# THE EFFECT OF INTERMITTENT CYCLE TRAINING TIME AND INTENSITY ON AEROBIC CAPACITY

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# 1. Abstract

**Introduction:** Aerobic exercise capacity outperforms established clinical risk factors such as smoking, hypertension, obesity and diabetes in predicting all-cause mortality (Myer *et al.*, 2004). 'Lack of time' is the most commonly cited barrier to sufficient amounts of physical activity (Trost *et al*., 2002). High intensity interval training (HIT) is a time-efficient alternative to moderate intensity continuous training (MICT), but the feasibility for exercise-naïve individuals has been questioned. Success has depended on vigorous encouragement by the researchers and the presence of expensive specialised cycle ergometers.

**Aim:** To investigate whether two popular HIT protocols (30HIT and 60HIT) can increase aerobic exercise capacity without verbal encouragement or specialised cycle ergometers, such that HIT interventions can be delivered in a real life setting independent of instructors.

**Methods:** Twenty-eight previously sedentary males (n=6) and females (n=22) aged 18-55 participated (28±2 y, BMI 25±1 $kg.m^2$). In a randomised counterbalanced cross-over design, participants completed either 6 weeks of 30HIT (4-8x30s with 120s active recovery) or 60HIT (6-10x60s with 60s active recovery). Training sessions were completed on a Wattbike, 3 times per week. Participants were told to reach > 80% of maximal heart rate ($HR_{max}$). $VO_{2peak}$ and Watt $_{max}$ were assessed pre and post each intervention, with a 4-6 weeks wash-out period between interventions.

**Results:** $VO_{2peak}$ increased post intervention in 30HIT (37±1 to 38±1 $ml.min^{-1}.kg^{-1}$) and 60HIT (35±1 to 38±1 $ml.min^{-1}.kg^{-1}$). There was a significant main effect of training on $VO_{2peak}$ ($P < 0.001$), with no difference between training modes ($P$=0.849). When normalized to Watt $_{max}$ those participants producing higher peak power output (PPO) improved their $VO_{2peak}$ significantly more than those producing a low PPO, irrespective of group (30HIT $P$<0.05, 60HIT $P$<0.05), despite all participants achieving the target heart rate.

**Conclusion:** Non-encouraged self-paced 30HIT and 60HIT can increase aerobic capacity. Participants were only guided by their heart rate, but when investigated further the participants reaching a higher PPO during the intervals had the greatest improvement in aerobic capacity.

# 2. Acknowledgments

Firstly, I wish to acknowledge my supervisors Juliette Strauss, Matthew Cocks, Sam Shepherd and Anton Wagenmakers for your continuous support and guidance. Secondly the rest of Team Anton, Katie Whytock, Sam Scott and Raffaella Rodighiero, thank you for all the cannulas and help throughout this year. Also thank you to the extremely helpful technicians Gemma Miller and Dean Morrey.

This study would not have been possible or been as enjoyable without my wonderful participants. I hope that any future studies I conduct will also have such interesting and lovely participants involved.

Mum and dad without your constant support I wouldn't be where I am today. You have always encouraged me to keep going and to continue aiming higher, even when I ring you crying because my hard-drive has broken. Thank you Benjamin for always being there, through the ups and downs.

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# 3. Introduction

### *3.1 Physical inactivity and aerobic capacity*

Levels of physical inactivity are rising in many countries with major implications for health and the prevalence of non-communicable diseases such as cardiovascular disease, type II diabetes and cancer. Physical inactivity has been identified as the fourth leading risk factor for global mortality (6% of deaths globally) (WHO, 2010). According to the National Institute for Health and Care Excellence (NICE, 2006), inactivity is costing the national economy in England £8.2 billion per year. Lower levels of aerobic exercise capacity have been associated with high risk of all-cause mortality (Myers *et al.*, 2004; Kodama *et al.,* 2009). A study from Lee *et al.* (2010) further reported that moderate to high level of cardiorespiratory fitness, as well as an improved cardiorespiratory fitness are associated with a lower risk of mortality, regardless of age, smoking status, body composition and other risk factors. However, Blair *et al*., (1989) reported that higher levels of physical fitness appear too delay all-cause mortality suggesting that increasing physical activity and reducing sedentary behaviour will protect the general public from early mortality.

### *3.2 Moderate intensity continuous training*

Traditionally, moderate intensity continuous training (MICT) has been the preferred method of training to elicit adaptations that facilitate elevated aerobic capacity. This leads to an improvement in performance and disease prevention. MICT has long been seen as the best method to increase aerobic exercise capacity and various health aspects in sedentary participants. It is only recently though that clinical trials are beginning to show that exercise training can reduce the risk for obesity and metabolic syndrome to include hypertension, type 2 diabetes, cardiovascular disease (MacAuley *et al.,* 2015). MICT elicits various cardiac and vascular adaptations (Blomquist & Saltin, 1983), leading to an improvement in aerobic capacity (Berthouze *et al., 1995*), blood pressure (Arroll & Beaglehole, 1992) and insulin sensitivity (Colberg *et al.,* 2010). Due to the effectiveness of MICT the current public health guidelines recommend at least 150 minutes of moderate intensity exercise per week. Despite the known importance of physical activity to improving health 12.5

million people in England failed to achieve 30 minutes of moderate intensity physical activity per week within a 28-day period during 2013. (Sport England, Active People Survey, 2013). Many individuals consider the lengthy time requirement associated with MICT to be a barrier to performing exercise regularly (Booth *et al*.; 1997, Trost *et al.,* 2002), as the most commonly cited barrier for physical activity is 'lack of time' (Trost *et al.,* 2002). Therefore, less time consuming alternative approaches to decrease physical inactivity are needed.

### ***3.3 Defining high intensity interval training***

High Intensity Interval Training (HIT) is a potential alternative to MICT, inducing similar or even superior changes in a range of physiological, performance and health-related markers, in both healthy individuals and diseased populations. HIT involves alternating bouts of intense exercise with low intensity recovery periods. Fox *et al.* (1975) maintained HIT typically involves a work interval duration ranging from 1-8 min and eliciting an oxygen demand equal to around 90-100% $V0_{2max}$ and a rest interval varying from 30 secs to 5 min (Seiler & Sjuresen, 2004). Buchheit and Laursen (2013) suggested different groupings of HIT depending on the intensity and time duration of the intervals; long intervals [>45s], short intervals [<45s], repeated sprints training [<10s] all out sprints, sprint interval training (SIT) [20-30s] all out sprints, this approach is used to categorise protocols in **Table 1**. Following the recent interest in HIT in clinical populations Weston *et al.* (2014) have proposed an easier classification, whereby the term 'HIT' is used in the case of intervals near to maximal or at a target intensity between 80-100% $HR_{max,}$ whereas SIT to be used for protocols that involve 'all out' or supramaximal efforts, in which target intensities correspond to workloads greater than 100% of $VO_{2max.}$ The conflicting definitions are understandable as HIT protocols can differ greatly by manipulating certain variables, such as the intensity and duration of the interval, intensity and duration of the recovery period, number of intervals and duration of the intervention (**Figure 1**). This also makes HIT a complex training approach to study and implement optimally. Physiological adaptations to HIT are also highly variable and therefore, providing general recommendations to the general public is difficult.

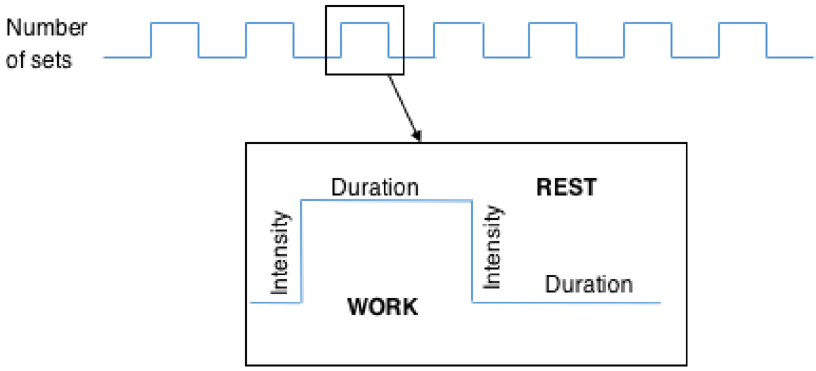


**Figure 1.** Illustration of the different factors incorporated when designing a HIT programme. Adapted from Buchheit (2008).

### *3.4 Historical approach to HIT research*

Athletes and coaches have historically used HIT to improve exercise performance in the preparation period for important competitive events (Stoggl & Sperlich 2014, 2015). Even as early as 1920 athletes, such as Paavo Nurmi, were using a form of HIT in their training programmes. It was further popularised in the 1950s by the Olympic Champion Emil Zatopek. It was not until this time that interval training was first described in a scientific journal by Reindell and Roskamm (1959). The appearance of HIT amongst elite athletes is the first evidence of its effectiveness, specifically to increase $VO_{2max}$ and therefore maximal running speed at specific distances (i.e. 'best practice' theory) (Buchheit and Laursen 2013). Initial studies were carried out in athletic populations, and were designed to optimise training responses. Astrand and co-workers published several ground-breaking papers in the 1960s on the acute physiological responses to HIT (Astrand *et al.,* 1960; Christensen *et al.,* 1960). Astrand *et al.* (1960) demonstrated by using 0.5, 1, 2 or 3 minute periods of work and rest that manipulating the work and rest duration during interval training can dramatically impact physiological responses during prolonged exercise. They found that when heavy work was split into short periods (0.5 or 1min) the load on the cardiorespiratory system became submaximal and this coincided with a higher workload tolerance during exercise periods lasting 1 hour.

### *3.5 Aerobic interval training in a clinical setting*

Following on from the initial studies used to improve performance of athletes, research began into sedentary and diseased populations. The first studies to investigate the effect of HIT on health were carried out by Helgerud *et al.* (2007) and Wisloff *et al.* (2007). Both researchers compared the effect of four intervals of 4 minutes duration at 90-95% $HR_{max}$ interspersed with 3 minutes of active rest at 70% $HR_{max}$ on aerobic capacity. This protocol was named aerobic interval training (AIT), however following the suggestion from Weston *et al.* (2014) AIT also comes under the HIT definition. Helgerud *et al* also compared AIT to 15s of running at 90-95% $HR_{max}$ followed by 15s active rest at 70% $HR_{max,}$ running at lactate threshold (85% $HR_{max}$ for 24.25min) and running at 70% $HR_{max}$ for 45mins. AIT improved aerobic capacity, measured as $VO_{2max}$, beyond that of the lactate threshold or the MICT conditions. The aftermath of this study resulted in a flurry of work investigating AIT as a method to improve health in a number of at risk populations. Hypertensive patients (Molmen-Hansen *et al.,* 2012), patients with cardiovascular failure (Wisloff *et al.,* 2007) and metabolic syndrome (Tjonna *et al.,* 2008) have all seen a superior increases in aerobic capacity following AIT compared to MICT. Even though the 4x4min protocol has been shown to be extremely effective at increasing aerobic capacity and having major benefits on health in patients with cardiovascular failure and metabolic syndrome, this type of HIT is very demanding and may only be successful in a clinical setting with continuous encouragement and motivation by the doctors and nurses. Therefore, because the participant needs to keep pushing themselves throughout the interval to maintain the intensity, sedentary and diseased populations are unlikely be able to complete the long-interval sessions unsupervised. The AIT protocol takes 40minutes to complete therefore it may not represent a training modality to increase participation, especially given that the main barrier for participation in physical activity is time commitment.

### *3.6 Wingate style sprint interval training*

As AIT does not reduce the time commitment to exercise, Wingate style sprint interval training (SIT) protocols, containing only 2 minutes of intense exercise, have begun to increase in popularity within the research. The most common model employed in SIT sessions from the literature has been the Wingate test, which consists of a 30s ‘all out’ cycling effort. Subjects typically perform four to six 30 s bouts separated by 4 to 4.5 min of recovery. This method has been shown to be a time-efficient strategy for rapid physiological and performance improvement that are comparable to traditional MICT (Burgomaster *et al.,* 2008; Rakobowchuk *et al.,* 2008; Cocks *et al.,* 2013; Shepherd *et al.,* 2013). This training protocol is extremely low-volume as only 15 minutes of ‘all-out’ exercise over 2 weeks was enough to increase skeletal muscle oxidative capacity (Burgomaster *et al.* 2005). When Wingate SIT was compared against MICT over 6 weeks, similar improvements were seen in markers of skeletal muscle and cardiovascular adaptations in both the HIT and MICT groups (Burgomaster *et al.,* 2008; Rakobowchuk *et al.,* 2008; Cocks *et al.,* 2013; Shepherd *et al.,* 2013,). These improvements were seen even though the SIT protocol involved 90% lower weekly training volume and 67% lower time commitment (1.5h vs 4.5 hours per week). Despite its effectiveness Wingate SIT has been criticised. A critical question that has been controversial among health professionals is still whether it is safe for individuals to complete “all out” sprints.

### *3.7 Constant workload approaches*

The ‘all-out’ protocol used in Wingate SIT is very demanding and requires encouragement and/or high level of internal motivation; therefore it is not regarded to be a practical modality for sedentary populations. Due to these criticisms of ‘all out’ protocols, researchers began to investigate alternatives, one potential alternative is a constant work load. Constant work load SIT or HIT protocols differ from ‘all-out’ protocols as the work load is maintained at a constant wattage throughout of the intervals. Unlike ‘all-out’ HIT where the workload will vary within each interval depending on the level of fatigue the participant has developed throughout the training session. This protocol could be a more effective approach to HIT in the general population as the ‘all-out’ protocol is very challenging and therefore constant load would negate the all out nature but with reduced rest, which may be safer and better tolerated by sedentary participants. Little *et al.* (2010) used a protocol which consists of 10 x 60s work bouts at a constant load of 100% peak power output, eliciting a heart rate above 90% $HR_{max,}$ followed by 60s recovery. The protocol has a reduced intensity in the interval, which allows for the reduced rest period. This results in a time efficient HIT protocol with only 10 minutes high intensity work completed in a 20-minute session. To maintain the nature of Wingate SIT, Cocks *et* *al.* (2015) developed a SIT protocol designed to maintain the anaerobic nature of 'all-out' protocols whilst utilising the accessibility of the constant load modality. Therefore, the work intensity during the intervals was clamped at 200% $W_{max.}$ Constant workload approaches have been used and proven to be effective in healthy lean (Little *et al.,* 2010) and obese and diseased populations (Little *et al.,* 2011; Cocks *et al.,* 2016). Therefore, suggesting that constant load protocols are time efficient and effective interventions which can induce adaptations beneficial to improving health.

### *3.8 All-out sprint protocols*

Wingate-style SIT and the constant work load studies are both effective interventions, but there has been some criticism in the literature questioning the time efficiency of these approaches as in many studies with longer intervals a single session lasted ~20 to 30 minutes, not including the warm-up and cool down (Gillen & Gibala 2014). In response to this criticism, more recent studies have investigated the effect of very brief SIT protocols involving a total session time of 10 minutes, including warm up and cool down. The protocol used by Gillen *et al.* (2014) included 3 x 20s 'all-out' sprints with a 2-minute recovery between bouts. This very brief protocol improved aerobic capacity (12%) when performed 3 times per week for 6 weeks, in overweight/obese participants. Gillen *et al.* (2016) then directly compared this 3 minute per week SIT protocol to traditional MICT over 12 weeks. Participants aerobic exercise capacity improved to the same extent as MICT, despite a 5-fold lower training volume and total training time.

### *3.9 Confusing public health message*

Various HIT/SIT protocols have therefore been established as time-saving alternatives to MICT, but all of the different approaches mentioned thus-far have led to an extremely confusing public health message. Evidence of this is illustrated by **Table 1** outlining a number of different HIT protocols used within the literature. There are conflicting methods used by researchers in terms of intensity and duration of intervals, intensity and duration of rest periods, number of intervals and duration of intervention. The vast amount of HIT protocols used by researchers has resulted in an inability to compare the results of the HIT protocols. More importantly it has led to a very confusing public health message, as members of the public are unaware which protocol is best to improve health. Likewise, the HIT protocols used in a laboratory are often completed using specialised equipment. But the general public are not trained in the usage of specialised equipment (e.g. Wingate bike) and may be put off by the complicated nature to carry out a HIT session. The increase time commitment associated with going to a gym/laboratory to perform a HIT session could also decrease motivation. Furthermore, the majority of the studies conducted involve high levels of encouragement from the researchers in a highly controlled laboratory environment. Therefore, questions remain around the feasibility and effects of HIT interventions implemented on a larger scale beyond the confines of the laboratory (Harcastle *et al*., 2014). The only papers to the researcher's knowledge to provide information into the outcome of HIT in a 'real-world' setting are Lunt *et al.* (2014) and Shepherd *et al.* (2015).

In the study of Lunt *et al.* (2014) overweight, inactive participants were randomized into three groups; MICT (~50mins walking at 65-75% $HR_{max}$), AIT (4x4 mins fast walking/jogging at 85-95% $HR_{max}$, 3 mins easy walking) and Wingate style running (3-6 x 30s all-out, 4 mins easy walking). The exercise interventions lasted for 12 weeks with 3 weekly sessions. The intensity of MICT and AIT were both measured using heart rate monitors. As the participants improved their fitness the workload during MICT was increased to keep them in the set heart rate zone. More intervals were added to the Wingate style protocol. All exercise sessions were held outdoors in a 459-acre public park. Modest changes in aerobic capacity were seen, with the largest change (10%) in the AIT group. Shepherd *et al.* (2015) used a dedicated cycling suite at the University of Birmingham Sports Centre to carry out a 'spinning class' style HIT intervention consisting of 15-60s intervals interspersed with 45 to 120s rest. This group-based HIT intervention improved aerobic capacity to a similar extent to that of an MICT control condition, HIT 9±4%, MICT 8±3%. In the study of Shepherd *et al.* (2015) during the HIT sessions the average maximum heart rate obtained at the end of each interval was equivalent to 91±6% $HR_{max}$. No encouragement was provided by a member of the research group but the sessions were led by a trained instructor appointed by the University Sports Centre. Heart rate was projected on a screen and could be seen by all individuals attending the class. However it is important to note that, apart from Shepherd *et al*. (2015) all other HIT studies have a member of the research group encouraging the participants throughout the session. Therefore, it is still relatively unknown whether sedentary populations can maintain the intense nature of exercise needed to prompt beneficial adaptations to health.

From the research both 30s and 60s HIT protocols have been established as successful time efficient protocols i.e. less than 20 minutes. 30s and 60s HIT interventions have been shown to be extremely effective interventions under laboratory conditions, in comparison to MICT. Based on the available research the current American College of Sports Medicine (ACSM) guidelines encourage a heart rate >80% $HR_{max}$ during a HIT session in order to induce adaptations (Roy, 2013). However how exercise naïve individuals will cope with the self-paced nature of these different interval lengths is unknown.

### *3.10 Aim*

The aim of this study was to identify if two popular HIT training protocols, consisting of 30s or 60s interval durations, can improve aerobic exercise capacity without verbal encouragement or specialised equipment. We also aimed to investigate whether the ACSM recommendations are applicable in a real world intervention. Finally, we investigated how individual differences in heart rate and power output response to the intervals could affect change in aerobic exercise capacity in both exercise conditions.

**Table 1.** Characteristics of repeated sprint training (RST), sprint interval training (SIT), short high intensity interval training (Short HIT) and long high intensity interval training (Long HIT).

| Paper | Interval Duration | Sets | Rest Duration | Interval workload/intensity | Equipment | Intervention Duration | Session Duration (excluding warm up/cool down) |
|---|---|---|---|---|---|---|---|
| **RST** | | | | | | | |
| Admanson *et al.* (2014) | 6s | 10 | 1min | All Out | Cycling (Monark Peak Bike) | 16 sessions, 8wks | 11min |
| Gunnarsen & Bangsbu (2012) | 10s | 20-25 | 50s (active) | 90-100% $V0_{2max}$ | Track | 7 wks | 15-20min |
| Hazell *et al.* (2010) | 10s | 4-6 | 2 min or 4 min (active) | All Out | Cycle ergometer | 3d/wk, 2wk | 8.7-25min |
| Heydari *et al.,* (2012) | 8s | 60 | 12s (active) | 80-90% $HR_{max}$ | Cycle ergometer | 12 wks | 20min |
| Hureau *et al.,* (2014) | 10s | 1-10 | 30s (active) | All Out | Cycle ergometer | 2 sessions, 6 days | 6.6min |
| Linossier *et al.* (1993) | 8-13 x 5s | 2 | 55s, 15min between sets | All Out | Cycle ergometer | 4d/wk, 7wks | 31-41min |
| Serpiello *et al.,* (2011) | 5x 4s | 3 | 20s, 4.5min between sets | All Out | Treadmill | 4 wks | 19.5min |
| Skleryk *et al.,* (2013) | 10s | 8-12 | 80s | All Out | Cycle ergometer | 2 wks | 12-16min |

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|---|---|---|---|---|---|---|---|
| Trapp *et al.,* (2008) | 8s | Max 60 | 12s | All Out | Cycle ergometer | 15 wks | 5-20mins |
| **SIT** | | | | | | | |
| Allemeier *et al.* (1994) | 30s | 3 | 20min | All Out | Cycle ergometer (Monark Crescent) | 2-3d/wk, 6wk | 1h 1.5min |
| Astorino *et al.* (2012) | 30s | 4-6 | 5 min (active) | All Out | Cycle ergometer (Monark Vansbro) | 3d/wk, 2wk | 22-33min |
| Babraj *et al. (*2009) | 30s | 4-6 | 4min (active) | All Out | Cycle ergometer (Lode Excalibur) | 2wk | 18-27min |
| Bailey *et al.* (2009) | 30s | 4-6 | 4 min | All Out | Cycle ergometer (Monark) | 6 sessions over 2wk | 18-27min |
| Barnett *et al.* (2004) | 30s | 3-6 | 3 min (passive) | All Out | Cycle ergometer | 3d/wk, 8wk | 10.5-21min |
| Bayati *et al.* (2011) | 30s | 3-4 or 6-8 | 2min or 4 min | All Out or 125% $P_{max}$ | Cycle ergometer | 3d/wk, 4wk | 13.5-22.5min or 15-23min |
| Burgomaster *et al.* (2008) | 30s | 4-6 | 4.5 min (active) | All Out | Cycle ergometer | 3d/wk, 6wk | 20-30min |
| Cocks *et al.* (2013) | 30s | 4-6 | 4.5min (active) | All Out | Cycle ergometer | 3d/wk, 6wk | 20-30min |
| Dalleck *et al. (2010)* | 30s | 6-8 | 3.5 min (active) | 110-120% $P_{max}$ | Cycle ergometer (Viasprint 150P) | 1-2 d/wk, 6wk | 24-32min |
| Esfarjani and Laursen (2007) | 30s | 7-12 | 4.5 min | 130% $V02_{max}$ | Treadmill | 2d/wk, 10wk | 35-60min |
| Gillen *et al.,* (2016) | 20s | 3 | 2min | All Out | Cycle ergometer | 3d/wk, 12wk | |
| Harmer *et al.(2000)* | 30s | 12 | 3-4 min (passive) | All Out | Cycle ergometer (Monark) | 3d/wk 7wk | 14-45min |
| Hazell *et al.* (2010) | 30s | 4-6 | 4 min | All Out | Cycle ergometer | 3d/wk, 2wk | 18-27min |

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|---|---|---|---|---|---|---|---|
| Hovanloo *et al.* (2013) | 30s | 4-6 | 4min | All Out | Cycle ergometer | 2wks | 18-27min |
| Keating *et al.*(2014) | 30s-60s | 4-6 | 2min | 120% $VO2_{peak}$ | Cycle ergometer | 12wks | 10-18min |
| MacDougll *et al.* (1998) | 30s | 4-10 | 4min, - 30s after wk 3 (active) | All Out | Cycle ergometer (Monark) | 3d/wk, 7wk | 18min-40min |
| Macpherson *et al.*(2011) | 30s | 4-6 | 4min (active) | All Out | Treadmill | 3d/wk 6wk | 18-27min |
| Mckenna *et al.* (1997) | 30s | 4-10 | 3-4min | All Out | Cycle ergometer (Monark) | 3d/wk 7wk | 18-35min |
| Metcalfe *et al.* (2012) | 10-20s | 2 | 3.5-3.8min | All Out | Cycle ergometer | 6wks | 4mins |
| Parra *et al.* (2000) | 15 & 30s | 2-7 | 45s & 12min | All Out | Cycle ergometer | 2d/wk, 6wks | 7-34.5min |
| Rakobowchuk *et al.*(2012) | 30s | 20-25 | 1 min | 100% $P_{max}$ | Lode Excalibure | 3d/wk, 6wks | 30-40min |
| Richards *et al. (*2010) | 30s | 4-7 | 4min | All Out | Cycle ergometer | 2wks | 18-31.5min |
| Rodas *et al.* (2000) | 15 & 30s | 2-7 | 45s & 12min | All Out | Cycle ergometer | 14 sessions in 2wks | 7-34.5min |
| Rowan *et al.* (2012) | 30s | 5-10 | 3.5-4.5min (active) | All Out | Running | 2d/wk, 5wk | 20-25min |
| Shaban *et al. (*2014) | 30s | 4 | 4mins (active) | All Out | Cycle ergometer | 3d/wk, 2wks | 18mins |
| Shepherd *et al.* (2013) | 30s | 4-6 | 4mins | All Out | Cycle ergometer | 3d/wk, 6 wk | 18-27min |

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|---|---|---|---|---|---|---|---|
| Stathis *et al.* (1994) | 30s | 3-10 | 3-4min | All Out | Cycle ergometer (Repco) | 3d/wk, 7wk | 13.5-45min |
| Tong *et al.* (2011) | 30s | 20 | 1min (active) | 120% $P_{max}$ | Cycle ergometer | 3d/wk, 6wk | 30min |
| Trilk *et al.* (2011) | 30s | 4-7 | 4min (active) | All Out | Cycle ergometer | 3d/wk, 4 wks | 18-31.5min |
| Whyte *et al.* 2010 | 30s | 4-6 | 4.5mins (active) | All Out | Cycle ergometer (Excalibur) | 2wks | 18-27min |
| **Short HIT** | | | | | | | |
| Boyd *et al.,* (2013) | 60s | 8-10 | 60s | 70% or 100% PPO | Cycle ergometer | 3d/wk, 3wks | 16-20mins |
| Currie *et al.,* (2013) | 1min | 10 | 1min (active) | 80-104% PPO | Cycle ergometer | 3d/wk, 12 wks | 20min |
| Dunham and Harms (2012) | 60s | 5 | 3min | 90% $P_{max}$ | Cycle ergometer (Sensormedics 800) | 3d/wk, 4wks | 20min |
| Esfandiari *et al.,* (2014) | 60 | 8-12 | 75s | 95-100% $V0_{2max}$ | Cycle ergometer | 6 sessions, 2wks | 18-24mins |
| Green and Fraser (1988) | 60s | Fatigue, max 24 | 4min | 120% $V0_{2max}$ | Cycle ergometer | 3d/wk, 1wk | 120mins |
| Hood *et al.,* (2011) | 60s | 10 | 1min (active) | 60% PPO | Cycle ergometer | 6 sessions, 2wks | 20mins |
| Jacobs *et al.*(2013) | 60s | 8-12 | 75s | 100% $P_{max}$ | Cycle ergometer | 6 sessions over 2wk | 18-24mins |
| Klonizakis *et al.,* (2014) | 60s | 10 | 1min (active) | 100% PPO | Cycle ergometer | 3d/wk, 2wks | 20min |
| Larsen *et al.,* (2015) | 60s | 5 | 1.5min (active) | 128% PPO | Cycle ergometer | 3d/wk, 6 wks | 14.5min |
| Laursen *et al.,* (2002) | 60s | 20 | 2 mins (active) | 100% $P_{max}$ | Cycle ergometer | 4 sessions, 2wk | 60mins |

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|---|---|---|---|---|---|---|---|
| Little *et al.,* (2011) | 60s | 10 | 60s (active or passive) | 90% $HR_{max}$ | Cycling (life cycle) | 3d/wk, 2wks | 20min |
| Mitranun *et al.,* (2014) | 60s | 4-6 | 4min (active) | 80-85% $V0_{2Peak}$ | Treadmill | 3d/wk, 12wks | 20-24min |
| Mybo *et al.,* (2010) | 2min | 5 | 2min | >95% HR | Treadmill | 12wks | |
| Simoneau *et al.,* (1986) | 15-90s | 10-15 | HR return to 120-130 bts/min | 60-90% PPO | Cycle ergometer (Monark) | 4-5d/wk, 15wks | |
| Terada *et al.,* (2013) | 1min | 7-14 | 3min | 100% $V0_{2reserve}$ | Treadmill & Cycle ergometer | 12 wks | 30-60mins |
| **Long HIT** | | | | | | | |
| Conraads *et al.,* (2015) | 4min | 4 | 3min (active) | 90-95% $HR_{max}$ | Cycle ergometer | 3d/wk, 12wks | 28mins |
| Fu *et al.,* (2013) | 3min | 5 | 3min (active) | 80% $V0_{2peak}$ | Cycle ergometer | 12wks | 30mins |
| Grieco *et al.,* (2013) | 5min | 5 | 5min (active) | 90-100% $HR_{reserve}$ | Cycling (Monark) | 3d/wk, 3wks | 50mmin |
| Heggelund *et al.,* (2011) | 4min | 4 | 3min (active) | 80-95% $HR_{max}$ | Treadmill | 3d/wk, 8wks | 28mins |
| Hollekim-strand *et al.,* (2014) | 4min | 4 | 3min | 90-95% $HR_{max}$ | Treadmill | 12wks | 28mins |
| Iellamo *et al.,* (2014) | 4min | 4 | 3min (active) | 70-85% $HR_{reserve}$ | Treadmill | 12wks | 28mins |
| Karstoft *et al.,* (2013) | 3min | 10 | 3min (active) | 70% peak energy expenditure rate | Walking | 5d/wk, 16wks | 60min |
| Leggate *et al.,* (2012) | 4min | 10 | 4min | 85% $V0_{2peak}$ | Cycle ergometer | 3d/wk, 2wks | 80mins |
| Lunt *et al.,* (2014) | 4 min | 4 | 3min (active) | 85-95% $HR_{max}$ | Walking | 3d/wk, 12wks | 28mins |
| Marikawa *et al.,* (2011) | 2-3min | 5 | 3min | 70-85% $V02_{peak}$ | Walking | 4d/wk, 16wks | 25-30min |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Molmen-Hansen *et al.,* (2012) | 4min | 4 | 3min (active) | 90-95% $HR_{max}$ | Uphill treadmill walking/running | 3d/wk, 12wks | 28mins |
| Mora-Rodriguez *et al.,* (2014) | 4min | 4 | 3min (active) | 90% $HR_{max}$ | Cycle ergometer | 3d/wk, 16wks | 28mins |
| Moreira *et al.,* (2008) | 2min | 6-18 | 60s | 120% Aerobic threshold | Cycle ergometer | 3d/wk, 12wks | 20-60mins |
| Perry *et al.,* (2008) | 4min | 10 | 2min | 90% $V0_{2peak}$ | Cycle ergometer | 3d/wk, 6wks | 60mins |
| Poole & Gaesser (1985) | 2mins | 10 | 2mins | 105% $V0_{2max}$ | Cycle ergometer (Monark) | 3d/wk, 8wks | 40mins |
| Rognmo *et al.,* (2012) | 4min | 4 | 3min (active) | 85-95% $HR_{max}$ | Walking | 3d/wk, 10wks | 28mins |
| Schjerve *et al.,* (2008) | 4min | 4 | 3min (active) | 85-95% $HR_{max}$ | Treadmill walking | 3d/wk, 12wks | 28mins |
| Stensuold *et al.,* (2010) | 4min | 4 | 3min | 90% $HR_{peak}$ | Treadmill | 12wks | 28mins |
| Talanian *et al.,* (2010) | 4min | 10 | 2min | 90%$V0_{2peak}$ | Cycle ergometer | 3d/wk, 6wks | 60min |
| Tjonna *et al.,* (2008) | 4min | 4 | 3min (active) | 90% $HR_{max}$ | Treadmill | 3d/wk, 16wks | 28mins |
| Wisloff *et al.,* (2007) | 4min | 4 | 3min (active) | 90-95% $HR_{max}$ | Uphill treadmill walking | 3d/wk, 12wk | 28mins |

BW, body weight; HR, heart rate; $HR_{max,}$ maximum heart rate; $HR_{reserve}$, the difference between the maximum and resting heart rate value; $P_{max=,}$ Peak watt workload; $P_{max}$, Peak wattage workload; PPO, peak power output; $T_{max}$, time for which exercise at VO2 max can be sustained; $V02_{max}$, maximum oxygen uptake; $V0_{2reserve}$, the difference between the maximum and resting $VO_2$ value; $VO2_{peak}$, highest maximum oxygen uptake value.

# 4. Methods

### *4.1 Participants*

Twenty-eight previously sedentary (defined as performing less than 150 min moderate intensity exercise per week) males (n=6) aged 18-45 and females (n=22) aged 18-55, with a BMI <32 kg.m$^{-2}$, participated in the study (**Table 1**.). Participants were free of diagnosed cardiovascular and metabolic disease and other contraindications to perform exercise, ascertained through a medical screening process (see below). Pregnant or breast feeding participants were excluded. The participants gave written informed consent and all procedures were performed in compliance with the Declaration of Helsinki for human experiments and approved by the Coventry and Warwickshire NHS Research Ethics Committee.

***Table 1.*** *Participant characteristics pre and post 6 weeks of training*.

| | 30HIT | | 60HIT | |
|---|---|---|---|---|
| | Pre-training | Post-Training | Pre-Training | Post-Training |
| Age (y) | 28.0 ± 2 | - | - | - |
| Height (cm) | 165.6 ± 2 | - | - | - |
| Weight (kg) | 769.9 ± 3 | 69.5 ± 3 | 69.7 ± 3 | 69.0 ± 3 |
| BMI(kg.m$^{-2}$) | 25.4 ± 1 | 25.2 ± 1 | 25.3 ± 1 | 25.1 ± 1 |
| $Watt_{max}$ (W) | 179.5 ± 7 | 199.5 ± 8* | 179.8 ± 7 | 194.4 ± 8* |

*Values are means ± SEM. N = 28 *P < 0.05, main effect of training.*

### *4.2 Pre-exercise screening*

To assess participant's cardiovascular risk and their suitability to undertake the study a Framingham Heart Study Coronary Heart Disease Risk Prediction Score was calculated (Anderson *et al.*, 1991). Briefly the following information was collected and used to calculate a 5-year risk score: age, systolic blood pressure, total and HDL cholesterol, history of smoking, diabetes and resting ECG abnormalities were evaluated through a 12 lead ECG. Participants with a low risk score (<10% risk of developing coronary heart disease in the next 5 years) were deemed eligible to take part in the study, as suggested by the American Heart Association (Gibbons *et al.,* 2002). Participants were also asked to complete the International Physical Activity Questionnaire to assess current physical activity levels.

### *4.3 Protocol*

The study used a randomised counterbalanced cross-over design. Participant's maximal oxygen consumption during incremental exercise ($VO_{2peak}$) and maximal power output at $VO_{2peak}$ ($Watt_{max}$ ($W_{max}$)) were first determined. Participants were then randomised to either 6 weeks of 30HIT (30s high intensity, 'all out' efforts interspersed with 120s active recovery) or 60HIT (60s high intensity efforts interspersed with 60s active recovery) (**Figure 2**) Both 30HIT and 60HIT required participants to train 3 times per week (18 sessions in total). Following this $VO_{2peak}$ and $W_{max}$ were reassessed in the final week of training (as a replacement of session 17). 4-6 weeks after the last training session participants began a second experimental period identical in all respects to the first, except the alternative training intervention was conducted, 30HIT or 60HIT (**Figure 3).** During the 4-6 week wash-out period participants were instructed to return to their pre intervention levels of physical activity.

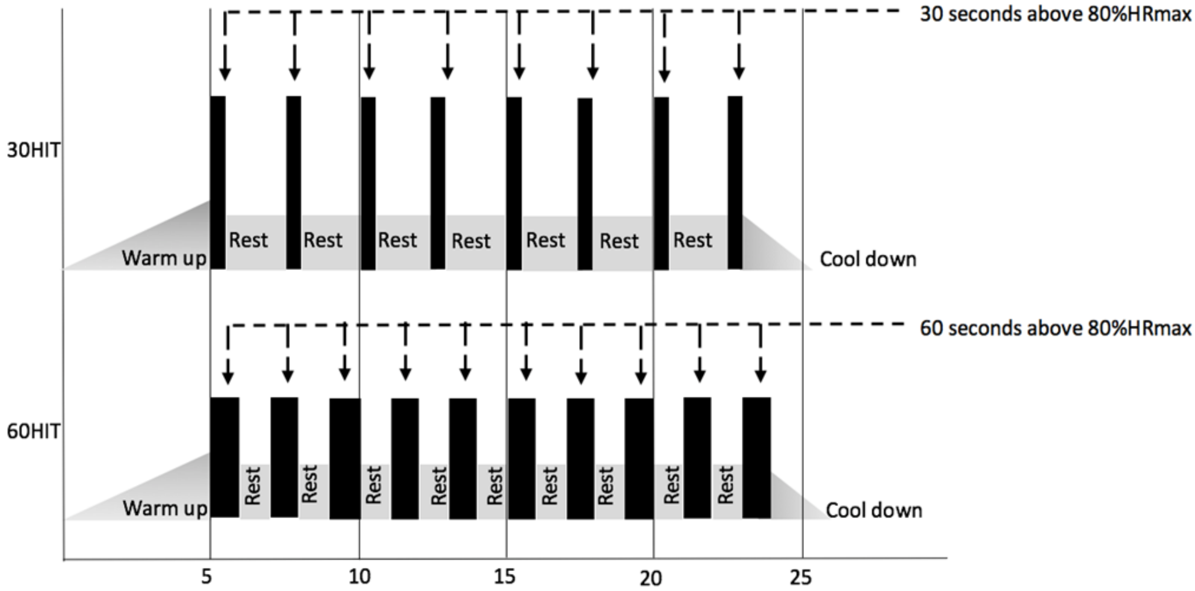


***Figure 2. Schematic of 30HIT and 60HIT protocol during week 6.*** *During 30HIT participants were advised to reach above a heart rate of 80% predicted heart rate max for 30 seconds followed by 2 minutes active rest. During 60HIT participants were advised to keep their heart rate > 80% of their predicted maximal heart rate ($HR_{max}$) for 60 seconds followed by 60 seconds active rest. The intensity of the training session was self-selected by the participant.*

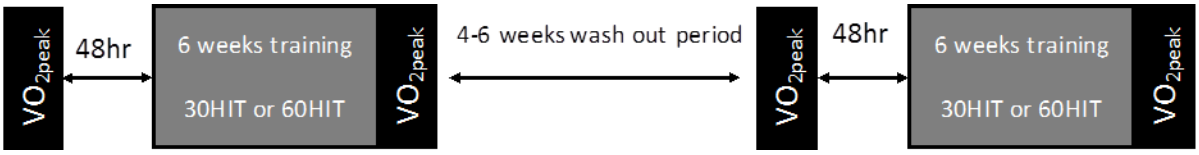


***Figure 3.*** *Protocol overview*

### *4.4 Aerobic Capacity*

An incremental exercise test to exhaustion was conducted using an electronically braked cycle ergometer (Lode Excalibur, Holland) to determine $VO_{2peak}$ and $W_{max}$. Briefly, participants started cycling at 25W for females and 65W for males for 3 mins; following this the workload was increased by 35 W every 3 mins until volitional fatigue. $VO_{2peak}$, the highest $VO_2$ achieved over a 15 second recording period, was assessed using an online gas collection system. (Moxus modular oxygen uptake system, AEI technologies, Pittsburgh, PA). Participants were also fitted with a heart rate monitor (Polar H7, Kempele, Finland) to determine their maximum heart rate ($HR_{max}$).

### *4.5 High Intensity Training*

All training sessions were conducted in the laboratory at Liverpool John Moores University. Participants trained 3 times per week for 6 weeks during both interventions. To be eligible to complete the study with the post-training evaluation participants had to complete > 80% of training sessions during each intervention, and could not miss more than one training session in one week. All training sessions were supervised by members of the research team.

All training sessions were conducted on a Wattbike Trainer (Nottingham UK). The Wattbike is an air-braked cycle ergometer which calculates power output via a load cell located next to the chain, calculating the sum of all forces applied to the chain through the cranks. The Wattbike has been shown to provide accurate data on power output when compared to the "gold standard" SRM Powermeter (Hopker *et al.,* 2010). The Wattbike permitted participants to manually adjust resistance using an airbrake, thereby controlling the exercise intensity at which they were working. Participants were also provided with a heart rate monitor for all training sessions (Polar H7, Kempele, Finland). Data on each training session (power output, cadence and heart rate) was immediately downloaded to the Wattbike PowerHub (Wattbike, version 2.1.0), a cloud based storage application, for offline analysis of each training session. During the session annotations were placed within the data to mark the start and end of each interval.

Each HIT training session began with a short (5 minutes) warm up of low intensity cycling, after which participants performed repeated high intensity efforts of either 30 seconds (30HIT) or 60 seconds (60HIT) duration. For both 30HIT and 60HIT participants were instructed to adjust the air brake resistance and pedal at a cadence that they perceived to elicit an intense effort by the end of each interval. Heart rate feedback was provided on the Wattbike screen to allow the participants to self-adjust their 'effort' in subsequent intervals in order to achieve a heart rate equivalent to >80% predicted heart rate maximum ($PHR_{max}$), calculated using the equation 80% $HR_{max}$ = (220 – participants age) x 0.8. During the active recovery period participants were advised to lower the air brake resistance and continue to pedal at a lower cadence. No further feedback (cadence or power output) or instructions on exercise intensity were provided to participants. Verbal encouragement was only given during the first interval of the first training session as a familiarisation to the intensity at which they should be performing to elicit the target heart rates. However, no encouragement was provided after this first session if the volunteers did not reach the > 80% $HR_{max}$ target.

During the 30HIT intervention participants completed four intervals during week one, five intervals in week 2, six intervals in weeks 3 and 4, seven intervals in week 5 and eight intervals in week 6 (**Table 2**). During the 60HIT intervention participants completed six intervals during week 1, seven intervals in week 2, eight intervals in weeks 3 and 4, nine intervals in week 5 and ten intervals in week 6 (**Table 3**.)

***Table 2.*** *Characteristics of 30HIT protocol*

| Week | Number of intervals (mins) | Total Interval Duration (mins) | Total Rest Duration (mins) | Total Time Taken (mins) |
|---|---|---|---|---|
| 1 | 4 | 2 | 8 | 15 |
| 2 | 5 | 2.5 | 10 | 17.5 |
| 3 | 6 | 3 | 12 | 20 |
| 4 | 6 | 3 | 12 | 20 |
| 5 | 7 | 3.5 | 14 | 22.5 |
| 6 | 8 | 4 | 16 | 25 |

***Table 3.*** *Characteristics of 60HIT protocol.*

| Week | Number of intervals (mins) | Total Interval Duration (mins) | Total Rest Duration (mins) | Total Time Taken (mins) |
|---|---|---|---|---|
| 1 | 6 | 6 | 6 | 17 |
| 2 | 7 | 7 | 7 | 19 |
| 3 | 8 | 8 | 8 | 21 |
| 4 | 8 | 8 | 8 | 21 |
| 5 | 9 | 9 | 9 | 23 |
| 6 | 10 | 10 | 10 | 25 |

## 5.6 Data Analysis

All heart rate data was normalised to participants predicted $HR_{max}$ (predicted $HR_{max}$ = 220 – participants age) (predicted $HR_{max}$, $PHR_{max}$) or participant's maximal heart rate achieved on the incremental exercise test (actual $HR_{max}$, $AHR_{max}$). All data on power output was normalised to the participant's measured $W_{max}$ during the pre-testing incremental exercise test. Data recorded on Wattbike Power Hub was used to calculate mean heart rate ($HR_{mean}$) per interval, peak heart rate ($HR_{peak}$) per interval, time spent above 80% $HR_{max}$ per interval, mean power output (MPO) per interval and peak power output (PPO) per interval (**Figure 4**). Individual interval values were first obtained from Wattbike Power Hub (**Figure 5**). Training session means were then calculated. Finally, intervention means were calculated. Only these intervention means are presented in the results section. Data from the first training session where verbal encouragement was received was excluded from this analysis. Identical analysis methods were used for both 30HIT and 60HIT. For the highest and lowest power outputs, the top and bottom 25% (n=7) of participants were used in the data analysis. Weight (kg), BMI ($kg.m^{-2}$), $W_{max}$ (W) and $VO_{2peak}$ ($ml.kg^{-1}.min^{-1}$) were analysed using a two-way within subjects ANOVA, using the within subject factors training (pre and post) and intervention (30HIT and 60HIT). All other variables were analysed using an independent *t*-test. All analyses were performed using statistical analysis software (SPSS for windows version 21.0.0.1 (SPSS, Chicago, IL, USA). Significance was set at $P \leq 0.05$. Data are presented as means ± SEM.

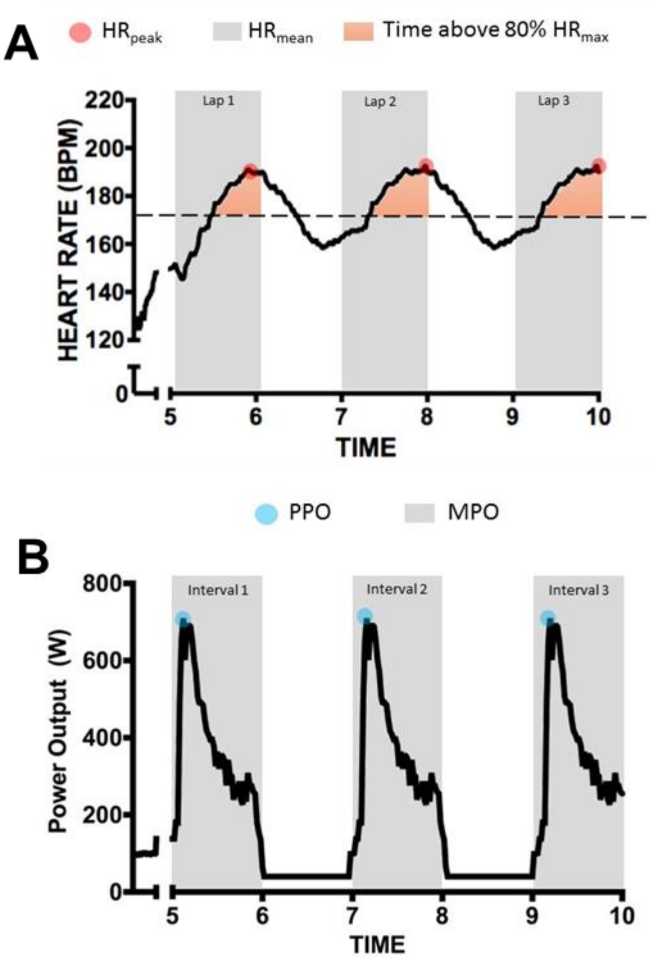


***Figure 4. Outline of the data analysis conducted on training sessions.*** A) Shows a definition of peak heart rate ($HR_{peak}$), mean heart rate ($HR_{mean}$) and time spent above 80% $HR_{max}$. *$HR_{peak}$, the highest heart rate achieved during the interval; $HR_{mean}$, mean heart rate for the interval; Time above 80% $HR_{max}$, percentage of the interval spent above 80% of participant's maximum heart rate. Dashed line indicates 80% of the participants predicted $HR_{max}$. Analysis was identical for both 30HIT* and 60HIT. B) Diagram defining peak power output (PPO) and mean power output (MPO). *PPO, highest power output during the interval; MPO, average power output for the interval. Analysis was identical for both 30HIT and 60HIT*

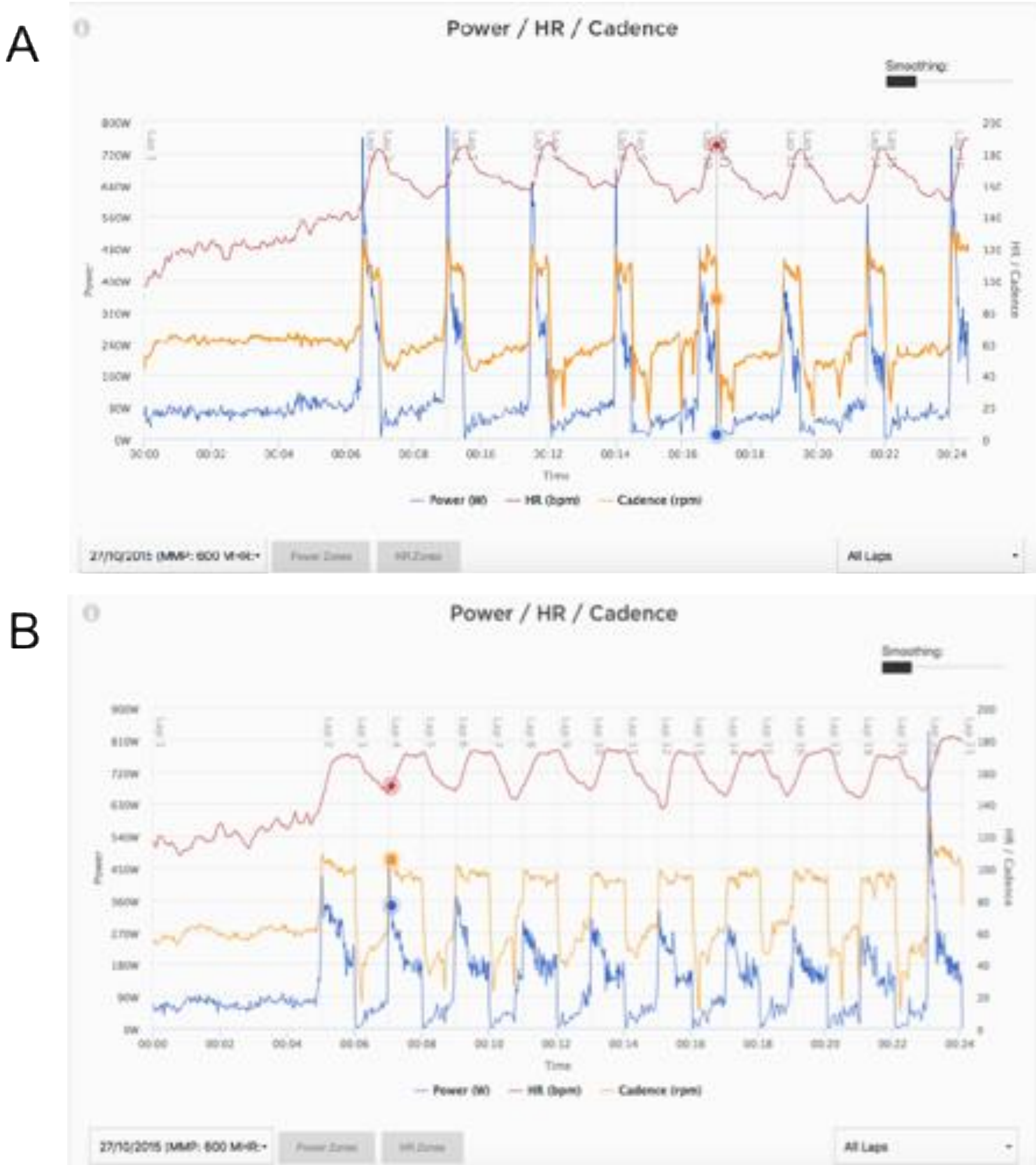


***Figure 5.*** *Screenshot from WattBike PowerHub. A) Data shows a single 30HIT training session. B) Data shows a single 60HIT training session.*

# 5. Results

## 5.1 Training effect

There was a significant main effect of training on $VO_{2peak}$ ($P$ < 0.001), with no difference between training modes ($P$=0.849). $VO_{2peak}$ increased 4±2% and 8±2% in 30HIT and 60HIT, respectively (**Figure 6**). An improvement in $VO_{2peak}$ was observed in 17 participants in 30HIT and 19 participants following six weeks of 60HIT (**Figure 7**). There was a significant main effect of training on $W_{max}$ ($P$ < 0.001), with no difference between training modes ($P$=0.553) (**Table 1**).

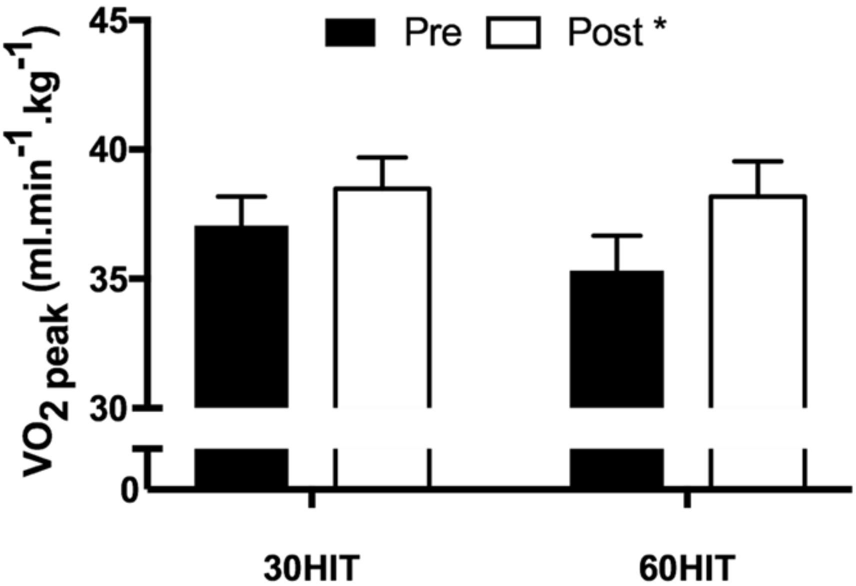


***Figure 6. Effect of six weeks of 30 seconds high intensity interval training (30HIT) and 60 seconds high intensity interval training (60HIT) on aerobic capacity.*** ** P <0.05, main effect of training.*

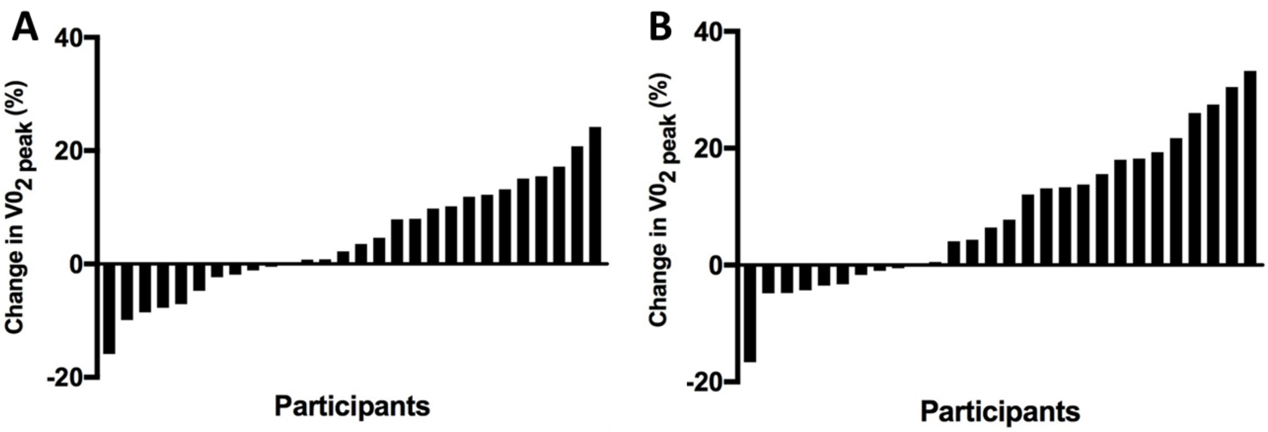


***Figure 7. Individual change in aerobic capacity.****A) Individual change in aerobic capacity following 30 seconds high intensity interval training (30HIT). B) Individual change in aerobic capacity following 60 seconds high intensity interval training (60HIT).*

## 5.2 Training Sessions

The peak heart rate achieved by participants during 30HIT and 60HIT was not significantly different when expressed as a percentage of predicted $HR_{max}$ ($PHR_{max}$) (*P*=0.735) or actual $HR_{max}$ ($AHR_{max}$) (*P*=0.332) (**Table 4**). The mean heart rate achieved by participants during 30HIT and 60HIT was not significantly different when expressed as percentage of $PHR_{max}$ (*P*=0.253). However when expressed as $AHR_{max}$ 60HIT had a significant higher mean heart rate (P=0.012) (**Table 4**). The percentage of the interval spent above 80% was significantly higher in 60HIT compared to 30HIT when calculated as a percentage of $AHR_{max}$ (*P*= 0.001) and $PHR_{max}$ (*P*=0.05). The 30HIT training modality had a significantly higher peak power output compared to 60HIT when expressed as a percentage of $W_{max}$ (*P*<0.001) (**Table 4**). The mean power output during 30HIT intervals was also higher *(P*<0.001) compared to 60HIT (**Table 4**). Further descriptive information outlining the percentage of participants achieving the target heart rate and the target power outputs is shown in **Table 5.**

***Table 4. Description of heart rate and power output during intervals.***

| | 30HIT | 60HIT |
|---|---|---|
| HRmax (bpm) | 170.8 ± 3 | 172.5 ± 2 |
| HRmean (bpm) | 154.3 ± 3 | 160.2 ± 3 |
| PPO (W) | 433.2 ± 29 † | 310.1 ± 22 |
| MPO (W) | 289.5 ± 16 † | 192.0 ± 8 |
| % interval >80% $AHR_{max}$ | 58.3 ± 5 | 84.5 ± 6* |
| % interval >80% $PHR_{max}$ | 52.7 ± 6 | 72.9 ± 6* |
| $HR_{peak}$ as a % of $AHR_{max}$ | 89.8 ± 1 | 90.8 ± 1 |
| $HR_{peak}$ as a % of $PHR_{max}$ | 87.7 ± 2 | 89.2 ± 1 |
| $HR_{mean}$ as a % of $AHR_{max}$ | 81.7 ± 1 | 84.6 ± 1* |
| $HR_{mean}$ as a % of $PHR_{max}$ | 80.0 ± 2 | 82.9 ± 1 |
| PPO as a % of $W_{max}$ | 233..4 ± 10 † | 170.3 ± 8 |
| MPO as a % of $W_{max}$ | 160.7 ± 5 † | 105.6 ± 2 |

*Table 4: % of interval >80% $AHR_{max}$, percentage of the interval spent above 80% actual $HR_{max}$;*
*% interval >80% $PHR_{max}$, percentage of the interval spent above 80% predicted $HR_{max}$; $HR_{peak}$ as a % of $AHR_{max}$, peak heart rate as a percentage of actual $HR_{max}$; $HR_{peak}$ as a % of $PHR_{max}$, peak heart rate as a percentage of predicted $HR_{max}$; $HR_{mean}$ as a % of $AHR_{max}$, mean heart rate as a percentage of actual $HR_{max}$; $HR_{mean}$ as a % of $PHR_{max}$, mean heart rate as a percentage of predicted $HR_{max}$; PPO as a % of $W_{max}$, peak power output as a percentage of $W_{max}$; MPO as a % of $W_{max}$, mean power output as a percentage of $W_{max}$. *indicates significantly higher than 30 HIT ($P <0.05$). † indicates significantly higher than 60HIT ($P <0.05$).*

***Table 5. Percentage of participants achieving above the target heart rate (80%$AHR_{max}$) and above power outputs previously recommended[1,2]***

| | 30HIT | 60HIT |
|---|---|---|
| $HR_{peak}$ | | |
| >80% $AHR_{max}$ | 96% | 100% |
| >80% $PHR_{max}$ | 82% | 100% |
| $HR_{mean}$ | | |
| >80% $AHR_{max}$ | 59% | 85% |
| >80% $PHR_{max}$ | 56% | 59% |
| PPO | | |
| >200% $W_{max}$ | 68% | - |
| >100% $W_{max}$ | - | 100% |
| MPO | | |
| >200% $W_{max}$ | 7% | - |
| >100% $W_{max}$ | - | 59% |

*Table 2: $HR_{peak}$ >80% AHR, percentage of participants achieving a peak heart rate of above 80% of their actual $HR_{max}$; $HR_{peak}$ >80% PHR, percentage of participants achieving a peak heart rate of above 80% their predicted $HR_{max}$; $HR_{mean}$>80% AHR, percentage of participants achieving a mean heart rate of above 80% of their actual $HR_{max}$; $HR_{mean}$>80% PHR, percentage of participants achieving a mean heart rate of above 80% of their predicted $HR_{max}$; PPO>200% $W_{max}$ percentage of participants achieving a peak power output of above 200% of their $W_{max}$; PPO>100% $W_{max}$ percentage of participants achieving a peak power output of above 100% of their $W_{max}$; MPO>200% $W_{max}$ percentage of participants achieving a mean power output of above 200% of their $W_{max}$; MPO>100% $W_{max}$ percentage of participants achieving a mean power output of above 100% of their $W_{max}$. [1]A target PPO of 200% $W_{max}$ was set by Cocks et al (2015) in a continuous workload protocol building up to seven 30 sec high intensity intervals. [2]A target PPO of 100% $W_{max}$ was set by Little et al (2010) in a continuous workload protocol involving ten 60 sec high intensity intervals.*

### 5.3 Relationship between power output and change in $VO_{2peak}$

When participants in both groups were split in quartiles (n=7 in each quartile) on the basis of the peak power output (PPO) achieved during the intervals those in the highest PPO quartile improved their $VO_{2peak}$ significantly more than those in the lowest PPO quartile, irrespective of group (30HIT $P<0.05$, 60HIT $P<0.05$), (**Figure 8**). The improvement in $VO_{2peak}$ did not differ between the highest and lowest quartile when the split was based on the mean power output (MPO) achieved during the intervals (30HIT $P=0.412$, 60HIT $P=0.142$), (**Figure 8**).

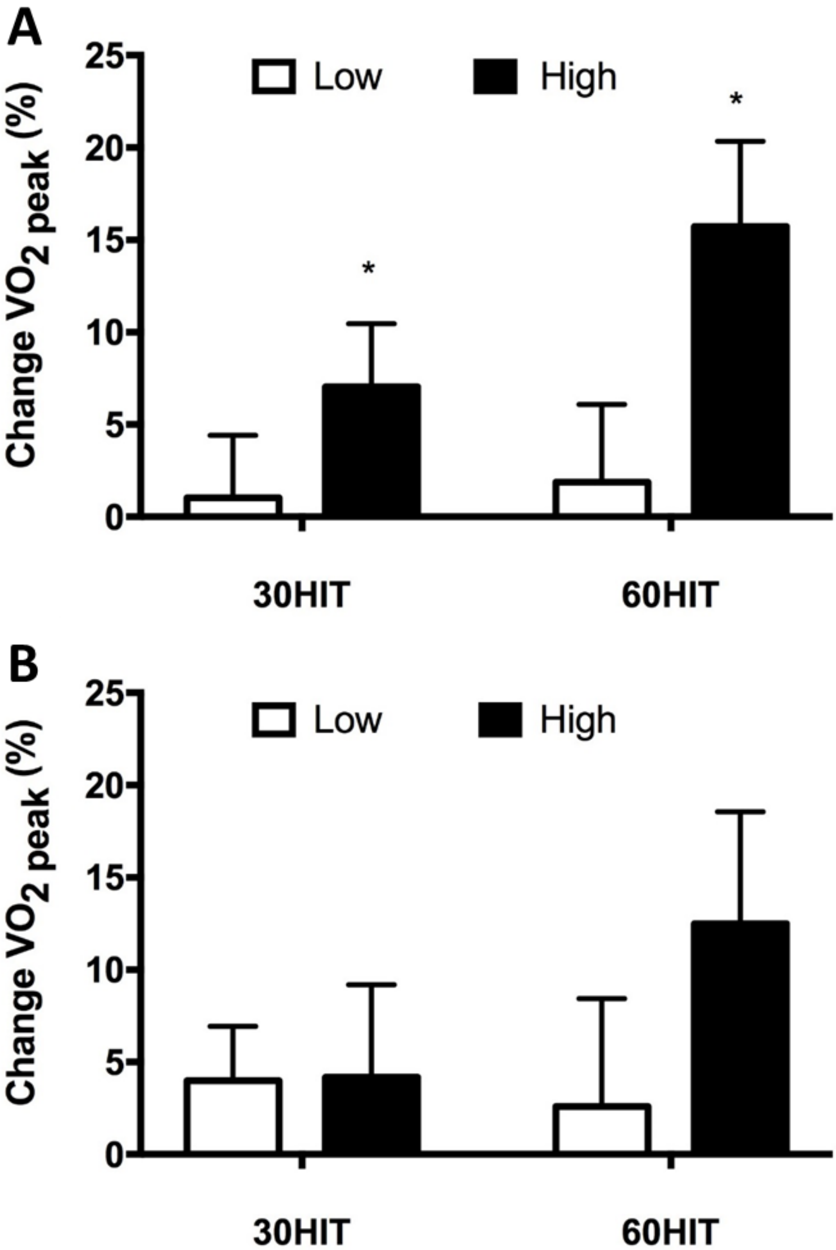


***Figure 8. Change in $VO_{2peak}$ comparing participants producing a low and high power output.*** A) Change in $VO_{2peak}$ comparing the quartiles (n=7 participants in each quartile) producing the lowest and highest peak power output (PPO). B) Change in $VO_{2peak}$ comparing the quartiles producing the lowest and highest mean power output (MPO). *Indicates a higher increase in $VO_{2peak}$ in the quartile with the highest PPO ($P < 0.05$).

### 5.4 Effect of the 4-week washout period

In both groups, there was no significant difference between participants first pre-training $VO_{2peak}$ and the pre-training $VO_{2peak}$ following the washout period (*P*=0.316). Therefore, the effects of training on aerobic capacity were lost during the 4 week wash out period, where participants resumed their normal lifestyle.

# 6. Discussion

This was the first study to use a cross-over design to investigate two popular low-volume HIT protocols, with the aim to explore whether previously sedentary individuals are able to achieve larger increases in $VO_{2max}$ with 30 second high intensity bouts (interspersed with 2 min active recovery) or with 60 second high intensity bouts (interspersed with 1 min active recovery). A second aim of the study was to instruct the volunteers to aim to complete the high intensity bouts with a mean HR > 80% $HR_{max}$ without further verbal encouragement by the researchers leading the exercise interventions to investigate whether significant increases in $VO_{2peak}$ are achieved when the volunteers themselves choose the peak power output (PPO) and % $HR_{max}$ during the high intensity bouts. In order for the volunteers to make these choices the HIT sessions were delivered on Wattbikes with the volunteers choosing cadence and air resistance (power output) as means to select the power profile they felt comfortable with.

The study found that both HIT conditions (30HIT and 60HIT) improved aerobic exercise capacity ($VO_{2max}$) with the difference between the HIT protocols not being significant (**Figure 6**). Similar increases in $VO_{2peak}$ were observed despite large differences in power outputs between the protocols (Table 4). During 60HIT more participants were able to achieve the recommended HR of > 80% $HR_{max}$ than during 30HIT (Table 4), suggesting 60HIT is a more achievable protocol for the general public without external encouragement by instructors. Interestingly, despite achieving the recommended HR, the quartile of participants producing the lowest PPOs had a smaller ($P<0.05$) increase in $VO_{2max}$ than the quartile of those producing the highest PPO in both HIT protocols (**Figure 8**). In summary our results show that HIT is effective in a ‘real-world’ setting, however, the quartile analysis in **Figure 8** suggests that the current recommendation of the ACSM (Roy, 2013) that all exercise intensities leading to mean heart rates > 80% $HR_{max}$ will give measurable $VO_{2max}$ benefits in all individuals may need further investigation.

### *6.1 Aerobic capacity*

In the current study improvements in aerobic capacity were seen following 6 weeks of 30HIT (4±2%) and 60HIT (8±2%). These changes were in line with the 6-10% increase that was reported in a recent meta-analysis consisting of laboratory-based interventions involving intervals lasting between 30 and 60 seconds (Weston *et al.,* 2014). In a ‘real-world’ setting similar to the current study Shepherd *et al.* (2015) reported a similar increase in aerobic capacity (9±4%) following a 10 week group based cycling intervention. Like the current study participants performed the intervals on a commercially available ‘spinning’ bike at a self-selected intensity guided by heart rate.

One of the most attractive features of HIT is that adaptations are achieved with a very low time commitment. In keeping with the time efficiency of HIT, total cycling time commitment was kept low in the present study (<30 minutes per session). Training sessions involved 2-4 min of high intensity exercise in 30HIT and 6-10min in 60HIT spread out over ~15-25 min training sessions. Therefore, total weekly average time commitment was <1.5h. Given that ‘lack of time’ is the number one perceived barrier to performing regular exercise (Godin *et al.,* 1994; Trost *et al.,* 2002) a HIT program similar to the ones employed in this study may be a practical and time efficient exercise strategy.

Interestingly, despite using self-regulated realistic conditions the current study produced similar increases in $VO_{2peak}$ to two highly controlled laboratory interventions using 30 and 60 second intervals. The 30HIT protocol has previously been used in obese sedentary participants (Cocks *et al*., 2015) using a constant load of 200% $W_{max}$ for the duration of the intervals. Participant’s $VO_{2max}$ increased to a similar extent as in the current study (7%). Using the 60s protocols Gillen *et al*. (2013) found a significant increase in aerobic capacity (12%) after a 6-week intervention.

The improvement in aerobic capacity seen in the research was reproduced using readily available gym equipment without the need for participant encouragement. This improvement in aerobic capacity is especially important as it demonstrates that the general public can motivate themselves to achieve a high enough intensity to develop adaptations without reinforcement from an external source. Like the current study Little *et al.* (2011) used a heart rate target (90% $HR_{max}$) to define the minimal intensity to improve metabolic health and insulin sensitivity using a 60s HIT intervention in type 2 diabetes patients. Although the target HR was 10% higher than the current study, this study was delivered under controlled conditions in the laboratory. A HR target of 90% during the interval could be an issue to sedentary participants without encouragement and if they fail to meet the target they may get demotivated and drop out of the intervention. In the current study the use of the ACSM guidelines of 80% $PHR_{max}$ was a high enough intensity to significantly improve aerobic capacity.

### *6.2 Training Intensity*

The amount of time spent above 80% $PHR_{max}$ was significantly higher in the 60HIT condition, compared to 30HIT therefore it could be argued that this may have had an impact on the aerobic capacity. There was not a significant difference between the groups change in $VO_{2peak}$ (30HIT 4±2% vs 60HIT 8±2%), although lack of statistical power could be a contributing factor. It could be that these responses would continue to diverge and reach significance although this is speculative at this stage. The difference in the time spent above 80% $HR_{max}$ could be explained by the different rest durations periods involved in the differing protocols. 30HIT has a longer rest period (2 min), therefore HR returns nearer to resting levels compared to 60HIT where the rest period is 60 seconds. In effect, HR is already elevated at the start of a 60HIT interval compared to a 30HIT interval. While HR is expected to reach maximal values (>90%) for HIT exercise, this is not always the case, especially for shorter <30s to medium intervals 1-2min. Tucker *et al.* (2015) compared the heart rate between two HIT protocols (16x1min vs 4x4min) and noted that the 90% $HR_{peak}$ may not be attainable until at least the fifth interval, despite a higher power output in the earlier intervals. This is related to the well-known HR lag response at exercise onset, which is slower to respond compared to the $VO_2$ response (Davis *et al.,* 1971). Also when exercise intensity ceases after the work interval HR inertia at exercise cessation can create an overestimation of the actual work/load that occurs during recovery (Seiler, 2005). Therefore the recorded heart rate during training sessions may not be reflecting the intensity of the work actually carried out. The interval intensity could potentially be under estimated especially in the 30HIT protocol with the shorter intervals and longer recovery periods.

The laboratory-controlled study of Cocks *et al.* (2015) recommended participants carry out 30s intervals at 200% $W_{max}$. However, in the current study, only 68% of the participants could reach a PPO value above 200% $W_{max}$ in the 30HIT condition, and only 2 participants produced a MPO greater than 200% $W_{max}$. Although 30HIT requires less interval time commitment than its counterpart, 60HIT, the training requires essentially an 'all-out' effort to reach the heart rate target >80% $HR_{max}$. 'All-out' sprints require a high level of participant motivation, therefore may not be a viable option for the general public to complete by themselves (Little *et al.,* 2010). Suggested contraindications to HIT training are mentioned in a recent review describing the effects of HIT on participants with lifestyle-induced cardiometabolic disease (Weston *et al.,* 2014). In the 60HIT condition all participants were able to reach a PPO >100% $W_{max}$, and 59% were able to maintain this power output throughout the interval. Consequently, 60HIT may be a more viable option for the general public as they are able to maintain the lower wattage throughout the interval.

Using the 80% $PHR_{max}$ target lead to a significant increase in $VO_{2peak}$ in both HIT conditions. However, there are some discrepancies when scrutinising the changes in aerobic capacity on an individual level; some participants improved in response to the training whereas others saw no change or even a decrease in aerobic capacity (**Figure 7**). Interestingly, this could be explained by the individual variation in heart rate and power output achieved in the training sessions (i.e. the effort of each individual). In line with the recommendations from the ACSM, the only target for the level of intensity given to the participants in the present study was to achieve a heart rate greater than 80% $PHR_{max}$ (Roy 2013). During 30HIT, 82% of the participants achieved a $HR_{peak}$ above this recommendation and every participant in the 60HIT group achieved their 80% max HR target. Again, when looking at the $HR_{mean}$ during the intervals just over half of the 30HIT (56%) and 60HIT (59%) participants were able to maintain a $HR_{mean}$ above 80% $PHR_{max}$. Therefore, if the majority of the participants were reaching a similar $HR_{peak}$ and $HR_{mean}$ the change in aerobic capacity has to be explained by an alternative factor, potentially their differing power outputs could provide an insight. The participants that benefited from the greatest improvements in aerobic capacity were those who produced the highest PPO throughout the high intensity intervals. The majority of current studies do not report the power outputs of the training sessions, therefore this is a difficult hypothesis to compare against the literature.

This study clearly demonstrates that participants from a sedentary population, of mixed gender and age, can maintain the intense nature of a HIT protocol. Participants were able to complete two popular HIT protocols without encouragement and showed a significant increase in aerobic capacity. This demonstrates that sedentary members of the public are able to self-motivate and self-regulate a HIT protocol to a high enough intensity to elicit positive adaptation to health. This contradicts arguments of some researchers that the extremely hard nature of HIT make it 'inappropriate for a largely sedentary population' (Hardcastle *et al.,* 2014). Biddle (2015) also argues that due to the vigorous nature of HIT, the confidence of the participant is decreased as they become unable to continue the effort throughout the interval. He further argues that with these feelings of unpleasantness, HIT also requires planning and self-regulation. He concludes that making exercise harder and more painful is unlikely to boost the public's positive attitude towards exercise. Even without encouragement this novel study has shown an increase in aerobic capacity following HIT. This research confirms that HIT is an important potential public health intervention, despite the view of Biddle (2015). As the epidemiological studies of Myers *et al.* (2004) have shown that aerobic exercise capacity outperforms physical activity levels and established clinical risk factors such as smoking, hypertension, obesity and diabetes in predicting all-cause mortality, our expectation is that the first Randomised Clinical Trials comparing the benefits of HIT and MICT on a long-term basis will come to the conclusion that HIT is at least as effective as MICT in reducing the risk of all-cause mortality.

### *6.3 Future directions*

The current study only looked at the effect of low volume HIT on aerobic exercise capacity. Previous research has demonstrated improvements in cardiovascular and metabolic health in response to low volume HIT (Gibala *et al.,* 2006; Burgomaster *et al.,* 2008; Little *et al.,* 2010; Cocks *et al.,* 2013, 2016; Shepherd *et al., 2013,* 2015). Therefore, future research is needed to determine the effect of self-selected low volume HIT training on health markers such as insulin sensitivity, body composition and arterial stiffness. When participants used self-paced spinning bikes Shepherd *et al.* (2015) reported similar improvements in whole body insulin sensitivity, whole body fat mass, mean arterial pressure and reduction in cardiovascular risk factors compared to MICT in an 18-60 year old sedentary population. We only recruited healthy participants free of metabolic or cardiovascular disease in this study, and therefore we cannot generalise our results to a diseased population. However, laboratory-based low volume HIT protocols have proved effective in improving health markers in people with type 2 diabetes and patients with lifestyle induced cardiometabolic disease (Little *et al*., 2011, Western *et al.,* 2015). Therefore, highlighting the potential for 'real world' low volume HIT interventions to be effective in diseased populations.

In the current study we have shown the effects of 6 weeks self-controlled HIT training, and the longest HIT interventions to date are up to 12 weeks in duration, to the authors knowledge. Therefore, we do not know the long term effects of HIT on physiological responses and adaptations and/or adherence rates in sedentary populations. Even though the intervals in the current study were self-controlled and no encouragement was provided, all training sessions were supervised by a member of the research team. This could affect the work carried out by participants during the HIT sessions. Equally this was still a lab-based intervention. Future HIT studies need to be taken completely into the 'real world' in order to determine whether it is an intervention that could improve people's health and be rolled out into a community setting. An example of a more 'real' test of adherence was demonstrated by Shepherd *et al.* (2015) using a group based HIT protocol on spinning bikes (Star Trac UK Ltd., Buckinghamshire, UK) in a local sports centre.

The use of predicted heart rate as a measure of interval intensity needs further investigation as it does not appear to be a completely effective means of measuring intensity. However, it could provide a relatively cheap and potentially reliable way for the general public to monitor their exercise intensity. Although this may still create a problem as members of the public may not want to buy a heart rate monitor or know how to use one. Power output has been shown to be an important factor in intensity prescription, but most current gym equipment does not provide this information. Equally, even if gym equipment did provide power output, e.g. a Wattbike, the participant would be unaware of their $W_{max}$ without a laboratory-based test. Furthermore, power output is only applicable to cycling HIT protocols.

However, we do not need one solution for all. Alternative HIT programmes should be used in order to engage more of the sedentary population. Home-based HIT using body weight exercises could be a more practical option for most of the general public. Home-based HIT has the potential to increase compliance, as participants wouldn't have to pay for, or travel to a local gym to exercise. More research needs to be completed regarding how to quantify the intensity of exercises such as stair climbing, hill running and body weight exercises. A potential alternative used to prescribe intensity could be the rate of perceived exertion (RPE), this could be a free and useful measure of exerciser intensity, but the reliability and validity of this method requires further investigation.

### *6.4 Conclusion*

In conclusion, non-encouraged self-controlled 30s and 60s intervals can increase aerobic capacity. Although participants were only guided by their heart rate, when investigated further the participants reaching a higher PPO during the intervals had the greatest improvement in aerobic capacity. Therefore, in terms of the guidelines for HIT, there is a need for investigations into alternative methods to more accurately quantify the power output profile and the HIT bouts. All participants completing 60HIT were able to achieve the power output suggested by the literature in their PPO and over half of the participants were able to achieve an MPO above the suggested 100%. Thus, in HIT sessions where no encouragement is given 60HIT may be a more feasible protocol. Furthermore, the current study shows the importance of understanding training load during an intervention. As a result, future studies should begin to produce far more detailed information on participants training heart rates and power outputs during the subsequent low volume HIT bouts in specific protocols used in future intervention studies.

# 7. References


Allemeier, C.A., Fry, A.C., Johnson, P.E.T.E.R., Hikida, R.S., Hagerman, F.C. and Staron, R.S., (1994). Effects of sprint cycle training on human skeletal muscle. *Journal of Applied Physiology*, *77*(5), pp.2385-2390.

Anderson, K.M., WOLSON, P., Odell, P.M. and Kannel, W.B., (1991). An updated coronary risk profile: a statement fo rhealth professionals. *Circulation*, *83*(1), pp.356-362.

Arroll, B. and Beaglehole, R., (1992). Does physical activity lower blood pressure: a critical review of the clinical trials. *Journal of clinical epidemiology*, *45*(5), pp.439-447.

Astorino, T.A., Allen, R.P., Roberson, D.W., Jurancich, M., Lewis, R. and McCarthy, K., (2012). Attenuated RPE and leg pain in response to short-term high-intensity interval training. *Physiology & behavior*, *105*(2), pp.402-407.

ÅStrand, I., ÅStrand, P.O., Christensen, E.H. and Hedman, R., (1960). Intermittent muscular work. *Acta Physiologica Scandinavica*, *48*(3-4), pp.448-453.

Babraj, J.A., Vollaard, N.B., Keast, C., Guppy, F.M., Cottrell, G. and Timmons, J.A., (2009). Extremely short duration high intensity interval training substantially improves insulin action in young healthy males. *BMC endocrine disorders*, *9*(1), p.3.

Bailey, S.J., Winyard, P., Vanhatalo, A., Blackwell, J.R., DiMenna, F.J., Wilkerson, D.P., Tarr, J., Benjamin, N. and Jones, A.M., (2009). Dietary nitrate supplementation reduces the O2 cost of low-intensity exercise and enhances tolerance to high-intensity exercise in humans. *Journal of Applied Physiology*, *107*(4), pp.1144-1155.

Barnett, C., Carey, M., Proietto, J., Cerin, E., Febbraio, M.A. and Jenkins, D., (2004). Muscle metabolism during sprint exercise in man: influence of sprint training. *Journal of Science and Medicine in Sport*, *7*(3), pp.314-322.

Bayati, M., Farzad, B., Gharakhanlou, R. and Agha-Alinejad, H., (2011). A practical model of low-volume high-intensity interval training induces performance and metabolic adaptations that resemble 'all-out'sprint interval training. *J Sports Sci Med*, *10*(3), pp.571-576.

Berthouze, S.E., Minaire, P.M., Castells, J.O.S.I.A.N.E., Busso, T.H.I.E.R.R.Y., Vico, L.A.U.R.E.N.C.E. and Lacour, J.R., (1995). Relationship between mean habitual daily energy expenditure and maximal oxygen uptake. *Medicine and science in sports and exercise*, *27*(8), pp.1170-1179.

Biddle, S.J. and Batterham, A.M., (2015). High-intensity interval exercise training for public health: a big HIT or shall we HIT it on the head?. *International Journal of Behavioral Nutrition and Physical Activity*, *12*(1), p.1.

Blair, S.N., Kohl, H.W., Paffenbarger, R.S., Clark, D.G., Cooper, K.H. and Gibbons, L.W., 1989. Physical fitness and all-cause mortality: a prospective study of healthy men and women. *Jama*, *262*(17), pp.2395-2401.

Blomqvist, C. G. & Saltin, B. (1983). Cardiovascular Adaptations to Physical-Training. Annual Review of Physiology, 45, 169-189.

Booth, M.L., Bauman, A., Owen, N. and Gore, C.J., (1997). Physical activity preferences, preferred sources of assistance, and perceived barriers to increased activity among physically inactive Australians. *Preventive medicine*, *26*(1), pp.131-137.

Boyd, J.C., Simpson, C.A., Jung, M.E. and Gurd, B.J., (2013). Reducing the intensity and volume of interval training diminishes cardiovascular adaptation but not mitochondrial biogenesis in overweight/obese men. *PLoS One*, *8*(7), p.e68091.

Buchheit, M., (2008). The 30-15 intermittent fitness test: accuracy for individualizing interval training of young intermittent sport players. *The Journal of Strength & Conditioning Research*, *22*(2), pp.365-374.

Buchheit, M. and Laursen, P.B., (2013). High-intensity interval training, solutions to the programming puzzle. *Sports medicine*, *43*(5), pp.313-338.

Burgomaster, K.A., Hughes, S.C., Heigenhauser, G.J., Bradwell, S.N. and Gibala, M.J., (2005). Six sessions of sprint interval training increases muscle oxidative potential and cycle endurance capacity in humans. *Journal of applied physiology*, *98*(6), pp.1985-1990.

Burgomaster, K. A., Howarth, K. R., Phillips, S. M., Rakobowchuk, M., MacDonald, M. J., McGee, S. L., & Gibala, M. J. (2008). Similar metabolic adaptations during exercise after low

Christensen, E.H., Hedman, R. and Saltin, B., (1960). Intermittent and continuous running (A further contribution to the physiology of intermittent work.). *Acta Physiologica Scandinavica*, *50*(3-4), pp.269-286.

Cocks, M., Shaw, C. S., Shepherd, S. O., Fisher, J. P., Ranasinghe, A. M., Barker, T. A., ... & Wagenmakers, A. J. (2013). Sprint interval and endurance training are equally effective in increasing muscle microvascular density and eNOS content in sedentary males. *The Journal of physiology*, *591*(3), 641-656.

Cocks, M., Shaw, C. S., Shepherd, S. O., Fisher, J. P., Ranasinghe, A., Barker, T. A., & Wagenmakers, A. J. (2015). Sprint interval and moderate-intensity continuous training have equal benefits on aerobic capacity, insulin sensitivity, muscle capillarisation and endothelial eNOS/NAD (P) Hoxidase protein ratio in obese men. *The Journal of physiology*.

Colberg, S.R., Sigal, R.J., Fernhall, B., Regensteiner, J.G., Blissmer, B.J., Rubin, R.R., Chasan-Taber, L., Albright, A.L. and Braun, B., (2010). Exercise and type 2 diabetes the American College of Sports Medicine and the American Diabetes Association: joint position statement. *Diabetes care*, *33*(12), pp.e147-e167.

Conraads, V.M., Pattyn, N., De Maeyer, C., Beckers, P.J., Coeckelberghs, E., Cornelissen, V.A., Denollet, J., Frederix, G., Goetschalckx, K., Hoymans, V.Y. and Possemiers, N., (2015). Aerobic interval training and continuous training equally improve aerobic exercise capacity in patients with coronary artery disease: the SAINTEX-CAD study. *International journal of cardiology*, *179*, pp.203-210.

Currie, K.D., Dubberley, J.B., McKelvie, R.S. and MacDonald, M.J., (2013). Low-volume, high-intensity interval training in patients with CAD. *Med Sci Sports Exerc*, *45*(8), pp.1436-42.

Dalleck, L., Bushman, T.T., Crain, R.D., Gajda, M.M., Koger, E.M. and Derksen, L.A., (2010). Dose-response relationship between interval training frequency and magnitude of improvement in lactate threshold. *International journal of sports medicine*, *31*(08), pp.567-571.

Davies, C.T., Di Prampero, P.E. and Cerretelli, P., (1972). Kinetics of cardiac output and respiratory gas exchange during exercise and recovery. *Journal of applied physiology*, *32*(5), pp.618-625.

Dunham, C. and Harms, C.A., (2012). Effects of high-intensity interval training on pulmonary function. *European journal of applied physiology*, *112*(8), pp.3061-3068.

England, S., (2006). Active people survey. *Online. HTTP:< www. sportengland. org*.

Esfandiari, S., Sasson, Z. and Goodman, J.M., (2014). Short-term high-intensity interval and continuous moderate-intensity training improve maximal aerobic power and diastolic filling during exercise. *European journal of applied physiology*, *114*(2), pp.331-343.

Esfarjani, F. and Laursen, P.B., (2007). Manipulating high-intensity interval training: Effects on, the lactate threshold and 3000m running performance in moderately trained males. *Journal of science and medicine in sport*, *10*(1), pp.27-35.

Fox, E.L., (1975). Differences in metabolic alterations with sprint versus endurance interval training programs. In *Metabolic Adaptation to Prolonged Physical Exercise* (pp. 119-126). Birkhäuser Basel.

Fu, T.C., Wang, C.H., Lin, P.S., Hsu, C.C., Cherng, W.J., Huang, S.C., Liu, M.H., Chiang, C.L. and Wang, J.S., (2013). Aerobic interval training improves oxygen uptake efficiency by enhancing cerebral and muscular hemodynamics in patients with heart failure. *International journal of cardiology*, *167*(1), pp.41-50.

Gibala, M. J., Little, J. P., Van Essen, M., Wilkin, G. P., Burgomaster, K. A., Safdar, A., ... & Tarnopolsky, M. A. (2006). Short-term sprint interval versus traditional endurance training: similar initial adaptations in human skeletal muscle and exercise performance. *The Journal of physiology*, *575*(3), 901-911.

Gibbons, R.J., Balady, G.J., Bricker, J.T., Chaitman, B.R., Fletcher, G.F., Froelicher, V.F., Mark, D.B., McCallister, B.D., Mooss, A.N., O'Reilly, M.G. and Winters, W.L., (2002). ACC/AHA 2002 guideline update for exercise testing: summary article: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (Committee to Update the 1997 Exercise Testing Guidelines). *Journal of the American College of Cardiology*, *40*(8), pp.1531-1540.

Gillen, J.B. and Gibala, M.J., (2013). Is high-intensity interval training a time-efficient exercise strategy to improve health and fitness?. *Applied Physiology, Nutrition, and Metabolism*, *39*(3), pp.409-412.

Gillen, J.B., Percival, M.E., Ludzki, A., Tarnopolsky, M.A. and Gibala, M., (2013). Interval training in the fed or fasted state improves body composition and muscle oxidative capacity in overweight women. *Obesity*, *21*(11), pp.2249-2255.

Gillen, J.B., Percival, M.E., Skelly, L.E., Martin, B.J., Tan, R.B., Tarnopolsky, M.A. and Gibala, M.J., (2014). Three minutes of all-out intermittent exercise per week increases skeletal muscle oxidative capacity and improves cardiometabolic health. *PLoS One*, *9*(11), p.e111489.

Gillen, J.B., Martin, B.J., MacInnis, M.J., Skelly, L.E., Tarnopolsky, M.A. and Gibala, M.J., (2016). Twelve Weeks of Sprint Interval Training Improves Indices of Cardiometabolic Health Similar to Traditional Endurance Training despite a Five-Fold Lower Exercise Volume and Time Commitment. *PloS one*, *11*(4), p.e0154075.

Godin, G., Desharnais, R., Valois, P., Lepage, L., Jobin, J. and Bradet, R., (1994). Differences in perceived barriers to exercise between high and low intenders: observations among different populations. *American Journal of Health Promotion*, *8*(4), pp.279-385.

Green, H.J. and Fraser, I.G., (1988). Differential effects of exercise intensity on serum uric acid concentration. *Medicine and science in sports and exercise*, *20*(1), pp.55-59.

Grieco, C.R., Swain, D.P., Colberg, S.R., Dowling, E.A., Baskette, K., Zarrabi, L., Gandrakota, R., Kotipalli, U., Sechrist, S.R. and Somma, C.T., (2013). Effect of intensity of aerobic training on insulin sensitivity/resistance in recreationally active adults. *The Journal of Strength & Conditioning Research*, *27*(8), pp.2270-2276.

Hardcastle, S.J., Ray, H., Beale, L. and Hagger, M.S., (2014). Why sprint interval training is inappropriate for a largely sedentary population. *Frontiers in psychology*, *5*, p.1505.

Harmer, A.R., McKenna, M.J., Sutton, J.R., Snow, R.J., Ruell, P.A., Booth, J., Thompson, M.W., Mackay, N.A., Stathis, C.G., Crameri, R.M. and Carey, M.F., (2000). Skeletal muscle metabolic and ionic adaptations during intense exercise following sprint training in humans. *Journal of applied physiology*, *89*(5), pp.1793-1803.

Hazell, T. J., MacPherson, R. E., Gravelle, B. M., & Lemon, P. W. (2010). 10 or 30-s sprint interval training bouts enhance both aerobic and anaerobic performance. *European journal of applied physiology*, *110*(1), 153-160.

Heggelund, J., Nilsberg, G.E., Hoff, J., Morken, G. and Helgerud, J., (2011). Effects of high aerobic intensity training in patients with schizophrenia—A controlled trial. *Nordic journal of psychiatry*, *65*(4), pp.269-275.

Helgerud, J., Hoydal, K., Wang, E., Karlsen, T., Berg, P., Bjerkaas, M., ... & Hoff, J. (2007). Aerobic High-Intensity Intervals Improve VO~ 2~ m~ a~ x More Than Moderate Training. *Medicine and science in sports and exercise*, *39*(4), 665.

Heydari, M., Freund, J. and Boutcher, S.H., (2012). The effect of high-intensity intermittent exercise on body composition of overweight young males. *Journal of obesity*, *2012*.

Hollekim-Strand, S.M., Bjørgaas, M.R., Albrektsen, G., Tjønna, A.E., Wisløff, U. and Ingul, C.B., (2014). High-intensity interval exercise effectively improves cardiac function in patients with type 2 diabetes mellitus and diastolic dysfunction: a randomized controlled trial. *Journal of the American College of Cardiology*, *64*(16), pp.1758-1760.

Hood, M.S., Little, J.P., Tarnopolsky, M.A., Myslik, F. and Gibala, M.J., (2011). Low-volume interval training improves muscle oxidative capacity in sedentary adults. *Medicine and science in sports and exercise*, *43*(10), pp.1849-1856.

Hopker, J., Myers, S., Jobson, S.A., Bruce, W. and Passfield, L., (2010). Validity and reliability of the Wattbike cycle ergometer. *International journal of sports medicine*, *31*(10), pp.731-736.

Hovanloo, F., Arefirad, T. and Ahmadizad, S., (2013). Effects of sprint interval and continuous endurance training on serum levels of inflammatory biomarkers. *Journal of Diabetes & Metabolic Disorders*, *12*(1), p.1.

Hureau, T.J., Olivier, N., Millet, G.Y., Meste, O. and Blain, G.M., (2014). Exercise performance is regulated during repeated sprints to limit the development of peripheral fatigue beyond a critical threshold. *Experimental physiology*, *99*(7), pp.951-963.

Iellamo, F., Caminiti, G., Sposato, B., Vitale, C., Massaro, M., Rosano, G. and Volterrani, M., (2014). Effect of High-Intensity interval training versus moderate continuous training on 24-h blood pressure profile and insulin resistance in patients with chronic heart failure. *Internal and emergency medicine*, *9*(5), pp.547-552.

Jacobs, R.A., Flück, D., Bonne, T.C., Bürgi, S., Christensen, P.M., Toigo, M. and Lundby, C., (2013). Improvements in exercise performance with high-intensity interval training coincide with an increase in skeletal muscle mitochondrial content and function. *Journal of Applied Physiology*, *115*(6), pp.785-793.

Karstoft, K., Winding, K., Knudsen, S.H., Nielsen, J.S., Thomsen, C., Pedersen, B.K. and Solomon, T.P., (2013). The effects of free-living interval-walking training on glycemic control, body composition, and physical fitness in type 2 diabetic patients a randomized, controlled trial. *Diabetes care*, *36*(2), pp.228-236.

Keating, S.E., Machan, E.A., O'Connor, H.T., Gerofi, J.A., Sainsbury, A., Caterson, I.D. and Johnson, N.A., (2014). Continuous exercise but not high intensity interval training improves fat distribution in overweight adults. *Journal of obesity*, *2014*.

Klonizakis, M., Moss, J., Gilbert, S., Broom, D., Foster, J. and Tew, G.A., (2014). Low-volume high-intensity interval training rapidly improves cardiopulmonary function in postmenopausal women. *Menopause*, *21*(10), pp.1099-1105.

Kodama, S., Saito, K., Tanaka, S., Maki, M., Yachi, Y., Asumi, M., ... & Sone, H. (2009). Cardiorespiratory fitness as a quantitative predictor of all-cause mortality and cardiovascular events in healthy men and women: a meta-analysis. *Jama*, *301*(19), 2024-2035.

Laursen, P.B., Blanchard, M.A. and Jenkins, D.G., (2002). Acute high-intensity interval training improves Tvent and peak power output in highly trained males. *Canadian Journal of Applied Physiology*, *27*(4), pp.336-348.

Lee, D.C., Artero, E.G., Sui, X. and Blair, S.N., (2010). Review: Mortality trends in the general population: the importance of cardiorespiratory fitness. *Journal of Psychopharmacology*, *24*(4 suppl), pp.27-35.

Leggate, M., Carter, W.G., Evans, M.J., Vennard, R.A., Sribala-Sundaram, S. and Nimmo, M.A., (2012). Determination of inflammatory and prominent proteomic changes in plasma and adipose tissue after high-intensity intermittent training in overweight and obese males. *Journal of Applied Physiology*, *112*(8), pp.1353-1360.

Linossier, M.T., Denis, C., Dormois, D., Geyssant, A. and Lacour, J.R., (1993). Ergometric and metabolic adaptation to a 5-s sprint training programme. *European journal of applied physiology and occupational physiology*, *67*(5), pp.408-414.

Little, J. P., Safdar, A., Wilkin, G. P., Tarnopolsky, M. A., & Gibala, M. J. (2010). A practical model of low-volume high-intensity interval training induces mitochondrial biogenesis in human skeletal muscle: potential mechanisms. *The Journal of physiology*, *588*(6), 1011-1022.

Little, J. P., Gillen, J. B., Percival, M. E., Safdar, A., Tarnopolsky, M. A., Punthakee, Z., ... & Gibala, M. J. (2011). Low-volume high-intensity interval training reduces hyperglycemia and increases muscle mitochondrial capacity in patients with type 2 diabetes. *Journal of Applied Physiology*, *111*(6), 1554-1560.

Lunt, H., Draper, N., Marshall, H.C., Logan, F.J., Hamlin, M.J., Shearman, J.P., Cotter, J.D., Kimber, N.E., Blackwell, G. and Frampton, C.M., (2014). High intensity interval training in a real world setting: a randomized controlled feasibility study in overweight inactive adults, measuring change in maximal oxygen uptake. *PLoS One*, *9*(1), p.e83256.

MacAuley, D., Bauman, A. and Frémont, P., (2015). Exercise: not a miracle cure, just good medicine. *BMJ*, *350*, p.h1416.

Macpherson, R.E., Hazell, T.J., Olver, T.D., Paterson, D.H. and Lemon, P.W., (2011). Run sprint interval training improves aerobic performance but not maximal cardiac output. *Med Sci Sports Exerc*, *43*(1), pp.115-122.

McKenna, M.J., Heigenhauser, G.J., McKelvie, R.S., MacDougall, J.D. and Jones, N.L., (1997). Sprint training enhances ionic regulation during intense exercise in men. *The Journal of physiology*, *501*(3), pp.687-702.

Metcalfe, R.S., Babraj, J.A., Fawkner, S.G. and Vollaard, N.B., (2012). Towards the minimal amount of exercise for improving metabolic health: beneficial effects of reduced-exertion high-intensity interval training. *European journal of applied physiology*, *112*(7), pp.2767-2775.

Mitranun, W., Deerochanawong, C., Tanaka, H. and Suksom, D., (2014). Continuous vs interval training on glycemic control and macro-and microvascular reactivity in type 2 diabetic patients. *Scandinavian journal of medicine & science in sports*, *24*(2), pp.e69-e76.

Molmen-Hansen, H.E., Stolen, T., Tjonna, A.E., Aamot, I.L., Ekeberg, I.S., Tyldum, G.A., Wisloff, U., Ingul, C.B. and Stoylen, A., (2012). Aerobic interval training reduces blood pressure and improves myocardial function in hypertensive patients. *European journal of preventive cardiology*, *19*(2), pp.151-160.

Mora-Rodriguez, R., Ortega, J.F., Hamouti, N., Fernandez-Elias, V.E., Garcia-Prieto, J.C., Guadalupe-Grau, A., Saborido, A., Martin-Garcia, M., de Prada, V.G., Ara, I. and Martinez-Vizcaino, V., (2014). Time-course effects of aerobic interval training and detraining in patients with metabolic syndrome. *Nutrition, Metabolism and Cardiovascular Diseases*, *24*(7), pp.792-798.

Moreira, M.M., Souza, H.P.C.D., Schwingel, P.A., Sá, C.K.C.D. and Zoppi, C.C., (2008). Effects of aerobic and anaerobic exercise on cardiac risk variables in overweight adults. *Arquivos brasileiros de cardiologia*, *91*(4), pp.219-226.

Myers, J., Kaykha, A., George, S., Abella, J., Zaheer, N., Lear, S., ... & Froelicher, V. (2004). Fitness versus physical activity patterns in predicting mortality in men. *The American journal of medicine*, *117*(12), 912-918.

National Institute for Health and Clinical Excellence. (2006). National costing report – Four commonly used methods to increase physical activity.

Parra, J., Cadefau, J.A., Rodas, G., Amigo, N. and Cusso, R., (2000). The distribution of rest periods affects performance and adaptations of energy metabolism induced by high-intensity training in human muscle. *Acta Physiologica Scandinavica*, *169*(2), pp.157-165.

Perry, C.G., Heigenhauser, G.J., Bonen, A. and Spriet, L.L., (2008). High-intensity aerobic interval training increases fat and carbohydrate metabolic capacities in human skeletal muscle. *Applied Physiology, Nutrition, and Metabolism*, *33*(6), pp.1112-1123.

Poole, D.C. and Gaesser, G.A., (1985). Response of ventilatory and lactate thresholds to continuous and interval training. *Journal of Applied Physiology*, *58*(4), pp.1115-1121.

Rakobowchuk, M., Tanguay, S., Burgomaster, K.A., Howarth, K.R., Gibala, M.J. and MacDonald, M.J., (2008). Sprint interval and traditional endurance training induce similar improvements in peripheral arterial stiffness and flow-mediated dilation in healthy humans. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, *295*(1), pp.R236-R242.

Rakobowchuk, M., Harris, E., Taylor, A., Baliga, V., Cubbon, R.M., Rossiter, H.B. and Birch, K.M., (2012). Heavy and moderate interval exercise training alters low-flow-mediated constriction but does not increase circulating progenitor cells in healthy humans. *Experimental physiology*, *97*(3), pp.375-385.

Reindell H and Roskamm H (1959) Ein Beitrag zu den physiologischen Grundlagen des Intervall training unter besonderer Berück- sichtigung des Kreilaufes. Schweiz Z Sportmed:1–8

Richards, J.C., Johnson, T.K., Kuzma, J.N., Lonac, M.C., Schweder, M.M., Voyles, W.F. and Bell, C., (2010). Short-term sprint interval training increases insulin sensitivity in healthy adults but does not affect the thermogenic response to β-adrenergic stimulation. *The Journal of physiology*, *588*(15), pp.2961-2972.

Rodas, G., Ventura, J.L., Cadefau, J.A., Cussó, R. and Parra, J., (2000). A short training programme for the rapid improvement of both aerobic and anaerobic metabolism. *European journal of applied physiology*, *82*(5-6), pp.480-486.

Rognmo, Ø., Moholdt, T., Bakken, H., Hole, T., Mølstad, P., Myhr, N.E., Grimsmo, J. and Wisløff, U., (2012). Cardiovascular risk of high-versus moderate-intensity aerobic exercise in coronary heart disease patients. *Circulation*, *126*(12), pp.1436-1440.

Roy, B.A., (2013). High-Intensity Interval Training: Efficient, Effective, and a Fun Way to Exercise: Brought to you by the American College of Sports Medicine www. acsm. org. *ACSM's Health & Fitness Journal*, *17*(3), p.3.

Schjerve, I.E., Tyldum, G.A., Tjønna, A.E., Stølen, T., Loennechen, J.P., Hansen, H.E., Haram, P.M., Heinrich, G., Bye, A., Najjar, S.M. and Smith, G.L., (2008). Both aerobic endurance and strength training programmes improve cardiovascular health in obese adults. *Clinical science*, *115*(9), pp.283-293.

Seiler, S. and Sjursen, J.E., (2004). Effect of work duration on physiological and rating scale of perceived exertion responses during self-paced interval training. *Scandinavian journal of medicine & science in sports*, *14*(5), pp.318-325.

Seiler, S.T.E.P.H.E.N. and Hetlelid, K.J., (2005). The impact of rest duration on work intensity and RPE during interval training. *Medicine and Science in Sports and Exercise*, *37*(9), p.1601.

Serpiello, F.R., McKenna, M.J., Stepto, N.K., Bishop, D.J. and Aughey, R.J., (2011). Performance and physiological responses to repeated-sprint exercise: a novel multiple-set approach. *European journal of applied physiology*, *111*(4), pp.669-678.

Shaban, N., Kenno, K.A. and Milne, K.J., (2014). The effects of a 2 week modified high intensity interval training program on the homeostatic model of insulin resistance (HOMA-IR) in adults with type 2 diabetes. *The Journal of sports medicine and physical fitness*, *54*(2), pp.203-209.

Shepherd, S.O., Cocks, M., Tipton, K.D., Ranasinghe, A.M., Barker, T.A., Burniston, J.G., Wagenmakers, A.J. and Shaw, C.S. (2013). Sprint interval and traditional endurance training increase net intramuscular triglyceride breakdown and expression of perilipin 2 and 5. *The Journal of physiology*, *591*(3), pp.657-675.

Shepherd, S. O., Wilson, O. J., Taylor, A. S., Thøgersen-Ntoumani, C., Adlan, A. M., Wagenmakers, A. J., & Shaw, C. S. (2015). Low-Volume High-Intensity Interval Training in a Gym Setting Improves Cardio-Metabolic and Psychological Health. *PloS one*, *10*(9), e0139056.

Simoneau, J.A., Lortie, G., Boulay, M.R., Marcotte, M., Thibault, M.C. and Bouchard, C., (1986). Inheritance of human skeletal muscle and anaerobic capacity adaptation to high-intensity intermittent training. *International journal of sports medicine*, *7*(03), pp.167-171.

Skleryk, J.R., Karagounis, L.G., Hawley, J.A., Sharman, M.J., Laursen, P.B. and Watson, G., (2013). Two weeks of reduced-volume sprint interval or traditional exercise training does not improve metabolic functioning in sedentary obese men. *Diabetes, Obesity and Metabolism*, *15*(12), pp.1146-1153.

Stathis, C.G., Febbraio, M.A., Carey, M.F. and Snow, R.J., (1994). Influence of sprint training on human skeletal muscle purine nucleotide metabolism. *Journal of Applied Physiology*, *76*(4), pp.1802-1809.

Stöggl, T. and Sperlich, B., (2014). Polarized training has greater impact on key endurance variables than threshold, high intensity, or high volume training. *Frontiers in physiology*, *5*, p.33.

Stöggl, T.L. and Sperlich, B., (2015). The training intensity distribution among well-trained and elite endurance athletes. *Frontiers in physiology*, *6*.

Talanian, J.L., Holloway, G.P., Snook, L.A., Heigenhauser, G.J., Bonen, A. and Spriet, L.L., (2010). Exercise training increases sarcolemmal and mitochondrial fatty acid transport proteins in human skeletal muscle. *American Journal of Physiology-Endocrinology and Metabolism*, *299*(2), pp.E180-E188.

Terada, T., Friesen, A., Chahal, B.S., Bell, G.J., McCargar, L.J. and Boulé, N.G., (2013). Feasibility and preliminary efficacy of high intensity interval training in type 2 diabetes. *Diabetes research and Clinical practice*, *99*(2), pp.120-129.

Tjonna, A., Stolen, T., Bye, A., Volden, M., Slordahl, S., Odegard, R., ... & Wisloff, U. (2009). Aerobic interval training reduces cardiovascular risk factors more than a multitreatment approach in overweight adolescents. *Clinical science*, *116*, 317-326.

Tong, T.K., Chung, P.K., Leung, R.W., Nie, J., Lin, H. and Zheng, J., (2011). Effects of non-Wingate-based high-intensity interval training on cardiorespiratory fitness and aerobic-based exercise capacity in sedentary subjects: a preliminary study. *Journal of Exercise Science & Fitness*, *9*(2), pp.75-81.

Trapp, E.G., Chisholm, D.J., Freund, J. and Boutcher, S.H., (2008). The effects of high-intensity intermittent exercise training on fat loss and fasting insulin levels of young women. *International journal of obesity*, *32*(4), pp.684-691.

Trilk, J.L., Singhal, A., Bigelman, K.A. and Cureton, K.J., (2011). Effect of sprint interval training on circulatory function during exercise in sedentary, overweight/obese women. *European journal of applied physiology*, *111*(8), pp.1591-1597.

Trost, S.G., Owen, N., Bauman, A.E., Sallis, J.F. and Brown, W., (2002). Correlates of adults' participation in physical activity: review and update. *Medicine and science in sports and exercise*, *34*(12), pp.1996-2001.

Weston, M., Taylor, K.L., Batterham, A.M. and Hopkins, W.G., (2014). Effects of low-volume high-intensity interval training (HIT) on fitness in adults: a meta-analysis of controlled and non-controlled trials. *Sports Medicine*, *44*(7), pp.1005-1017.

Weston, K.S., Wisløff, U. and Coombes, J.S., (2014). High-intensity interval training in patients with lifestyle-induced cardiometabolic disease: a systematic review and meta-analysis. *British journal of sports medicine*, *48*(16), pp.1227-1234.

Wisloff, U., Stoylen, A., Loennechen, J. P., Bruvold, M., Rognmo, O., Haram, P. M., Tjonna, A. E., Helgerud, J., Slordahl, S. A., Lee, S. J., Videm, V., Bye, A., Smith, G. L., Najjar, S. M., Ellingsen, O. & Skjaerpe, T. (2007). Superior cardiovascular effect of aerobic interval training versus moderate continuous training in heart failure patients: A randomized study. *Circulation,* 115**,** 3086-94.

Whyte, L.J., Gill, J.M. and Cathcart, A.J., (2010). Effect of 2 weeks of sprint interval training on health-related outcomes in sedentary overweight/obese men. *Metabolism*, *59*(10), pp.1421-1428.

World Health Organization. (2010). Global recommendations on physical activity for health.