises several activities typical of football, including: changes in direction, jumps, and backwards running[41]. Similar changes in football performance and cardiorespiratory fitness were also observed, in a parallel experimental group, following small-sided game-based training[33]. The authors of this study concluded that HIIT and small-sided game training were equally effective modes of aerobic training for use with youth football players. Another important consideration is that the training interventions were completed in addition to the players' regular football training (technical and tactical sessions). Although the authors reported that this additional football-specific training was performed at low intensities, it is possible that it provided an additional training stimulus. It is, therefore, impossible to isolate the effect of HIIT and establish a causal and independent relationship between the training interventions and the changes in sport-specific outcome measures.

Faude and colleagues[32] found that 4 weeks of HIIT resulted in no improvement in 100 or 400 m swim times in competitive adolescent swimmers; however, they did report that 7 out of 9 swimmers swam personal best times (PBs) in the 3 months after the HIIT training cycle. Whether these PBs can be attributed to HIIT directly is questionable. In another swimming study by Sperlich *et al.*[38], described previously, competitive performance was assessed before and after 5 weeks of HIIT and high volume training (HVT). Significant changes in 2000 m swim time and scoring on the *LEN* ("Ligue Européenne de Natation", the European Governing Body) international pointing system for competition performance were reported only after HIIT (not HVT); however, the magnitude of these effects were small ($d \leq 0.48$). Moreover, the group reduction in 100 m swim times was trivial ($d \leq 0.18$). Based on these differences between HIIT and HVT, Sperlich *et al.*[38] concluded that high training volumes provided no advantage compared to lower volumes of HIIT. They went on to suggest that the use of HIIT may enable a greater proportion of training time to be spent on technical development, whilst conferring similar benefit to physiological parameters.

The efficacy of a two week shock microcycle of HIIT to enhance cycling performance in young triathletes has been assessed using average power output (PO in watts) during a 20 min time trial (TT) performance test[40], which is deemed a valid and reliable simulation of a race event in adults[42]. Wahl *et al.*[40] also compared passive and active recovery by dividing the 16 girls and boys equally into two separate training groups. Time trial average PO increased significantly from 2.9 to 3.3 $W \cdot kg^{-1}$ in the passive group ($d=0.66$; 12%); whereas the change in the active recovery group was only small ($d=0.24$; ~3%) and within the reported coefficient of variation for this performance measure. The increase in 20 min TT performance was despite non-significant, trivial ($d \leq 0.19$) changes in peak $\dot{V}O_2$ in both groups; interestingly, the total cycling distance achieved during the TT was not reported. This finding led the authors to recommend that when working with athletes, the measurement of performance should represent the main criterion for the efficacy of a training programme as physiological parameters may not be sensitive to change.

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High Intensity Interval Training for Health

Cardiorespiratory fitness

In line with the general paediatric exercise science and medicine literature, CRF is one of the most commonly measured outcome variable in studies that have that examined the efficacy of HIIT in young people (Tables 34.1 and 34.2). Although it is normally defined as peak $\dot{V}O_2$, some studies have included endurance performance measures (e.g., 20-m multistage fitness test; MSFT[14,27,55]), maximal endurance speed[56], running economy[26] or gas exchange threshold[44]. Whilst it can be argued that most young people rarely exercise at intensities that would elicit peak $\dot{V}O_2$, it has a strong empirical relationship with cardiometabolic health; therefore, the results from health-focused HIIT studies including MSFT will be included.

We are aware that numerous early studies employed interval training techniques, common to endurance athletes, with healthy young people; however, they were not designed specifically to examine the efficacy of HIIT. Consequently, their study design features often do not allow us to isolate the independent effect of the high intensity elements of the research. Nevertheless, much can be learnt from these pioneers. For example, Rotstein *et al.*[37] reported a large (d=1.41; 8%) increase in peak $\dot{V}O_2$ in 16, 10 to 11 year old boys who completed a series of 150 to 600 m runs, 3 $\text{times}\cdot\text{week}^{-1}$ over nine weeks, compared with an age and activity matched non-training control group (Table 34.2). The precise exercise intensity was not provided, but described as being suitable to each participant's condition at baseline and it is not clear how long it took the boys to complete the various intervals. Moreover, each training session lasted 45 min with a 15 to 20 min warm-up; so, it does not fit the time efficient model HIIT is characterised as regularly. Despite all of these limitations, in the context of this chapter, this study was published when there was considerable doubt whether it was possible for children (i.e., preadolescents) to increase their CRF via exercise training[57] and the mean baseline peak $\dot{V}O_2$ was an impressive 54 $mL \cdot kg^{-1} \cdot min^{-1}$. Before attempting to tease-out potential moderators of HIIT effects on CRF, the focus will now turn to a study[44] that adopted a very similar research design as Burgomaster *et al.*,[4] which stimulated the recent renewed interest in HIIT. In Barker *et al*'s study[44], ten adolescent boys were exposed to only six maximal intensity, cycling training sessions spanning 14 days (Table 34.2). The training progressed from 4 × 30-s "all-out" sprints on the bike (i.e., Wingate anaerobic tests) with 4 min active recovery in session one to 7 × 30-s sprints in the final session. The change in peak $\dot{V}O_2$ was small (d=0.30; 5%) whether expressed relative to body mass or not. Interestingly, the mean change of 2.7 $mL \cdot kg^{-1} \cdot min^{-1}$ is almost identical to that found in a recent meta-analysis of eight studies with adolescents[58] who completed between 13 and 36 HIIT sessions over 5 to 15 weeks. The authors[44] justified the exclusion of a control group by suggesting that growth or maturation changes would be minimal over just two weeks. They indicated any changes could be ascribed to HIIT because the participants agreed to suspend their habitual organised sports activities for the duration of the study; a similar argument has been posited by the same group below in a different study measuring endothelial and autonomic function[45].

Numerous potential moderators may influence the size of the HIIT-induced effect, the most obvious being the training programme components and participant characteristics or behaviours. Costigan *et al.*[58] included 20 HIIT studies with adolescents in a meta-analytic review recently, from eight of these it was found that study duration, type of comparison group and risk of bias were not significant moderators. After we reviewed studies with participants ranging from healthy weight to obese, it would appear that obese participants are more likely to experience large gains in CRF following HIIT[46,47,48,51,53]. It was apparent that the obese participants in these studies were exposed to a greater dose (volume) of the high intensity exercise stimulus – this was usually because the training programme extended over a longer period (minimum 12 weeks[46,47,48,51,53] vs. 2 to 9 weeks[34,35,37,44,50,55]) than in healthy weight young people coupled with a lower baseline level of fitness, which is more susceptible to change and has been highlighted previously[59]. Whilst changes in healthy weight prepubescent girls[34] and late-adolescent boys and girls[55] range from large to trivial respectively, closer scrutiny of both studies reveals that McManus *et al.*[34] only reported changes in absolute peak $\dot{V}O_2$, which may not account completely for subtle changes in body size over the eight week training period. Buchan and colleagues[55] measured endurance performance via the MSFT rather than oxygen consumption; however, other publications by this same group, using the same training intervention, but with a heterogeneous mixed-sex sample that included healthy and overweight participants, found that changes in MSFT performance were small[14]. It should be noted that most effect sizes reported by Buchan *et al.*[14] appeared to be inflated compared with pairwise values derived from the means and standard deviations provided in their results (i.e., mean difference$\cdot SD^{-1}_{(pooled)}$) – it is not clear how they calculated their effect sizes specifically.

A key question when examining so-called “traditional” MCT has been whether biological maturation is an important moderator. Katch[57] hypothesised that training-induced changes in cardiovascular function could only be small before the onset of puberty because of a maturational "trigger point", which had been proposed initially by Gilliam and Freedson[60] after scrutinising the findings of their small mixed-sex, school-based training study. However, Shephard[61] cited early study design limitations, including inadequate sample sizes, missing control groups, poor training programme characteristics relative to baseline levels of fitness and inadequate exposure to the training stimulus, when dismissing differences in the training response between children and adolescents. Whilst there is now considerable evidence from MCT studies that a blunted adaptation is common in children, scrutiny of the small number of HIIT studies that have measured peak $\dot{V}O_2$ appear to be equivocal. There is considerable heterogeneity from the nine available studies with prepubertal children[26,27,34,37,43,46,50,52,54]. After randomly assigning 45 prepubertal boys equally to sprint interval training (SIT), continuous cycling training (CCT) and habitual control (CON) groups, Williams *et al.*[54] found that peak $\dot{V}O_2$ did not change meaningfully in SIT (n=12; d=-0.11), whereas CCT experienced a small increase (n=13; d=0.35); as expected CON was virtually unchanged (n=14; d=0.04). It is possible that the relatively high baseline fitness (~55 $mL \cdot kg^{-1} \cdot min^{-1}$) of the boys contributed to this outcome; however, a direct comparison with the Rotstein study[37], where prepubertal, healthy weight boys also had a high baseline, but increased their peak $\dot{V}O_2$ substantially, does not support this. The contrasting large (d=1.00; ~15%) increase in peak $\dot{V}O_2$ reported in a well-controlled study of Brazilian children by Corte de Araujo *et al.*[46] was most likely because the children were obese with very low baseline fitness (~26 $mL \cdot kg^{-1} \cdot min^{-1}$). Furthermore, the substantial inter-study difference in total HIIT times (108 min[46] vs. 72 min[54]) will have been a critical factor – the obese boys and girls also "recovered" at 50% of their peak aerobic velocity between the high intensity running bouts whereas the boys in the Williams[54] study rested passively. When considering inter-study differences, the contribution of a warm-up, exercise recovery periods between repetitions, and an active cool-down should not be underestimated when they are incorporated into every training session.

The influence of participant sex on the training effect could be an important factor; however, it is very difficult to identify an independent sex effect that is not due to baseline differences in peak $\dot{V}O_2$ or maturation. The majority of HIIT studies we reviewed recruited mixed-sex samples (Tables 34.1 and 34.2) and often pooled the participants after failing to find a statistically significant sex by time interaction, which should not be interpreted as meaning the study was powered adequately from the outset. In the study with the largest sample[55], there was an imbalance between the number of girls (n=12) and boys (n=30) who completed the HIIT; this is not meant as a criticism, we know from first-hand experience that girls are more difficult to recruit than boys. The statistical analyses included power calculation details, but fell short of partitioning the sample into sub-groups to account for the independent sex effect. Only two studies were identified that included girls exclusively[34,51] with both reporting large increases in peak $\dot{V}O_2$. Racil[51] studied obese, post-adolescent girls with a total HIIT time of 264 min, whereas McManus[34] recruited healthy weight, prepubertal girls who accumulated 72 min of HIIT over eight weeks; direct comparisons are obviously difficult. Hence, more research with girls is needed and their data should be analysed separately from boys in studies designed specifically to address this intriguing question.

Total HIIT time calculated from the training characteristics included in Table 34.2 is a possible moderator. This should not be confused with volume, a composite of time and intensity, which was too complicated to estimate because of the intra- and inter-study variation in intensity. The HIIT time varied from 16.5 min[44] to 416 min[47] – these equated to 2.75 and 16 min of exercise per training session respectively. Despite the dichotomous training times, the effect sizes were small[44] and small to moderate[47] depending on the factor used to scale the peak $\dot{V}O_2$ data. This comparison is included specifically to highlight that there are a multitude of factors that determine to what extent young participants adapt when exposed to chronic exercise stimuli; the amount of training is just one them. About half of the studies that measured peak $\dot{V}O_2$ before and after HIIT reported a large effect[34,35,37,46,48,50,51,53], with the remaining being small to trivial (Table 34.2). A very recent study[49] was designed, using novel analytical techniques, to examine whether HIIT training effects are dose-dependent; the final sample was 26, 16 year old boys assigned randomly to one of five training groups (n ≅ 5 per group). Each group completed 4 × 20-s near maximal effort bursts across a variety of exercise modes with the dose being titrated from 1 to 5 sets per session (i.e., 80 to 400-s HIIT per session), twice a week for eight weeks. Whilst the exercise fidelity was good, the quadratic trend used to identify the dose-adaptation explained less than 2% of the variance in the data. The authors highlighted the wide variation in individual responses across all five groups despite group one doing only a fifth of the exercise volume compared with those in group five. This likely reflected large differences in baseline fitness ranging from 34 to 41 $mL\cdot kg^{-1}\cdot min^{-1}$. Finally, many studies rationalise HIIT training by claiming it may be more efficacious than MCT for increasing health via improvement in peak $\dot{V}O_2$; however, few include an MCT comparison group to examine this directly[34,35,37,46,48,50,51,53]. Notwithstanding difficulties in matching participant characteristics in independent groups, three studies[37,50,53] found HIIT (10.0%) was more efficacious than MCT (2.8%) and four[34,35,46,48] had similar effects HIIT (9.8%) ≅ MCT (9.5%); all of these studies were better than a habitual control group. Although Williams *et al.*[54] concluded that neither HIIT nor MCT changed peak $\dot{V}O_2$, the small MCT-induced increase (d=0.35; 5.1%) was marginally better than HIIT (d=-0.11; -1.6%).

<< INSERT TABLE 34.3 HERE >>

Body size and composition

Obesity is at the forefront of public consciousness because it is more overt than many other health problems and it has numerous disease co-morbidities[63]. It is, therefore, not surprising that measurement of various body size variables are as common in HIIT studies as cardiorespiratory fitness; in fact, researchers have questioned whether fitness or fatness may be more important from a public health perspective[64]. Most readers will be aware that changes in body size or composition, particularly adipose tissue, require longer-term exposure to an exercise-induced energy deficit; however, it is a critical adjunct to dietary intervention and lasting weight or fat loss. Most HIIT interventions in young people are between 2 and 13 weeks long, which is relatively short when considering meaningful changes in body composition; hence, of the 17 studies shown in Table 34.3, 13 found only trivial or small changes. Although some studies reported that the changes in body size were statistically significant[49,46], the effect sizes suggest these are unlikely to meaningful; however, it is possible that prolonged adherence to HIIT may result in changes that have long-term health implications if sustained. On-going growth and maturation can confound exercise interventions unless controlled adequately with well-matched comparison groups; although the HIIT group may not reduce body size or composition, it is possible that the exercise could delay changes relative to habitual controls[55], but this has yet to be shown consistently and with adequate dietary control.

Of the studies that reported a moderate or large change in body size measures[37,47,51,53,62], two used skinfolds[37,62] with healthy and overweight prepubertal participants, respectively. Neither controlled for habitual dietary or physical activity variations over the intervention period, but the relative changes (~12%) were very similar and, seemingly, impressive following only nine and six weeks of HIIT. Using bioelectrical impedance analysis (BIA), 11 mixed-maturation, obese, 15 year old girls reduced their body fat from 37% to 34% (~8%) over 12 weeks[51]. The total HIIT time (264 min) is one of the highest reported in this rare girls only study; differences in maturation between the girls were accounted for statistically, and, although diet was measured at baseline, it was not clear if it or habitual physical activity changed over the 12 weeks. Racil *et al.*[51] concluded that HIIT may be a better approach to improving health in "young women" than moderate intensity training, but added that their study was an important first step. The two studies from Wisløff's team, in Norway[47,53], with obese adolescents are included here because of the large total HIIT time (~416 min) and the studies are well-designed and controlled. They are, however, considered to be proof of concept studies with small mixed-sex samples, which precludes widespread application of the results. The same HIIT protocol, consisting of 4 × 4 min bouts of uphill walking or running at 90 to 95% HR_{max} per session, was completed twice a week for three months. In the Tjønna study[53], 13 of the 20 HIIT participants who completed the three month HIIT also trained at home or in a gym for a further nine months (not included in HIIT time calculations shown in Table 34.3) twice a week. Dual-energy x-ray absorptiometry (DXA) derived measures showed that changes in body fat were small in both studies regardless of training programme length ($d \leq -0.43$; ~5%). However, a moderate effect ($d = -0.67$; ~7%) for waist circumference was evident after 12 months[53]. It is important to note that eight and a further seven participants were lost to follow-up after the 3 month and 12 month training periods, respectively; though, it was suggested the data did not differ from those who completed all measurements. Ingul *et al.*[47] have suggested that the objective of exercise interventions for obese adolescents should be weight stagnation rather than reduction with subtle improvements in lean and adipose tissue; when allied with improved CRF, see above, it should be possible to "decrease the risk of developing obesity-related comorbid conditions despite minimal weight loss" (p.858).

Biochemical metabolites

We identified eight HIIT studies that included blood samples (Table 34.3); due to the wide array of metabolites measured in these studies, we will attempt to identify study or participant characteristics that may have exerted a meaningful influence on the results. Racil *et al*'s[51] study with obese adolescents girls stands out for its numerous adaptations indicative of improved physical health (see Tables 34.2 and 34.3). Large (d≥0.80), significant reductions in fasting concentrations of insulin (d=-2.78; 27%), triacylglycerol (TAG) (d=-0.83; 7%), low-density lipoprotein cholesterol (LDL-C) (d=-1.29; 12%), total cholesterol (TC) (d=-1.17; 7%) and homeostatic model assessment for insulin resistance (HOMA-IR) (d=-2.28; 30%) were found; whereas, high density lipoprotein cholesterol (HDL-C) increased (d=1.20; 6%) over the 12 weeks. In contrast, a small reduction in fasting glucose concentration was reported (d=-0.23), which is a common finding in the other HIIT studies reviewed[14,45,49,55]. The only exception was Tjønna *et al.*[53] who reported meaningful reductions in obese adolescents after 3 and 12 months of training; this study measured both fasting glucose and after an oral glucose load test (d=-0.58 to -0.94). Meaningful reductions in fasting insulin[46,53] and HOMA-IR[46] were also reported in other studies with obese participants who completed HIIT programmes with total exercise times ranging from 108 to 416 min. This improvement in glucose control and insulin sensitivity is less likely to be experienced by participants who are relatively healthy at the start of short interventions[14,45,55].

Changes in the lipid profile varied considerably across the studies, which will be a function of the large day-to-day variability[65] (particularly for TAG), baseline concentrations and total training time, but the small group of HIIT studies provide little empirical direction on moderators. Half (four) of the HIIT studies that estimated changes in LDL-C reported significant reductions, with effects ranging from small[49] to large[51,52]. Only the obese boys who completed the running programme by Koubaa *et al*.[48] had a moderate (d=0.78; 4%) increase in HDL-C, which was similar in relative terms to Racil's[51] girls above. However, a lack of dietary control means it is not possible to be certain changes were exercise-induced in this Tunisian study[48]. Measurement of high sensitivity C-reactive protein (hs-CRP), adiponectin and interleukin 6 (IL-6) are still rare in HIIT studies with young people[14,49,51,53,55] and the results are inconsistent. For example, effect sizes for adiponectin range from -1.41 (51% reduction)[14] to 2.43 (34% increase)[51]; although an increase in this adipose tissue derived adipokine has been found in obese adults undergoing chronic exercise training, it has not been shown consistently[66]. Only Logan[49] reported a significant increase in IL-6 across their five small training groups, ranging from 5 to 62%, but the omnibus effect size (d=0.45) probably underestimated within group pairwise effects. Two separate studies by Buchan *et al*.[14,55] reported small reductions ($d \leq -0.35$) in IL-6 after 54 min of HIIT spanning seven weeks. Finally, only two studies[45,49] stated explicitly that their post-intervention measures were completed at least 48 hours after the final training session to ensure the results reflected a chronic training adaptation rather an acute, last exercise bout response. It is unfortunate that this important design feature is rarely built into the studies, which means it is difficult to differentiate acute responses from chronic adaptations.

Vascular health

In this final health-related sub-section, HIIT-induced adaptations in blood pressure and endothelial function (flow mediated dilation; FMD) will be examined. Although blood pressure is often measured in exercise studies with young people, endothelial function is still considered a "novel" cardiovascular disease (CVD) risk factor that may precede changes in more "traditional" risk factors in the atherosclerotic pathway[67]. Significant decreases in systolic blood pressure (SBP) are reported in the majority of HIIT studies (Table 34.3); the magnitude of effects are small[55], moderate[14,47,53] and large[46,48] (d=-0.36 to -1.00; 2 to 8%). Higher baseline SBP (≥125 mm Hg) in obese young people who experienced the greatest total HIIT times (>100 min), or longest training programmes (>12 weeks), appear to be requisite characteristics for meaningful reductions in SBP. Although fewer studies found significant or meaningful reductions in diastolic blood pressure (DBP), they were those that managed to supervise their young obese or overweight charges through HIIT programmes lasting at least 12 weeks[47,48,53] (Table 34.3).

Tjønna *et al.*[53], see above for HIIT details, used high-resolution vascular ultrasound to measure FMD with random, investigator blinded analyses in their study of obese boys and girls. They reported improvements of 5.1% and 6.3% above baseline after three and 12 months of training respectively; this compared well with the multidisciplinary training group (3.9% and return to baseline) who experienced standard clinical practice over the same period. The authors linked concomitant changes in HDL-C, blood glucose and insulin with enhanced bioavailability of nitrous oxide (NO), the primary regulator of endothelial function, and large increases in the anti-inflammatory hormone adiponectin (see above). Importantly, they hypothesised that exercise training improves endothelial function regardless of changes in body size providing CRF improved – this may be a very important strategy to consider when helping overweight or obese young people to choose to exercise regularly. Also from Norway, Ingul *et al.*[47] designed a HIIT study to see if it "corrected" impaired measures of resting and exercise cardiac function in obese adolescents when compared with a lean group of age and sex matched 13 to 16 year olds. Interested readers are encouraged to refer to the publication directly to access the methods, which are too detailed to include here; the Dubois body surface area (m^2) formula[68] was used to scale cardiac dimensions for between group differences in body size. The 32 min of HIIT per week over 3 months increased most measures of systolic function and left ventricular (LV) volumes that were impaired originally so that pre-training obese vs. lean group differences were eradicated; these included large effects for stroke volume index (d=1.13), global strain rate (d=1.94), fractional shortening (d=1.22) and peak systolic tissue velocity (S`; d=1.00). In contrast, LV end-systolic volume and cardiac output were virtually unchanged. Similarly, significant HIIT-induced normalisation of diastolic function in the obese group was seen, with large effects for deceleration time (DT; d=-1.33) and isovolumetric relaxation time (IVRT; d=-0.81). Echo with tissue doppler and doppler flow velocities revealed pre-intervention impaired mitral annulus excursion (MAE; 24%), flow velocity time integral of the LV outflow tract (16%), global strain rate (32%), global strain (22%) and peak early tissue doppler velocity (18%) in the obese versus lean at both rest and exercise. However, most of these impairments were resolved following HIIT with small to moderate, non-significant differences (d≤-0.62) between the obese and lean groups. Although the difference in global strain was more than halved, it was still large (d=-0.90) and in favour of the lean participants (~8.5%). In contrast, MAE improved to such an extent at rest that it was slightly higher in the obese group (d=0.77). Despite these very promising changes in the exercise trained obese adolescents, the authors[47] highlighted that they need to be replicated in a multicentre study with a representative sample and intent-to-treat research design.

The very low volume, HIIT used by Bond and colleagues[45] consisted of just six training sessions spread over two weeks similar to previously published studies with sedentary[69] and type-2 diabetic adults[70]. The study was designed so that it was possible to separate the acute response, from the last exercise session, and the chronic two week training adaptation by including pre-exercise, 1-day post-exercise and 3-day post-exercise measurements; however, a non-exercise matched control group was not included due to the brevity of the training period. Statistically significant changes ($P \leq 0.04$) in FMD, baseline arterial diameter and heart rate variability (HRV) were found; effect sizes ranged from small to large ($d=0.39$ to 0.97). The 1-day post-exercise effects were larger than those found 3-days after the last exercise training session (compared with the pre-exercise baseline). There were also some subtle, but noteworthy differences between fasting and postprandial measures, which could mean post-meal measurements provide a more insightful window to metabolism than overnight fasting conditions. The postprandial reductions in FMD and HRV were expected given the test breakfast meal had a very high energy content of 7134 kJ (~1704 kcal) amounting to a large proportion (≥82%) of the samples' measured mean daily energy intakes. The authors highlighted the primary study outcomes as: (i) a HIIT-induced improvement in endothelial function and HRV in boys and girls; (ii) changes in novel and traditional CVD risk factors may occur independently; and (iii) the changes (Δ) in endothelial function and HRV were transient ($\%\Delta\text{1-day} > \%\Delta\text{3-day}$), which suggest their findings may reflect an acute response from the last exercise training bout rather than a chronic physiological or metabolic adaptation.

Time efficiency and enjoyment of HIIT

Two commonly cited potential advantages of HIIT, compared with MCT, are the purported time-efficiency of the exercise modality and the enjoyment associated with this form of training. Although, the amount of time spent exercising (i.e., actively engaged in power-producing activity) during HIIT is relatively small, it is questionable how much time may actually be 'saved' by this form of exercise, especially when one considers the time committed to an appropriate warm-up, active or passive recovery between interval repetitions and, finally, post-session recovery. The importance of exercise volume *per se*, and the impact this may have on long-term exercise adherence, should not be dismissed and may represent an interesting avenue for future research with young people.

Physical activity enjoyment has been identified as a consistent predictor of childhood physical activity levels[71]. Unfortunately, very little research exists that has quantified exercise enjoyment during HIIT with young people. Encouragingly, however, evidence derived from studies conducted with adults suggests that HIIT may be a more enjoyable form of exercise, compared with continuous, steady-state exercise of a lower intensity[70,72,73,74]. Furthermore, a recent study conducted with children indicates that the perceived enjoyment of steady-state exercise may be increased by the addition of intermittent all-out sprints, despite the latter exercise resulting in a greater total amount of work compared to steady-state exercise alone[12]. Although additional research is required to confirm this finding, it raises important questions surrounding the optimal manipulation of exercise intensity and duration to maximise enjoyment and adherence, during childhood and adolescence. Longitudinal experimental studies are undoubtedly warranted to examine perceived enjoyment during HIIT as well as adherence to this form of exercise over a prolonged period of time. Such studies may also provide valuable insight into the extent to which this form of exercise training can be tolerated and sustained by young people and help to further delineate the priority that should be afforded to this form of training.

Conclusion

It is clear from our comprehensive search and critical appraisal of the literature that research examining the efficacy of HIIT in young people is still in its infancy. Nevertheless, there are some promising findings for sports performance and health outcome measures. However, these are all based on training studies that are limited by their brevity and need to be followed-up with longer studies involving both male and female, children and adolescents in more representative samples. There is insufficient evidence to suggest that young people, even highly motivated athletes, can sustain such high intensity exercise over longer than three consecutive months and retain their interest, motivation and enjoyment whilst remaining free from exercise training-induced injury. These issues must be addressed systematically before we can be confident in prescribing this type of training for performance or health gains in young people.

Summary

- Inclusion of HIIT in programmes for young athletes may compliment moderate continuous activity in light of widespread non-compliance with the current international recommendations for physical activity in young people.
- Despite recent growth in the number of scientific studies examining the efficacy of HIIT in young people, longitudinal studies are rare; these studies have focused on both sports performance and health outcomes with athletes and non-athletes. This dual focus reflects the continued interest in maximising sports performance, but also the growing concern about perceived low levels of cardiometabolic fitness and the high proportion of young people who are overweight or obese, with related co-morbidities, in this segment of the population.
- Cardiorespiratory fitness, defined as peak $\dot{V}O_2$, has been the most popular outcome measure of sports performance and health-related studies with young people. HIIT can increase peak $\dot{V}O_2$ meaningfully, but whether it is better than alternative exercise regimes has yet to be confirmed reliably. Longer-term studies, which include comprehensive, valid measures of compliance, injuries and enjoyment are required.
- Explosive strength (power) gains following HIIT in young athletes are small to moderate, but do not appear to be impaired. Recovery time, built into individual training sessions

and cycles, should be considered carefully when leading into competitive performance.

- The effect of HIIT on direct measures of sports performance are limited to only a few studies and the results suggest that the gains are moderate at best. However, it should be recognised that even small gains in performance for young people who are already well-trained may be meaningful if maintained and applied consistently.
- Changes in body size and composition following HIIT have, typically, been trivial to small, which reflects study design more than the efficacy of the training *per se*. This is because HIIT has only been prescribed typically from 2 and 13 weeks in the scientific literature.
- The small number of studies taking blood samples before and after HIIT make it difficult to identify any trends in the variety of biochemical metabolites investigated; reductions in fasting insulin and LDL-C are promising findings to date, particularly in obese girls and boys. However, these need to be verified in larger studies extended over longer periods.
- Finally, three HIIT studies have focused on vascular health; unsurprisingly, they are dependent on the baseline levels of the outcome variables like systolic blood pressure and cardiac function. Again, more well-controlled research is required to reach firmer conclusions.

8,664 words

Tables 2,321 words

Grand total (excluding references and title page) 10,985 words

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Table 34.1 Prospective high-intensity interval training (HIIT) studies with children and adolescents that assessed athletic performance outcomes.

Citation	HIIT sample	Control sample	Sex	Sport	Age (years)	Length (wk)	Training programme	Performance (Δ%)		
Baquet *et al.*[26]	33	20[a]	M & F	N/A	8-11	7	F2, 30-min of short intermittent aerobic running (10 or 20 s) at 100 to 130% MAS.	Peak $\dot{V}O_2$: MS:	+8*† +5*†	
Baquet *et al.*[27]	36	36[a]	M &F	N/A	8-11	7	F2, 30-min of high-intensity intermittent running (10 or 20 s) at 100 to 130% MAS.	MS: SBJ:	+5 *† +10*†	
Breil *et al.*[28]	13	8[b]	M & F	Alpine Skiing	16-17	11 days	Shock Micro-cycle of HIIT. 15 high-intensity aerobic interval sessions in 11 days. 4 × 4-min at 90-95% HRmax, 3-min recovery periods.	Peak $\dot{V}O_2$ PPO: VT: Lac_{max}: Tlim: CMJ: SJ:	+6* +6* +10* +11* +5 -5* -4*	
Buchheit *et al.*[29]	**G1:**15 **G2:**17	N/A	M & F	Handball	15.5	10	**G1:** F2, HIIT, 12-24 × 15-s runs at 95% MAS, with 15-s passive recovery. **G2:** F2, Small-sided handball games performed over similar time period.	 V_{IFT}: T_{lim}: RSA: 10m Sprint: CMJ:	**G1:** +6* +36* +3* +1 +3	**G2:** +7* +27* +5* +2 +3
Buchheit *et al.*[30]	**G1**: 7 **G2**: 8	N/A	M	Football	14.5	10	**G1**: F1, Repeated Sprint Training: 2-3 sets of 5-6 × 15 to 20m repeated shuttle sprints with 14-s of passive or 23-s of active recovery. **G2:** F1, Explosive Strength Training: 4-6 series of 4-6 explosive strength exercises.	 10m Sprint: 30m Sprint: RSAmean: CMJ: Hop:	**G1:** +2 +2* +3* +7* +14*	**G2:** +33 +2* +1* +15*† +28*
Chamari *et al.*[24]	18	N/A	M	Football	14.0	8	F2, 1 session 4 × 4 min at 90-95% HRmax. 3 min active recovery. 1 session 4 × 4 min small sided	Peak $\dot{V}O_2$: Peak $\dot{V}O_2$ (abs):	+8 +15*	

							games (4 × 4 players) at 90 -95% HRmax.	RE: Hoff-Test:	+14* +10*	
Delextrat & Martinez[31]	**G1:** 9 **G2:** 9	N/A	M	Basketball	**G1:** 16.0 **G2:** 16.3	6	**G1**: F2, HIIT. Intermittent running at 95% maximal aerobic performance. 15-s exercise bouts interspersed with 15-s of active recovery for 8-13 min. e.g. 2 × (8-13 min of 15-s – 15-s). **G2:** F2, Small-sided games. 2 vs 2 small sided games. e.g. 2 × (2-3 × 3-min 45s – 4-min 15s).	$V_{IFT:}$ Defence: Offence:	**G1:** +3* -3 +4*	**G2:** +4* +5 +7*
Faude *et al.*[32]	**G1 & G2:** 10 Crossover	N/A	M & F	Swimming	16.6	4	**G1**: F6, HIIT, 30.8% above individual anaerobic threshold. Various interval duration and repetitions. **G2:** F6, High-volume Training, 23.3% above individual anaerobic threshold. Various interval duration and repetitions.	IAT: T_{100}: T_{400}:	**G1:** +* -1 0	**G2:** +* -1 0
Impellizzeri *et al.*[33]	**G1:** 15 **G2:** 14	N/A	M	Football	17.2	4 & 8	**G1:**F2, Generic Interval Training. 4× 4-min at 90-95% HRmax with 3-min active recovery. **G2:** F2, Small-sided Football Games.	Peak $\dot{V}O_2$: $\dot{V}O_2$ at LT: V at LT: Eckblom: Distance run: HI running: LI running: Walking:	**G1:** +8* +13* +9* +14* +6* +23* +18* -9*	**G2:** +7* +11* +10* +16* +4* +26* +7* -8*
McManus *et al.*[34]	**G1**: 11 **G2**: 12	7[a]	F	N/A	9.6	8	**G1:** F3**,** Sprint Running. 3×10-s maximal speed sprints with 10-s rest followed by 3×30-s sprints with 90-s rest. Increased to 4, 5 and 6 sets after two, four and six	Peak $\dot{V}O_{2:}$ PPO:	**G1:** +8* +10*	**G2:** +10* +20*

							weeks, respectively. **G2:** F3, Cycle Ergometer Exercise 20-min cycling at HR 160-170 b·min^{-1}.	MPO:	+3	-1
McManus *et al.*[35]	**G1**:10 **G2**:10	15[a]	M	N/A	10.3	8	**G1:** F3, Interval training. 7×30-s maximal speed sprint on cycle ergometer with 2-min 45-s active recovery. **G2:** F3, Continuous training**.** 20-min steady state cycling at HR 160-170 b·min^{-1}.	Peak $\dot{V}O_2$: PPO: $\dot{V}O_2$ at VT:	**G1:** +12* +33*† +22*†	**G2:** +6* +22 +3
McMillan *et al.*[25]	11	N/A	M	Football	16.9	10	F2, Football-specific running. 4×4-min at 90-95% HRmax separated by 3-min recovery at 70% HRmax.	Peak $\dot{V}O_2$: RE: CMJ: SJ: 10m Sprint:	+10* 0 +3* +7* 0	
Meckel *et al.*[36]	**G1**:11 **G2**:13	N/A	M	Football	14.3	7	**G1:** F3, Short-sprint repetition training. 4-6 sets of 4×50m reps of all out sprints with 2- and 4-min rest between reps and sets, respectively. **G2:** F3, Long-sprint repetition training. 4-6 200m reps at 85% max 100m speed with 5-min rest between reps.	Peak $\dot{V}O_2$: T_{250} 30m Sprint $T_{4\times10}$ SBJ:	**G1:** +7* +4* +3* +3* +1	**G2:** +10* +3* +2* +1* +2
Rotstein *et al.*[37]	16	12[a]	M	N/A	10.8	9	F3, Interval Running. 1-2 sets of 3×600m with 2.5-min rest, 5×400m with 2-min rest and 6×150m with 1.5-min rest. Varying intensity.	Peak $\dot{V}O_2$: T_{1200} PPO MPO LAIV	+8* +10* +14* +10* +2*	

Sperlich *et al.*[38]	**G1 & G2:** 26 Crossover	N/A	M & F	Swimming	10.5	5	**G1:** F5, HIIT. 30-min, 50-300m intervals. Intensity 92% personal best 100m freestyle time. **G2:** F5, High Volume Training. 60-min, 100-800m intervals, Intensity 85% personal best for each distance.	Peak $\dot{V}O_2$: Lac_{max} LEN: T_{2000}: T_{100}:	**G1:** +12* +26* +17* +3* +2	**G2:** +9* -24* +6 0 +2
Sperlich *et al.*[39]	**G1**: 9 **G2**: 8	N/A	M	Football	13.5	5	**G1**: F3-4, HIIT. < 30-min running session (4-15 × 30-s – 4min) at 90-95% HRmax. Intervals separated by 1- to 3-min jogging at 50-60% HRmax. **G2:** F3-4**,** High Volume Training. 45 to 60-min exercise session at 50-70% HRmax.	Peak $\dot{V}O_2$: $T_{1000:}$ 20m Sprint: 30m Sprint: 40m Sprint: Drop Jump: CMJ: SJ:	**G1:** +7* +4* +4* +4* +3* +15 +12 +11	**G2:** +2 +2 +4* +4* +3* +7 +26 +14
Wahl *et al.*[40]	**G1:** 8 **G2:** 8	N/A	M & F	Triathlon	15.4	2	Shock Micro-cycle. 15 sessions within three, 3-day training blocks over 14 days. HIIT training at 90-95% HRmax. 40-s – 4-min intervals. Variable sets and repetitions. **G1:** Active recovery **G2:** Passive Recovery	Peak $\dot{V}O_2$: TT_{PO} (W) $TT_{Lactate}$ Wingate PPO: Wingate MP:	**G1:** -1 +3 +12 +2 +5*	**G2:** +3 +14* +23* -2 -2

Peak $\dot{V}O_2$ – peak oxygen uptake (mL·kg^{-1}·min^{-1}); **MS** – maximal speed (velocity) at the end of a graded field test; **SBJ** – standing broad jump; **PPO** – peak power output; **VT** – ventilatory threshold; **Lac_{max}** – maximal blood lactate concentration; **T_{lim}** – time to exhaustion at relative, pre-intervention exercise intensity; **CMJ** – counter movement jump; **SJ** – squat jumps; **V_{IFT}** – velocity reached at end of the 30-15_{IFT} test; **RSA (mean)** – mean sprint time during repeated sprint ability test; **10/20/30/40-m Sprint** – sprint time over 10/20/30/40 metres; **Hop** – mean height during hopping test; **Peak $\dot{V}O_2$ (abs)** – peak oxygen uptake (L·min^{-1}); **RE** – running economy; **Hoff-Test** – football-specific circuit; **Defence** – defensive agility; **Offence** – offensive agility; **IAT** – individual anaerobic threshold; **T_{100}** – maximal 100-m swim time; **T_{400}** – maximal 400-m swim time; **$\dot{V}O_2$ at LT** – oxygen uptake at lactate threshold; **Vat LT** – velocity at lactate threshold; **Eckblom** – football-specific endurance test; **Distance run** – distanced run during competitive football match; **HI running** – time spent in high-intensity running during competitive football match; **LI running** – time spent in low-

intensity running during competitive football match; **Walking** – time spent walking during competitive football match; **MPO** – mean power output; **$\dot{V}O_2$ at VT** – oxygen uptake at ventilatory threshold; **T_{250}** – 250-m running time; **$T_{4\times10}$** – 4 × 10-m shuttle running time; **T_{1200}** – 1200-m running time; **LAIV** – lactate inflection point velocity; **LEN** – “Ligue Européenne de Natation”, the European governing body – international pointing system for competition performance; **T_{2000}** – maximal 2000-m swim time; **TT_{PO}** – time trial power output; **$TT_{Lactate}$** – time trial blood lactate concentration; **Wingate PPO** – peak power output during Wingate test; **Wingate MP** – mean power out during Wingate test.
***** Significant difference pre- to post-intervention; † Significant difference between-groups. [a] Habitual Physical Activity; [b] Habitual Training.

Table 34.2 Peak oxygen consumption (peak $\dot{V}O_2$): prospective high intensity interval training (HIIT) studies with children and adolescents that included a comparison with either an untrained control or at least two different training programmes

Citation	**Sample sizes**[a]	**Sex & body size**[b]	**Age (years)**	**Length (wk)**	**HIIT (min)**[c]	**HIIT Training Programme**	**Peak $\dot{V}O_2$ (Δ%)**[d]
Baquet *et al.*[26]	33:20 (53)	M & F NW-OB	8-11	7	93	F2[e], 4 sets × 5-10 reps × 10-20-s @ 100-130% MAS run	8[§] vs -2
Baquet *et al.*[27]	22:22:19 (77)	M & F NW-OW	8-11	7	152	F3, 5 sets × 5-10 reps × 10-20-s @ 100-130% MAS run	5[§] vs 7[§] vs -2
Baquet *et al.*[43]	22:22:19 (77)	M & F NW-OW	8-11	7	152	F3, 5 sets × 5-10 reps × 10-20-s @ 100-130% MAS run	
Baquet *et al.*[56]	503:48	M & F NW-OW	10-16	10	35	F1[e], 2 sets × 10 reps × 10-s @ 100-120% MAS run	
Barker *et al.*[44]	10 (10)	M NW	15	2	16.5	F3, 1 set × 4-7 reps × 30-s "all-out" cycling	5[§]
Bond *et al.*[45]	13 (16)	M & F NW-OW	13	2	54	F3, 1 set × 8-10 reps × 60-s @ 90% peak aerobic cycling power	3
Buchan *et al.*[14]	17:16:24	M & F NW-OW	16	7	54	F3, 1 set × 4-6 reps × 30-s "all-out" running	
Buchan *et al.*[55]	42:47	M & F NW	16	7	54	F3, 1 set × 4-6 reps × 30-s "all-out" running	
Corte de Araujo[46]	15:15 (39)	M & F OB	8-12	12	108	F2, 1 set × 3-6 reps × 60-s @ MAS run	15[§] vs 13[§]
Ingul *et al.*[47]	10:10 (20)	M & F OB	14	13	416	F2, 1 set × 4 reps × 240-s @ 90% HR_{max} run	9[§]
Koubaa *et al.*[48]	14:15	M OB	13	12	504	F3, 1 set × 7 reps × 120-s @ 80-90% MAS run	11[§] vs 5[§]
Lau *et al.*[62]	15:21:12 (48)	M & F OW	11	6	54	F3, 1 set × 12 reps × 15-s @ 120% MAS run	
Logan *et al.*[49]	5:5:6:5:5 (29)	M NW-OB	16	8	21 to 107	F2, 1-5 sets × 4 reps × 20-s "all-out" various exercise modes	5 vs 7[§] vs 3 vs 9[§] vs 7[§]

McManus *et al.*[34]	11:12:7 (45)	F NW	9	8	72	F3, 3-6 × 10s + 3-6 × 30s “all-out” running	$8^{\S}$ vs $10^{\S}$ vs -2
McManus *et al.*[35]	10:10:15 (45)	F NW	10	8	84	F3, 3-6 × 10s + 3-6 × 30s “all-out” cycling	$11^{\S}$ vs $8^{\S}$ vs 2
Nourry *et al.*[50]	9:9 (24)	M & F NW	10	8	187	F2, 4 sets × 5-10 reps × 10-20-s @ 100-130 MAS run	$16^{\S}$ vs -1
Racil *et al.*[51]	11:11:12 (36)	F OB	16	12	264	F3, 2 sets × 6-8 reps × 30-s @ 100-110 MAS run	$8^{\S}$ vs $5^{\S}$ vs 1
Rosenkranz*[52]	8:8 (18)	M & F NW-OW	7-12	8	107	F2, 4 sets × 5-10 reps × 10-20-s @ 100-130 MAS run	$25^{\S}$ vs -8
Rotstein *et al.*[37]	16:12 (28)	M NW	10-11	9	Not known	F3, 1-2 sets: 3 × 600-m + 5 × 400-m + 6 × 150-m, ‘high’ intensity running	$8^{\S}$ vs 2
Tjønna† *et al.*[53]	22:20 (54)	M & F OW-OB	14	12	384	F2, 1 set × 4 reps × 240-s @ 90% HR_{max} run	$9^{\S}$ vs 0
							$11^{\S}$ vs -1
Williams *et al.*[54]	12:13:14 (45)	M NW	10	8	72	F3, 3-6 × 10s + 3-6 × 30s “all-out” running	-2 vs 5

a HIIT:Other training:Habitual control (starting total sample size)
b M – male, F – female; NW – normal weight, OW – overweight, OB - obese
c Total HIIT time (does not include warm-up or cool down)
d Percentage changes for HIIT vs other training and/or habitual control
e F – weekly training frequency (e.g., F3 = 3 sessions per week)
§ Significant within HIIT group change
* Low maximum heart rates suggest peak $\dot{V}O_2$ were invalid
† Top row of results (n=20) 3 months of HIIT; bottom row of results (n=13) 12 months of HIIT

Table 34.3 Body size, biochemical metabolites and vascular health: prospective high intensity interval training (HIIT) studies with children and adolescents that included a comparison with either an untrained control or at least two different training programmes (only HIIT group results displayed for biochemical metabolites).

Citation	**Body Size (Δ%)**[a]	**Biochemical Metabolites (Δ%)**[a]						**Vascular Health (Δ%)**[a]		
		Glu[b]	**Ins**	**TAG**	**HDL**	**LDL**	**TC**	**SBP**	**DBP**	**FMD**
Baquet *et al.*[26]	%BF -4 vs -3									
Baquet *et al.*[27]	%BF 1 vs 1									
Baquet *et al.*[43]	BMI 1 vs 1 vs -2									
Baquet *et al.*[56]	%BF 9 vs 6									
Barker *et al.*[44]	BMI <1							1	3	
Bond *et al.*[45]		0	<1	-8	5	-5	-2	-2 & 0	-11 & -11	F 15[§] & 15[§] P 29[§] & 17[§]
Buchan *et al.*[14]	%BF -3 vs -11[§] vs 0	-9	112	65[§]	20	-24	3	-5 vs -4 vs -4	-3 vs 0 vs -6	
Buchan* *et al.*[55]	WC <1 vs 2	2	8	10	21	-44[§]	-16	-4[§] vs -3	-1 vs -6	
Corte de Araujo[46]	%BF -3 vs -3	-3	-29[§]	-10	7	2	<1	-8[§] vs 0	-6 vs -8	
Ingul *et al.*[47]	%BF -5[§]							-6[§]	-13[§]	
Koubaa *et al.*[48]	WC -2			-6[§]	4[§]	-2	-1	-2[§] vs -2[§]	-3[§] vs -2	
Lau *et al.*[62]	ΣSF -14[§] vs -1 vs 8[§]									

Logan *et al.*[49]	-1 vs -4§ vs -6§ vs -2 vs -6§							-6§ to 5§	-13§ to 3	
Nourry *et al.*[50]	%BF -8 vs -3									
Racil* *et al.*[51]	%BF -8§ vs -5§ vs -1	-2	-27§	-7§	6§	-12§	-7§			
Rosenkranz[52]	%BF -10 vs -4	6	-	-17	22	-36§	-13§	-2 vs -2	-4 vs -2	
Tjønna† *et al.*[53]	%BF -12§ vs -3§	-6§	-29§	-11	10			-7§ vs -2§	-8§ vs -3	5§ vs 4
	%BF -3§ vs <1	-6§	-34§	-18	10			-6§ vs -4§	-7§ vs -1	6§ vs 1

Participant and training characteristics are displayed in Table 34.2

a HIIT vs other training and/or habitual control

b All fasting: Glu – glucose, Ins – insulin, TAG – triacylglycerol, HDL & LDL – high & low density lipoprotein cholesterol, TC – total cholesterol

* plasma metabolites presented to only one decimal place, which may have led to inflated %Δ estimations

§ Significant within HIIT group change

† Top row of results (n=20) 3 months of HIIT; bottom row of results (n=13) 12 months of HIIT