All-out sprinting: reliability and sensitivity of testing, and the effects of work-to-rest ratio and exercise modality

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A thesis submitted in partial fulfilment of the
requirements of Edinburgh Napier University,
for the award of Doctor of Philosophy by Published Works

June 2022

Acknowledgements

There are many individuals I would like to thank for their direct and indirect contribution to this thesis.

Professor Geraint Florida-James and Dr Lesley Ingram-Sills for being so much more than just supervisors. Your continual guidance, never-ending encouragement, constructive and thorough feedback and, most importantly, a great sense of humour has made the process of writing this thesis enjoyable. I appreciate your support and friendship. You are truly a dream team of supervisors!

Dr John Babraj for starting me on this research path. I greatly value your time, expertise, mentorship, and friendship, and I have learnt a huge amount from you over the years.

My previous and current colleagues, mentors, and co-authors. I have been lucky to work with and learn from so many of you.

Many friends (you know who you are) for just being there when I need you.

My family - ačiū už nuolatinę meilę ir palaikymą, kurį jaučiu net ir per atstumą.

My beautiful and caring wife Rhiannon for her continued love, support, and advice. Thank you for always believing in me. You inspire me to grow academically and personally.

Professor Greg Atkinson and Professor Richard Davison for their time and expertise during examination of the thesis.

Abstract

This PhD thesis by Published Works consists of six peer-reviewed journal articles relating to the overall theme of all-out sprint testing and training. The purpose of the thesis was, firstly, to investigate the performance reliability and test sensitivity of the 6- and 30-s Wingate Anaerobic Tests (WAnT), and secondly, to measure the effects of work-to-rest (W:R) ratios and exercise modality (cycling and running) during all-out training on physiological and performance adaptations in healthy participants.

In Publication 1, no significant differences in peak power output (PPO) and mean power output (MPO) across four trials of a 6- and 30-s WAnT were found in physically active males and females. Furthermore, test sensitivity of both WAnT protocols was generally marginal in both sexes, and only male MPO in the 30-s test displayed good test sensitivity. Publication 2 was a 2-week cycling repeated sprint training (RST) intervention in competitive runners. The results showed that the type and magnitude of adaptations is dependent on the prescribed W:R ratio. Specifically, greater improvements in endurance performance tests, as measured by the 3-km running time-trial (TT), time-to-exhaustion (TTE) and peak oxygen uptake ($\dot{V}O_{2peak}$) were demonstrated with shorter rest periods (1:3 W:R ratio), whereas longer rest periods (1:8 and 1:12 W:R ratios) resulted in higher power outcomes (PPO and MPO). Publication 3 demonstrated improvement in tests requiring endurance intensive efforts (10-km cycling TT, TTE and critical power), following a 4-week cycling sprint interval training (SIT) in female-only participants. However, twice weekly cycling SIT sessions did not provide adequate stimulus to significantly increase cardiorespiratory fitness ($\dot{V}O_{2peak}$) in healthy young females. Publication 4 reported a significant change in lactate kinetics following a 6-week cycling RST in adolescent academy level male football players. These changes were associated

with the improvements in different performance measures. Specifically, maximal blood lactate kinetics was shown to correlate with sprint and power parameters, while endurance performance was related to maximal blood lactate clearance. Publication 5 directly compared acute physiological adaptations in response to two weeks of cycling SIT and uphill run sprint training (UST) in recreationally active males. While there was no significant improvement in $\dot{V}O_{2peak}$ following either training modality, the UST was effective at improving TTE and ventilatory threshold by 11% and 3%, respectively. Finally, Publication 6 measured the effectiveness of a longer, 6-week UST to improve physical characteristics in competitive male footballers. Twice weekly UST performed alongside normal football training significantly enhanced endurance measures (YYIR1 distance: +11.9%; estimated $\dot{V}O_{2peak}$: +2.9%; 3-km TT: -4%), increased leg and back strength (+10%) and decreased time taken to complete change of direction test (-3.2%).

Collectively, these findings have practical implications for testing selection and training prescription in research and practice. One of the key outcomes was provision of valuable data on testing and training responses during all-out sprinting in female participants. Specifically, both WAnT protocols (i.e., 6- or 30-s) can be reliably used when testing male and female participants. With regards to training prescription, the 1:8 W:R ratio during cycling all-out training appears to be optimal when targeting adaptations associated with explosive, high-intensity, and endurance intensive efforts. If access to a cycle ergometer is not possible, though, then the UST performed on a 6-10% slope offers an effective and freely accessible alternative. Finally, recommendations for future research are also presented to facilitate further advancement on this topic.

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List of abbreviations

ADP: adenosine diphosphate

AMP: adenosine monophosphate

AMPK: AMP-activated protein kinase

ANOVA: analysis of variance

ANCOVA: analysis of covariance

ATP: adenosine triphosphate

BLC_{max}: maximum blood lactate concentration

BM: body mass

CI: confidence interval

CL: confidence limit

Cohen's *d*: the uncorrected effect size

CP: critical power

CrI: credible interval ('Bayesian confidence interval')

$ES_{0.5}$: 0.5-quantile, the median effect size value

FI: fatigue index

GXT: graded exercise test

Hedges' *g*: the corrected effect size

HIIT: high-intensity interval training

HR: heart rate

HR_{max}: maximal heart rate

HR_{peak}: peak heart rate

IET: incremental exercise test

LT: lactate threshold

MC: menstrual cycle

MCT: monocarboxylate transporter

MICE: moderate-intensity continuous exercise

MPO: mean power output

OC: oral contraceptives

PCr: phosphocreatine

PFK: phosphofructokinase

PGC1α: peroxisome proliferator-activated receptor-γ coactivator 1-α

PPO: peak power output

$\dot{Q}_{max}$: maximal cardiac output

RPE: rating of perceived exertion

RST: repeated sprint training

SD_{IR}: standard deviation for individual responses

SEM: standard error of measurement

SIT: sprint interval training

SWC: smallest worthwhile change

TT: time-trial

TTE: time-to-exhaustion

TW: total work

UST: uphill sprint training

$\dot{V}CO_2$: carbon dioxide production

$\dot{V}O_2$: oxygen consumption

$\dot{V}O_{2max}$: maximal oxygen uptake

$\dot{V}O_{2peak}$: peak oxygen uptake

WAnT: Wingate Anaerobic Test

$\dot{W}_{LI}$: power associated with the lactate inflection point

$\dot{W}_{LT}$: power associated with the lactate threshold

$\dot{W}_{max}$: maximal power output

$\dot{W}_{peak}$: peak power output

$\dot{W}_{\dot{V}O2max}$: power associated with the $\dot{V}O_{2max}$

W:R: work-to-rest ratio

YYIR1: Yo-Yo Intermittent Recovery Level 1

Chapter 1: Introduction

Interval training involves repeated intense bursts of exercise separated by low-intensity recovery periods or complete rest (Viana et al., 2018). It is broadly categorised into two forms: high-intensity interval training (HIIT) and sprint interval training (SIT) (Gibala & Hawley, 2017). HIIT protocols are infinitely variable, but the majority of interventions use submaximal efforts lasting between 1-4 minutes and eliciting ≥80% of maximal heart rate (HR_{max}) (Gibala & Hawley, 2017). In contrast, SIT is characterised by maximal (all-out) efforts of ≤30-s performed at a workload that is above the maximal oxygen uptake ($\dot{V}O_{2max}$) (Gibala & Hawley, 2017). SIT is also called Wingate-based training because a typical training session consists of repeated 30-second Wingate Anaerobic Tests (WAnT) (MacInnis & Gibala, 2017). Studies by Macdougall et al. (1998), Hargreaves et al. (1998) and Parolin et al. (1999) described the metabolic, enzymatic and performance responses in skeletal muscle during repeated 30-s all-out cycling bouts separated by 4-min recovery periods (i.e., 1:8 work-to-rest ratio), which later became a basis for the 'traditional' SIT protocol.

The reported physiological changes after SIT include improvements in $\dot{V}O_{2max}$ (Weston et al., 2014), skeletal muscle oxidative capacity (Burgomaster et al., 2005), aerobic and anaerobic metabolism (Rodas et al., 2000), muscle glycogen content (Gibala et al., 2006), muscle buffering capacity (Messonnier et al., 2007), muscle oxygenation (Jones et al., 2015) and work efficiency (Hebisz et al., 2017). The adaptive responses to SIT are also associated with improvements in aerobic and anaerobic performance tests. A 2-week SIT intervention in young healthy adults using the Wingate protocol has been shown to increase 5- and 10-km self-paced cycling TTs performance by 5.2% and 9.6%, respectively (Hazell et al., 2010; Burgomaster et al., 2006). In elite level female field hockey players, just one additional SIT session per week performed for a 6-week block elicited significant performance improvements in the 30-15 Intermittent Fitness Test (Jones et al., 2015). Furthermore, enhanced anaerobic performance after SIT is demonstrated by significant increases in peak and mean power output (Linossier et al., 1997; Hazell et al., 2010). Some of the above changes are observed in as little as two weeks, which suggests that SIT is a viable and efficient low-volume training method to improve health and performance measures in non-athletic and athletic populations (Milanović et al., 2015; Weston et al., 2014). More recently, SIT protocols consisting of shorter duration (≤10-s) maximal efforts called repeated sprint training (RST) have been shown to be just as effective at inducing physiological and performance improvements as longer sprints (Fiorenza et al., 2019; Hazell et al., 2010).

Similarly, 6-, 10-, 15- and 20-s WAnTs have been proposed as effective alternatives to the 30-s WAnT (Attia et al., 2014; Hachana et al., 2012; Herbert et al., 2015; Zajac et al., 1999). Evidence demonstrates that the greatest metabolic demands and signalling responses occur in the early stages of a sprint thereby providing support for the use of shorter duration all-out sprints in training and testing (Fiorenza et al., 2019; Gaitanos et al., 1993). Despite the widespread use of WAnTs to assess changes in anaerobic performance, test reliability and sensitivity across repeated trials of different sprint durations (6- and 30-s) have not been investigated. However, reliable and sensitive protocols are required in order to accurately detect and quantify training-induced changes in anaerobic performance (Currell & Jeukendrup, 2008; Hopkins et al., 2001).

All-out training encompasses a large variation of protocols, which makes direct comparison between the studies difficult and subsequently limits the optimal training prescription for health and performance (Viana et al., 2018). This is somewhat expected, since training prescription is a complex process which requires manipulation of several acute programme variables including interval intensity, interval duration, recovery intensity, recovery duration, exercise modality, number of intervals, number of series, series duration, time between series and between series recovery intensity (Buchheit & Laursen, 2013). However, the impact each of these training variables and their combination have on acute and chronic adaptive responses should be carefully considered when planning SIT and RST. Currently, the effects of work-to-rest ratio (W:R ratio) and exercise modality are not fully understood. Schoenmakers et al. (2019) have recently highlighted that the effects of varying W:R ratios during SIT remain largely unknown because very few studies directly investigated the impact of this acute programme variable. A meta-analysis by Weston et al. (2014) reported that the modifying effect of an increase in W:R ratio (i.e., longer recovery between sprints) on changes in $\dot{V}O_{2max}$ is unclear, but there are possible moderate and likely small improvements in mean and peak sprint power output, respectively. This suggests that the W:R ratio during SIT/RST impacts the magnitude of aerobic and anaerobic adaptations differently. Therefore, despite the majority of SIT studies using a 1:8 W:R ratio (Burgomaster et al., 2005; Hazell et al., 2010), it should be selected depending on the targeted adaptations and desired performance outcomes.

With regards to exercise modality, most all-out studies to date have been completed in an exercise laboratory setting (Astorino et al., 2012; Hazell et al., 2010). The use of highly specialised cycle ergometers allows a precise control of the external resistance applied during cycling, which determines exercise intensity (Burgomaster et al., 2005). Additionally, stationary cycle ergometers offer a non-weight bearing exercise modality with minimal eccentric contraction of leg muscles, which minimises the effect of body mass (BM) on the workload (Gist et al., 2014). This may be beneficial to the athletic populations looking to lower the overall impact load during training or sedentary individuals whose BM can influence the workload. However, cycling ergometers are relatively costly to acquire thereby reducing ecological validity of cycling all-out training. From a training specificity point of view, cycling modality may not be relevant to all sports and activities, particularly in running-based sports, such as football (Ross & Leveritt, 2001). Therefore, running all-out training can offer a practical alternative to a cycling-based training with reported health (MacPherson et al., 2011) and athletic benefits (Koral et al., 2018). However, the uphill sprint training (UST) as an all-out running approach has received little scientific interest, which is surprising given that exercise modality is another key variable when designing training programmes, especially for team sports athletes (Buchheit & Laursen, 2013).

1.1 Research aims

Therefore, the aim of the work presented in this PhD thesis by Published Works was two-fold. First, to investigate the performance reliability and test sensitivity of the WAnT. Second, to study the effects of two training variables, namely W:R ratio and exercise modality, on physiological and performance changes in athletic and non-athletic participants. These findings have important practical implications for testing selection and training prescription by practitioners and researchers. Winter & Nevill (2014) suggested that the quality of research in sport and exercise sciences should be primarily defined by two metrics: 1) if it advances knowledge and understanding 2) if it changes practice. Therefore, the body of work presented herein will add to the current theoretical and practical understanding of all-out testing and training protocol designs. Specifically, the objectives were to:

- Determine the reliability and sensitivity of a shorter (6-s) and longer (30-s) WAnT and examine sex differences between physically active males and females.
- Measure the effects of work-to-rest ratios during cycling RST.
- Investigate the effects of cycling SIT in female-only participants.
- Study lactate kinetics as a mechanism that underpins performance adaptations following cycling RST.
- Compare early physiological and performance adaptations between cycling SIT and UST.
- Establish UST effectiveness on changes in physical characteristics.

1.2 Details of publications

These objectives will be met by presenting the work and findings of the six publications detailed below. In addition, **Figure 1** is a diagrammatic representation of the relationship between publications and how the thesis developed sequentially into a coherent and significant body of original research.

1. **Kavaliauskas, M.,** & Phillips, S. M. (2016). Reliability and sensitivity of the 6 and 30 second Wingate tests in physically active males and females. *Isokinetics and Exercise Science*, 24 (3), 277-284. https://doi.org/10.3233/IES-160632

2. **Kavaliauskas, M.**, Aspe, R. R., & Babraj, J. (2015). High-intensity cycling training: the effect of work-to-rest intervals on running performance measures. *Journal of Strength and Conditioning Research*, 29 (8), 2229-2236. https://doi.org/10.1519/JSC.0000000000000868

3. **Kavaliauskas, M.**, Steer, T. P., & Babraj, J. (2016). Cardiorespiratory fitness and aerobic performance adaptations to a 4-week sprint interval training in young

healthy untrained females. *Sport Sciences for Health*, 13 (1), 17-23. https://doi.org/10.1007/s11332-016-0313-x

4. Thom, G., **Kavaliauskas, M.**, & Babraj, J. (2019). Changes in lactate kinetics underpin soccer performance adaptations to cycling-based sprint interval training. *European Journal of Sport Science*, 20 (4), 486-494. https://doi.org/10.1080/17461391.2019.1635650

5. **Kavaliauskas, M.**, Jakeman, J., & Babraj, J. (2018). Early adaptations to a two-week uphill run sprint interval training and cycle sprint interval training. *Sports*, 6 (3), 72. https://doi.org/10.3390/sports6030072

6. **Kavaliauskas, M.**, Kilvington, R., & Babraj, J. (2017). Effects of in-season uphill sprinting on physical characteristics in semi-professional soccer players. *The Journal of Sports Medicine and Physical Fitness*, 57 (3), 165-170. https://doi.org/10.23736/S0022-4707.16.06066-7

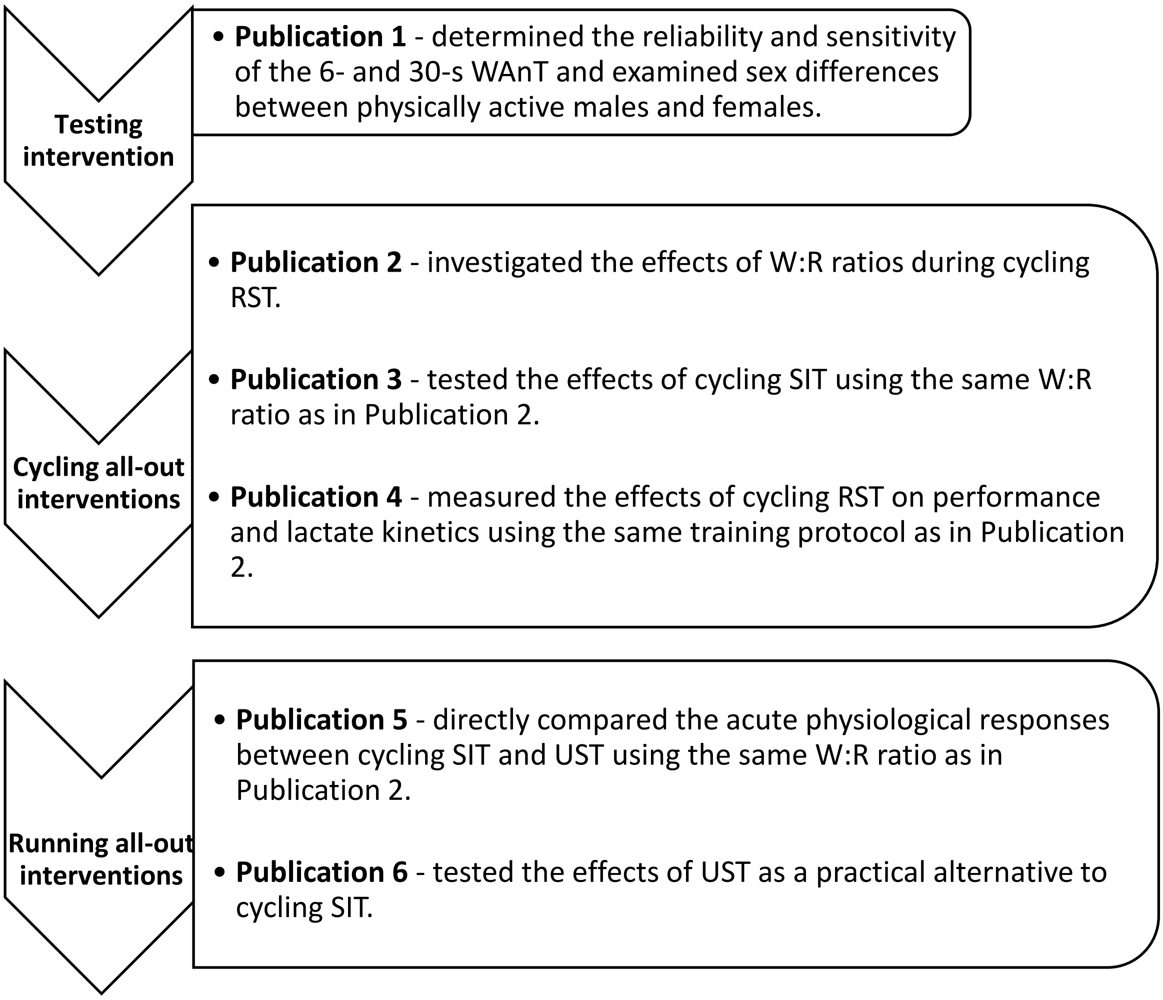

Figure 1. A brief description of each publication and a schematic representation of the relationship between publications.

1.3 Thesis structure

The thesis comprises five main chapters. **Chapter 2** provides a critical review of the scientific literature on all-out training and the modifying effects of work-to-rest ratio and exercise modality on physiological and performance responses. In **Chapter 3**, my philosophical positioning on research is briefly outlined followed by presentation of the six experimental studies in the format of the academic journal in which they have been published. **Chapter 4** is a general discussion of the body of work, which includes critical appraisal of each publication, a summary of findings and my personal reflections.

Chapter 5 summarises the findings from the six publications and concludes the thesis, whilst directions for future research are also suggested.

Chapter 2: Literature review

This chapter provides a critical review of the literature on anaerobic performance assessment as well as the physiological adaptations and performance benefits following all-out sprint training. The review will focus on the impact of two key training variables, namely work-to-rest (W:R) ratio and exercise modality (cycling and running) on adaptive responses and performance changes. The implications of these variables for the design of training programmes will also be discussed. Finally, this chapter will set the scene for the findings from six publications presented and discussed in **Chapters 3** and **4.**

2.1 The Wingate Anaerobic Test (WAnT)

The WAnT is a maximal (all-out) intensity cycle ergometer test against a constant braking force (traditionally set at 7.5% BM for a Monark ergometer) lasting 30-s (Driss & Vandewalle, 2013). The WAnT is considered the 'gold standard' of anaerobic power measurement with three main indices calculated: the peak power output (PPO), mean power output (MPO), and fatigue index (FI) (Driss & Vandewalle, 2013). PPO is the highest mechanical power over a 1- or 5-s period, often considered the most important measure of the WAnT (Lunn & Axtell, 2019). MPO is the average power of the entire 30-s test, and FI is the decline in power expressed as a percentage of the PPO value (Beneke et al., 2002). The WAnT is commonly used not just as an assessment of anaerobic power performance, but also as a standardised method to analyse responses to an all-out exercise (Bar-Or, 1987). In fact, popularity of the 'traditional' SIT protocol consisting of repeated 30-s WAnTs can be attributed to the early studies by Macdougall et al., (1998), Hargreaves et al., (1998) and Parolin et al., (1999) describing the metabolic, enzymatic and performance responses in skeletal muscle.

More recently, time-shortened WAnT protocols ranging from 6- to 20-s have been proposed as good alternatives to the original 30-s WAnT (Attia et al., 2014; Hachana et al., 2012; Herbert et al., 2015; Zajac et al., 1999). For example, the 6-s WAnT has been shown to be a valid measure of the PPO compared with the 30-s WAnT (Herbert et al., 2015). It has also been proposed that shorter tests may be more specific to the short bursts of maximal-intensity efforts observed in field-based teams sports (Bishop et al., 2001). In addition, the 30-s WAnT is generally associated with physical discomfort, such as nausea, dizziness, and headaches (Attia et al., 2014; Wittekind et al., 2011). Thus, time-shortened WAnT protocols may help reduce side effects thereby increasing compliance to the test and provide reliable and valid results in both athletic and clinical populations (Driss & Vandewalle, 2013; Hachana et al., 2012). However, despite the popularity of the WAnT, there is little published data, especially in female participants, on the performance reliability and test sensitivity of different test durations (i.e., 6- and 30-s). Such information is required, though, to ensure that training-induced changes in anaerobic performance in all populations are detected and quantified accurately (Currell & Jeukendrup, 2008; Hopkins et al., 2001).

2.2 SIT terminology and protocols

Sprint interval training (SIT) is characterised by repeated bouts of brief intermittent exercise performed at the intensity corresponding to a power output or velocity at and above maximal oxygen uptake ($\dot{V}O_{2max}$) interspersed with passive or active recovery periods (Weston et al., 2014). Based on the duration of the sprints, it can be divided into either short (≤10-s, repeated sprint exercise or training (RST)) or long (10- to 30-s; sprint interval exercise or training) sprints performed at the relative intensities ≥100% maximal power output ($\dot{W}_{max}$) measured during the incremental exercise test (Granata et al., 2018). As shown in **Figure 2**, the fixed-intensity approach corresponding to all-out or supramaximal intensity (≥100% $\dot{W}_{max}$) is used in both SIT protocols (Granata et al., 2018). There is now a convincing body of literature demonstrating that SIT of different durations induces favourable local (muscle) and central (cardiovascular, respiratory, neural, and hormonal) adaptations, which are mainly attributed to its all-out intensity (Gibala & Hawley, 2017). In fact, exercise intensity is a critical training variable because it determines the extent and dynamics of homeostatic perturbations, including systematic responses, metabolic changes, and mechanical stress (Black et al., 2017). Four domains of exercise intensity have been identified based on power outputs associated with specific metabolic thresholds, namely the lactate threshold (LT) and the critical power (CP) (Burnley & Jones, 2018). The four exercise intensity domains are: moderate (below the LT), heavy (between LT and CP), severe (above CP until $\dot{V}O_{2max}$ is attained), and extreme (task failure occurs before $\dot{V}O_{2max}$ is attained) (Burnley & Jones, 2018).

The conceptual framework of CP allows to study and understand metabolic and physiological mechanisms underpinning exercise performance, including high-intensity intermittent exercise (Burnley & Jones, 2018). The two-parameter CP model describes the hyperbolic relationship between power output (intensity) and time to task failure (duration) within the severe-intensity domain (Jones & Vanhatalo, 2017). It is comprised of two distinct parameters: the CP, which is represented by the asymptote of the power-duration relationship, and the curvature constant, known as *W´*, which indicates the fixed amount of work that can be performed above CP (Jones & Vanhatalo, 2017). Additionally, the CP represents the heavy-severe domain boundary within which a physiological steady state in multiple measures, such as blood lactate, pH and $\dot{V}O_2$ can be achieved (Chidnok et al., 2013). In contrast, exercise in the severe- and extreme-intensity domain results in a non-steady physiological state where these variables cannot be stabilised (Chidnok et al., 2013). Thus, from the bioenergetics point of view, CP reflects the highest sustainable oxidative metabolic rate, whilst *W´* (i.e., work above CP) requires a greater contribution from anaerobic processes (Jones & Vanhatalo, 2017). The concept of CP helps to understand physiological responses and exercise tolerance whilst also providing insight into the mechanistic basis of fatigue across different intensity domains (Jones & Vanhatalo, 2017). For example, exercise intolerance within the severe-intensity domain (>CP) is primarily associated with high levels of metabolic perturbation (i.e., low values of muscle pH, ATP and PCr, and high values of blood lactate) (Black et al., 2017; Burnley & Jones, 2018). Whereas fatigue development during the heavy-intensity exercise (>LT, <CP) has been largely attributed to intermediate changes in muscle metabolic perturbation and glycogen depletion (Black et al., 2017).

The task-dependent nature of fatigue, depending on the sprint duration and/or recovery periods, also leads to differential metabolic and ionic disturbances during multiple-sprint exercise protocols (Fiorenza et al., 2019). This has been examined by comparing the degree of neuromuscular and metabolic fatigue between short- (18 x 5-s) and long-duration (6 x 20-s) sprint protocols matched for total work and W:R ratio (Fiorenza et al., 2019). The study showed that both the central (neural) and peripheral (muscular) types of fatigue affected the capacity to repeat all-out efforts in endurance-trained individuals (Fiorenza et al., 2019). Specifically, a higher degree of peripheral fatigue, including more extensive intramuscular accumulation of lactate and H^+ and lower levels of glycolysis was observed following long sprints when compared to short sprints. Interestingly, similar degrees of central fatigue were reported between both protocols, but a greater development of peripheral fatigue following long-duration sprints led to larger decreases in cycling performance (lower PPO and MPO values) (Fiorenza et al., 2019). These findings have practical implications for training programme design with the specific physiological adaptations and performance benefits following SIT and RST protocols discussed in the below sections.

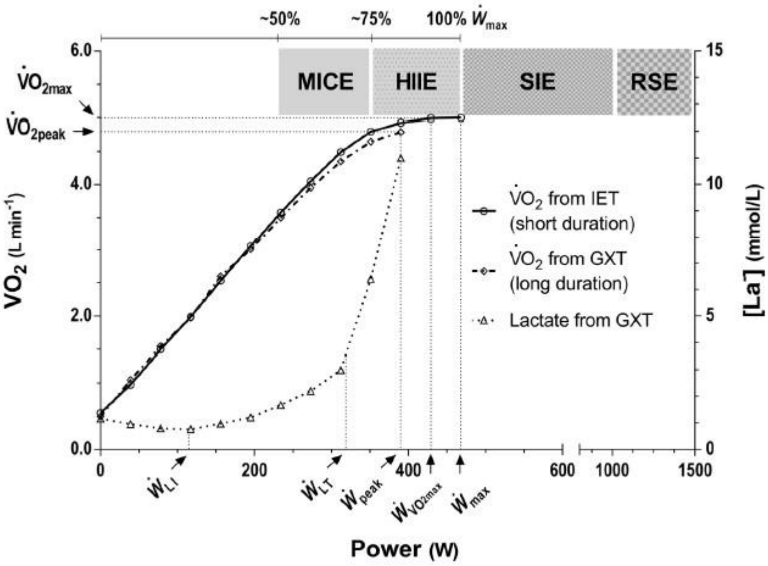

Figure 2. Sprint interval exercise (SIE) and repeated sprint exercise (RSE) intensity in relation to the maximal power output (Ẇmax) measured during the incremental exercise test. Figure adapted from Granata et al. (2018).

2.3 SIT: adaptations and performance benefits

The widely reported cardiovascular, metabolic and neuromuscular adaptations following SIT include increases in $\dot{V}O_{2max}$ (MacPherson et al., 2011; Weston et al., 2014), skeletal muscle oxidative capacity and mitochondrial content (Burgomaster et al., 2005, 2008), aerobic and anaerobic metabolism (Nevill et al., 1989; Rodas et al., 2000), muscle glycogen content (Gibala et al., 2006), muscle buffering capacity (Messonnier et al., 2007), muscle oxygenation (Jones et al., 2015), and work efficiency (Hebisz et al., 2015).

Some of these adaptations have been shown to occur as little as two weeks, but are comparable to or even superior to the traditional endurance training, especially when total work is matched (MacInnis & Gibala, 2017). Training-induced improvements between SIT and endurance training are similar despite large differences in time commitment and total weekly training volume, which may be up to 90% lower with SIT (Gibala et al., 2012; Gillen et al., 2016). Effectiveness of SIT may be explained by higher power outputs and ability to sustain larger training stimulus (time above 90% of $\dot{V}O_{2max}$) compared to a bout of constant-intensity exercise (Rønnestad et al., 2015). The reduced total training volume coupled with numerous physiological, health and performance benefits has helped SIT to progressively grow in popularity in non-athletic and athletic populations (Jones et al., 2015; MacInnis & Gibala, 2017; Stepto et al., 1999). Specific physiological adaptations and performance benefits following SIT can be developed by manipulating numerous training variables, such as work interval intensity and duration and recovery interval intensity and duration, to stress either aerobic or anaerobic energy metabolism (Seiler & Hetledid, 2005).

The absolute power output of the exercise bout determines the rate of adenosine triphosphate (ATP) demands (Hargreaves & Spriet, 2020). SIT protocols require maximal power output that largely rely on anaerobic component reflected by the high blood lactate concentration (**Figure 2**) (Psilander et al., 2010). Furthermore, high absolute power outputs achieved during SIT necessitate the recruitment of both type I (slow twitch) muscle fibres and particularly type II (fast twitch) muscle fibres (Gibala and Hawley, 2017). As a result, there is a high metabolic disturbance, including a rapid rate of fuel depletion and large net ATP breakdown which triggers skeletal muscle adaptative responses to this form of training (Skelly & Gillen, 2018). Indeed, the global transcriptome in skeletal muscle and blood analyses revealed profound local and systematic stress induced by three 30-s maximal sprints (Rundqvist et al., 2019). The rate of change of cellular dynamics and disturbances to whole-body homeostasis are extensive following SIT, which is attributed to the recruitment and adaptation of type II muscle fibres (Gibala & Hawley, 2017). For example, a large reduction in the muscle glycogen (35%), phosphocreatine (PCr) (83%) and ATP (50%) content in type II muscle fibres has been demonstrated after a single 30-s all-out cycling sprints (Esbjörnsson-Liljedahl et al., 1999). This demonstrates the large contribution of the anaerobic metabolic pathway to meet the high absolute energy demands associated with repeated work-rest cycles (Gibala & Hawley, 2017). Other research has indicated that SIT leads to higher resting muscle glycogen and PCr content, greater activity levels of glycolytic enzymes, including creatine kinase, glycogen phosphorylase, phosphofructokinase (PFK), hexokinase and lactate dehydrogenase and enhanced buffering capacity (Linossier et al., 1997; Macdougall et al., 1998; Rodas et al., 2000; Barnett et al., 2004; Burgomaster et al., 2005). In addition, SIT has been shown to rapidly increase the glucose transporter type 4, monocarboxylate transporter (MCT) 1 and 4 proteins associated with glucose and lactate transport/H^+ (Burgomaster et al., 2007). Collectively, these changes result in a higher anaerobic energy provision and greater buffering capacity which can help explain the significant improvements across a range of anaerobic performance variables, including PPO, MPO, total work (TW), maximal anaerobic capacity (Linossier et al., 1997; Macdougall et al., 1998; Zinner et al., 2016, Fiorenza et al., 2019). Indeed, a recent systematic review and meta-analysis by Hall et al., (2020) compared the effects of SIT on a range of physical performance measures in healthy individuals and reported the largest pooled effect size for anaerobic outcomes ($ES_{0.5}$ = 0.57 [95%CrI: 0.33 – 0.86]). Increased anaerobic power (e.g., peak power) and capacity (e.g., mean power, total work) after SIT can be largely attributed to improvements in both anaerobic and aerobic metabolism.

The contribution of aerobic metabolism has been found to account for ~50% of energy production during the second 30-s sprint (Bogdanis et al., 1996). Gaitanos et al. (1993) also estimated a significant shift to aerobic metabolism with repeated shorter (6-s) maximal cycling sprints (Gaitanos et al., 1993). This demonstrates that the aerobic energy pathway plays an important role in ATP production, particularly during recovery periods irrespective of sprint duration. In fact, improvement in aerobic energy production has been suggested as the primary mechanism of adaptation to six sessions of SIT in healthy male participants (Zinner et al., 2016). This is further demonstrated by the large increases in the activity of oxidative enzymes, such as citrate synthase (~38%), 3-β-hydroxyacyl CoA dehydrogenase (~60%), malate dehydrogenase (~29%), and succinate dehydrogenase (~65%) following SIT programmes (Macdougall et al., 1998; Rodas et al., 2000; Burgomaster et al., 2005). The impact of SIT on cardiovascular structure and function has also been investigated (Raleigh et al., 2018). $\dot{V}O_{2max}$ is an important physiological measure of cardiovascular fitness and is one the most frequently assessed outcomes in response to SIT (Weston et al., 2014). Previous systematic reviews and meta-analyses have consistently reported moderate effect size (d = 0.63 - 0.69) improvements in $\dot{V}O_{2max}$ following SIT (Sloth et al., 2013; Gist et al., 2014; Weston et al., 2014; Vollaard et al., 2017). For example, a meta-analysis conducted by Sloth et al. (2013) included twenty-one studies in healthy sedentary and recreationally active young adults with a range of SIT protocols (10- to 30-s sprints) used across randomised controlled trials, matched-controlled trials and non-controlled trials. The authors reported a moderate effect (g = 0.63 [95%CI: 0.39 to 0.87]) of SIT on changes in

$\dot{V}O_{2max}$ corresponding to increases of 4.2-13.4% (Sloth et al., 2013). Similarly, the meta-analysis by Gist et al. (2014), which included only SIT interventions using the repeated 30-s Wingate all-out protocol showed a moderate effect (*d* = 0.69 [95%CI: 0.46 to 0.93]) of SIT compared with no-exercise controls, but no effect (*d* = 0.04 [95%CI: -0.17 to 0.24]) of SIT when compared to traditional endurance training. More recent meta-analysis by Vollaard et al. (2017) further confirmed the effectiveness of a repeated 30-s SIT intervention on $\dot{V}O_{2max}$ (7.8% [90%CL: ±4.0]). The physiological mechanisms underpinning increase in $\dot{V}O_{2max}$ appear to differ depending on the length of SIT intervention with peripheral adaptations, such as improvements in skeletal muscle oxidative capacity reported in short duration (2-6 weeks) studies, whereas central adaptations (e.g., increase in maximal cardiac output ($\dot{Q}_{max}$)) manifesting after longer training periods (>6 weeks) (Raleigh et al., 2018). Acute changes in muscle oxygenation levels during a SIT session consisting of 6 x 30-s all-out sprints further demonstrate that peripheral mechanisms underlie improvements in endurance exercise capacity (Buchheit et al., 2012). Despite the decrease in cycling power production, the authors observed an increase in oxygen extraction with successive sprint repetitions, which highlights the greater reliance on aerobic metabolism as the session progresses (Buchheit et al., 2012). Higher muscle deoxygenation during exercise after SIT may be linked to the increase in mitochondrial content within the skeletal muscle (Jacobs et al., 2013).

SIT is the major regulator of AMP-activated protein kinase (AMPK) activity (Gibala et al., 2012). AMPK is an energy-sensing, cellular ‘fuel gauge’ which is intensity-dependent as it is activated by increases in AMP:ATP or ADP:ATP ratios and low muscle glycogen availability (Kahn et al., 2005). For example, Gibala et al., (2009) demonstrated significant increases in AMPK and p38 mitogen-activated protein kinase signalling pathways in young males following four repeated 30-s all-out cycling sprints. The increase in AMPK was associated with an increase in the peroxisome proliferator-activated receptor-γ coactivator 1-α (PGC1α), which is regarded as the 'master switch' of mitochondrial biogenesis in skeletal muscle (Coffey & Hawley, 2007). In fact, a single session of SIT (4 x 30-s all-out cycling sprints) has been shown to increase the nuclear PGC1α protein content even after 3 hours of recovery which coincided with increased messenger ribonucleic acid expression of mitochondrial genes (Little et al., 2011). Genetic markers for mitochondrial biogenesis after one sessions of SIT (7 x 30-s all-out sprints) are even increased in well-trained cyclists (mean ± SD $\dot{V}O_{2peak}$: 68.0 ± 1.0 ml·kg^{-1}·min^{-1}) (Psilander et al., 2010). More recently, Granata et al. (2017) has demonstrated that SIT (4 x 30-s all-out sprints) represents a more potent stimulus for upregulation of the nuclear PGC1α protein than endurance training. Specifically, the SIT-induced increase in the nuclear PGC1α protein content was 2.3-fold immediately after training and 1.7-folds 3 hours post-SIT (Granata et al., 2017). From a performance point of view, an increase in nuclear PGC1α protein content is associated with the elevated oxidative capacity which would be expected to enhance exercise performance (Hawley et al., 2018). Indeed, physiological adaptations coincide with enhancement in exercise tolerance (i.e., TTE) and performance-related tests, such time-trial in recreationally active individuals (Burgomaster et al., 2005; Burgomaster et al., 2006) as well as elite athletes (Stepto et al., 1999; Jones et al., 2015). For example, performance during a cycling TTE test was doubled (26 ± 5 vs. 51 ± 11 min) after just 2 weeks of SIT (6 sessions in total) in recreationally active individuals (mean ± SD $\dot{V}O_{2peak}$: 44.6 ± 3.2 ml·kg^{-1}·min^{-1}) (Burgomaster et al., 2005). Similarly, 6 sessions of SIT consisting of repeated Wingate tests in young healthy adults improved 5- and 10-km self-paced cycling TT performance by 5.2% and 9.6%, respectively (Burgomaster et al., 2005, Hazell et al., 2010). However, a recent study by Bertschinger et al., (2020) failed to report a significant improvement during cycling TTE test at a constant load (67% of $\dot{W}_{max}$) in untrained males (mean ± SD $\dot{V}O_{2max}$: 45.2 ± 6.6 $ml \cdot kg^{-1} \cdot min^{-1}$). Interestingly, there were no SIT-induced changes in endurance performance despite the authors using the same SIT protocol reported by Burgomaster et al. (2005) and participants with similar baseline levels of cardiovascular fitness. The differences in findings between the two studies highlight the importance of more replication studies, which is only possible if the training and testing protocols are standardised and clearly explained. Nevertheless, SIT provides a sufficient stimulus to effectively improve the performance even in more highly trained individuals. For example, in competitive triathletes, two weeks of SIT (6 sessions) reduced a self-paced 10-km cycling TT by 10% indicating a significant improvement, which was strongly associated with lower blood lactate levels (Jakeman et al., 2012). Incorporating six sessions of SIT over 3 weeks also led to further gains in performance in elite cyclists as demonstrated by their 2.4% improvement in 40-km cycling TT (Stepto et al., 1999). The effectiveness of SIT in elite cyclists (mean ± SD $\dot{V}O_{2max}$: 73.9 ± 7.0 $ml \cdot kg^{-1} \cdot min^{-1}$) may be associated with higher mechanical and metabolic stress when compared to long 5-min intervals matched for time and effort (Almquist et al., 2020). Specifically, SIT resulted in higher MPO (14%) and longer working time above 90% $\dot{V}O_{2max}$ (54%) and 90% HR_{peak} (153%) than longer intervals without significant differences in rating of perceived exertion (RPE) or blood lactate concentration. Performance and physiological changes following SIT were also reflected in the more pronounced response of selected endocrine markers, such as increases in testosterone, growth hormone and testosterone-to-sex hormone-binding globulin, as well as prolonged cortisol responses

(Almquist et al., 2020). These findings further demonstrate the role of exercise intensity in the adaptive responses in systematic functions.

While the SIT protocol consisting of 3-7 repeated 30-s Wingate tests is still common, more recently shorter RST protocols have been shown to be just as effective (Hazell et al., 2010; Zelt et al., 2014). SIT is performed in the highest exercise domain, but the greatest metabolic demands and signalling responses occur in the early stages of a sprint (Fiorenza et al., 2019). Moreover, the all-out strategy of SIT (i.e., non-paced maximal efforts) may be dependent upon the sprint duration because it has been shown that participants are likely to adopt subconscious pacing strategy in sprints longer than 15-s (Wittekind et al., 2011). This was reflected in indices of power and fatigue when compared across the sprint durations ranging from 5- to 45-s in healthy male participants (mean ± SD $\dot{V}O_{2peak}$: 54.8 ± 0.5 ml·kg^{-1}·min^{-1}). Specifically, significantly lower PPO and MPO were achieved in the initial 10-s of the 45-s sprint (PPO: 902 ± 104 W, MPO: 738 ± 63 W) compared to the 15-s test (PPO: 1004 ± 146 W, MPO: 774 ± 73 W). Similarly, there were significantly lower fatigue indices during the first 15-s of the 30- and 45-s tests (35 ± 8.6 and 31.3 ± 10.8, respectively) compared to the 15-s sprint (42.1 ± 7.8) (Wittekind et al., 2011). These findings suggest that participants exert their ‘true’ maximal cycling power only in sprints of up to 15-s, with some pacing evident in longer sprint durations (i.e., >15-s). In contrast, Ansley et al., (2004) found that 30-s is a pre-programmed ‘end point’ during the WAnT with no evidence of pacing strategy up to that point.

Nevertheless, shorter duration SIT protocols (5- to 20-s) have been used in recent studies with no evidence that they compromise physiological and performance adaptations (Benítez-Flores et al., 2018; Fiorenza et al., 2019; Yamagishi & Babraj, 2017).

Due to the similarity to the maximal-intensity efforts typically performed in field-based team sports, shorter duration RST protocols lasting less than 10-s are believed to be more representative of sporting demands (Billaut & Basset, 2007). For example, a strong correlation (r = 0.76) between repeated 5 x 6-s maximal cycling sprints and 15-m sprint performance has been reported in team sports players (Bishop et al., 2001). A comparison of shorter (5-s) and longer (20-s) sprints matched for training volume (total sprint time) showed that the effectiveness of shorter sprints is not reduced but, in fact, increased as evidenced by greater physiological and mechanical responses (Benítez-Flores et al., 2018). Acute cardiorespiratory (HR and $\dot{V}O_2$) and mechanical responses (MPO, TW) were significantly higher following very short sprints (16 x 5-s with 24-s of recovery) compared to longer sprints (4 x 20-s with 120-s of recovery). In addition, lower levels of metabolic (respiratory exchange ratio and blood lactate) and neuromuscular fatigue (rate of fatigue and countermovement jump performance) were reported following a training session with shorter maximal efforts (Benítez-Flores et al., 2018).

Several studies have also directly compared the effects of shorter sprint durations (10- to 15-s) with the longer 30-s protocol (Hazell et al., 2010; Zelt et al., 2014; Yamagishi & Babraj, 2017). For example, the effects of 10-s and 30-s cycling SIT bouts on aerobic ($\dot{V}O_{2max}$ and 5-km cycling TT) and anaerobic (30-s WAnT) performance in young adults (mean ± SD $\dot{V}O_{2max}$: 47.0 ± 6.7 ml·kg^{-1}·min^{-1}) were found to be similar between the groups with no evidence of reduced sprint duration negatively affecting performance changes (Hazell et al., 2010). An increase in $\dot{V}O_{2max}$ after two weeks SIT (6 sessions in total) was significant in both the 30-s (9.3%) and the 10-s (9.2%) groups. Both training groups also significantly improved the 5-km TT (30-s: 5.2%, 10-s: 3.5%), PPO (9.5% and 8.5%, respectively) and MPO (12.1% and 6.5%, respectively). However, only the absolute rest duration (4-min) was matched between the groups meaning that the W:R ratio was different (1:8 vs. 1:24) and could have contributed to the findings. In another study with different W:R ratios between the training groups (1:9 vs. 1:19), the 50% reduction in sprint duration (30-s vs. 15-s) did not diminish maximal and submaximal performance gains in healthy men (Zelt et al., 2014). After 4 weeks of SIT, there were significant improvements in $\dot{V}O_{2peak}$ (30-s: 4%, 15-s: 8%), PPO and MPO, LT and CP tests in both groups. Physiological and performance adaptations to two different sprint duration protocols (30-s vs. 15-s) with the matched W:R ratio (1:8) performed twice per week for nine weeks were investigated by Yamagishi and Babraj (2017). In agreement with the findings by Zelt et al. (2014), the authors showed that reduction in training volume by 50% does not impair the changes in $\dot{V}O_{2peak}$, TTE, and 10-km cycling TT in moderately trained individuals as significant improvements were observed in both groups (Yamagishi & Babraj, 2017).

2.4 Sex-based differences in SIT

It is important to note that majority of SIT studies describing physiological adaptations and performance benefits used males-only or mixed-sex groups. Therefore, the data on sex-based differences in the adaptive responses to SIT are currently limited and inconclusive.

Astorino et al., (2011) found no differences in the magnitude of improvement in $\dot{V}O_2$max, Wingate-derived power output and fat oxidation between recreationally active males and females matched for age, physical activity and $\dot{V}O_2$max. These findings may be explained by similar acute adaptive responses of genes associated with skeletal muscle remodelling following a single bout of SIT in males and females (Skelly et al., 2017). Indeed, there appears to be no sex-related differences in the reduction of ATP

(50%), PCr (83%) and glycogen (35%) content in type II fibres after a single 30-s maximal cycling sprint (Esbjörnsson-Liljedahl et al., 1999). This suggests that type II muscle fibre recruitment, which is one of the mechanisms explaining SIT potency (see Section 2.3), is similar between males and females. In addition, no sex differences were reported in $\dot{V}O_{2max}$, 40-km cycling TT performance or power output when normalised to fat-free mass after 3 weeks of SIT (9 sessions in total) (Scalzo et al., 2014). However, the subtle sex-specific adaptive responses were observed as demonstrated by higher muscle protein synthesis and mitochondrial biogenesis in males compared to females (Scalzo et al., 2014). The metabolic differences between males and females seem to extend to the recovery period post-SIT. A recent study by Forsyth and Burt (2019) reported higher estimated energy expenditure and absolute fat oxidation rates in males when compared with eumenorrheic females immediately after a bout of 4 x 30-s SIT. While metabolic and adaptative mechanisms in response to SIT are different between males and females, aerobic and anaerobic performance improvements following SIT appear to be independent of sex (Astorino et al., 2011; Scalzo et al., 2014). Indeed, one of the longest SIT studies to date demonstrated that SIT programme of just 4 min/week (4 x 20-s maximal cycling sprints, 3 days/week) increased $\dot{V}O_{2max}$ in female participants by 18.7% compared to 6% in males (Bagley et al., 2016).

Another important variable to consider when studying and comparing the physiological adaptations and exercise performance following SIT in female participants is the influence of oral contraceptives (OC). It has been recently demonstrated that OC dampen central adaptations as reflected by smaller improvements in $\dot{V}O_{2peak}$, $\dot{Q}_{max}$, and pulmonary oxygen uptake kinetics when compared to naturally menstruating, recreationally active females after four weeks of SIT (Schaumberg et al., 2017;

Schaumberg et al., 2020). These findings would suggest the role of hormonal response in mediating adaptative responses to SIT as briefly mentioned in Section 2.3. Interestingly, the reduction in central adaptations did not negatively affect exercise performance during the time-to-fatigue test as the magnitude of improvement after training was similar in both groups (Schaumber et al., 2020). This suggests that mechanisms underpinning changes in exercise performance following SIT are not just different between males and females, but also differ within females depending on whether they are OC users or experiencing natural menstrual cycles (MC). Indeed, non-significant difference in the time-to-fatigue test between groups was explained by the greater improvements in peripheral adaptations, namely increased muscle oxygen utilisation in OC users, compared to the MC group (Schaumber et al., 2020). Additionally, the improvement in anaerobic performance as measured by PPO was pretty much identical between OC and MC groups (13.1% and 13.8%, respectively) (Schaumber et al., 2017). These findings suggest that despite the divergent adaptive responses in OC users and naturally menstruating females, changes in aerobic and anaerobic performance are very similar. However, determining the magnitude of change across aerobic and anaerobic variables in females requires further research.

2.5 Individual responses to SIT

There has lately been a lot of interest in individual responses to exercise training within the scientific community (Pickering & Kiely, 2019). From a practical point of view, understanding interindividual variability in response to interventions could provide useful information on the mechanisms of adaptation, including the role of biological sex, thereby helping personalise training prescription. Unsurprisingly, several SIT studies have also attempted to interpret individual data and classify participants into different responder categories (Astorino & Schubert, 2014; Bonafiglia et al., 2016; Gurd et al., 2016; Schulhauser et al., 2021).

A retrospective study by Astorino and Schubert (2014) compared individual responses to two protocols of interval training in young, healthy males and females. Changes in $\dot{V}O_{2max}$, heart rate and fat oxidation were measured and revealed a higher percentage of 'non-responders' following a 2-week low-volume SIT in mixed-sex participants when compared to a 12-week high-volume high-intensity interval training (HIIT) in just female participants. Specifically, frequency of 'non-responders' in all variables was 35-45% in the SIT group with a lower range (5-35%) reported in the HIIT group. However, the observed discrepancies in the interindividual variability between HIIT and SIT programmes may be due to the study design which was not time- or volume-matched (Astorino & Schubert, 2014). Dissimilar training protocols of different intensities may also help explain why there was only one 'non-responder' to all variables across both interventions with the level of responsiveness significantly affected by the baseline values of $\dot{V}O_{2max}$, exercise HR, respiratory exchange ratio and body fat.

Bonafiglia et al. (2016) performed a randomised crossover study investigating the individual responses in $\dot{V}O_{2peak}$, lactate threshold and submaximal HR following three weeks of endurance training and SIT. At the group level, there were significant improvements in all three measures with no differences observed between the two protocols. The individual responses data showed that the percentage of participants demonstrating a non-response in all three measures was higher following SIT (24%) than endurance training (5%). Similar to the findings of Astorino and Schubert (2014), there was not a single 'non-responder' to both exercise modalities, which suggests that the existence of true ‘non-responders’ to exercise is unlikely and switching to the other training stimulus can reduce the incidence of ‘non-response’.

Gurd et al. (2016) analysed data from five previously published studies on the incidence of non-response in $\dot{V}O_{2peak}$, lactate threshold, and 500 kcal time-to-completion tests. The overall rate of ‘non-responders’ in those tests following 3-6 weeks of SIT were 22%, 55% and 44%, respectively. However, their findings suggest that the incidence of ‘non-responders’ can be reduced once the optimal training dose of SIT is reached. For example, the group changes in $\dot{V}O_{2peak}$ were greater with no ‘non-responders’ observed when SIT was performed four times per week in comparison to a 37% of ‘non-responders’ when training was performed three times per week (Gurd et al., 2016). Longer interventions also resulted in a lower rate of non-response as demonstrated by 22% of ‘non-responders’ for $\dot{V}O_{2peak}$ following 3-6 weeks of SIT compared to 35% reported after 2 weeks (Gurd et al., 2016; Astorino & Schubert, 2014). Therefore, it appears that the individual response rate for $\dot{V}O_{2max}$ is higher following more frequent and longer SIT programmes (Gurd et al., 2016; Astorino & Schubert, 2014).

The individual response rates across three different SIT protocols were not examined until very recently when Schulhauser et al. (2021) directly compared responsiveness in aerobic and anaerobic variables after traditional (4-6 bouts of 30-s sprints with 4-min rest) and two modified (8-12 bouts of 15-s sprints with 2-min rest and 24-36 bouts of 5-s sprints with 40-s rest, respectively) SIT protocols. All groups performed 4 weeks of training matched for total exercise duration (2-3 minutes) and using the same 1:8 W:R ratio. At the group level there was no significant difference in the proportion of $\dot{V}O_{2max}$, 5-km TT, and anaerobic capacity (except time to peak speed) ‘responders’ across the three SIT protocols. However, the highest percentage of ‘responders’ for $\dot{V}O_{2max}$ was in the 30-s group (64%) compared to the 15-s (39%) and 5-s (41%) groups (Schulhauser et al., 2021). Similarly, the 30-s group had more ‘responders’ for 5-km TT performance (70%) compared to the other two training groups (15-s: 41%; 5-s: 35%). In contrast, the highest percentage of ‘responders’ for the anaerobic variable of time to peak speed was observed in the 15-s group (48%), followed by the 5-s (35%), and only 13% in the 30-s group. With regards to sex differences, male and female participants have been reported to have similar incidences of response in $\dot{V}O_{2max}$ (M: 47.6%; F: 48%), but not in 5-km TT (M: 54.8%; F: 38.5%), peak speed (M: 46.7%; F: 25%) or minimum speed (M: 11.1%; F: 20.8%) in the 30-s all-out running sprint test (Schulhauser et al., 2021).

The above findings suggest a large degree of interindividual differences in training responses following SIT, but such results should be interpreted with caution. Firstly, it is important to note that the classification of responsiveness is outcome parameter specific following a particular intervention (Pickering & Kiely, 2019). Therefore, the term ‘global responder/non-responder’ is inaccurate because a person may show different individual patterns of response across a range of outcomes even with a repeated exposure to the same training intervention (Pickering & Kiely, 2019). Secondly, biostatisticians have recently highlighted major pitfalls with the individual response categorisation into ‘responders’ and ‘non-responders’ from observed values in a single or multiple intervention sample (Atkinson et al., 2019). For example, reporting response rates based on responder counts is highly sensitive to the mean group changes rather than true individual responses (Atkinson et al., 2019). The approach of responder counting is affected by the confounding influence of random measurement error (instrumentation and/or biological noise) and/or within-subject variability (real physiological responses resulting from factors independent of the intervention)

(Swinton et al., 2018; Atkinson et al., 2019). Since both sources of variation are inevitable in physiological research, it requires appropriate study design and robust statistical approaches when examining individual response heterogeneity (Atkinson et al., 2019). Indeed, true individual differences in training responsiveness can only be quantified with appropriate statistical approaches. For example, in parallel-group randomised control trials, the standard deviation for individual responses (SD_{IR}) is a recommended metric to quantify individual response differences that are attributable to exercise training intervention *per se* (Atkinson et al., 2019). SD_{IR} represents the difference between the standard deviations of the changes between intervention and control groups, which estimates the true variance in individual responses, whilst accounting for the confounding effects of random and within-subject variability (Atkinson et al., 2019).

2.6 The impact of work-to-rest ratio

Training responses to SIT are likely to be influenced not just by individual's unique physiological characteristics, other factors (e.g., sleep, nutrition, recovery), but also the specific design of training intervention. As outlined in Section 2.3, training variables are manipulated to primarily stress either aerobic or anaerobic metabolic systems. The W:R ratio is one of the aspects that affects the training stimulus and subsequently the adaptative responses to SIT. Changes in the intensity and duration of work and rest intervals alter the relative demands of metabolic pathways (Holloszy & Coyle, 1984). This is particularly important given the all-out nature of SIT as recovery duration determines the overall intensity of exercise (Billaut & Basset, 2007). Further evidence for the importance of carefully managed recovery strategies during SIT has been recently provided by a study on muscle fibre typology and its effects on time to recover from 3 x 30-s all-out Wingate tests in recreationally active males (Lievens et al., 2020). The authors tested twenty participants with different estimated percentages of fast- and slow-twitch fibres in the right gastrocnemius medialis muscle. Although there were no significant differences in MPO or TW done across all Wingate tests, FI (total power drop) over three repeated Wingate tests was significantly higher in the fast-twitch group (-61%) compared to the slow-twitch group (-41%). As expected, the extent of fatigue between muscle typologies also affected the timeframe of recovery as the slow-twitch group fully recovered 20 minutes post-SIT, while the fast-twitch group had not recovered even 5 hours after the Wingate tests as measured by the maximal voluntary contraction and electrical stimulation of the quadriceps. These findings show the direct impact of muscle typology on the SIT results (Lievens et al., 2020). Training protocols, including recovery periods should therefore be individualised accordingly. The most common protocol of SIT consists of four to six repetitions of 30-s maximal efforts separated by 4 minutes of recovery i.e., 1:8 W:R ratio (Macdougall et al., 1998; Burgomaster et al., 2005). Interestingly, very few SIT interventions have directly investigated the impact of W:R ratios on physiological adaptations and performance outcomes. To date, most studies have examined the W:R ratios ranging from 1:2 to 1:24 with the summary of the key findings presented in **Table 1**. These findings are discussed through the published data on acute physiological responses to different W:R ratios (**Table 2**).

Table 1. A summary of the effects of different W:R ratios during cycling SIT and RST protocols.

Study	Participants' characteristics (n, M/F, age, baseline $\dot{V}O_{2max}$, training background)	Training Intervention	Cycling SIT protocols				Key findings
			Repetitions	**Work (duration [s], intensity)**	**Rest (s)**	**W:R ratio**	
Hazell et al., 2010	48, 35M/13F, 24.0 ± 3.2 yr, 47.0 ± 6.7 ml·kg^{-1}·min^{-1}, 26 kinesiology students, 19 ultimate Frisbee players and 3 physically active participants	2 wks, 3 sessions/wk	4-6x	30-s all-out sprints against 100 g·kg·BM^{-1}	240-s	1:8	Improvements in 5-km cycling TT were similar across all groups (1:8: +5.2%; 1:24: +3.5%; 1:12: 3.0%). $\dot{V}O_{2max}$ increased in the 1:8 (+9.3%) and 1:24 (+9.2%), but not the 1:12 group. Similarly, PPO (1:8: +9.5%; 1:24: +8.5%) and MPO (1:8: +12.1%; 1:24: +6.5%) improvements were higher in the 1:8 and 1:24 groups compared to the 1:12 group.
				10-s all-out sprints against 100 g·kg·BM^{-1}	240-s	1:24	
				10-s all-out sprints against 100 g·kg·BM^{-1}	120-s	1:12	
Lloyd Jones et al., 2017	30, M, 21.0 ± 4.0 yr, Baseline $\dot{V}O_{2max}$ not reported, Physically active participants from a range of sports	2 wks, 3 sessions/wk	20x	6-s all-out sprints against 7.5% of BM	48-s	1:8	Significant improvement in 10-km cycling TT (6-s: +5.1%; 30-s: +6.2%) in both groups matched for total sprint duration (2-min) and W:R ratio (1:8), despite no change in $\dot{V}O_{2max}$ in either group. PPO was also increased in both groups (6-s: +9.0%; 30-s: +20.0%).
			4x	30-s all-out sprints against 7.5% of BM	240-s	1:8	

Lloyd Jones et al., 2019	36, 24M/12F, 24 ± 4.0 yr, 53 ± 8.5 ml·kg^{-1}·min^{-1}, Physically active participants	2 wks, 3 sessions/wk	10x 6-s all-out sprints against 7.5% of BM	48-s	1:8	Significant improvements in 10-km cycling TT (1:8: +3.8%; 1:10: +1.4%; 1:12: +3.9%), PPO (1:8: +5.5%; 1:10: +4.6%; 1:12: +5.1%) and MPO (1:8: +4.3%; 1:10: +4.2%; 1:12: +2.8%) in all three training groups. All protocols also significantly improved fatigue profile as measured by S_{dec} (1:8: -2.0%; 1:10: -1.6%; 1:12: -1.2%).
				60-s	1:10	
				72-s	1:12	
Olek et al., 2018	14, M, 20.4 ± 0.3 yr, 50.5 ± 1.0 ml·kg^{-1}·min^{-1}, Physically active participants	2 wks, 3 sessions/wk	4-6x 10-s all-out sprints against 7.5% of BM	60-s	1:6	Significant improvement in $\dot{V}O_{2max}$ in both groups (1:6: +13.6%; 1:24: +11.9%). PPO, MPO and TW also increased significantly in both groups. However, only 1:6 protocol (60-s rest) improved EPO (+10.8%). No changes in beta-hydroxyacyl CoA-dehydrogenase, carnitine palmitoyl-transferase, malate dehydrogenase, and lactate dehydrogenase enzymes.
				240-s	1:24	
McGinley & Bishop, 2017	14, F, 24.0 ± 6.0 yr, 39.3 ± 5.3 ml·kg^{-1}·min^{-1}, Recreationally active participants	10 wks, 3 sessions/wk (1-4 wks), then 1 session/wk (5-10 wks)	4-10x 30-s sprints at 200-350% LT completed	60-s	1:2	Both groups had a similar improvement in $\dot{V}O_{2peak}$ (+6%), but higher improvement in TW during the RSA test in the 1:10 group (300-s rest). W:R ratio did not influence the adaptive response in acid/base transport proteins as upregulation of monocarboxylate transporter, sodium/hydrogen exchanger and carbonic anhydrase proteins was found in both groups.
				300-s	1:10	

Note: Age and baseline $\dot{V}O_{2max}$ values are presented as mean ± standard deviation.

Abbreviations: BM: body mass; EPO: end power output; LT: lactate threshold; MPO: mean power output; PPO: peak power output; RSA: repeated-sprint ability test; S_{dec} (%): performance decrement; TT: time trial; TW: total work; $\dot{V}O_{2max}$: maximal oxygen uptake; W:R: work-to-rest ratio

Table 2. A summary of the acute responses to cycling RST protocols with different W:R ratios.

Study	Participants' characteristics (n, M/F, age, baseline $\dot{V}O_{2max}$, training background)	Cycling RST protocols: Repetitions	Work (duration [s], intensity)	Rest (s)	W:R ratio	Key findings
Glaister et al., 2005	25, M, 20.6 ± 1.5 yr, Baseline $\dot{V}O_{2max}$ not reported, Physically active students	20x	5-s all-out against 7.5% of BM	10-s	1:2	PPO (+3.9%) and MPO (+27.3%) were higher with lower measures of fatigue (-16.1%), end RPE (-8.0%) and [Bla] (-29.0%), RER (-9.3%) and HR_{mean} (-10.1%) in longer recovery group (1:6).
				30-s	1:6	
Ohya et al., 2013	8, M, 25.5 ± 2.6 yr, 51.0 ± 5.9 ml·kg^{-1}·min^{-1}, Heathy participants	10x	5-s all-out sprints against 7.5% of BM	25-s	1:5	PPO and MPO decrement over repeated sprints were the lowest in the 1:20 recovery group (100-s rest). Mean $\dot{V}O_2$ and [Bla] were higher 1:5 > 1:10 > 1:20, whilst muscle reoxygenation was 29.5 ± 7%, 40.6 ± 10.5% and 39.5 ± 10.6%, respectively.
				50-s	1:10	
				100-s	1:20	
La Monica et al., 2016	8, M, 23.5 ± 4.0 yr, Baseline $\dot{V}O_{2max}$ not reported, Healthy, recreationally trained participants	10x	6-s all-out sprints against 7.5% of BM	12-s	1:2	$\dot{V}O_{2rest}$ was highest in the 1:2 protocol compared with the 1:3 and 1:4 protocols (~12% and ~20% higher, respectively). In contrast, TW and MPO measures were lowest with the 1:2 ratio (12-s rest).
				18-s	1:3	
				24-s	1:4	
Shi et al., 2018	13, M, 26.2 ± 6.2 yr, 61.3 ± 9.1 ml·kg^{-1}·min^{-1}, Endurance runners	40x	6-s all-out sprints against 7.5% of BM	15-s	1:2.5	Cycling PPO and MPO were highest with the 1:10 ratio, which progressively decreased with shorter recovery times (15-s and 30-s). Longest rest (1:10) also resulted in the lowest RPE. In contrast, total time spent above 80% $\dot{V}O_{2max}$ increased as the passive recovery time decreased (i.e., 1:2.5 > 1:5 > 1:10).
				30-s	1:5	
				60-s	1:10	

Baker et al., 2007	8, M, 26.6 ± 7.8 yr, Baseline $\dot{V}O_{2max}$ not reported, University students	8x	6-s all-out sprints against 7.5% of BM and FFM	30-s	1:5	Cycling PPO was higher and FI lower in both the FFM and TBM conditions in 1:10 vs. 1:5 protocol. HR was higher with shorter recovery (1:5), but no differences in RPE and end [Bla] reported between the two W:R ratios.
				60-s	1:10	
Monks et al., 2017	10, M, 23.8 ± 4.8 yr, Baseline $\dot{V}O_{2max}$ not reported, Competitive team sports players	10x	10-s all-out sprints against 10% of BM	30-s	1:3	PPO was lower by 16.1% with the 1:3 protocol (30-s) compared to the 1:18 protocol (180-s). Additionally, the rate of decline in PPO during RSA was higher with less rest (1:3).
				180-s	1:18	
Danek et al., 2020	12, M, 24.9 ± 4.1 yr, 52.4 ± 7.8 $ml \cdot kg^{-1} \cdot min^{-1}$, Healthy, physically active but not competing at a professional level participants	2x	Three bouts of 10-s all-out sprints against 7.5% of BM	30-s between sprints and 18-min between series	1:3	PPO and RPE were similar between both groups. However, MPO and TW were ~3.0% higher with the longer recovery (1:24). In contrast, there were higher $\dot{V}O_{2peak}$ (+4.7%), HR_{peak} (+3.7%), and VE_{peak} (19.8%) values with shorter 30-s (1:3) recovery period.
		6x	10-s all-out sprints against 7.5% of BM	240-s	1:24	

Note: Age and baseline $\dot{V}O_{2max}$ values are presented as mean ± standard deviation.

Abbreviations: [Bla]: blood lactate concentration; BM: body mass; FFM: fat-free mass; FI: fatigue index; HR: heart rate; HR_{mean}: average heart rate; HR_{peak}: highest heart rate during specific exercise modality; MPO: mean power output; PPO: peak power output; RER: respiratory exchange ratio; RPE: rating of perceived exertion; RSA: repeated-sprint ability test; TBM: total body mass; TW: total work; VE_{peak}: peak pulmonary ventilation; $\dot{V}O_2$: volume of oxygen; $\dot{V}O_{2max}$: maximal oxygen uptake; $\dot{V}O_{2peak}$: peak oxygen uptake; $\dot{V}O_{2rest}$: lowest oxygen value during rest period

The results from Lloyd Jones et al. (2017) suggest that 2 weeks of short (6-s) and long (30-s) duration sprints are similarly effective in endurance and sprint performance changes as long as they are matched for W:R (1:8) ratio and total sprint duration (2-min). There were significant and similar size improvements in 10-km cycling TT (6-s: 5.1%; 30-s: 6.2%) and PPO (6-s: +9%; 30-s: +20%) in both groups. The same authors (Lloyd Jones et al., 2019) also examined the effects of three W:R ratios (1:8, 1:10 and 1:12) on different performance parameters. Irrespective of the W:R ratio, power output, performance decrement during repeated all-out sprints and 10-km cycling TT improved significantly after 2 weeks of SIT with no difference between the groups. This suggests that any of those W:R ratios is appropriate when prescribing SIT to improve both aerobic and anaerobic performance. Olek et al. (2018) compared the effects of an even greater range of W:R ratios (1:6 vs. 1:24) on aerobic and anaerobic measures. In contrast to the findings of Lloyd Jones et al. (2017) who reported no changes in $\dot{V}O_{2max}$, Olek et al. (2018) found significant improvements in $\dot{V}O_2$max after just two weeks of SIT (6 sessions in total). The increase in $\dot{V}O_{2max}$ was slightly higher in the 1:6 group (13.6%) compared to the 1:24 group (11.9%), but there was no significant difference between the groups. The similar magnitude of change in $\dot{V}O_{2max}$ in both groups may be explained by a significant rise in citrate synthase activity, which was not affected by the recovery duration (Olek et al., 2018). Furthermore, the authors also reported a significantly improved end power output (+10.8%) with reduced recovery time between bouts (1:6 vs. 1:24), which indicates a greater fatigue resistance during maximal efforts (Olek et al., 2018). In agreement with Olek et al.'s (2018) findings, Hazell et al. (2010) also demonstrated a significant improvement in $\dot{V}O_{2max}$ with the 1:8 (+9.3%) and 1:24 (+9.2%) W:R ratios. In a female-only study by McGinley and Bishop (2017) a magnitude of increase in $\dot{V}O_{2peak}$ after a 10-week SIT intervention was similar (~6%) in both 1:2 (1-min rest) and 1:10 (5-min rest) groups. No difference between the

1:2 and 1:10 groups reported by McGinley and Bishop (2017) is surprising because shorter recovery duration imposes a greater metabolic stress on the oxidative system and therefore is expected to be more effective at improving aerobic capacity during SIT than longer rest periods. This has been supported by several recent studies investigating the acute cardiorespiratory responses to SIT protocols with different recovery durations. For example, Shi et al. (2018) showed that the total time spent above 80% $\dot{V}O_{2max}$ in endurance trained male athletes increased as the passive recovery time decreased (i.e., 1:2.5 > 1:5 > 1:10). In addition, La Monica et al. (2016) demonstrated that the $\dot{V}O_{2rest}$ quantified as the lowest O_2 value during a given rest period was significantly higher in the 1:2 protocol when compared with the 1:3 and 1:4 protocols (~12% and ~20%, respectively). More recently, Danek et al. (2020) reported a greater acute cardiorespiratory response as evidenced by higher $\dot{V}O_{2peak}$, HR_{peak}, and peak pulmonary ventilation values in healthy male participants performing repeated 10-s sprints interspersed with shorter 30-s (1:3) versus longer 4-min recovery (1:24 ratio) periods.

The results from the aforementioned SIT studies across different sprint durations (5- to 30-s) indicate that irrespective of the sprint duration ≤1:6 W:R ratios are likely to be advantageous for improvements in the aerobic capacity and endurance performance (Olek et al., 2018; La Monica et al., 2016; Shi et al., 2018). However, insufficient rest in between sprints caused by lower W:R ratios negatively affects markers of the anaerobic fitness, including TW, PPO and MPO (Glaister et al., 2005; McGinley & Bishop, 2017; Ohya et al., 2013). A comparison of acute responses using the 1:2 and 1:6 ratios revealed that the latter resulted in ~4% higher PPO and ~27% MPO, and ~16.1% lower measures of fatigue compared to the 1:2 ratio (Glaister et al., 2005). The significant differences between the two recovery protocols in performance measures were also reflected in different physiological responses. For example, the 1:6 ratio resulted in a lower average heart rate, respiratory exchange ratio, blood lactate concentration and RPE (Glaister et al., 2005). Following a 10-week SIT programme a higher improvement in TW performed during the RSA test was seen only in the 1:10 ratio group, but not in the 1:2 ratio group (McGinley & Bishop, 2017). Similarly, the influence of longer recovery duration is also evident in PPO and MPO with the highest power output observed in the 1:10 group compared to 1:2.5 and 1:5 ratios (Shi et al., 2018). Additionally, the positive effects of longer (1:10) compared to shorter (1:5) rest on PPO even exist when resistive forces are calculated based on the fat-free mass and not just the total BM (Baker et al., 2007). Greater TW, PPO, MPO and lower percentage decrease in PPO with longer recovery durations can be explained by an increase in anaerobic capacity, improved PCr resynthesis (McGinley & Bishop, 2017) and differences in muscular reoxygenation (Ohya et al., 2013). Specifically, the level of muscular reoxygenation was higher in the 1:10 protocol (40.6 ± 10.5%) compared to the 1:5 ratio (29.5 ± 7%) (Ohya et al., 2013). It has also been suggested that during repeated all-out sprint training peripheral fatigue has an early onset (i.e., within the first five sprints), whereas central fatigue, as quantified by decreased voluntary activation of the knee extensors, occurs towards the end of the sprint protocol (Monks et al., 2017). Therefore, TW, PPO, MPO, rate of decline in PPO and even perceived pain are negatively impacted during subsequent sprints without long enough recovery required for the metabolic and neural processes to return to homeostasis (La Monica et al., 2016; Ohya et al., 2013; Monks et al., 2017; Schoenmakers et al., 2019). Recent evidence suggests that the W:R ratio during SIT has opposite effects and should be prescribed based on the targeted physiological adaptations and performance outcomes with high W:R ratios (long rest periods) more beneficial for anaerobic performance, whereas low W:R ratios (short rest periods) more effective for aerobic outcomes (Hall et al., 2020).

Studies described above have investigated the influence of recovery duration between sprints (i.e., within-session) with much less research available on the effects of recovery between sessions. In addition, fixed duration rest periods within SIT session are commonly used but may not be representative of exercise and recovery pattern seen in many sports as rest periods between actions are never standardised (Billaut & Basset, 2007). Therefore, it is not just the total recovery duration but also the recovery pattern distribution that is likely to influence training responses and should be considered when optimising the W:R ratio prescription (Parra et al., 2000). Only a small number of SIT studies have directly studied the modifying effects of varying duration and patterns of rest intervals within and between sessions on cardiovascular, metabolic, neural and performance responses.

Billaut and Basset (2007) tested the effects of the same total recovery duration (270-s) but three different recovery patterns on mechanical performance during 10 x 6-s cycling sprints in healthy male participants. The experimental conditions were constant (30-s between each sprint), increasing (from 10-s to 50-s over 10 sprints) or decreasing (from 50-s to 10-s over 10 sprints) patterns of recovery. Earlier reductions in MPO and PPO as well as lowest overall TW performed over the 10 sprints were observed in the increasing recovery protocol. In contrast, the decreasing recovery pattern resulted in the highest fatigue index (-15.8%) compared with the increasing and constant recovery patterns (-5.1% and -10.1%, respectively). Differences in performance results were also reflected in neuromuscular responses indicating distinct fatigue processes across recovery patterns. For example, the greatest level of fatigue as quantified by maximal voluntary contraction was reported in the decreasing recovery pattern which helps to explain the highest percentage decrement in PPO observed in that condition.

With regards to the rest periods between sessions, Parra et al. (2000) measured the influence of two different patterns of rest on SIT performance and energy metabolism in ten physically active male participants. Group 1 trained daily for 2 weeks, whereas Group 2 trained for 6 weeks resting for 2 days between sessions. All participants were required to perform a progressive SIT protocol consisting of 2-7 bouts of maximal 15- and 30-s sprints against 7.5% of BM with the workload matched between the groups. Significant increases in enzymatic activities related to glycolysis (PFK – 107% and 68% and aldolase 46% and 28%, respectively) and aerobic (citrate synthase – 38% and 28.4% and 3-β-hydroxyacyl CoA dehydrogenase – 60% and 38.7%, respectively) metabolism were reported in both groups. Somewhat surprisingly, however, only Group 2 significantly improved the PPO (20%) and MPO (14%), with smaller and non-significant changes (3% and 3%, respectively) reported in Group 1 post-SIT. This shows the complex nature of exercise-induced fatigue because despite a significant increase in the resting intramuscular PCr concentration (22%), glycogen level (32%) and creatine kinase activity (44%), only a 3% power improvement was observed during a 30-s WAnT following daily SIT. These findings also have implications for training prescription, particularly rest periods between the sessions, as SIT performed every day resulted in high levels of fatigue and reduced muscle function, which consequently impaired short duration cycling power production. In contrast to the findings by Parra et al. (2000), daily SIT for 5 days per week for 4 weeks (20 sessions in total) significantly increased PPO and MPO during the two 30-s bouts of maximal pedalling in physically active males (mean ± SD $\dot{V}O_{2max}$: 47.7 ± 4.8 $ml \cdot kg^{-1} \cdot min^{-1}$) (Ijichi et al., 2015). However, methodological differences between the two studies may help explain the contrasting findings with regards to changes in anaerobic performance. For example, participants in the Ijichi et al. (2015) study were required to cycle against resistance equal to 5% of BM as opposed to the more commonly used 7.5% of BM employed by Parra et al. (2000). More recently, a study by Yasar et al. (2019) examined the recovery timeframes between sessions for PPO restoration following 3 x 20-s maximal sprints in young (mean ± SD age: 24 ± 3 years) and older (mean ± SD age: 70 ± 8 years) adults. The findings showed that time to recover PPO from a single SIT session is similar between young and older participants and it occurs after 3 days of rest. The study only compared 3 and 5 days of rest, but it has important implications for SIT prescription suggesting that training sessions can be scheduled every three days, without a reduction in PPO. However, currently there is little research on the effects of recovery distribution during SIT and as such it remains an important area for future research. Moreover, to fully understand the effects of SIT in broader training plans it should be studied in combination with other commonly used training modalities (e.g., resistance training). Using the previously described CP model (see Section 2.2), exercise tolerance during high-intensity intermittent bouts has been found to be a function of four independent variables: work interval power output, work interval duration, recovery interval power output, and recovery interval duration (Morton & Billat, 2004). This shows that high-intensity efforts are dependent not just on the absolute capacity of finite *W´* but also on its repeated depletion and reconstitution throughout the session (Chorley & Lamb, 2020). The *W´* has been shown to increase following eight weeks of repeated maximal cycling bouts (5 x 60-s, 3 days/week) and the *W´* recovery between bouts is a function of both duration and intensity of the recovery interval (Jenkins & Quigley, 1993; Chidnok et al., 2013). However, the reconstitution of *W´* is a complex topic and more precise models are required to fully understand it mechanistically (Chorley & Lamb, 2020). Nevertheless, it is clear that the rate and/or total utilisation and reconstitution of *W´* are directly impacted by the intensity and duration of both work and recovery parts of the session.

2.7 The impact of exercise modality

To date, the majority of SIT studies have been completed in exercise laboratories using specialised cycling ergometers (Astorino et al., 2012; Hazell et al., 2010). The use of cycling-based SIT reduces its ecological validity and application to running-based sports, particularly field-based sports, where ability to sprint rapidly offers a competitive advantage (Ross & Leveritt, 2001). In addition, running is a preferred exercise modality by many and a few studies investigating the effectiveness of running-based SIT have reported numerous health (MacPherson et al., 2011; Willoughby et al., 2016) and performance benefits (Jakeman et al., 2016; Koral et al., 2018). These improvements included increases in $\dot{V}O_{2max}$ and TTE, reduction in TT, as well as higher peak and mean sprint speed (MacPherson et al., 2011; Willoughby et al., 2016, Koral et al., 2018). However, as in the cycling-based SIT literature, there is considerable variation in running SIT all-out protocols as presented in **Table 3**.

Table 3. A summary of the key findings from studies using running-based SIT protocols.

Study	Participants' characteristics (n, M/F, age, baseline $\dot{V}O_{2max}$, training background)	Training Intervention	Running SIT protocols	Key findings
MacPherson et al., 2011	10, 6M/4F, 24.3 ± 3.3 yr, 46.8 ± 5.1 ml·kg^{-1}·min^{-1}, Healthy, recreationally active participants (Frisbee players and university students)	6 wks, 3 sessions/wk	4-6 x 30-s maximal sprints on a treadmill, 4-min rest	Significant improvement in $\dot{V}O_{2max}$ (+11.5%), 2-km running TT (-4.6%), a-vO_2 difference (+7.1%), but no change in $\dot{Q}_{max}$
Litleskare et al., 2020	13, 5M/8F, 25.0 ± 1.0 yr, 50.5 ± 1.6 ml·kg^{-1}·min^{-1}, Healthy participants	8 wks, 3 sessions/wk	5-10 x 30-s near maximal sprints (regulated subjectively and verified using HR) on slightly uphill terrain, 3-min rest	Significant increase in $\dot{V}O_{2max}$ (+5.5%) with no change in $\dot{Q}_{max}$. Also improvements in 20-m shuttle run (+15%), 60-m sprint (+4.6%) and RSA performance
Mohr et al., 2007	7, M, 24.6 ± 0.6 yr, 49.0 ± 1.6 ml·kg^{-1}·min^{-1}, Healthy, normally active, but not training for competition participants	8 wks, 3-6 sessions/wk	8 x 30-s sprints at ~130% of $\dot{V}O_{2max}$, 1.5-min rest	Significant improvements in the TTE (+12.8%), YYIRL2 performance (+28.7%) and reduction in FI during RSA (-53.8%).

Willoughby et al., 2016	14, 7M/7F, 22.9 ± 3.1 yr, Healthy, inactive adults	4 wks, 3 sessions/wk	4-6 x 30-s all-out sprints on a non-motorised treadmill, 4-min rest	Significant improvements in $\dot{V}O_{2max}$ (+3.9), 2-km running TT (-5.9%), peak sprint speed (+9.3%) and mean sprint speed (+6.8%).
Kim et al., 2011	11, M, 20.0 ± 1.10 yr, 49.84 ± 4.1 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$, Well-trained judoists	8 wks, 4 sessions/wk	6-10 x 30-s maximal sprints on a treadmill, 4-min rest	Significantly increased anaerobic performance as measured by PPO (+17%) and MPO (+22%)
Denham et al., 2015	20, M, 18-25 yr*, 49.6 ± 4.6 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$, Healthy, untrained participants	4 wks, 3 sessions/wk	3-8 x 30-s all-out sprints on a track, 4-min rest	Significant improvements in $\dot{V}O_{2max}$ (+4.5%) and 5-km running TT (-4.5%).
Koral et al., 2018	16, 12M/4F, 21.1 ± 3.6 yr, 61.5 ± 2.8 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ (males) & 47.9 ± 3.2 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ (females), Trained trail runners	2 wks, 3 sessions/wk	4-7 x 30-s all-out sprints on a track, 4-min rest	Significant improvement in TTE at MAS (+42%) and 3-km running TT (-5.7%)

Note: Age and baseline $\dot{V}O_{2max}$ values are presented as mean ± standard deviation. * only the age range was reported.

Abbreviations: a-vO_2: arteriovenous oxygen; FI: fatigue index; HR: heart rate; MAS: maximal aerobic speed; MPO: mean power output; PPO: peak power output; $\dot{Q}_{max}$: maximal cardiac output; RSA: repeated-sprint ability test; TT: time-trial; TTE: time-to-exhaustion; $\dot{V}O_{2max}$: maximal oxygen uptake; YYIRL2: the Yo-Yo Intermittent Recovery Level 2 test

Aerobic adaptations and endurance performance changes following running-based SIT include significant improvements in $\dot{V}O_{2max}$ (3.9% - 11.5%), 2-km (4.6 - 5.9%) and 5-km running TT (4.5%), TTE (12.8%), the Yo-Yo Intermittent Recovery Level 2 performance (28.7%), and the fatigue index (53.8%) (Denham et al., 2015; Litleskare et al., 2020; MacPherson et al., 2011; Mohr et al., 2007; Willoughby et al., 2016). In fact, as little as two weeks of progressive running SIT resulted in a significant improvement in TTE at maximal aerobic speed (MAS) (42%) and a significant decrease in 3-km running TT (-5.7%) in trained trail runners (Koral et al., 2018). These changes appear to be underpinned by peripheral adaptations as measured by changes in the skeletal muscle arterial-venous oxygen difference (MacPherson et al., 2011). Additionally, there was a significant increase in muscle ion transport proteins, namely MCT1 and Na^+-K^+-ATPase β_1-isoform, which was associated with performance improvement (Mohr et al., 2007).

Running SIT also provides sufficient stimulus for improvements in anaerobic performance regardless of the participants' training status. For example, after a 4-week running SIT programme in young, inactive adults peak sprint speed and mean sprint speed increased by 9.3% and 6.8%, respectively (Willoughby et al., 2016). Similar magnitude of change in PPO (12%) and MPO (6%) during the 30-s sprint was previously reported in recreational runners (Nevill et al., 1989). In elite judo players, a progressive running SIT over 8 weeks resulted in an even higher increase in PPO (17%) and MPO (22%) (Kim et al., 2011). Improvements in anaerobic performance can be attributed to a higher ATP resynthesis from anaerobic metabolism (Nevill et al., 1989).

The running SIT studies reviewed so far in this section were performed on level surfaces either on the treadmill or the track (MacPherson et al., 2011; Willoughby et al., 2016; Denham et al., 2015; Koral et al., 2018). One method to further increase intensity of such training is by using different gradients (Sloniger et al., 1997). Therefore, it seems reasonable to assume that performing SIT on sloped surfaces (i.e., uphill sprint training (UST)) creates additional stimulus subsequently leading to further mechanical and metabolic adaptations (Padulo et al., 2013). For example, sprinting at a 7% slope has been shown to elicit greater acute HR, metabolic (oxygen and blood lactate) and mechanical cost compared to flat sprinting (Padulo et al., 2013). Higher bioenergetic demands of uphill sprinting occurs due to a significantly greater percentage (9%) of skeletal muscle volume activated in the lower extremity required to counteract the gravitational force compared to level sprinting (Sloniger et al. 1997).

Barnes et al., (2012) attempted to identify the optimal uphill gradient on physiological and performance measures in well-trained runners (mean ± SD $\dot{V}O_{2max}$: 63.9 ± 5.9 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$). A 6-week uphill training programme consisting of various sprint durations (8-s to 25-min) and W:R ratios (1:1 to 1:6) was performed on five different gradients ranging from 4% to 18%. Surprisingly, no specific uphill training approach was associated with greater gains in 5-km TT performance and the mean improvement over all intensities was 2%. However, greatest improvements in running economy (+2.4%) and neuromuscular characteristics were only observed at the highest intensities (i.e., shortest sprint durations). In agreement with the findings from Barnes et al.'s (2012) study, comparison between level-grade and uphill interval training on a 10% grade (10-14 bouts of 30-s maximal sprints) in well-trained distance runners (mean ± SD $\dot{V}O_{2max}$: 60.9 ± 8.5 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$) showed that both training modalities can invoke significant performance improvements in a TTE test at the speed associated with $\dot{V}O_{2max}$ (V_{max}) following 6 weeks of training (Ferley et al., 2013). Running economy, which is one of the key physiological determinants of endurance performance was also significantly increased and may explain positive changes observed in a functional performance test (Ferley et al., 2014). More importantly, the total weekly training time in the uphill group was nearly 50% less than the level-grade interval group (10-14 vs. 18-27 $min \cdot wk^{-1}$, respectively), which shows that UST can be a practical, sport-specific and time-efficient training method. Despite the use of UST in the applied setting to enhance metabolic, muscular and neuromuscular processes in distance runners (Ferley et al., 2014), there is a paucity of research on its effect on physiological responses and performance-related outcomes in team sports players.

Ibba et al. (2014) compared the acute physiological responses after two different UST protocols performed by young male football players on a 10% slope. A submaximal repeated intermittent running protocol with shorter rest periods (1:3 W:R ratio) resulted in a significantly higher HR (9.1%) compared to the repeated sprinting session with longer recovery between the sprints (1:25 W:R ratio). In contrast, the mean blood lactate was more than twice higher in the repeated sprint group ($p < 0.05$). These findings demonstrate that metabolic responses to UST are largely dependent on the protocol used. With regards to improvements in sprint-based measures, Jakeman et al. (2016) found that four weeks of progressive UST on an 8% slope significantly improved maximal sprint speed (12.1%) in semi-professional female field hockey players. A significantly higher $\dot{V}O_{2max}$ (5.3%) has been reported after an 8-week UST on a slight uphill (inclination 5-8%) performed by healthy participants (mean ± SD $\dot{V}O_{2max}$: 50.9 ± 1.8 $ml \cdot kg^{-1} \cdot min^{-1}$) (Sandvei et al., 2012). The improvement in cardiorespiratory fitness is comparable with the 7.6% increase in $\dot{V}O_{2max}$ elicited by an 8-week cycling-based SIT in recreationally active males (Barnett et al., 2004). Interestingly, the direct comparison of the effects of SIT following either a cycling or running protocol is very limited and primarily focused on the total excess postexercise oxygen consumption after both modalities (Townsend et al., 2014). This means that the mechanisms underlying the adaptations during cycling and running SIT remain largely unknown.

2.8 Conclusion

The WAnT is a popular all-out test to assess anaerobic power performance, but there is little sex-disaggregated data concerning its reliability and sensitivity. With regards to training prescription, current evidence shows that both SIT and RST protocols performed at fixed all-out intensities elicit favourable anaerobic and aerobic adaptations in healthy non-athletic and athletic populations. However, to date, most studies have used male-only or mixed-sex groups. Therefore, the adaptive responses in female participants are still not fully understood. Additionally, there is surprisingly little research on some training variables, particularly the W:R ratios and exercise modality and their modifying effects on cardiovascular, metabolic and performance responses. The rest interval is an integral part of the SIT prescription process, yet most previous research has focused on determining the optimal work interval intensity and duration. The use of only cycling exercise interventions limits the wider application of SIT and RST protocols. Accordingly, other exercise modalities, such as UST, should be considered, but the comparison between cycling and running methods is limited. A better understanding of these training variables can help optimise the prescription of SIT programmes by matching training demands with the needs of the sport and the athlete/participant. The gaps identified in this literature review will be critically discussed through the published data presented in **Chapters 3** and **4.**

Chapter 3: Published Works

The purpose of this chapter is twofold. First, to outline my philosophical positioning which is fundamental to my approach to research, but also supports understanding of the methodological link between publications. Second, to present the published works as a portfolio of evidence for the award.

3.1 Philosophical positioning

A paradigm is a set of basic beliefs (worldview) which defines the way scientific questions are framed and asked and how research is performed (Hassmén et al., 2016). Paradigms are distinguished by general assumptions upon which research is based and developed (Hassmén et al., 2016). Specifically, the beliefs held by the researcher about the nature of the world to be studied (ontology) and how knowledge is constructed (epistemology) have important implications for how research is performed (methodology) (Hassmén et al., 2016).

Positivism is the dominant paradigm of natural sciences, including physiology, the discipline which these published works are grounded in. Positivist research is framed by a realist or externalist ontology, which assumes that a single and objective reality exists (Hassmén et al., 2016). Reality, then, is driven by natural laws and mechanisms that are measurable. In addition, positivist researchers adopt a dualist and objectivist position that assumes the researcher and the researched 'object' are independent entities (Hassmén et al., 2016). The researcher is therefore capable of studying the object without influencing or being influenced by it, using empirical and mathematical methods to study measurable variables (Pisk, 2014). Based on these ontological and epistemological conditions, positivist assumptions framed the methodological approach and methods used across the published works. For instance, all studies were guided by ontological realism which posits physiological and performance changes are natural and measurable mechanisms (e.g., $\dot{V}O_{2peak}$, power output, time-trial) from which an objective reality can be established. Furthermore, objectivist positioning was achieved by use of standardised laboratory conditions (Publications 1-4) to minimise external influences and researcher bias. Even in the case of field-based studies (Publications 5 and 6) which offer more externally valid environments, use of standardised interventions (e.g., training modality) and testing protocols (e.g., estimated aerobic capacity) ensured participants were not influenced by the researcher.

3.2 Methodology of the published works

Six peer-reviewed journal articles presented in the 'Portfolio of Evidence' section below relate to the overall theme of all-out sprint testing and training. **Figure 3** is a diagrammatic representation of the methodological link and the non-chronological development between the published works. All six publications are grouped into three separate yet interconnected intervention categories – 'Testing intervention', 'Cycling all-out interventions' and 'Running all-out interventions'. Specifically, Publication 1 was a testing intervention investigating the reliability and sensitivity of the 6-s and 30-s WAnTs in male and female participants. A good level of performance reliability was found for both test durations in both sexes which validates the use of the 30-s WAnT in Publication 2 and Publication 4. Publication 2, Publication 3 and Publication 4 used all-out cycling training interventions to measure the effectiveness of RST and SIT protocols. The findings from Publication 2 showed that the type and magnitude of adaptations are dependent on the W:R ratio, which subsequently informed training prescription, namely the use of 1:8 W:R ratio in Publication 3, Publication 4 and Publication 5. Publication 5 and Publication 6 were also training interventions but used an all-out running approach in the form of UST. Publication 5 directly compared early physiological and performance adaptations following two weeks of all-out training using both modalities (cycling SIT and running UST). Whereas Publication 6 tested the efficacy of the longer (6 weeks) UST intervention on football specific physical characteristics.

Participants were all healthy, but from different performance categories based on their physical activity and competition levels. These ranged from untrained (Publication 3) and recreationally active (Publication 1 and Publication 5) participants, to competitive runners (Publication 2) as well as academy level (Publication 4) and semi-professional (Publication 6) football players. Additionally, two studies recruited both male and female participants (Publication 1 and Publication 2), one was female-only study (Publication 3) and the last three studies recruited male-only participants (Publication 4, Publication 5 and Publication 6). Finally, an average cohort age ranged from the youngest participants (15 ± 0.5 years) in Publication 4 to the oldest (39 ± 8.5 years) in Publication 2.

3.2.1 Sample size rationalisation

The research realities, specifically adherence and commitment to the all-out training and testing approach, meant that convenience sampling of motivated participants was largely implemented across all six studies. Subsequently, the portfolio captures data from participants across different demographics including targeted research with underrepresented populations in this area, such as female participants and adolescent athletes. The total sample size per study ranged from n = 8 (Publication 3) to n = 32 (Publication 2). However, the control or intervention group sizes were not higher than 10 participants (Publication 1) in any of the six publications.

The sample sizes were chosen based on practical limitations, namely time, cost, and resource allocation. Lakens (2022) has recently outlined the six most widely used approaches to justify sample size in a quantitative empirical study: 1) measuring (almost) the entire population 2) resource constraints 3) *a priori* power analysis 4) planning for a desired accuracy 5) heuristics, and 6) no justification. Time and cost are two main resource limitations faced by all scientists (Lakens, 2022), which largely determined the sample size selection in all six publications presented in this thesis. In addition, a high level of commitment from participants is required to perform the all-out sprinting, especially during training interventions, which may partly explain small sample sizes often observed in SIT studies. For example, nine was the median group size of SIT interventions included in a systematic review investigating the effects of SIT on physical performance (Hall et al., 2020). Thus, the sample sizes in Publications 1-6 are comparable to other studies in this field. However, it is noteworthy that from the methodological quality point of view only nine out of fifty-five (16%) studies included in the review by Hall et al. (2020) demonstrated *a priori* sufficient power for their statistical analysis. While underpowered studies are common in sport and exercise science research, low statistical power is associated with several problems such as overestimation of the true effect size, increased rate of type 1 (false positive) and type 2 (false negative) errors, imprecision in population estimates, and reduced replicability of findings (Abt et al., 2020). Therefore, rigorous sample size estimation is important not just from an ethical perspective, but also to help address issues of statistical power and precision of effect size estimates commonly observed in SIT research (Batterham & Atkinson, 2005; Hall et al., 2020).

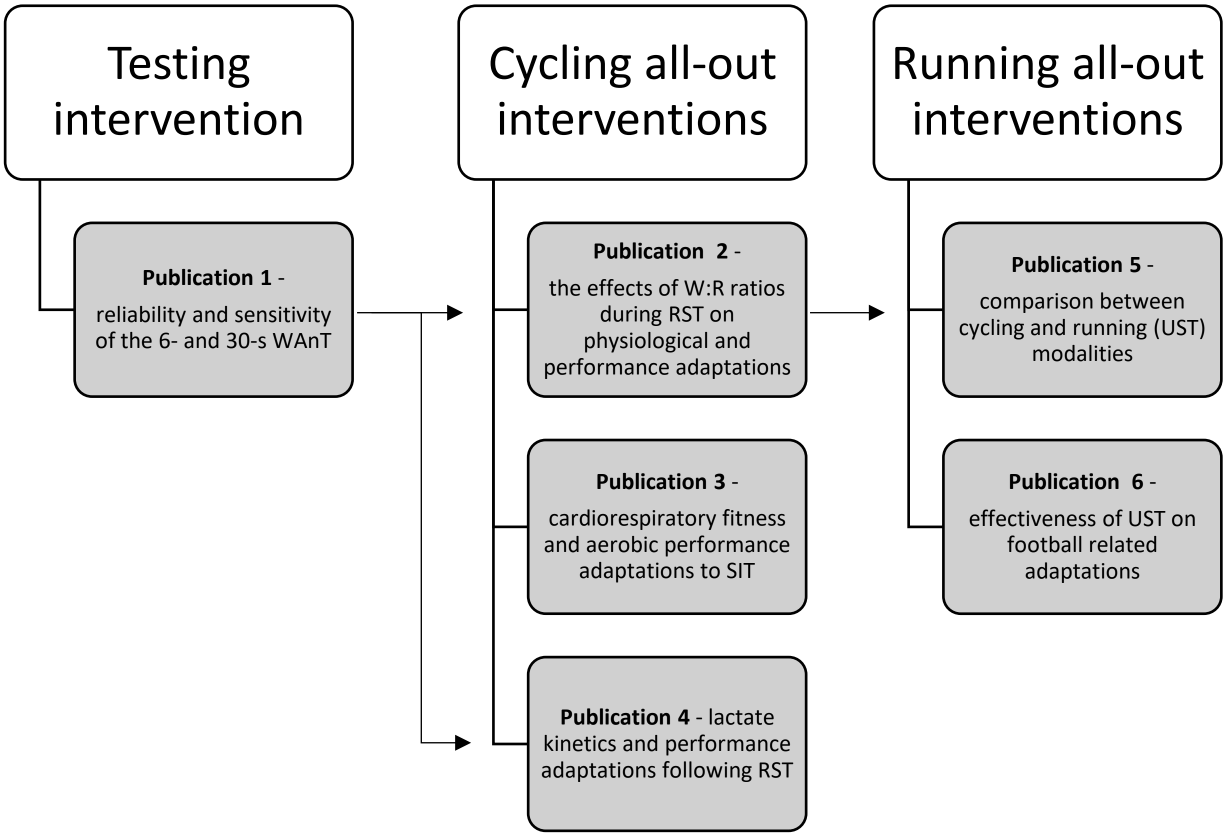

Figure 3. A schematic representation of the methodological link between the published works.

3.3 The Portfolio of Evidence

The remainder of this chapter contains six experimental studies that have been published in peer-reviewed academic journals since 2015. The studies are presented in the format of each respective academic journal. They are presented in non-chronological order to create intellectual flow between the outputs and demonstrate a coherent, significant and original body of work, as shown below.

1. **Kavaliauskas, M.,** & Phillips, S. M. (2016). Reliability and sensitivity of the 6 and 30 second Wingate tests in physically active males and females. *Isokinetics and Exercise Science*, 24 (3), 277-284. https://doi.org/10.3233/IES-160632

2. **Kavaliauskas, M.**, Aspe, R. R., & Babraj, J. (2015). High-intensity cycling training: the effect of work-to-rest intervals on running performance measures. *Journal of Strength and Conditioning Research*, 29 (8), 2229-2236. https://doi.org/10.1519/JSC.0000000000000868

3. **Kavaliauskas, M.**, Steer, T. P., & Babraj, J. (2016). Cardiorespiratory fitness and aerobic performance adaptations to a 4-week sprint interval training in young healthy untrained females. *Sport Sciences for Health*, 13, 17-23. https://doi.org/10.1007/s11332-016-0313-x

4. Thom, G., **Kavaliauskas, M.**, & Babraj, J. (2019). Changes in lactate kinetics underpin soccer performance adaptations to cycling-based sprint interval training. *European Journal of Sport Science*, 20 (4), 486-494. https://doi.org/10.1080/17461391.2019.1635650

5. **Kavaliauskas, M.**, Jakeman, J., & Babraj, J. (2018). Early adaptations to a two-week uphill run sprint interval training and cycle sprint interval training. *Sports*, 6 (3), 72. https://doi.org/10.3390/sports6030072

6. **Kavaliauskas, M.**, Kilvington, R., & Babraj, J. (2017). Effects of in-season uphill sprinting on physical characteristics in semi-professional soccer players. *The Journal of Sports Medicine and Physical Fitness*, 57 (3), 165-170. https://doi.org/10.23736/S0022-4707.16.06066-7

3.3.5 Publication 5

sports

MDPI

Article

Early Adaptations to a Two-Week Uphill Run Sprint Interval Training and Cycle Sprint Interval Training

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Received: 28 June 2018; Accepted: 26 July 2018; Published: 27 July 2018

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Abstract: This study sought to compare early physiological and performance adaptations between a two-week cycle sprint interval training (SIT) and uphill run sprint training (UST) programs. Seventeen recreationally active adult males (age = 28 ± 5 years; body mass (BM) = 78 ± 9 kg) were assigned to either a control (n = 5), SIT (n = 6), or UST (n = 6) group. A discrete group of participants (n = 6, age = 33 ± 6 years, and body mass = 80 ± 9 kg) completed both training protocols to determine acute physiological responses. Intervention groups completed either a run or cycle peak oxygen uptake (VO_2peak) test (intervention type dependent) prior to and following two weeks of training. Training comprised of three sessions per week of 4 × 30-s "all-out" sprints with a four-minute active recovery between bouts on a cycle ergometer against 7.5% of body mass in the SIT group and on a 10% slope in the UST group. The VO_2peak values remained unchanged in both training groups, but time-to-exhaustion (TTE) was significantly increased only in the UST group (pre—495 ± 40 s, post—551 ± 15 s; p = 0.014) and not in the SIT group (pre—613 ± 130 s, post—634 ± 118 s, p = 0.07). Ventilatory threshold (VT) was significantly increased in both training groups (SIT group: pre—1.94 ± 0.45 $L{\cdot}min^{-1}$, post—2.23 ± 0.42 $L{\cdot}min^{-1}$; $p < 0.005$, UST group: pre—2.04 ± 0.40 $L{\cdot}min^{-1}$, post—2.33 ± 0.34 $L{\cdot}min^{-1}$, $p < 0.005$). These results indicate that UST may be an effective alternative to SIT in healthy individuals.

Keywords: high-intensity interval training; training adaptations; lactate; ventilator threshold

1. Introduction

Cycle sprint interval training (SIT) consisting of repeated brief "all-out" cycle sprints interspersed with recovery periods offers a time-efficient alternative to traditional endurance training [1]. A commonly studied SIT protocol involves 30-s Wingate tests against 7.5% of body mass repeated four to six times separated by 4 min of recovery [2]. For example, six sessions of SIT performed over two weeks have been shown to improve skeletal muscle oxidative metabolism and cycling time to exhaustion in recreationally active individuals [3]. Seven weeks of progressive SIT in healthy men significantly increased glycolytic and oxidative muscle enzyme activity, maximum short-term power output, and maximal oxygen uptake (VO_2max) [4]. Similarly, aerobic and anaerobic adaptations as demonstrated by improvements in a 5-km cycling time trial, VO_2max, peak, and average power output have been found after two weeks of SIT in healthy, young adults [5].

Although SIT offers a low-volume training paradigm with significant health and performance benefits, previous studies mainly used specialized cycle ergometers to control the intensity of the exercise [3–6]. While cycle ergometers are accurate, they are not always ecologically valid and may be relatively costly to acquire. The uphill sprint training (UST), which is also called running SIT, may offer a viable option in the training prescription "menu" to elicit training adaptations in a short time frame without needing access to any specialized equipment. However, it may not always be possible to complete the UST outdoor where weather and/or a suitable incline cannot be controlled. Since there are both advantages and disadvantages to these training approaches, it would be of use to understand to what extent these approaches can be used interchangeably to allow practitioners the scope to select the most appropriate training approach for their need.

Previous research has demonstrated that UST is an effective training modality in a range of exercise programs and athletic activities. For example, eight weeks of UST has been shown to increase VO_2max and insulin sensitivity and reduce plasma low density lipoprotein-cholesterol in healthy young participants [7]. Similarly, a more recent study by Willoughby et al. [8] found that four weeks of UST improves cardiorespiratory and anaerobic fitness in young and middle-aged adults. In addition, the efficacy of UST has been demonstrated in athletic populations including the semi-professional male soccer players [9], semi-professional female field hockey players [10], and well-trained distance runners [11]. While both sprinting protocols appear to lead to similar improvements in cardiorespiratory fitness in non-athletic populations (cycling—6.2–7.8% [12,13], running—3.9–11.5% [9,10], no studies have directly measured early physiological responses between SIT and UST in healthy, recreationally-trained male adults.

Therefore, the primary aim of this study was to compare early physiological and performance adaptations, which is represented by peak oxygen uptake (VO_2peak), time-to-exhaustion (TTE), and the ventilatory threshold (VT) following six sessions of SIT and UST performed over two weeks. The secondary aim was to determine acute physiological responses following both protocols to help understand mechanisms underpinning the training adaptations. We hypothesized that six sessions of UST would lead to similar early physiological adaptations compared to SIT.

2. Materials and Methods

2.1. Participants

Seventeen healthy, recreationally active men (minimum 3 sessions per week of 45 min with moderate intensity exercise) participated in the training study. Participants were randomly allocated to a control group (CG), sprint interval training (SIT) group, or an uphill sprint training (UST) group. A discrete group (DG) of 6 participants completed both training protocols to determine acute physiological responses. The characteristics of the participants are presented in Table 1.

All groups were asked to continue with their regular daily activities and training programs throughout the study period. Participants were also asked to refrain from any vigorous exercise 24 h before each test. The participants were informed of the experimental protocol both verbally and in writing before giving informed consent. The study protocol was approved by the Abertay University Ethics Committee and conducted in accordance with the Declaration of Helsinki.

Table 1. Characteristics of all participants (mean ± standard deviation).

Characteristic	CG (n = 5)	SIT (n = 6)	UST (n = 6)	DG (n = 6)
Age (years)	27 ± 4	32 ± 7	25 ± 5	33 ± 6
Body Mass (kg)	77 ± 9	74 ± 8	84 ± 9	80 ± 9
BMI (kg·m^{-2})	25 ± 4	23 ± 2	26 ± 3	25 ± 3

2.2. Procedures

2.2.1. Baseline Testing

After reporting to the Human Performance Laboratory, the UST group completed only the run VO_2peak test and the SIT group completed only the cycle VO_2peak test. The control group completed both run and cycle VO_2peak tests in a randomized fashion separated by a minimum of 48 h.

2.2.2. Run VO_2Peak

Participants performed an incremental treadmill test to volitional exhaustion on a motorized treadmill (H/P/Cosmos Mercury, Nussdorf-Traunstein, Germany) to determine VO_2peak via breath by breath analysis (Metalyzer®3B gas analyzer, Cortex, Leipzig, Germany), which was described by Harling et al. [14]. In addition, time-to-exhaustion (TTE) was recorded using a Quantum 5500 stop clock (EA Combs Ltd., London, UK). Participants performed a standardized warm-up on a treadmill for 5 min at 7.5 $km \cdot h^{-1}$. The incremental test then began at 10 $km \cdot h^{-1}$ with the speed increased by 1 $km \cdot h^{-1}$ every minute until volitional exhaustion. At the end of the test, participants walked on the treadmill for 5 min at 5 $km \cdot h^{-1}$ at a 0% inclination. The VO_2peak calculated as the highest oxygen consumed over a 30-s period and ventilatory threshold was calculated using the V-slope method [15].

2.2.3. Cycle VO_2Peak

Participants performed an incremental cycling test to volitional exhaustion to determine the VO_2peak using breath by breath analysis (Metalyzer®3B gas analyzer, Cortex, Leipzig, Germany). The test was designed to produce a similar time to exhaustion as the run VO_2peak test described above. The TTE was recorded using a Quantum 5500 stop clock (EA Combs Ltd., London, UK). The participants performed a 5 min warm up cycling at 60 W (Monark 894E Peak bike, Monark Exercise AB, Vansbro, Sweden). The test then began with the participant cycling at 60 W for 1 min and the intensity increased by 25 W every minute until volitional exhaustion or the participant could not maintain a cadence of 60 $r \cdot min^{-1}$. During the test, participants could pedal faster than 60 $r \cdot min^{-1}$. At the end of the test, participants cycled for 5 min at 30 W. The VO_2peak calculated as the highest oxygen consumed over a 30-s period and the ventilatory threshold was calculated using the V-slope method [15]. Both VO_2peak tests were repeated after two weeks for the control group and three days after the completion of training for the intervention groups. All tests were performed within 2 h of the same time of the day.

2.2.4. Sprint Interval Training Protocol

The SIT protocol was similar to the protocol used previously [16]. Six sprint interval sessions were spread over 14 days with a minimum of 24 h of rest between sessions. Each training session consisted of 4 × 30-s "all-out" cycling efforts against 7.5% of body mass with 4 min of active recovery between sprints (1:8 work-to-rest ratio). Resistance was automatically applied to the cycle ergometer (Monark 894E Peak bike, Monark Exercise AB, Sweden) once the participant was cycling at 110 $r \cdot min^{-1}$, which initiated the start of the 30-s cycle sprint. During recovery, participants remained on the bike and cycled at a low cadence (<50 $r \cdot min^{-1}$) without resistance. Peak and average power output was automatically calculated for each sprint in the six training sessions using the Monark Anaerobic Test Software version 2.24.2 (Monark Exercise AB, Vansbro, Sweden).

2.2.5. Uphill Sprint Training Protocol

The UST protocol consisted of six uphill sprint sessions spread over 14 days with a minimum of 24 h of rest between sessions. Similar to previous studies [11,17], each training session consisted of 4 × 30-s "all-out" uphill sprint efforts on a 10% slope. During a 4-minute recovery, subjects walked back down the hill to the starting position. Average power output during the uphill sprint was calculated using the following equations as described by di Prampero [18].

Work = Potential Energy = $m \times g \times d \times \sin\theta$ where m is the participants mass in kg, g is the force of gravity, d is the distance covered in 30 s, and θ is the angle of the hill.

Power = W/t where W is the work done and t is the time duration of the sprint.

2.2.6. Acute Responses to both Training Protocols

Six participants from the discrete group performed 2 × 30-s "all-out" efforts using both sprint interval and uphill sprint training protocols in a randomized order on different days separated by at least 24 h. Heart rate (Polar Electro, Kempele, Finland), VO_2, and VCO_2 (MetaMax®3B gas analyser, Cortex, Leipzig, Germany) were recorded continuously throughout the sprint and each 4 min recovery period averaged over 5 s.

2.2.7. Lactate Measurement

Fingertip blood samples were taken immediately upon completion of each sprint and compared to a sample taken prior to the training session to analyze blood lactate concentration. The skin was punctured using an Accu-check single use lancet (Roche Diagnostics, Burgess Hill, UK) and pressure applied to the finger to draw the capillary blood. The initial drop was discarded and the second drop was taken for lactate analysis using the Lactate Pro blood lactate meter (Arkray Inc., Kyoto, Japan). A cotton pad was placed on the incision and pressure applied until bleeding had stopped.

2.3. Statistical Analysis

Data are expressed as a mean ± standard deviation. Area under the curve for heart rate (HR), VO_2, and VCO_2 was calculated using the standard trapezoid rule [19]. The Shapiro-Wilk test was used to determine whether data were normally distributed and a paired sample *t*-test was used to compare the acute and training effect within a group. An unpaired *t*-test was used to compare between groups [7]. The null hypothesis was rejected at the 5% level ($p < 0.05$). Effect size between the groups was calculated using the method of Morris and DeShon for repeated measure design to allow for the correction for different sample sizes and pre-test values [20]. The effect size for the acute response was calculated as Cohen's *d*, which allows for measuring the difference between the groups in terms of their common standard deviation. For both, the effect size was defined as follows: $d < 0.2$ trivial effect, 0.2–0.5 small effect, 0.6–1.1 moderate effect, and 1.2–1.9 as a large effect [21].

3. Results

3.1. Training Results

3.1.1. VO_2Peak

At baseline, the VO_2peak was similar between training groups (SIT: 49 ± 7 mL·kg^{-1}·min^{-1}, UST: 48 ± 4 mL·kg^{-1}·min^{-1}, $p > 0.05$) and did not significantly change in both groups called SIT (pre: 49 ± 7 mL·kg^{-1}·min^{-1}, post: 49 ± 7 mL·kg^{-1}·min^{-1}, $p > 0.05$) and UST (pre: 48 ± 4 mL·kg^{-1}·min^{-1}, post: 50 ± 6 mL·kg^{-1}·min^{-1}, $p > 0.05$) after two weeks of training. However, there was a small effect size between groups with a greater change in UST ($d = 0.34$).

3.1.2. Time-to-Exhaustion

There was no significant difference in the TTE for the cycling and running protocols in the control group (running TTE: 426 ± 71 s, cycling TTE: 515 ± 102 s, $p > 0.05$). There were also no significant changes in the TTE during the cycling and running protocols in the control group after two weeks (running TTE: 426 ± 71 s vs. 441 ± 94 s, $p > 0.05$, cycling TTE: 515 ± 102 s vs. 537 ± 101 s, $p > 0.05$). At baseline, TTE was similar between training groups (SIT: 613 ± 135 s, UST: 495 ± 40 s, $p > 0.05$, Figure 1). Following 2 weeks of training, the TTE had increased by ~3% in the SIT group and ~11% in the UST group (SIT: 613 ± 135 s vs. 634 ± 118 s, $p = 0.07$, UST: 495 ± 40 s vs. 551 ± 15 s, $p = 0.014$, Figure 1). The magnitude of the change in TTE was significantly different between the training groups (SIT: 3 ± 5%, UST: 11 ± 9%, $p = 0.04$). There was a small effect size between training groups with a greater change in UST ($d = 0.34$) and a large effect size between the control group and the UST group ($d = 0.71$).

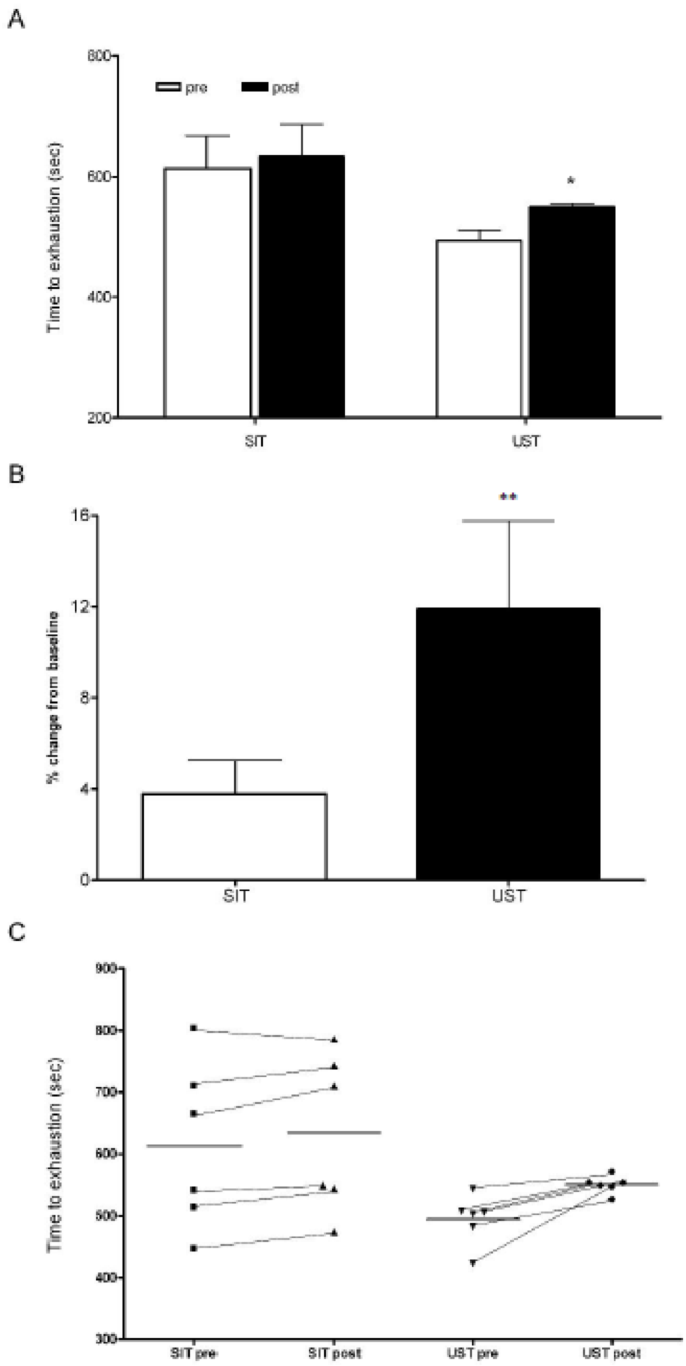

Figure 1. Absolute percentage and individual changes in time-to-exhaustion in SIT and UST groups. (**A**) Absolute changes pre-SIT and post-SIT and UST, * $p < 0.05$ pre-compared to post; (**B**) Percentage change from the baseline in SIT and UST groups, ** $p < 0.05$ SIT compared to UST; (**C**) Individual changes in time-to-exhaustion pre-SIT and post-SIT and UST.

3.1.3. Ventilatory Threshold

At baseline, there was no significant difference in the VT for either of the training group (SIT: 1.94 ± 0.45 L·min^{-1}, UST: 2.04 ± 0.40 L·min^{-1}, $p > 0.05$, Figure 2). In both training groups, the VT was significantly increased after two weeks of training (SIT: pre—1.94 ± 0.45 L·min^{-1}, post—2.23 ± 0.42 L·min^{-1}, $p < 0.005$; UST: pre—2.04 ± 0.40 L·min^{-1}, post—2.33 ± 0.34 L·min^{-1}, $p < 0.005$; Figure 2). There was no significant difference in the magnitude of change between groups (SIT: 16 ± 11%, UST: 15 ± 6%; $p > 0.05$).

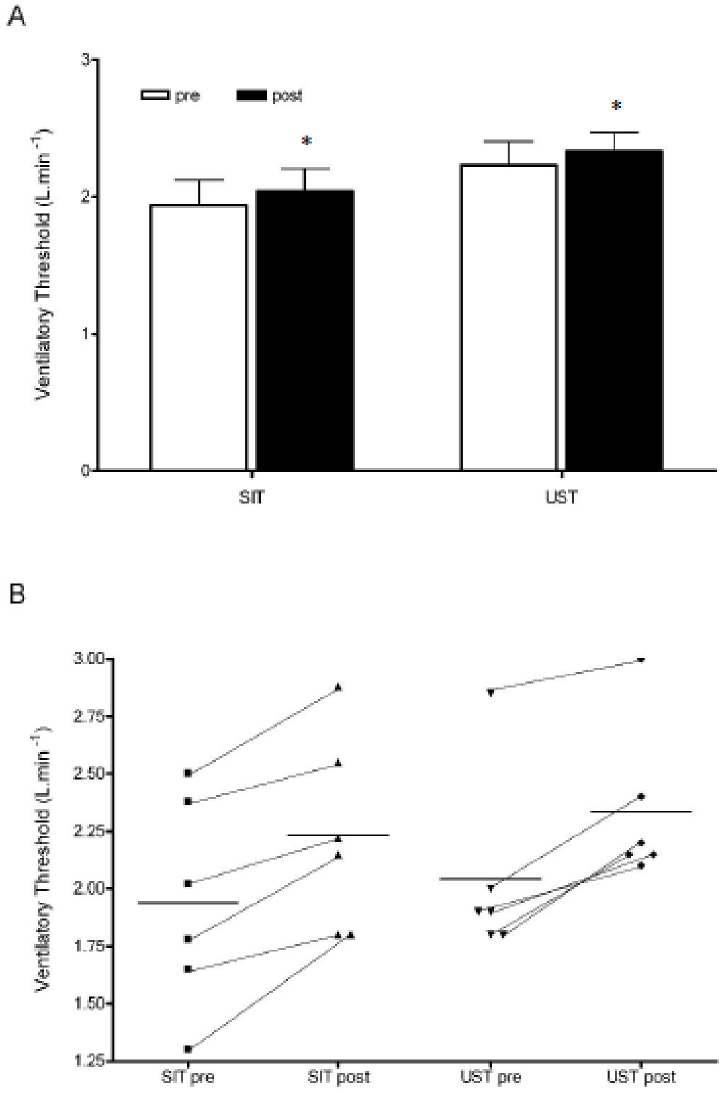

Figure 2. Absolute and individual changes in the ventilatory threshold in SIT and UST groups, (**A**) Ventilatory threshold pre-SIT and post-SIT and UST, * $p < 0.05$ pre compared to post; (**B**) Individual changes in ventilatory threshold pre-SIT and post-SIT and UST.

3.1.4. Average Power

In both groups, the average power produced was similar across all sessions (Table 2). The power drop between sprint 1 and 4 was significantly altered after UST but not SIT (UST session 1: 26 ± 4%, session 6: 14 ± 4%, $p = 0.001$, SIT session 1: 23 ± 11%, session 6: 17 ± 5%, $p = 0.18$). There was a large effect size for the power drop between the two groups with a greater improvement in UST ($d = 0.70$).

Table 2. Average power ($W \cdot kg^{-1}$) production and percentage drop-off in power between sprint 1 and 4 in all training sessions in both training groups.

Training	Sprint 1 Mean Power ($W \cdot kg^{-1}$)	Sprint 2 Mean Power ($W \cdot kg^{-1}$)	Sprint 3 Mean Power ($W \cdot kg^{-1}$)	Sprint 4 Mean Power ($W \cdot kg^{-1}$)	% Drop-Off between Sprint 1–4
SIT					
Session 1	7.7 ± 0.8	7.2 ± 0.5	6.5 ± 0.5	5.9 ± 0.8	23
Session 2	8.0 ± 0.7	7.4 ± 0.7	6.4 ± 0.8	6.3 ± 0.7	21
Session 3	8.0 ± 1.0	7.3 ± 0.6	6.6 ± 0.5	6.2 ± 0.7	23
Session 4	7.9 ± 0.9	7.3 ± 0.6	6.8 ± 0.8	6.5 ± 0.7	18
Session 5	7.9 ± 0.9	7.5 ± 0.5	6.8 ± 0.8	6.5 ± 0.6	18
Session 6	8.1 ± 0.9	7.6 ± 0.7	6.9 ± 0.6	6.7 ± 0.5	17
UST					
Session 1	7.4 ± 0.9	6.5 ± 0.9	5.6 ± 0.9	5.5 ± 0.6	26
Session 2	7.3 ± 1.0	6.6 ± 0.9	6.0 ± 1.0	6.0 ± 0.9	18
Session 3	7.0 ± 0.9	6.6 ± 1.0	6.1 ± 1.0	6.1 ± 0.8	13
Session 4	7.1 ± 1.0	6.5 ± 0.9	6.0 ± 0.8	5.8 ± 0.8	18
Session 5	7.1 ± 0.8	6.6 ± 0.9	6.2 ± 1.0	6.1 ± 0.8	14
Session 6	7.1 ± 0.8	6.5 ± 0.9	6.1 ± 1.0	6.1 ± 0.8	14

3.2. *Acute Responses of Training*

3.2.1. Blood Lactate

Blood lactate was similar between groups at the baseline (SIT: 1.9 ± 0.4 $mmol \cdot L^{-1}$, UST: 1.9 ± 0.2 $mmol \cdot L^{-1}$) and significantly higher after each sprint when compared to the baseline (SIT sprint 1: 10.2 ± 1.2 $mmol \cdot L^{-1}$, sprint 2: 14.1 ± 1.7 $mmol \cdot L^{-1}$; $p < 0.01$, UST sprint 1: 5.1 ± 2.4 $mmol \cdot L^{-1}$, sprint 2: 12.5 ± 2.2 $mmol \cdot L^{-1}$, $p < 0.001$, Figure 3). The rise in blood lactate was significantly greater after the first SIT sprint when compared to the first UST sprint (SIT sprint 1: 10.2 ± 1.2 $mmol \cdot L^{-1}$ vs. UST sprint 1: 5.1 ± 2.4 $mmol \cdot L^{-1}$, $p < 0.001$, $d = 2.70$, Figure 3). However, this difference was not significant following sprint 2, but there was still a large effect between the groups (SIT sprint 2: 14.1 ± 1.7 $mmol \cdot L^{-1}$ vs. UST sprint 2: 12.5 ± 2.2 $mmol \cdot L^{-1}$, $p > 0.05$, $d = 0.81$, Figure 3).

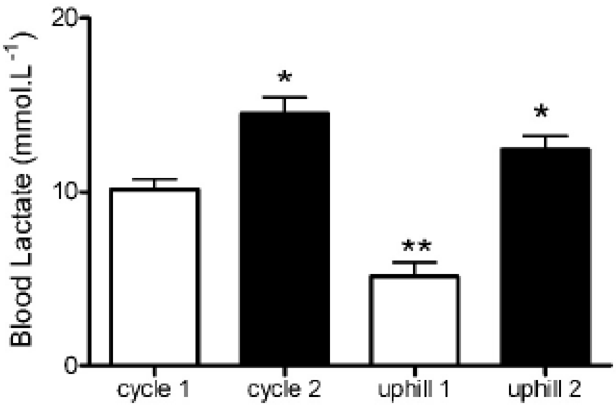

Figure 3. Blood lactate concentration following uphill run sprints and cycle sprints. * $p < 0.01$ sprint 1 compared to sprint 2. ** $p < 0.001$ cycle sprint 1 compared to uphill sprint 1.

3.2.2. Heart Rate, VO_2, and VCO_2

Heart rate increased during both SIT and UST protocols and remained elevated above resting during recovery (Figure 4A). There was no difference in the heart rate area under the curve (AUC) during both SIT and UST. However, sprint 1 in the UST group had a significantly greater AUC during recovery compared to sprint 1 in the SIT group (UST sprint 1: 36,510 ± 1119 beats vs. SIT sprint 1: 33,373 ± 2899 beats, $p < 0.05$, $d = 1.43$, Figure 4B). Heart rate AUC was significantly greater following sprint 2 compared to sprint 1 in the SIT group but not following sprint 2 in the UST group with a moderate effect between groups (SIT sprint 1: 33,373 ± 2899 beats vs. sprint 2: 36,496 ± 2954 beats; $p < 0.05$, UST sprint 1: 36,510 ± 1119 beats vs. sprint 2: 37,976 ± 1064 beats, $p > 0.05$, $d = 0.67$, Figure 4B).

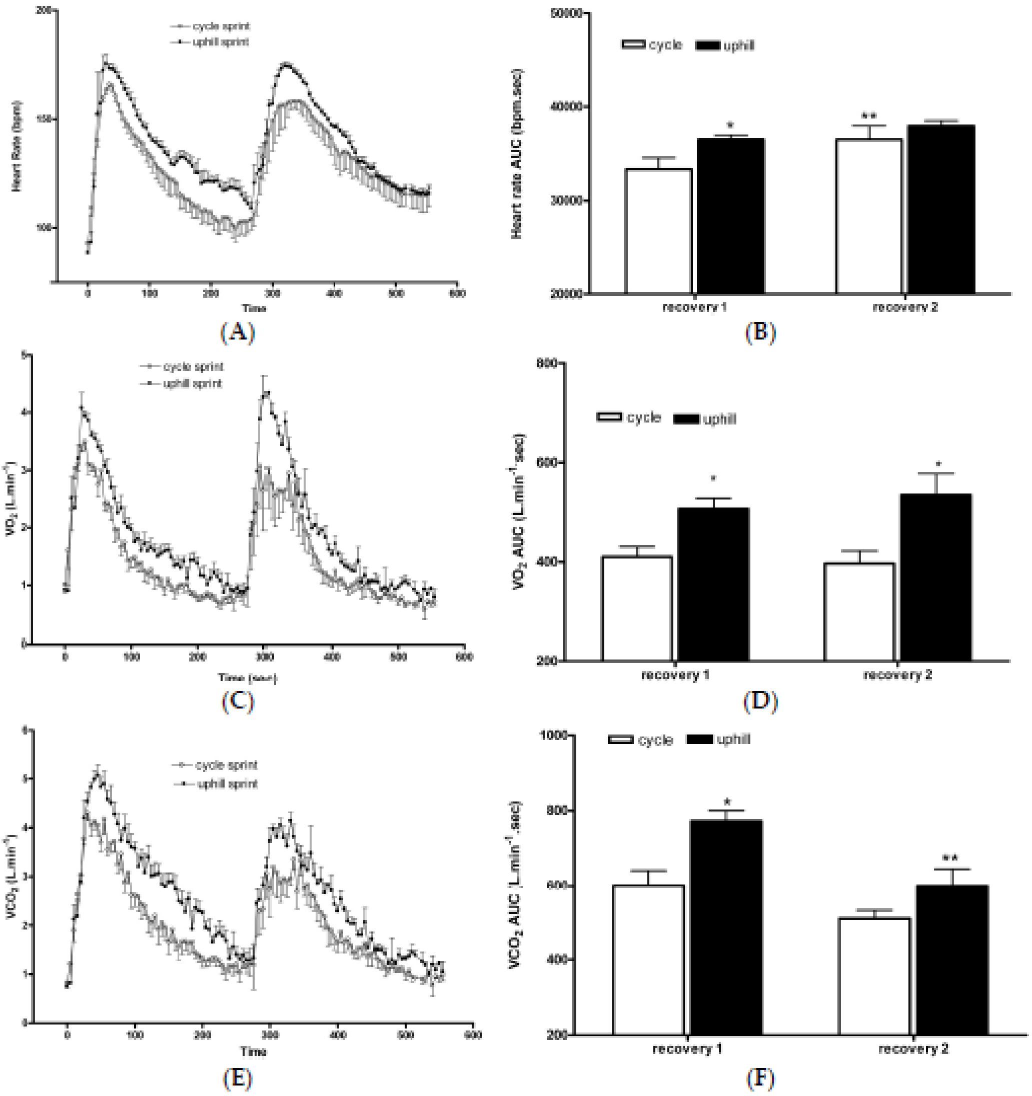

Figure 4. Changes in heart rate, VO_2, and VCO_2 during sprints and recovery. (**A**) Heart rate response; (**B**) Heart rate area under the curve, * $p < 0.05$ cycle sprint 1 compared to uphill sprint 1, ** $p < 0.05$ sprint 1 compared to sprint 2; (**C**) VO_2 response. (**D**) VO_2 area under the curve, * $p < 0.05$ sprint 1 compared to sprint 2; (**E**) VCO_2 response; F: VCO_2 area under the curve, * $p < 0.001$ cycle sprint 1 compared to uphill sprint 1, ** $p < 0.001$ sprint 1 compared to sprint 2.

VO_2 increased during both SIT and UST protocols and remained elevated above a resting heart rate during recovery (Figure 4C). There was no difference in VO_2 AUC during SIT and UST. However, the UST group had a greater AUC during the recovery of sprint 1 (d = 1.96) and 2 (d = 1.94) compared to sprint 1 and 2 of the SIT group (SIT sprint 1: 409 ± 53 mL·kg^{-1} vs. UST sprint 1: 507 ± 47 mL·kg^{-1}, $p < 0.05$, SIT sprint 2: 397 ± 52 mL·kg^{-1} vs. UST sprint 2: 535 ± 86 mL·kg^{-1}, $p < 0.001$, Figure 4D). VO_2 AUC was not different between sprint 2 and sprint 1 in the SIT group or sprint 2 and sprint 1 in the UST group ($p > 0.05$, Figure 4D).

VCO_2 increased during both SIT and UST protocols and remained elevated above resting during recovery (Figure 4E). There was no difference in VCO_2 AUC during SIT and UST. However, the UST group had a greater AUC during the recovery of sprint 1 compared to sprint 1 of the SIT group (SIT sprint 1: 601 ± 97 mL·kg^{-1} vs. UST sprint 1: 772 ± 64 mL·kg^{-1}, $p < 0.001$, d = 2.08, Figure 4F). VCO_2 AUC was significantly greater following sprint 1 when compared to sprint 2 only in the UST group but not in the SIT group with a large effect between groups (SIT sprint 1: 601 ± 97 mL·kg^{-1} vs. sprint 2: 509 ± 43 mL·kg^{-1}, $p > 0.05$, UST sprint 1: 772 ± 64 mL·kg^{-1} vs. sprint 2: 600 ± 90 mL·kg^{-1}, $p < 0.001$, d = 1.29, Figure 4F).

4. Discussion

While SIT has been shown to be an effective training modality for performance and health benefits in tightly controlled laboratory-based studies, it is not necessarily user-friendly. In the present study, we demonstrate the effectiveness of UST on a 10% incline to induce aerobic adaptations, which is represented by peak oxygen uptake (VO_2peak), time-to-exhaustion (TTE), and the ventilatory threshold (VT) that are similar in magnitude to those seen with SIT. In addition, different acute physiological responses to both training modalities are presented.

4.1. Training Adaptations

4.1.1. VO_2Peak

There were no improvements in VO_2peak over two weeks with either training protocol. This is similar to previous studies that found no change in VO_2peak following six SIT sessions performed over two weeks in eight recreationally active participants [3,22]. Conversely, others have shown a mean improvement between 6.3% to 9.3% in VO_2peak following only two weeks of SIT in young, active adults [5,23]. Two recent meta-analyses further supported the effectiveness of a 'traditional' SIT protocol on VO_2max improvement by demonstrating a likely moderate to large effect (6.2% to 7.8%) [12,13]. The differences in findings between studies can be attributed to a number of training parameters with the modifying effects on the magnitude of VO_2max. These include the maximum number of sprint repetitions in a training session, sprint duration, number of training sessions, work-to-rest ratios, baseline VO_2max, and training duration [12,13].

Contrasting effects on VO_2max have also been reported following running SIT protocols. For example, Sandvei et al. [7] demonstrated a 5.3% improvement in VO_2max in healthy, young participants following an eight-week 30 s progressive uphill (inclination 5% to 8%) sprinting protocol with a 3 min rest between each sprint. Additionally, MacPherson et al. [24] showed that running SIT, which consisted of four to six bouts of "all-out" 30-s sprints with 4 min of recovery performed three times per week for six weeks, increased VO_2max by 11.5% in healthy, recreationally active participants. In contrast, Ferley et al. [11] found no improvements in VO_2max after six weeks of UST in already well-trained participants (VO_2max—63.3 ± 8.0 mL·kg^{-1}·min^{-1}).

No changes in VO_2peak in the current study suggests that a minimum cumulative training volume required for cardiorespiratory fitness improvement has not been reached in either training group. Therefore, more studies are required to assess the effects of various training parameters and their interaction on the magnitude and time course of training-induced physiological adaptations following SIT and UST.

4.1.2. TTE

Six sessions of UST performed over two weeks resulted in an 11% improvement in TTE compared to a 3% increase in the SIT group despite no changes in the VO_2peak in both groups (Figure 1). The magnitude of the change in TTE was significantly larger in the UST group than in the SIT group (Figure 1).

Similar to the findings of the current study, Ferley et al. [11] also reported no changes in the VO_2max but did report a significant improvement of 31.7% during a functional TTE running test at the speed associated with VO_2max in response to a six-week UST in well-trained runners. A significant improvement in TTE following UST can be attributed to significantly greater aerobic metabolic demands as demonstrated by a higher heart rate (Figure 4B), VO_2 (Figure 4D), and VCO_2 (Figure 4F) values during the recovery from the sprint when compared to the SIT. It is important to mention that the differences in the TTE results between the two training groups may also be due to a relatively large variability in the SIT group, which is demonstrated by a high SD (Figure 1). Future studies should assess the effects of sprint training on TTE using a different testing protocol. For example, Burgomaster et al. [3] have reported a two-fold improvement in TTE at ~80% VO_2max following six sessions of SIT when using a continuous cycle protocol. Therefore, a continuous TTE cycle protocol at a fixed percentage of VO_2max may be a more sensitive measure for detecting improvements in fatigability than in incremental protocols. Alternatively, short time-trials (TT) have been shown to have a higher degree of ecological validity and a lower coefficient of variation (CV) scores for performance compared to TTE [25].

Nevertheless, relatively high levels of VO_2, heart rate, and ventilation, averaging above 80% of estimated maximal values, have been previously reported during and immediately after repeated SIT bouts in young, recreationally active, healthy adults [26]. This shows an increasing reliance on aerobic metabolism with each subsequent bout. The primary mechanism of adaptation to SIT involves enhancement of the supply and utilization of aerobic energy production [27]. Our results show that, compared to SIT, UST elicits even greater relative aerobic metabolic and cardiovascular responses, which subsequently leads to peripheral changes that may have an effect on muscle fatigability. As demonstrated in Table 2, average power production across all four sprints was significantly altered in the UST but not in the SIT group. The period after training both groups showed a different average power output profile between sprint 1–4. Specifically, except in session 1, the UST group demonstrated a lower absolute power drop-off between sprint 1–4, which occurred largely due to an improvement in power production in sprint 4 and little changes in sprint 1. Yet, the SIT group improved the average power production in both sprint 1 and 4, but the absolute drop-off still remained higher than in the UST group (Table 2).

4.1.3. VT

Our results demonstrate that the ventilatory threshold was significantly improved following two weeks of SIT and UST (Figure 2). The values for VT are similar to those reported previously for moderately active individuals [15]. VT has been shown to relate to lactate accumulation [15]. Following six sessions of the progressive 30-s "all-out" SIT programmer, it has been shown that skeletal muscle lactate accumulation is reduced during a two stage submaximal cycle test [3] and during a 30-s maximal sprint [28]. The decrease in lactate accumulation in skeletal muscle could be due to a decreased rate of glycogenolysis after SIT [3] or due to an increased activity of pyruvate dehydrogenase (PDH), which allows for an increased use of pyruvate in oxidative metabolism [29]. Furthermore, there is an increase in skeletal muscle MCT1 and MCT4 content after one and six weeks of 30-s sprint SIT [16], which may be linked with an increased skeletal muscle lactate uptake [30].

From a practical point of view, VT provides a better aerobic fitness index for sustainable submaximal work and competitive endurance performance than the VO_2peak [15]. Therefore, depending on their personal preference, practitioners and athletes can use either of these training modalities to improve VT and sporting performance.

4.2. Acute Responses

In the current study, the cardiovascular demand of UST and SIT was the same during the 30-s sprints (Figure 4A), which was supported by the similar average power production in each training session (Table 2). However, during the recovery phase after the first sprint, the cardiovascular demand was greater following the UST when compared to the SIT (Figure 4B). Following longer duration maximal and submaximal running and cycling heart rate has been shown to be greater for running exercise [31]. It was demonstrated that there is a lower venous return following cycling when compared to running, which results in a lower cardiac output and stroke volume [32]. Moreover, the 'muscle pump' efficiency is greater in running compared to cycling due to the erect position during running and the type of contraction performed [32]. A greater cardiovascular demand during the recovery phase in the UST group can be linked to a larger improvement in the TTE when compared to the SIT group (Figure 1).

Blood lactate concentration represents a balance between lactate production and lactate use. It has been proposed that lactate can be shuttled around the body from the site of production to other tissues or non-exercising skeletal muscle [33]. We observed that blood lactate accumulation following the first uphill sprint was significantly lower than accumulations following the first SIT bout (Figure 3). Limb blood flow has been shown to be greater after running than cycling [32] and, as such, lactate produced during the UST may have been more effectively shuttled to other tissues and non-exercised skeletal muscle than during the SIT. Additionally, a significantly greater oxygen demand (Figure 4D) and lower blood lactate concentration (Figure 3) following the first uphill sprint suggests that there may be a greater aerobic contribution during uphill sprinting when compared to SIT. This may have important practical considerations when designing training programs with the primary goal of enhancing aerobic adaptations.

5. Study Limitations

One of the limitations of the current study is a small sample size. Second, participants' training background was not controlled, but the randomization process should limit the possibility of it having an effect on the current findings. In addition, training protocols were only matched for the total duration of work (2 min), recovery (16 min), and the work-to-rest ratio (1:8), but not for the total work. However, average power outputs presented in Table 2 suggest that the external training load was similar in both training groups. Future studies should evaluate the magnitude of physiological adaptations when the total work is constant between the two different training groups. Therefore, there is a need for larger and longer studies to compare adaptations in response to the UST and SIT protocols.

6. Conclusions

In conclusion, we demonstrate that UST on a 10% incline results in similar training adaptations compared to an SIT protocol. From a practical point of view, this offers a free ecologically valid training modality to the 'traditional' laboratory-based SIT method. The mechanisms underpinning the training adaptations for this type of exercise still need to be elucidated. However, improvements in lactate metabolism are similar between both training regimens. The metabolic demands of a single training session are greater following the UST protocol with greater VO_2, VCO_2, and heart rate during the recovery from the sprint. However, these higher metabolic demands post-exercise were not related to increased blood lactate accumulation following uphill sprinting.

Author Contributions: Conceptualization, J.B. Formal analysis, M.K. and J.B. Investigation, J.B. and J.J. Methodology, J.B. Vizualization, M.K. and J.B. Writing—original draft, M.K. Writing—review & editing J.B., J.J., and M.K.

Funding: This research received no external funding.

Acknowledgments: The authors thank the participants for their time and effort.

Conflicts of Interest: The authors declare no conflict of interest.

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3.3.6 Publication 6

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J Sports Med Phys Fitness 2015 Dec 03 [Epub ahead of print]

THE JOURNAL OF SPORTS MEDICINE AND PHYSICAL FITNESS
Rivista di Medicina, Traumatologia e Psicologia dello Sport
pISSN 0022-4707 - eISSN 1827-1928
Article type: Original Article

The online version of this article is located at http://www.minervamedica.it

Effects of in-season uphill sprinting on physical characteristics in semi-professional soccer players

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Congresses: N/A
Funding: There was no funding
Conflicts of interest: There were no conflicts of interest
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ABSTRACT

Aim. Soccer performance is determined by a number of physiological adaptations that can be altered by high intensity training. However, the effectiveness of using an uphill sprint based protocol has not been demonstrated for soccer players. We sought to determine the effectiveness of an in-season uphill sprint training (UST) programme on soccer related physiological outcomes.

Methods. 14 male soccer players (age: 22 ± 8 years, height: 1.81 ± 8 m, body mass: 76 ± 12 kg) underwent testing (5-10-5 agility drill, Yo-Yo Intermittent Recovery Test Level 1, leg and back dynamometry & 3km time trial) at baseline and after 6 weeks of UST or normal activity. Participants were allocated to a control (n=7) or UST (n=7) group. The UST group took part in twice weekly training consisting of 10 x 10 sec sprints with 60s recovery on a 7% gradient for 6 weeks. The control group maintained normal activity patterns.

Results. 3km time trial, strength, agility and Yo-Yo performance were all significantly improved pre to post following 6 weeks of UST (Agility 3%, *d*=1.3; Strength 10%, *d*=-3.2; VO_2 max 3%, *d*=-1.4; 3-km TT 4%, *d*=1.3). In the control group 3km time trial, strength, agility and Yo-Yo performance remained unchanged after 6 weeks (Agility 0.1%, *d*=-0.2; Strength 2%, *d*=0.0; VO_2 max -0.1%, *d*=0.0; 3-km TT 1.3%, *d*=0.3).

Conclusion. Therefore in-season short duration UST is an effective way to improve soccer fitness in a time efficient manner.

Key words: High Intensity Training, Soccer, Endurance performance, Strength

Introduction

Quantification of physiological demands is complex as it is largely determined by the demands of positional groups, team tactics, opposition strategy and individual match-ups[1]. Players typically cover 10-12 km at an average intensity of approximately 70% of maximal oxygen uptake (VO_2 max) during games, thus relying on the aerobic production of energy [2]. Bishop et al.[3] suggest that a higher VO_2 max in soccer can prolong high-intensity performance, due to the greater contribution of aerobic metabolism during later sprints. Therefore aerobic metabolism becomes important in the second half of soccer games when the total distance covered and the number of high-intensity runs are reduced[4]. VO_2 max has also been associated with successful performance in soccer, with greater VO_2 max found in players of more successful clubs and national teams[4]. In addition to the high aerobic demand, the nature of the game requires players to repeatedly perform sprints, turns, tackles and jumps[5]. Therefore a high anaerobic capacity is also required to perform these types of movements[2].

Training for these diverse physical demands becomes challenging, especially during the in-season because of the high number of competitive fixtures, the need for frequent travel and because technical and tactical sessions are usually prioritised over physical training[6]. Other commitments (e.g., work/study) and accumulated fatigue may also result in a reduced physical capacity and lower performance level of soccer players as the season progresses. A significant decrease in aerobic fitness, from midseason to the end of the season, has been demonstrated in semi-professional male soccer players[7]. In contrast, Magal et al.[8] have demonstrated a significant improvement in VO_2max and sprint performance in collegiate male soccer players over the course of the soccer season. Nevertheless, seasonal changes in physiological parameters associated with soccer performance are expected to have an effect on the on-field performance of soccer players. Therefore, players and coaches face a challenge to maintain physical fitness whilst finding the time to enhance the tactical and technical qualities of the athlete.

High-intensity interval training (HIT) is a time-efficient training method defined as brief periods of intense exercise interspersed by a short recovery period[9]. Two weeks of Wingate-based HIT, consisting of 4-6 maximal 30 second sprints against 7.5% of body weight on a cycle ergometer, have been shown to improve aerobic performance and skeletal muscle oxidative metabolism[10], whilst 6 weeks of HIT appears to modify vascular function[11]. In soccer players, twice weekly aerobic HIT sessions for eight weeks, involving running on the flat, have been shown to improve aerobic capacity, lactate metabolism and running economy which subsequently results in an improved soccer performance[4, 12].

Intensity of exercise is crucial to the magnitude of training adaptation[13, 14]. Skeletal muscle adaptation to run training is directly related to the intensity of the running programme, with greater adaptations shown at >80% VO_2 peak[14]. Likewise cardiorespiratory adaptation is also greater with higher exercise intensity[13]. For sprint training the intensity can be altered via increasing mass (weighted vest, sledge), air resistance (parachute) or gradient (uphill sprinting)[15]. For example, uphill sprinting elicits a greater metabolic and mechanical cost compared to flat sprinting[15]. Despite its good ecological validity[16] and the use by coaches as a resistance-to-movement training method[17], there is little evidence of uphill sprinting as a time-efficient training method in soccer players. Acutely, uphill intermittent running produces a higher heart rate and blood lactate accumulation than uphill repeated sprinting in soccer players[18]. However, the effectiveness of a longer uphill sprinting programme during in-season on a range of physical characteristics in soccer players remains unknown. Therefore, the purpose of this study was to determine whether twice weekly shorter duration uphill sprinting training could elicit improvements in endurance, agility and strength parameters in soccer players. It was hypothesised that 12 sessions of short duration uphill sprinting training would significantly improve performance in endurance, agility and strength.

Materials and methods

Fourteen male soccer players (age: 22 ± 8 years, height: 1.81 ± 8 m, body mass: 76 ± 12 kg) from the Scottish Junior Football Association were recruited. All players had a minimum of 5 years' experience of training twice weekly and playing once weekly. Subjects were randomly allocated into 2 groups, control (age: 23 ± 7 years, height: 1.82 ± 8 m, body mass: 78 ± 14 kg, n=7) and uphill sprint training (UST) (age: 22 ± 8 years, height: 1.75 ± 8 m, body mass: 74 ± 11 kg, n=7). The control group were asked to maintain their current training and playing habits. The UST group maintained the same current training and playing whilst adding an uphill sprint protocol twice weekly. For the duration of the study all participants were requested to follow their normal diet. The study was carried out in the second half of competitive season (i.e. February to April). The study protocol was approved by the institutional Ethics Committee and conducted in accordance with the Declaration of Helsinki.

Baseline testing

Subjects carried out the following field tests after performing a standardised warm up, consisting of an aerobic warm-up of jogging for 5 minutes followed by standardised dynamic stretches.

5-10-5 agility test

Three cones were placed along a line 5 m apart and the participant straddled the middle cone and on the verbal command "go" he sprinted 5 m in a pre-determined direction (i.e., once to the right and once to the left) and touched the cone; turned and sprinted 10 m to the other cone; turned and sprinted back to the middle cone. The total time taken to complete this test was recorded in seconds using a stopwatch. Participants repeated the test twice, with 5 minutes recovery between tests, with the best time reported.

Yo-Yo Intermittent Recovery Test Level 1 (Yo-Yo IR1)

The participants were given 10 min passive recovery before performing the Yo-Yo Intermittent Recovery Test Level 1 on the football pitch. The test consisted of performing repeated 20-m shuttle runs between the starting line and finish line. Each shuttle was performed at increasing velocities with 10 s of active recovery between runs until exhaustion. The end of the test was considered when the participants had twice failed to reach the front line in time or felt unable to cover another shuttle at the dictated speed. The total distance covered during the test was recorded and then converted to a predicted VO_2 peak using the following equation: VO_2 peak = distance covered * 0.0084 + 36.4 [19].

Laboratory testing

Participants reported to the laboratory 48h after the field tests, having fasted for 4h prior to arrival. Upon arrival the participants' body composition was measured using a bioelectrical impedance analyser (Tanita TBF-300 Body Composition Analyser, Tanita Inc, USA). Participants were instructed to void their bladder prior to testing to ensure accurate assessment of body composition. Then the following performance tests were completed:

Leg and back strength

Participants stood on the dynamometer with a slight knee flexion as described previously[20] and then pulled as hard as possible. This was repeated on 3 occasions, with the average value recorded.

3-km time-trial

It has been estimated that 3 km time trials are run at 95% of VO_2 max and 92% of the velocity at VO_2 max[21] and peak running velocity during an incremental treadmill test is a good predictor of endurance performance[22]. Therefore 3km time-trial is an accurate measure of endurance performance and in soccer it has been demonstrated that enhanced aerobic endurance improves match performance[4].

Subjects rested for 5 min prior to performing a self-paced time-trial. The treadmill (H/P/Cosmos Mercury, Germany) was set at 1% gradient[23] and participants were given instructions to complete the test in the fastest time possible. The treadmill was set to an initial speed of $8km.h^{-1}$ and then the participants were free to control their own speed throughout the time-trial via a speed-up/slow down button. However, no visual feedback was given to the participants except for distance completed.

Training protocol

The 6 week training programme consisted of two outdoor training sessions per week on the days when players were not taking part in their regular training sessions. Training sessions were preceded by the standardised warm-up. Each session involved performing 10 x 10 second sprints, on a gradient of 7%, followed by a 60 second recovery period that involved walking back to the start (work-to-rest ratio 1:6). Participants were verbally encouraged to give an "all-out" effort in every sprint.

Post testing

Five days after the last training session participants repeated the baseline tests in the same order and at the same time of day (± 2h) to avoid diurnal variations in performance.

Data analysis

Data are expressed as means ± standard deviation. Data were checked for skewness and kurtosis and these values did not exceed twice the standard error, therefore the data were deemed to be normally distributed. Due to the small sample size the data were analysed using the methodology proposed by Hopkins[24] for controlled trials. The significance level was set at 0.05 ($P < 0.05$) and the Cohen's *d* effect size were calculated to quantify the magnitude of difference between groups. Further within group (pre to post) Cohen's d effect size were calculated using Morris and Deshon's equation[25]. Effect sizes were defined as follows: $d < 0.2$ trivial effect, 0.2 - 0.5 small effect, 0.6 - 1.1 moderate effect and >1.2 as a large effect[26].

Results

5-10-5 agility test

There were no significant differences in agility performance in the control group pre to post, but agility was significantly increased in the UST group pre to post (Table 1). The percentage change is significantly greater in the UST group compared to the control group (Table 2).

Leg and back dynamometry

There were no significant differences in isometric strength in the control group pre to post, but isometric strength was significantly increased in the UST group pre to post (Table 1). The percentage change is significantly greater in the UST group compared to the control group (Table 2).

Yo-Yo Intermittent Recovery Test Level 1

There were no significant differences in distance covered during the Yo-Yo test in the control group pre to post, but distance covered was significantly increased in the UST group pre to post (Table 1). The percentage change is significantly greater in the UST group compared to the control group (Table 2).

There were no significant differences in calculated VO_2 max in the control group pre to post, but VO_2 max was significantly increased in the UST group pre to post (Table 1). The percentage change is significantly greater in the UST group compared to the control group (Table 2).

3-km time-trial

There were no significant differences in time taken to complete the 3-km time-trial in the control group pre to post, but the time taken to complete the 3-km time-trial was significantly decreased in the UST group pre to post (Table 1). The percentage change is significantly greater in the UST group compared to the control group (Table 2).

Discussion

HIT interventions carried out in soccer players have previously been shown to improve sprint performance and aerobic capacity[4, 27]. However, these studies have utilised longer duration sprints, which have been performed on the flat, compared to the uphill sprint protocol of this study. This study demonstrates for the first time that 6 weeks of twice weekly uphill sprinting significantly reduces the time taken to complete a soccer specific agility test, increases estimated VO_2 peak and reduces time taken to complete a 3-km time trial (Table 1 & 2). Further, there was also a significant increase in leg and back strength (Table 1 & 2) after 6 weeks of uphill sprint training.

Time to complete the 5-10-5 agility test was decreased by 3.2% in the UST group, with a large within and between group effect size (Table 1 & 2). This improvement may reflect an increased acceleration speed following uphill sprints. It has been demonstrated that HIT involving longer duration sprints increases the acceleration phase and 40m sprint performance of soccer players[27], potentially due to greater anaerobic enzyme activity after HIT[28]. Alternatively improved neuromuscular adaptations may improve agility due to increased electrical activity[29] and more dispersed synapses[30] after HIT. These neural adaptations may improve power and work production, via increased motor unit recruitment, resulting in greater strength. Strength can be defined as the integrated response of several muscles contracting maximally during a task[31].

Agility is the ability to rapidly change direction and speed of movement as a result of a stimulus[3] and requires rapid force development and high power output, as well as the ability to perform ballistic movements[32]. It can be broken down into the time taken to reach maximum velocity[33] and is determined by the ability of the athlete to generate anaerobic power[34]. For soccer players, agility has been shown to be a key component of performance[33, 35]. Typically reaction ability over 5 to 10 m reflects game performance[35], allowing a faster change of direction and a faster sprint pace[36]. Meylan et al.[37] demonstrated that leg strength and power are important contributors to speed when changing direction quickly, with the push off action requiring a high volume of force generated.

Following 6 weeks of uphill sprint training, there was a 10% increase in leg and back strength, with a large within group effect size and a moderate between group effect size (Table 1 & 2). Ferley et al.[17] reported a significant improvement in isokinetic strength of between 3 and 5% in well-trained distance runners following 12 sessions of uphill (10% incline) sprint training. Strength improvement is generally associated with muscular hypertrophy or neural adaptations[38]. However, it is unlikely that skeletal muscle hypertrophy has occurred during the relatively short duration of the current training programme. Muscle hypertrophy is normally only detected after 8-12 weeks of resistance training[39] and we see no change in body mass (data not shown). Likewise, others have reported no change in % muscle mass in young adults following 8 weeks of uphill running HIT[40]. Therefore it seems likely that the increase in strength is due to neural adaptations rather than hypertrophy and importantly for soccer players occurs without any increase in body mass, as extra weight can impair performance[2].

Uphill sprint training has been shown to increase VO_2 peak by approx. 6% after 8 weeks[39] and is similar to that reported for cycle based HIT protocols[11]. In the current study we report a 3% increase in VO_2 peak after 6 weeks of uphill sprinting training as assessed by the Yo-Yo IR1 test, with a large within group effect size but a small between group effect size (Table 1 & 2). Further there was a 4% decrease in time taken to complete a 3km time trial, with a large within group effect size but a small between group effect size (Table 1 & 2). This suggests a small improvement in aerobic metabolism following 6 weeks of uphill sprinting, which may reflect the length of recovery given. A recent study by Kavaliauskas et al. Has demonstrated that a work to rest ratio of 1:3 produces greater aerobic adaptations compared to 1:8 or 1:12 work to rest ratios[41]. Ferley et al.[17] report an 8% improvement in submaximal endurance performance when running at 60 and 80% of lactate threshold velocity after 6 weeks of uphill sprint training. It has long been established that intensity of exercise is crucial to the magnitude of training adaptation[14]. Following cycle based HIT, improvements in aerobic metabolism have been shown to be largely regulated via increased mitochondrial density and activity[10] leading to improved time trial performance. With shorter duration cycle based sprints there is a rightward shift in the blood lactate curve resulting in improved time trial performance[41]. Therefore it seems reasonable to assume similar muscular adaptations are underpinning the improvement in aerobic performance in the current study. In soccer, improvements in aerobic capacity have been shown to increase distance covered and the total number of sprint performed during game play [31].

Conclusions

In conclusion, this study demonstrated for the first time that short duration uphill sprint training (consisting of 10 second sprints) completed in addition to usual training improves agility, endurance and strength measures in semi-professional male soccer players. Therefore, coaches and sport scientists can use uphill sprinting as a time-efficient training method, that is easily accesable, to optimise in-season training programmes. Future studies should look at the applicability of this type of training within an elite setting or the effect of sprint duration on performance adaptations.

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TITLES OF TABLES

Table 1.- Absolute changes in performance outcomes in the control and UST groups.

Table 2. - Percentage changes in performance outcomes in the control and UST groups.

Table 1.- Absolute changes in performance outcomes in the control and UST groups.

	CONTROL			UST		
	Pre	Post	*d*	Pre	Post	*d*
5-10-5 agility (s)	6.02 ± 0.14	6.03 ± 0.14	-0.2	5.96 ± 0.16	5.77 ± 0.23[a]	1.3
Leg & back dynamometer (kg)	131 ± 16	131 ± 23	0.0	127 ± 10	139 ± 11[a]	-3.2
YO-YO R1 test (m)	1164 ± 438	1171 ± 433	-0.1	1468 ± 409	1643 ±382[a]	-1.5
YO-YO R1 test (ml.kg^{-1}.min^{-1})	46.2 ± 3.7	46.2 ± 3.7	0.0	48.8 ± 3.4	50.2 ± 3.2[a]	-1.4
3km time trial (s)	1063 ± 127	1046 ±113	0.3	872 ± 70	835 ± 54[a]	1.3

[a] = $p<0.05$ pre versus post; *d* = within group cohen's d effect size

Table 2. - Percentage changes in performance outcomes in the control and UST groups.

	CONTROL % change	UST % change	*d*
5-10-5 agility	-0.1 ± 0.8	3.2 ± 3.3[a]	-1.4
Leg & back dynamometer	1.9 ± 4.9	-10.4 ± 9.6[a]	0.7
YO-YO R1 test distance	-1.2 ± 5.5	-13.4 ± 8.8[a]	0.4
YO-YO R1 test VO_2max	-0.1 ± 0.9	-2.9 ± 2.0[a]	0.4
3km time trial	1.3 ± 4.6	4.2 ± 3.4[a]	-0.2

[a] = $p<0.05$ UST compared to control; *d* = between groups Cohen's d effect size

Chapter 4: General Discussion

The aim of this chapter is to demonstrate how the six published works presented in **Chapter 3** form a coherent, original, and significant body of work on all-out sprint testing and training (see **Figure 3**). The originality and significance of each output are evaluated using the following criteria outlined in the Research Excellence Framework (REF) 2021:

> **Originality** - the extent to which the output makes an important and innovative contribution to understanding and knowledge in the field.
>
> **Significance** - the extent to which the work has influenced, or has the capacity to influence, knowledge and scholarly thought, or the development and understanding of policy and/or practice.

To do this, each output's contribution to current knowledge and understanding of the topic is presented, including discussion around supporting or contrasting evidence from literature that cited the output. To that end, **Table 4** shows the number of times each publication has been cited in peer-reviewed articles, professional outputs, and other scholarly work.

In addition, the importance of the published works was also highlighted during Edinburgh Napier University's internal REF inclusion and scoring processes which included three of the six publications (Publication 1, 2 and 3) presented in this portfolio. All three publications were submitted to Edinburgh Napier University's MiniREF Exercise (June 2018) and were assessed as 3*, thereby highlighting their scientific rigor and impact. The novelty and significance of each publication are outlined in greater detail below. Practical applications and future research recommendations are also provided throughout the chapter based on the findings of all six publications. This chapter is concluded by presenting personal reflections of my development as a researcher, including the extent of the contributions made to each publication.

Table 4. The impact factor of publishing journal (source: 2021 Clarivate Analytics) and the number of citations of each publication (source: Google Scholar, May 2022).

Publication	Impact Factor	Citations
1	0.52	11
2	3.78	29
3	Not rated	17
4	4.05	1
5	Not rated	6
6	1.64	13

4.1 Publication 1

Validity, reliability, and sensitivity are three important factors that contribute to a good performance test (Currell & Jeukendrup, 2008). Sensitivity can be described as the ability to detect small, but practically important changes in performance (Currell & Jeukendrup, 2008). For the test to be useful it must be adequately sensitive to detect adaptations after a training programme (Bok & Foster, 2021). The higher the test sensitivity, the more useful it is for knowing that the change in the outcome truly reflects training effects and not just a variation within the participants tested (Bok & Foster, 2021). While the 30-s WAnT has been previously reported to be valid and reliable (Bar-Or, 1987), sensitivity data are sparse. Similarly, before abbreviated WAnT protocols, including the maximal 6-s cycling test, can be used in research and practice, their reliability and sensitivity must be established.

Given that WAnT is a widely used method to assess the effectiveness of training interventions and monitor participant anaerobic power progress over time, sensitivity data would allow researchers and practitioners to evaluate its usefulness for detecting changes in performance. Also, despite previous suggestions that non-athletic females may appear to be less reliable in power measures than non-athletic males (Hopkins et al., 2001), there is little sex-disaggregated data concerning reliability and sensitivity of the WAnT protocols. This is because most previous studies have tested only male participants (Attia et al., 2014; Herbert et al., 2015; Jaafar et al., 2014; Mendez-Villanueva et al., 2007) with much less focus on female-specific normative data (Stickley et al., 2008; Zajac et al., 1999). Indeed, studies reporting reliability and sensitivity data in female participants performing shorter than 10-s WAnT protocols are lacking. Therefore, **Publication 1** was original in that it was the first paper to determine the absolute and relative performance reliability and test sensitivity of shorter (6-s) and longer (30-s) WAnT protocols over repeated trials in males and females. The outcome measures were PPO and MPO because they are the two most commonly reported and discussed anaerobic performance variables (Driss & Vandewalle, 2013).

Publication 1 results showed no significant changes in PPO and MPO across all four trials for both test durations (6- and 30-s) in males and females. Therefore, unlike previous suggested by Hopkins et al. (2001), physically active females are not less reliable in cycling power measures during the WAnT than nonathletic males. This is a very important finding, which adds to the sport and exercise field where there is a significant underrepresentation of female participants as they have been shown to represent <40%

of the total number of participants (Costello et al., 2014). Between-trials comparisons in both tests revealed a smaller random variation as measured by the standard error of measurement (SEM) in male PPO and MPO (≤3.9% and ≤2.9%, respectively) compared to female PPO and MPO (≤6.5% and ≤5%, respectively). Further analysis across all four trials of the 6- and 30-s sprints demonstrated a notably lower random variation for female PPO in trials 3-4 than trials 1-2. Female MPO was more stable across all trials during the 30-s test with the smallest variation (SEM 2.7%) between trials 1-2 in the 6-s sprint. With regards to the sensitivity of both tests, the smallest worthwhile change (SWC) was generally marginal (i.e., SEM > SWC) for both sexes. Across all four trials, only male MPO in the 30-s test displayed good test sensitivity (SEM < SWC).

Publication 1 findings have important implications for testing and training. From a testing standpoint, it is the first study to report non-significant changes in PPO and MPO during the repeated trials of the 6-s WAnT in both males and females. The 6-s WAnT therefore offers a good alternative to the 30-s WAnT making it more accessible to untrained and clinical populations. Furthermore, the shorter 6-s WAnT can provide more accurate indication of anaerobic power with greater relevance to athletes requiring short bursts of maximal-intensity efforts (Bishop et al., 2001).

No significant changes in PPO and MPO during both sprint durations suggest that researchers or practitioners may not require to do a familiarisation session to control for practice effects. However, it is recommended to familiarise female participants to both Wingate protocols using at least two familiarisation sessions as that would help detect genuine mean changes in PPO. This is an important finding that can improve the quality of future studies, especially when our recent methodological evaluation of SIT studies discovered limited reporting of familiarisation sessions (Hall et al., 2020). The testing results also add to the limited female-specific normative data for the maximal 6- and 30-s WAnTs, which can be used for comparison purposes. It is important to note, though, that all testing sessions in Publication 1 were performed on the mechanically braked cycle ergometer (Monark Ergomedic 894E, Sweden), so caution is required when comparing data collected using different types of ergometers. A recent study by Lunn and Axtell (2019) reported significant differences in absolute anaerobic power values (PPO, MPO and FI) between the Monark Ergomedic 894E and the Lode Excalibur Sport cycle ergometers, and a true proportional bias for all measures, including large effect sizes for PPO. This further demonstrates that due to differences in sprint durations, populations, protocols and equipment used, direct comparison of anaerobic power performance should not be made between the studies.

The generally marginal sensitivity of both sprint durations reported in males and females may be explained by participants' training status, which highlights another important practical application. Testing a sample of physically active participants unfamiliar with cycle sprinting using the 6- and 30-s WAnT does not provide sufficient sensitivity to detect SWC in PPO and MPO. Therefore, if the recruited sample does not adequately reflect the target population, then the testing results should not be used to quantify the genuine effect of an intervention. Lastly, Publication 1 appears to be the first study to show significantly higher PPO during the 6-s sprint compared to the 30-s sprint. This finding was expected since the rate of ATP provision from the anaerobic sources is higher during the maximal 6-s than 30-s sprint (Hargreaves & Spriet, 2020) and has implications for training prescription. If the primary goal of a training intervention is to improve PPO, then shorter duration sprints should be used. In addition, the generation of PPO has been previously suggested to be the main stimulus of SIT (Hazell et al., 2010), which may help explain the efficacy of training interventions using shorter sprint durations.

The impact of Publication 1 can be further demonstrated by providing the context of the citations. First and foremost, the 30-s WAnT was used in the testing battery of Publications 2 and 4. Several other experimental studies also employed the WAnT protocols as described in Publication 1 to assess anaerobic exercise performance in male and female participants (Duncan et al., 2019; Grgic & Mikulic, 2021; Pearson et al., 2021; Sarshin et al., 2020). Whereas other researchers used Publication 1 results as a basis to investigate Wingate testing further (Hernández-Belmonte et al., 2020; Lunn & Axtell, 2019; Stastny et al., 2018). For example, a study by Stastny et al. (2018) determined the effect of visual feedback on PPO during a repeated 6-s WAnT in elite male ice hockey players. The authors found that visual feedback can improve PPO during the first trial, with no further effects evident during the sixth bout of testing. Nevertheless, the study recommended providing visual feedback during all trials of WAnT to elicit peak performance. More recently, Hernández-Belmonte et al. (2020) analysed the validity and sensitivity of two time-shortened WAnTs (15- and 20-s) when compared to the 30-s test in young healthy participants. The study found a lower error and bias but higher sensitivity to individual changes for the 20-s sprint than the 15-s sprint. The authors therefore recommended the 20-s WAnT as an accurate and sensitive alternative to the 30-s test, which is less fatiguing and has potential to reduce the acute negative side effects. This provides further support for the use of time-shortened WAnT protocols, but the authors did not specify participants' gender, so it remains unclear whether their findings can be applied to both males and females.

While Publication 1 results have been used to inform the design of other research studies, there were some limitations that should be acknowledged and addressed in similar future research. Firstly, the MC phases or the information about OC use were not documented. This may have influenced the overall findings of the study, especially when some recent research suggests between-phases reductions in power and strength performance (Carmichael et al., 2021). However, most previous studies found no effect of the MC phases on the performance of anaerobic power in healthy adult females (Bushman et al., 2006; Pestana et al., 2017). Similarly, compared to normal menstruation, OC use did not influence PPO adaptations following the 4-week SIT programme in recreationally active women (Schaumberg et al., 2017). These findings provide further validation for Publication 1 data, but MC-based fluctuations in power measures should be researched further. Secondly, due to logistical reasons both the 6- and 30-s tests were completed on the same day which prevented randomisation of the order of the sprints. Lastly, the time of day was kept consistent only within-subjects but not between-subjects, so diurnal variations may have affected the testing results (Mirizio et al., 2020). Nevertheless, the impact of Publication 1 is evident in citations from a range of sport and exercise science disciplines.

4.2 Publication 2

Metabolic, enzymatic, cardiovascular and performance responses following Wingate-based training are well-documented in athletic and non-athletic populations (Bogdanis et al., 1995; Parolin et al., 1999; Rønnestad et al., 2015). The adaptive responses to SIT and RST programmes are often observed in as little as two weeks, which makes the all-out sprint training an effective method to elicit numerous health and performance benefits (Weston et al., 2014; Milanović et al., 2015). However, the type and magnitude of adaptations is dependent on numerous acute training variables and their combinations. Training programming is a complex process which involves manipulation of multiple variables such as interval intensity, interval duration, recovery intensity, recovery duration, exercise modality, number of intervals, number of series, series duration, time between series and between series recovery intensity (Buchheit & Laursen, 2013).

Consequently, researchers and practitioners are faced with a real challenge to effectively programme all-out training based on specific health and performance goals. The fact that previous all-out sprint training studies (Stepto et al., 1999; Hazell et al., 2010; Zelt et al., 2014) have mainly focused on determining the optimal work interval intensity and duration, with less research on the effects of rest intervals makes programming even more challenging. The rest period is an integral aspect of training prescription process and should also be carefully considered based on desired adaptations (Seiler & Hetlelid, 2005). Currently, there are very few cycling-based SIT and RST interventions (see **Table 2**) that have directly examined the impact of different W:R ratios on the types of adaptation. In one of the few studies by Hazell et al. (2010), the effects of three different W:R ratios (1:8, 1:12 and 1:24) were tested on aerobic and anaerobic performance. However, the total sprint duration was not matched across the three intervention groups, making it difficult to draw more definitive conclusions about the 'ideal' W:R ratio during all-out training.

A systematic review by Hall et al. (2020), of which I am a co-author, revealed that the most common W:R ratio in SIT literature is 1:8, which likely stems from the early work describing the acute and chronic effects following all-out training (Hargreaves et al., 1998; Macdougall et al., 1998; Sharp et al., 1986). However, alterations in W:R ratios during SIT have a modifying effect on cardiovascular and performance responses (Weston et al., 2014). In their meta-analysis, Weston and colleagues (2014) reported that an increase in W:R ratio has possible moderate and likely small improvements in MPO and PPO, respectively, but no modifying effects of changes in $\dot{V}O_{2max}$. These findings suggest that W:R ratio should be prescribed depending on the targeted adaptations. Therefore, **Publication 2** was original in that it measured the magnitude of change in aerobic and anaerobic performance using three different W:R ratio groups (1:3, 1:8 and 1:12) matched for total sprint duration (6 x 10-s all-out sprints). The 3-km TT was used as an ecologically valid test of endurance performance, whereas TTE and $\dot{V}O_{2peak}$ tested exercise tolerance and cardiorespiratory fitness, respectively (Currell & Jeukendrup, 2008). Similarly, WAnT PPO and MPO were used as measures of explosive and high-intensity efforts, respectively (Chamari & Padulo, 2015).

The first important finding from Publication 2 is that maximal cycling-based RST (6 x 10-s all-out sprints) provides sufficient, non-specific stimulus to improve running performance and anaerobic power measures in already trained female and male runners. The 'transferability' of training effect shown in this study has important practical implications for runners and other athletes looking for a low-volume training modality to improve performance and minimise the risk of overuse injuries. Short-term RST (6 sessions in total) on a cycling ergometer appears to be a time-efficient cross-training method with relatively fast performance gains. Therefore, it can be included in a normal sport specific training programme like in Publication 2 or used during periods when it is not possible to do high-volume training (e.g., rehabilitation or travel). The effectiveness of RST was later demonstrated in Publication 4 which used the same cycling-based protocol in academy football players.

Another important finding was that the magnitude of change in aerobic and anaerobic measures was dependent on the W:R ratio, which makes it a crucial variable when designing SIT/RST programmes. Specifically, the largest improvements in the 3-km TT (3.1 ± 4.0%) and TTE (6.4 ± 6.3%) tests were observed with the shortest recovery time (1:3 W:R ratio). This may be attributed to a greater cardiovascular demand of a training session with shorter recovery as participants in the 1:3 and 1:8 groups had significantly higher average HR when compared to the group with the longest recovery (1:12). However, $\dot{V}O_{2peak}$ did not change significantly in any of the groups, which suggests that improvements in the 3-km TT and TTE tests were associated with improvements in the anaerobic fitness. Both of those tests require endurance intensive efforts where oxidative phosphorylation is the predominant metabolic energy pathway, but given their relatively high intensity anaerobic metabolism also contributes to the energy provision (Chamari & Padulo, 2015). In fact, the importance of anaerobic fitness in strongly predicting endurance performance, including the TTE has been known for a long time (Houmard et al., 1991).

In contrast the 3-km TT and TTE results, MPO and PPO increased more with higher W:R ratios (1:8 and 1:12), but significant changes in PPO were only observed in the 1:8 group. In the two groups with longer recovery, the percentage increase in MPO was slightly larger in the 1:12 group (5.3 ± 5.9%) compared to the 1:8 group (4.6 ± 4.2%). This was reversed for PPO where the 1:8 group displayed a higher improvement (8.5 ± 8.2%) than the 1:12 group (7.1 ± 7.9%). These results offer guidance on the prescription of W:R ratio when targeting aerobic or anaerobic adaptations. The 30-s rest in between 10-s sprint bouts is not long enough to resynthesise ATP/PCr required for power development, whereas 120-s rest seems to be too long to promote aerobic adaptations. Therefore, if the aim of a RST programme is to improve both aerobic and anaerobic performance outcomes, then 80-s rest seems to be optimal.

Publication 2 is the most cited publication out of those included in this portfolio (see **Table 4**). It has been cited in a range of scholarly outputs, such as professional magazines, experimental studies, systematic reviews, and invited commentaries, which demonstrates its relevance and significance. Interestingly, the study results also featured in various popular health and fitness media outlets, such as Runners World website. With regards to the contribution to the peer-reviewed literature, Publication 2 data have been included in two systematic reviews analysing the effects of HIIT and SIT on physical performance measures (Girard et al., 2018; Rosenblat et al., 2021). It also informed the practical applications section in a recent commentary by Schoenmakers et al. (2019) on the moderating role of recovery duration during HIIT. In agreement with the findings from Publication 2, the authors proposed that ≥80-s recovery in between sprint bouts during SIT and RST facilitate higher work intensities thereby benefiting power adaptations (Schoenmakers et al., 2019). Whereas shorter than 80-s recovery periods increase the overall physiological stimulus of a training session which subsequently enhances aerobic adaptations. Further evidence for the moderating effect of W:R ratios during SIT was provided in our meta-analysis with the meta-regression showing a clear difference when split by outcome measures (Hall et al., 2020). The lower W:R ratios (i.e., shorter rest periods) were more effective for aerobic outcomes with longer rest intervals having more favourable effect on changes in anaerobic measures. This therefore highlights the importance of W:R ratios in training programme planning depending on the outcome goal.

There is evidence that the findings from Publication 2 have shaped the ongoing advancement of research relating to the impact of varying W:R ratios during RST/SIT on physiological adaptations. Publication 2 has been cited in several experimental studies (Yamagishi & Babraj, 2017; Lloyd Jones et al., 2019). For example, a study by Lloyd Jones et al. (2019) reported similar PPO adaptations following 2 weeks of SIT regardless of the different W:R ratios used in the three intervention groups (1:8, 1:10 and 1:12). However, based on the previously presented information about the optimal W:R ratios for aerobic and anaerobic changes, the results by Lloyd Jones et al. (2019) are not surprising since all three groups used higher than 1:8 ratio, which appears to provide sufficient rest for greater power development in subsequent sprints. The importance of longer rest periods in between sprints for power generating potential has been further supported by Benítez-Flores et al. (2019). In contrast to Publication 2, they found no significant improvements in PPO or TW following a 2-week RST programme (6 sessions of repeated 5-s all-out sprints). However, the absence of significant improvements in power production in Benítez-Flores et al.'s (2019) study may be explained by a lower 1:5 W:R ratio compared to the 1:8 used in Publication 2. More recently, Taylor and Jakeman (2021) used the research on W:R ratio, including Publication 2, as a base theory to postulate that a relatively steep gradient during uphill sprint training (UST) modality with a short rest interval, is likely to improve aerobically characterised adaptations, and the same UST performed on the same gradient but with longer rest would result in more anaerobic adaptations. This shows that Publication 2 did not just contribute to the continuing research on the importance of W:R ratio during cycling-based RST but also helped improve understanding of another training modality (i.e., UST).

As evidenced by citing literature, the study results have implications for practice and theory, yet it was not free of limitations. All participants were competitive runners from local clubs, and as part of the inclusion criteria their minimum weekly training mileage had to be 25 miles, but the individual training volume outside the study was not monitored or controlled. Thus, an interindividual variation in the training volume could have affected training responses in this study. Also, even though 58% of participants were females (14 females, 10 males) the MC phase was not controlled in Publication 2, and no information about the use of OC was reported. As explained in Literature review chapter, these factors may have influenced the overall results by attenuating training-induced changes in $\dot{V}O_{2peak}$ and $\dot{Q}_{max}$ (Schaumber et al., 2017; Schaumber et al., 2020). However, Publication 2 was never designed to consider gender for sub-group comparisons, which fails to identify potential differences in the adaptive responses between males and females. After realising that this was a methodological weakness and there is a gap in the literature, Publication 3 was developed to examine physiological adaptations to cycling SIT in female-only participants.

4.3 Publication 3

There is a significant underrepresentation of female participants in sport and exercise research, indicating that studies predominantly include males (Costello et al., 2014). In fact, data from articles published between 2011-2013 in three leading journals in sports and exercise science revealed that only 4-13% of the studies used female-only participants compared to 18-34% and 53-78% of studies that included males-only and both sexes, respectively (Costelo et al., 2014). Unsurprisingly, very similar sex bias also exists in SIT research as recently presented in our systematic review (Hall et al., 2020). Out of the 55 articles included in the review only two studies (4% of participants) comprised all female participants, which is in line with the statistics reported in the broader sport and exercise science literature (Costelo et al., 2014; Hall et al., 2020).

This means that training recommendations for female participants are often underpinned by research conducted in males without taking into consideration biological differences between the sexes (Emmonds et al., 2019). Sex is a biological characteristic that can affect the physiological response to equivalent 'dosage' of exercise (Ansdell et al., 2020). It has been previously suggested that there may be sex-based differences in the adaptive responses to as well as recovery from SIT (Forsyth & Burt, 2019; Gibala et al., 2014). However, divergent metabolic and molecular adaptations between males and females reported in response to SIT do not appear to negatively impact improvements in aerobic and anaerobic performance (Astorino et al., 2011; Scalzo et al., 2014). This has been confirmed by a systematic review and meta-analysis showing no evidence of sex on changes in TT performance or $\dot{V}O_{2max}$ following SIT (Rosenblat et al., 2021). However, the previously discussed underrepresentation of females in SIT research was also evident in studies analysed by Rosenblat et al. (2021)

with majority of participants being male (400 males, 91 females). This further highlights the importance of female-only studies to better understand sex-specific responses to SIT. Therefore, **Publication 3** has added to the equivocal data on adaptations following SIT in female participants. Specifically, the purpose of Publication 3 was to determine whether four weeks of SIT (8 sessions in total) can improve cardiorespiratory fitness ($\dot{V}O_{2peak}$) and performance in endurance intensive tests (10-km cycling TT, TTE, and CP) in young, healthy, untrained females. These outcome measures were chosen because they have functional significance from both health and exercise performance point of view.

Publication 3 found that twice weekly cycling SIT sessions (4 x 30-s all-out sprints with 4-min rest) for four weeks do not provide adequate stimulus to significantly increase $\dot{V}O_{2peak}$. The lack of improvement in $\dot{V}O_{2peak}$ could not have been influenced by the OC as all participants were naturally menstruating at the time of the study. Despite no changes in $\dot{V}O_{2peak}$, participants significantly improved performance in the 10-km TT, TTE and CP tests. Moreover, individual data from the three endurance intensive tests showed that there was a positive yet variable level of response in all participants (n = 8). Therefore, two sessions per week of a low-volume cycling SIT offers endurance performance, but not cardiorespiratory fitness benefits in healthy untrained young females. From a practical point of view, recreationally trained female participants could use SIT as an effective, low-volume method to enhance endurance intensive performance where the predominant metabolic energy pathway is oxidative phosphorylation.

Publication 3 adds to the current body of limited literature investigating responses to SIT in female participants. This is demonstrated by the inclusion of Publication 3 in a recent systematic review and meta-analysis investigating training programming variables to maximise TT performance for differing individuals (Rosenblat et al., 2021). Additionally, Publication 3 results demonstrated that changes in performance tests are likely to be underpinned by different mechanisms. Significant improvements in endurance intensive performance tests but not the $\dot{V}O_{2peak}$ after four weeks of SIT observed in Publication 3 may be explained by peripheral (e.g., increase in skeletal muscle oxidative capacity and mitochondrial biogenesis) rather than central (e.g., increase in $\dot{Q}_{max}$) adaptations. As stated by Raleigh et al. (2018), peripheral changes are reported within 2-6 weeks of training, whereas central factors start to manifest after longer training periods (>6 weeks). This is further supported by Bostad et al. (2021) who found a 6% increase in $\dot{Q}_{max}$ following a 12-week SIT intervention in untrained young adults (6 males, 9 females). The change in $\dot{Q}_{max}$ was also associated with the larger 21% improvement in $\dot{V}O_{2peak}$. However, exploratory secondary analyses in their study revealed a potential sex-based difference in the $\dot{Q}_{max}$ response, with an increase only in males, but no change in females at any time point. This suggests that females may have a blunted response to central adaptations, specifically changes in $\dot{Q}_{max}$ following SIT regardless of intervention length. Since an increase in $\dot{Q}_{max}$ is strongly correlated with increases in $\dot{V}O_{2peak}$ in untrained and moderately trained healthy young individuals (Montero et al., 2015) it may explain why $\dot{V}O_{2peak}$ remained unchanged in Publication 3.

In contrast to Publication 3, other SIT studies reported improvements in $\dot{V}O_{2max}$ in female participants ranging from 3.6% to 19% (Weston et al., 2014; Bagley et al., 2016). For example, Scalzo et al. (2014) showed a 7.6% increase in $\dot{V}O_{2max}$ in young, recreationally active females following a 3-week SIT programme consisting of three sessions per week. Despite similarities in participants' characteristics and a total number of sessions (9 vs.

8) between Scalzo et al.'s (2014) study and Publication 3, there were clear differences in training-induced changes in cardiorespiratory fitness. Contrasting findings between the studies can be attributed to the mediating effects of training variables, namely frequency and volume, on the time course and magnitude of physiological adaptations following SIT.

In Publication 3, a 4-week SIT programme performed twice per week did not provide enough stimulus required to reach a minimum effective training dose for changes in $\dot{V}O_{2peak}$ in young, untrained females. In contrast, Scalzo et al. (2014) reported a 7.6% increase in $\dot{V}O_{2max}$ after only three weeks of SIT, but unlike Publication 3, training was performed three times per week. The differences in findings between the two studies suggest that a shorter programme duration can be offset by higher training frequency. This has been shown by Stavrinou et al. (2018) who measured the effects of different HIIT frequency on cardiometabolic health markers in healthy inactive adults. They compared the magnitude of change and the time course of adaptations after training two and three times per week. In agreement with the findings in Publication 3, two sessions per week did not significantly improve $\dot{V}O_{2peak}$ (+2.2%, $p > 0.05$, $d = 0.11$) after four weeks of training, but a group training three times per week showed significant improvements in $\dot{V}O_{2peak}$ (+11.6%, $p = 0.002$, $d = 0.47$) (Stavrinou et al., 2018). Interestingly, $\dot{V}O_{2peak}$ was significantly and similarly increased in both twice (10.8%, $p = 0.017$, $d = 0.56$) and thrice (13.6%, $p = 0.001$, $d = 0.55$) per week training groups after eight weeks of training (Stavrinou et al., 2018). Training twice per week seems to affect the time course but not the magnitude of cardiovascular adaptations. While the optimal dose-response to SIT is still incompletely understood, training frequency is an important variable determining adaptations to SIT. As previously mentioned, the potential influence of the MC phase on physiological and performance outcomes should also be considered. All participants were asked about their menstruation cycle before each testing session in Publication 3, but no hormonal analysis was done to verify the MC phases, which may have impacted the results. However, at the time of Publication 3 there was no clear guidance on how to accurately track the MC. Since then, evidence-based guidelines have been developed on how to design and conduct female-focused research using appropriate experimental designs (Elliott-Sale et al., 2021). Therefore, larger, well-controlled female-only studies are still required in this area of research.

4.4 Publication 4

The RST and SIT interventions described in Publications 2 and 3 showed generally positive effects on several aerobic and anaerobic outcomes in competitive runners and healthy untrained females, respectively. However, specific physiological mechanisms likely to explain such performance improvements were not examined in those studies. A better understanding of the mechanistic bases of all-out training can help optimise training prescription, especially when even small variations in methodology between the studies can lead to contrasting results.

Bertschinger et al. (2020) conducted an interesting study where the authors replicated a popular SIT protocol consisting of six sessions of SIT (4-7 x 30-s all-out sprints with 4-min rest) performed over two weeks in healthy untrained men. Unlike the previous similar research (Burgomaster et al., 2005; Hazell et al., 2010), the authors found no significant improvements in a cycling TTE test or $\dot{V}O_{2max}$ showing the importance of replication studies to verify effectiveness of SIT in different populations. Thus, Publication 4 was designed to measure the impact of the same RST protocol as used in Publication 2 (6 x 10-s all-out cycling sprints with 80-s recovery) on the kinetics of blood lactate and performance tests in elite male adolescent players. Furthermore, the overall responses to cycling RST in elite youth football players had not been explored. Therefore, Publication 4 adds to the ever-increasing research data on training modalities that can be effectively prescribed in elite youth football.

All-out protocols require maximal power output that heavily rely on the anaerobic metabolic pathways to meet the high absolute energy demands (Beneke et al., 2002). A strong correlation between the mechanical power performed and phosphagen and glycolytic metabolic indicators shows the high demand for ATP during a brief maximal exercise (Cheetham & Williams, 1987). A high metabolic stress is also evident in high blood lactate concentrations (BLC) observed following maximal cycling training (Psilander et al., 2010). The accumulation of lactate is dependent on the exercise intensity and during all-out training contracting skeletal muscles produce and accumulate lactate, which is either removed by oxidation in the muscle fibres or is released to the blood and removed via the cell-cell lactate shuttle (Thomas et al., 2005). In fact, maximal short-term exercise performance is positively associated with the ability to tolerate high levels of BLC as well as the ability to remove lactate (Beneke et al., 2007; Thomas et al., 2005). Thus, it is reasonable to assume that adaptations to lactate metabolism could be a key determinant of football performance where players are required to undertake repeated bouts of high-intensity exercise (Aslan et al., 2012). For example, improvements in lactate kinetics and its parameters (e.g., rates of appearance and clearance) would allow players to maintain a greater game intensity with lower lactate accumulation (Best et al., 2013). However, changes in lactate kinetics parameters following cycling-based RST and their relationship to football performance adaptations had not been investigated prior to Publication 4. This made **Publication 4** original as it aimed to determine the effects of a six week, twice-weekly RST intervention (12 sessions in total) on lactate kinetics and performance characteristics in elite male academy football players. Football is an intermittent sport characterised by frequent high-intensity actions follower by longer periods of low to moderate intensity activity (Aslan et al., 2012). Therefore, the fitness battery in Publication 4 targeted the players' ability to perform explosive sprints (20-m sprint and PPO), high-intensity efforts (MPO), endurance intensive efforts ($\dot{V}O_{2peak}$ and TTE) (Chamari & Padulo, 2015).

The RST protocol produced significant improvements in 10-20-m sprint time (-4%), PPO (+24%) and MPO (+5%) during the 30-s WAnT, TTE (+5%), but no significant changes in 0-10-m sprint performance or the $\dot{V}O_{2peak}$. Publication 4 was the first paper to use a bi-exponential four-parameter model to assess blood lactate production and clearance in response to twice-weekly RST performed for six weeks. With regards to changes in lactate kinetics parameters, there was a significant increase in the extravascular release of lactate and the rate of lactate clearance. Furthermore, improvements in anaerobically and aerobically characterised aspects of performance were correlated with different parameters of lactate kinetics. Specifically, there were significant negative correlations between the extravascular release of lactate and the maximum post-training BLC (BLC_{max}) and the 20-m sprint speed. This suggests that sprint speed is associated with the ability of skeletal muscles to generate high concentrations of lactate from anaerobic glycolysis.

These findings are supported by Beneke et al. (2002) who reported a positive correlation between the BLC_{max} and a maximal short-term exercise performance. Similarly, higher PPO and MPO during the WAnT were underpinned by a greater ability to generate ATP from anaerobic glycolysis as evidenced by strong positive correlations between the two power measures and the extravascular release of lactate and BLC_{max}. In contrast, endurance adaptations (TTE and $\dot{V}O_{2peak}$) were significantly correlated with the rate of lactate clearance, turn point, and time to maximum blood lactate accumulation. This suggests that endurance performance is underpinned by the extent of lactate utilisation.

To date, Publication 4 has been cited once (see **Table 4**) by a study that developed and validated a prediction equation of absolute and relative peak power measures using a less fatiguing force-velocity test in male football players (Nikolaidis & Knechtle, 2021). Therefore, Publication 4 findings not only add to the current understanding of the effects of RST on football related performance outcomes, but also informed new testing protocols. Additionally, the study provided a novel insight regarding the adaptations in lactate kinetics following a cycling-based RST. The significant improvements in speed (10-20-m), power (WAnT PPO and MPO) and endurance (TTE) measures were achieved by adding just 18-min per week to the regular football training sessions. While the magnitude of change in $\dot{V}O_{2peak}$ was non-significant, it was still high (+9%) and comparable in magnitude (+10.8%) to a HIIT programme with a higher weekly training volume (32 minutes) performed in elite junior football players (Helgerud et al., 2001). Therefore, cycling-based RST offers a time-efficient method to produce rapid performance adaptations in elite adolescent football players. Moreover, the improvements in performance were linked to changes in lactate metabolism. From a practical point of view, all-out training should be prescribed to target enhancement in lactate metabolism which is positively associated with an increase in performance in young football players. Despite the novel and promising findings presented in Publication 4, it remains unknown whether other forms of all-out training performed in a ‘real-world’ outside a laboratory setting would lead to similar results. This was tested in Publication 5 which directly compared the physiological and performance adaptations following two weeks of all-out training using two training modalities (SIT and UST).

4.5 Publication 5

Publications 1-4 were all laboratory-based studies to help control for confounding variables and ensure high levels of internal validity. Like most research in this area, Publications 1-4 used a specialised cycling ergometer to precisely control for the external exercise resistance set proportional to participant's body mass (7 – 7.5% of BM). However, such cycling ergometers can be costly to acquire and are not specific to running-based activities, subsequently limiting the wider application of SIT and RST protocols. As a result, it is difficult to translate research findings from SIT/RST studies conducted in a tightly controlled laboratory environment to more ecologically valid practical settings.

The lack of transfer from laboratory settings to the field may be explained by a limited understanding about varying demands on individuals using different training modalities (Taylor & Jakeman, 2021). Training modality is an important variable when designing and managing SIT programmes but has received little scientific interest (Buchheit & Laursen, 2013). The importance of training modality in SIT prescription has been confirmed by Rosenblat et al. (2021) who found that in active individuals, running led to a 1.7% greater improvement in TT performance compared to cycling. There was no effect of SIT modality in inactive individuals, but that is somewhat expected, since participants' initial training status during SIT has been found to be the most influential moderator on changes in $\dot{V}O_{2max}$ favouring sedentary individuals (Weston et al., 2014). Interestingly, the effects of training modality on TT disappeared with higher training status as demonstrated by a non-significant difference between running and cycling in trained individuals (Rosenblat et al., 2021). This suggests that both running and cycling modalities could be used interchangeably when targeting endurance adaptations, especially in trained participants. Running is a preferred exercise modality by many and is specific to the demands of running-based sports, such as football (Ross & Leveritt, 2001). Therefore, an effective running alternative to maximal cycling-based training would allow practitioners and athletes to pick training modality based on the individual needs.

Anecdotally, uphill sprinting is a popular training modality in different sports. However, there is a limited amount of scientific literature on its physiological effects with previous research primarily focusing on the biomechanics of uphill running (Padulo et al., 2013). However, there are a few studies showing that UST effectively elicits training adaptations in healthy participants (Sandvei et al., 2012), semi-professional female field hockey players (Jakeman et al., 2016), and even well-trained distance runners (Ferley et al., 2013). Based on these findings, the UST may offer a viable training modality without needing access to any specialised equipment. However, the direct comparison of the effects of SIT using either cycling or running protocol is very limited with only one study (Townsend et al., 2014) looking at the differences in the total excess postexercise oxygen consumption following both modalities. Therefore, the extent to which these training modalities can be used interchangeably and the physiological mechanisms underpinning adaptations are still not fully understood.

Publication 5 was the first study to directly compare physiological and performance adaptations ($\dot{V}O_{2peak}$, TTE and the ventilatory threshold) following six sessions of SIT and UST in healthy recreationally active males. The study also determined the acute physiological responses following both protocols to help understand the mechanistic basis of the adaptations.

Publication 5 is the first study to show that SIT and UST all-out protocols matched for the total duration of work (2 min), recovery (16 min) and the W:R ratio (1:8) result in similar magnitude physiological adaptations after two weeks of training. SIT sessions were performed on a cycling-ergometer and consisted of 4 x 30-s all-out cycling efforts against 7.5% of BM with 4 min active recovery between bouts. Whereas UST sessions consisted of 4 x 30-s all-out running sprints on a 10% slope, with 4 min active recovery between sprints. No significant improvements in $\dot{V}O_{2peak}$ were found in either training modality. There is conflicting information regarding effectiveness of a short-term SIT on changes in $\dot{V}O_{2peak}$. In support to Publication 5 results, Burgomaster et al. (2005) and Bertschinger et al. (2020) reported no improvement in $\dot{V}O_{2peak}$ following six sessions of six in recreationally active and untrained participants, respectively. Conversely, other short-term SIT studies in young, active adults found a 6.3% - 9.3% increase in $\dot{V}O_{2peak}$ (Astorino et al., 2012; Hazell et al., 2010). Contrasting effects are also evident in response to the UST with some studies showing no improvement in $\dot{V}O_{2peak}$ (Ferley et al., 2013), while a study by Sandvei et al. (2012) found a 5.3% increase. The differences in findings between studies can be attributed to several training variables, such as sprint duration, intervention length, training frequency, W:R ratios that all have the modifying effects on the magnitude of $\dot{V}O_{2max}$ (Weston et al., 2014). This once again highlights the need for replicable protocols using standardised methods to further determine the effects of SIT and UST on performance outcomes.

Despite no changes in $\dot{V}O_{2peak}$ in both training groups, there was a significant improvement in TTE in the UST group (+11%), with a smaller, non-significant change found in the SIT group (+3%). TTE is a test of exercise tolerance, so its significant changes in the UST group can be explained by the greater effect on acute aerobic metabolic and cardiovascular responses as reflected in a higher HR, VO_2, and VCO_2 when compared to the SIT. Higher acute responses following UST can also be linked with early peripheral adaptations that have a positive effect on power-generating capacity. UST is a form of resisted sprint training performed at high running speeds which helps to increase the ability of the lower limb joints to generate power (Okudaira et al., 2021). The improvement in fatigue profile was evident in a lower absolute power drop-off across four repeated all-out sprints in the UST group, which occurred largely due to an improvement in power production in the latter sprints. The final physiological variable measured in Publication 5 was the ventilatory threshold, which provides a better aerobic fitness index for sustainable submaximal work than the $\dot{V}O_{2peak}$ (Gaskill et al., 2001). The ventilatory threshold was significantly enhanced in both training groups (SIT: +16%, UST: +15%), which suggests that practitioners and athletes can use either of these training modalities to target changes in the ventilatory threshold.

From a practical perspective, the UST offers an effective and easily accessible training modality with similar, and in some variables even superior, adaptations to the commonly used cycling-based SIT protocol. In fact, if the primary training goal is to quickly enhance aerobic adaptations, then UST intervention may be more effective than SIT, which is underpinned by higher acute metabolic and cardiovascular demands. Therefore, the choice between UST and SIT modalities should be made based on the personal preference and intended purpose of the training programme. However, the effects of longer-term UST programme should be investigated further since the intervention used in Publication 5 lasted only for two weeks (6 sessions). Additionally, it is not clear whether UST is effective when performed within a structured training programme in competitive players.

4.6 Publication 6

The early physiological and performance adaptations as well as acute responses following UST and SIT were described in Publication 5. The results in that study showed that UST offers an effective, field-based alternative to cycling SIT in healthy individuals. UST is a running form of SIT which is mode-specific to most team sports, including football. However, a greater understanding of UST effects over longer period is required to help optimise training programmes. Six weeks of UST has been shown to be a practical and sport-specific method to enhance metabolic and neuromuscular performance in well-trained distance runners (Ferley et al., 2014), but little research still exists on its effectiveness in field-based players.

The time available for conditioning in competitive football is often limited (Walker & Hawkins, 2018), which presents coaches and players with a real challenge to train diverse physical demands. It is particularly challenging during the in-season when players' busy schedules limit the number of sessions dedicated to fitness development because they prioritise technical and tactical training (Mujika et al., 2009). Data on seasonal variations in fitness variables clearly support this. For example, a significant decrease in aerobic fitness and the cessation of significant improvement in vertical jump, sprint, and agility from mid-season to the end of season has been reported in semi-professional male football players (Caldwell & Peters, 2009). Such seasonal changes in physical fitness are expected to impact the on-field performance of football players. As a result, there is a continued drive to find time-efficient, practical and effective training interventions to improve or at least maintain physical fitness during the competitive season in football players.

An in-season, HIIT programme consisting of two exercises (repeated 40-m sprints and intermittent runs at 120% of maximal aerobic speed) over 10 weeks has been previously shown to significantly improve maximal aerobic speed and 40-m sprint time in professional male football players (Dupont et al., 2004). An applied study by Dupont et al. (2004) shows that it is possible to improve physical qualities during the in-season period. However, due to greater mechanical demands compared to flat sprinting, UST may provide even greater specific overload stimulus to improve running speed and power production (Okudaira et al., 2021). Acute physiological effects in young male football players showed that the maximal uphill repeated sprinting (<4-s) is suitable for speed training without increasing the metabolic demand (Ibba et al., 2014). Evidence from previously described cycling RST studies, including Publications 2 and 4, shows that shortening duration of each sprint to 10-15-s does not diminish aerobic and anaerobic adaptations (Hazell et al., 2010; Yamagishi & Babraj, 2017). Thus, it is reasonable to expect that shorter (10-s) all-out uphill sprints are just as effective as longer, 30-s sprints, which were used in Publication 5. Furthermore, shorter uphill sprints used in **Publication 6** may not just offer an ecologically valid option to induce adaptations relevant to football performance, but also help reduce the total training time spent on physical conditioning. That way coaches and players could focus on the development of tactical, technical, and psychological qualities. However, the impact of a longer UST programme on physical fitness performed in addition to regular football training had not been examined. Therefore, the originality of Publication 6 is that it aimed to determine the effects of a 6-week in-season UST on physical performance in semi-professional football players. The testing battery targeted the diverse physical qualities associated with successful performance in football and included the total distance covered during the

Yo-Yo Intermittent Recovery Level 1 (YYIR1) test, the estimated $\dot{V}O_{2peak}$, 3-km running TT, leg and back strength, and change of direction speed (Caldwell & Peters, 2009).

The final paper in the portfolio (Publication 6) is the first study to show that 6 weeks of twice weekly UST (10 x 10-s all-out sprints on a 7% gradient with a 60-s recovery) performed alongside football specific training provides a potent in-season training stimulus for physiological changes associated with explosive, high-intensity, and endurance intensive efforts. Specifically, significant improvements were observed in the YYIR1 test (YYIR1 distance +11.9%; estimated $\dot{V}O_{2peak}$ +2.9%) and 3-km running TT (-4%) post-UST. Similarly, there were significant improvements in the leg and back strength (+10%) and a 3.2% reduction in time to complete change of direction test.

Publication 6 adds to the currently limited literature on UST and its performance benefits in football players. For example, the YYIR1 results from Publication 6 were included in a meta-analysis which computed reference values for sports at different levels and sexes (Schmitz et al., 2018). This provides evidence that Publication 6 findings added to the normative data on aerobic capacity in male football players. Practitioners and players can use these data to rate YYIR1 test performance and monitor training responses. Additionally, the results from Publication 6 were included in a recent systematic review with meta-analysis comparing the effects of different HIIT programmes on male football players' physical fitness (Clemente et al., 2021). Their meta-analyses revealed significant benefits of HIIT compared to controls in $\dot{V}O_{2max}$ (p = 0.018), field-based aerobic performance (p = 0.041), repeated sprint ability (p = 0.049), but no significant effects in sprint time (p = 0.080) (Clemente et al., 2021). Furthermore, there were no significant differences in any of the performance outcomes between HIIT types, such as short- and long-interval HIIT, RST, SIT and small-sided games (Clemente et al., 2021). These findings provide further support for the inclusion of short duration UST (two sessions a week) in a normal male football players training programme as reported in Publication 6. The UST may be particularly beneficial in the second half of a competitive season when fitness markers associated with successful performance in football have been found to decrease or plateau (Caldwell & Peters, 2009). However, a greater insight into the adaptations following UST would also help compare its effectiveness to other training approaches. For example, no clear differences were observed between different conditioning programmes (resistance, plyometric, sprint training and combined methods) on high-velocity football-related tasks (García-Ramos et al., 2018). Therefore, the effects of individual training methods and their combinations on physical performance measures should be studied further in 'real-world' settings.

Since Publication 6 appeared in the literature, the efficacy of UST has been demonstrated in other team sports, specifically female and male field hockey players (Jakeman et al., 2016; Taylor & Jakeman, 2021). A shorter, 4-week progressive UST on an 8% slope led to significant improvements in straight-line (~3%) and maximal (12.1%) sprint speed measures in semi-professional female field hockey players (Jakeman et al., 2016). In a recent study, performance parameters following two maximal running SIT protocols (uphill vs. flat) were compared in male field hockey players (Taylor & Jakeman, 2021). Following eight weeks of training (16 sessions in total) both groups significantly improved squat jump, 30-m sprint speed, repeated sprint time and hockey-specific shuttle efforts. In addition, the UST protocol (performed on a 6% slope) had small, nonsignificant additional positive effects in some performance adaptations compared to flat sprinting. Even greater performance benefits were found following UST than level-grade SIT in young football players (Ferley et al., 2020). An 8-week training intervention on a treadmill compared the effects of UST (5-30% grade) and level-grade SIT performed in combination with identical plyometrics and strength training on several performance measures (Ferley et al., 2020). The UST group improved significantly more in sprint speed, change of direction, hip flexor strength, and glycolytic bioenergetics than the level-grade SIT group (Ferley et al., 2020).

Collectively, these findings suggest that when compared to running SIT on level surfaces, the UST provides a higher overload stimulus and consequently results in greater performance gains in team sports players. While further research is required to better understand how the manipulation of slope affects performance adaptations following UST, the findings from Publication 6 and other relevant studies suggest that a 6-10% gradient is appropriate for field-based athletes.

4.7 Summary of findings

This chapter has evidenced that the published works presented in this portfolio have shaped and contributed to the ongoing advancement of research relating to the all-out sprint testing and training. Specifically, the research has i) informed procedures of the 6-s and 30-s WAnTs and provided normative values for males and females, ii) contributed to the development of knowledge on the moderating role of W:R ratios during RST, iii) examined aerobic and anaerobic adaptations as well as underpinning physiological mechanisms following RST and SIT, iv) contributed to the development of research on the efficacy of UST and specific guidelines for its prescription.

The mainstream approach of hypothesis testing in this field often relies on two basic analytical techniques – *t*-tests or analysis of variance (ANOVAs) (Hecksteden et al., 2018). These statistical tests were also used across the six publications presented in the thesis. However, in the context of randomised controlled trials perfect baseline balance between the treatment groups is unlikely, and therefore such chance imbalances should be considered in data analysis (Hecksteden et al., 2018). To address this an analysis of covariance (ANCOVA) has been proposed as an alternative 'gold standard' method allowing to adjust for any imbalances between the intervention and control groups at baseline (Vickers, 2005). Specifically, in an ANCOVA the dependent variable is the change from baseline to post-intervention, the independent variable is a nominal group variable, and the baseline scores as a covariate (Batterham & Atkinson, 2005). ANCOVA has been shown to be a superior analytical approach over a group x time interaction and percentage change analyses, therefore should be used in exercise randomised control trials, including SIT/RST studies (Vickers, 2005).

4.8 Personal reflections

To critically reflect on my development as a researcher, I have drawn upon the Vitae Researcher Development Framework (RDF). The RDF identifies four domains that encompass the knowledge, skills, and personal qualities of excellent researchers. The domains are as follows:

- Domain A: Knowledge and intellectual abilities
- Domain B: Personal effectiveness
- Domain C: Research governance and organisation
- Domain D: Engagement, influence and impact

This section will evidence my development as a researcher over time and across the six, non-chronologically presented publications with reference to each of the four domains. To support contextualisation of my reflections, details of my specific contribution to each publication included in this portfolio are presented in **Table 5**.

Table 5. My and co-authors' contribution to each publication.

Publication	Authors' Percentage Contribution	Authors' Contribution
Publication 1	M.K. 50% S.P. 50%	Conceptualisation – M.K. & S.P. Formal analysis – S.P. Investigation – M.K. & S.P. Methodology – S.P. Visualisation – S.P. Writing (original draft) – M.K. & S.P. Writing (review & editing) – M.K. & S.P.
Publication 2	M.K. 70% J.B. 20% R.A. 10%	Conceptualisation – M.K., R.A. & J.B. Formal analysis – M.K. & J.B. Investigation – M.K., R.A. & J.B. Methodology – M.K. & J.B. Visualisation – M.K. & J.B. Writing (original draft) – M.K. Writing (review & editing) – M.K., R.A. & J.B.
Publication 3	M.K. 50% J.B. 40% T.S. 10%	Conceptualisation – M.K & J.B. Formal analysis – J.B. Investigation – T.S. & J.B. Methodology – M.K. & J.B. Visualisation – J.B. Writing (original draft) – M.K. Writing (review & editing) – M.K., T.S. & J.B.
Publication 4	M.K. 20% J.B. 50% G.T. 30%	Conceptualisation – J.B. & G.T. Formal analysis – J.B. Investigation – G.T. Methodology – J.B. Visualisation – M.K. & J.B. Writing (original draft) – MK & J.B. Writing (review & editing) – M.K., G.T., & J.B.
Publication 5	M.K. 50% J.B. 40% J.J. 10%	Conceptualisation - J.B. Formal analysis - M.K. & J.B. Investigation - J.B. & J.J. Methodology - J.B. Visualisation - M.K. & J.B. Writing (original draft) - M.K. Writing (review & editing) - M.K., J.J. & J.B.
Publication 6	M.K. 60% J.B. 30% R.K. 10%	Conceptualisation – M.K. & J.B. Formal analysis – J.B. Investigation – J.B. & R.K. Methodology – M.K. & J.B. Visualisation – M.K. & J.B. Writing (original draft) – M.K. & J.B. Writing (review & editing) – M.K., R.K. & J.B.

4.8.1 Domain A: Knowledge and intellectual abilities

Completing an MSc in Sports Coaching at the University of Worcester (2012) gave me base of theoretical research methods knowledge and offered the opportunity to develop fundamental practical research skills (e.g., synthesising and critically reviewing literature, forming research questions, collecting and analysing quantitative data and reporting findings). Although this was fundamental to my development of knowledge in this area, my research career really started to develop when I moved to Abertay University as Teaching Fellow in Sport and Exercise Sciences in 2012. During this appointment I developed a deep enthusiasm for research. I was able to get ample practical experience in laboratory work on a regular basis, taking part in ongoing studies and supporting research activity. Early on, I became actively involved in SIT research, a strategic research priority within the Division of Sport and Exercise Sciences at the time, which was led by Dr Babraj. He provided me opportunities to pursue my own interests in the field and supported my development of early research inquiries and ideas. On reflection, Dr Babraj's support and mentorship in these early stages has enabled my development as an independent researcher. Over the following three years at Abertay University, I contributed to the conceptualisation and design of four research studies included in this portfolio (Publications 1-3 and 6, see **Table 5**). I also started to collaborate with other researchers in the field, namely Dr Phillips (University of Edinburgh) with whom I co-authored Publication 1. Ultimately, over this period, through experience of *doing* research, developing a research profile and building networks with key researchers in the field, I developed self-confidence and passion for working in this area.

My development of effective working relationships with key researchers in this field meant that, even following my appointment as a Teaching Associate at Edinburgh Napier

University in 2015, I have remained an active member of the SIT research group at Abertay University. I continued to collaborate with former colleagues, which led to further research outputs. For example, during research group discussions, the design of Publication 4 was directly informed by my earlier work, specifically Publication 2 (see **Figure 3**). I have also co-authored two other publications on this topic that are not presented in this portfolio, but listed below:

- Adamson, S., **Kavaliauskas, M.**, Yamagishi, T., Phillips, S., Lorimer, R., & Babraj, J. (2018). Extremely short duration sprint interval training improves vascular health in older adults. *Sport Sciences for Health*, 15 (1). 123-131. https://doi.org/10.1007/s11332-018-0498-2
- Adamson, S., **Kavaliauskas, M.**, Lorimer, R., & Babraj, J. (2020). The impact of sprint interval training frequency on blood glucose control and physical function of older adults. *International Journal of Environmental Research and Public Health*, 17 (2), 454. https://doi.org/10.3390/ijerph17020454

In addition to developing knowledge through research activity, the achievement of relevant professional qualifications has been very important for the development of my subject knowledge, intellectual development and engagement in the application of evidence-based knowledge. I have been a certified strength and conditioning specialist (CSCS) through the National Association of Strength and Conditioning (NSCA) since 2010. This requires submission of an evidence portfolio every three years to demonstrate my professional development, and this has included the development of my research skills in this field. In addition, in 2017 I became a BASES Accredited Sport and Exercise Scientist (physiology support). I achieved BASES Accredited status by completing the Supervised Experience programme which allowed me to improve my specialist laboratory competencies, testing and interpersonal skills required for the effective operation when working with a range of participants. This has also informed my teaching and mentoring of undergraduate and postgraduate students who are completing research in this field. Therefore, I am able to use my own research and professional experiences to promote a research-led approach.

4.8.2 Domain B: Personal effectiveness

Continuous professional development (CPD) is very important to my approach and effectiveness in research. I regularly attend and engage in relevant research seminars and workshops organised by the University and Schools Research Degree Teams. For example, I recently attended the Researcher Skills Forum to learn more about various research related topics, including using reference management software, advice on academic publishing and advancing my academic career. Also, as a BASES Accredited Member, I actively engage with the wider sport and exercise science community by attending relevant CPD workshops and academic conferences. For example, in 2019, I attended the BASES Student Conference, which presented many excellent networking opportunities. As a result, I got invited to be part of a research group with colleagues from two other Scottish universities (Robert Gordon University and Abertay University). Subsequently I became a co-author on a systematic review with meta-analysis investigating the effects of sprint interval training on physical performance which has been published in the Journal of Strength and Conditioning Research.

To date, my academic roles have been primarily focused on teaching and learning. I have worked in post-1992 higher education institutions in roles with limited workload deployment for research and scholarly activity. This has been challenging in terms of developing and maintaining research activity and my research profile. It has taken a great deal of perseverance. Time management has been key, as well as prioritisation of research activity when the ebbs of teaching activity occur naturally in the academic calendar. Working collaboratively with colleagues including those from other universities and responding quickly to potential research opportunities has also been key to ensure my research career is maintained. While these circumstances are not unique, many academics in higher education experience similar working patterns, it demonstrates my commitment and enthusiasm to developing my research career.

By gaining a PhD I hope to progress to a lecturer role which would allow me to focus more on developing a research career. For example, a key area for my development is research funding through grant application and commercial funding. I currently have limited experience in this, but it would benefit my academic career progress.

4.8.3 Domain C: Research governance and organisation

Increasingly I have developed my knowledge of research governance, standards and organisation. I regularly undertake CPD to ensure I am up to date with the latest health and safety requirements, ethical processes and GDPR (2018) legislation associated with doing research in this field. While this has always been central to my own research practice, more recently I have had to mentor postgraduate research students through university processes which are in place to ensure these standards. As such, I have had to lead on aspects of these processes and have had responsibility for creating risk assessments for laboratory- and field-based tests. In 2019, I successfully completed a 3-day 'Induction to Supervising Research Degree' course delivered by the University Research Degree Team. This allowed me to reflect on my supervisory practices, including the challenges of ensuring these important governance processes are implemented, and discuss this with colleagues from different research disciplines across the University. This gave me the opportunity to learn about the complexities of these processes for other fields, as well as my own, and discuss potential solutions to the challenges we had identified.

4.8.4 Domain D: Engagement, influence and impact

I was responsible for writing all six publications including scoping potential suitability of journals, working with their requirements (formatting, referencing and note systems) and complying with legal requirements, intellectual property rights and copyright processes. This has also given me the opportunity to network and liaise with editorial teams and Reviewers when critically reviewing and responding to their comments. As a result of engaging with the wider scientific community, I have since become a regular reviewer for several sport and exercise journals (i.e., Sports Medicine, Journal of Sports Science & Medicine, Sports, Journal of Functional Morphology & Kinesiology, and International Journal of Environmental Research & Public Health).

In addition to publishing my work in academic journals, I have also disseminated my research to the wider academic community by presenting my research at international conferences. For example, I attended and presented at the 2018 European College of Sport Science conference. Such experiences have helped me develop the ability to discuss and defend my work publicly. This, in turn, has supported my ability to operate effectively and with confidence in peer-review processes, allowing me to carefully consider peer comments and suggestions and where necessary providing rebuttals to defend ideas and arguments.

My dissemination of research, specifically linked with Publication 2 findings, has also attracted interest from popular, but lay, publications such as Men's Journal who have cited my work. Working with popular media offered a different publication experience and presented some challenges in ensuring key and accurate messages were communicated in the final publication. However, this was not always the case because the headlines were sensationalised and some findings from Publication 2 were reported inaccurately.

Undertaking work outside of academia has also allowed me to work with diverse populations and develop the wider impact of work in my field. I have been involved in several public engagement events which have included offering free fitness tests to women as part of the Dundee Festival (2015) and sports science consultancy work with female football players from different age groups (2019). These activities support the expansion of more accessible and equitable opportunities for diverse and underrepresented groups (e.g., women) to experience the benefits of sport and exercise research.

Due to my growing research profile, in 2019 I was contacted by a student wanting to do a self-funded master's by research (MRes) at Edinburgh Napier University. Since then, the student has successfully completed his project investigating the effects of menstrual cycle phases on repeated sprint ability. More recently, I have become a supervisor on a fully funded MRes project in partnership with a professional football club. This will be a good opportunity for me to develop my knowledge and experience of working with a research budget and the internal university systems associated with this. Similarly, I have been asked to join a supervisory team on a MRes project looking at the needs analysis and training considerations for shinty at another Scottish University (University of the Highlands and Islands). This will be another new opportunity to work and supervise externally, which will require effective teamwork and leadership skills.

Collectively, I feel the evidence presented in this section represents my development as an independent research and significant contribution to a coherent body of work through which I have successfully navigated complex research processes and fundamental researcher development skills.

Chapter 5: Conclusions and areas for future research

In summary, the aim of the research portfolio was two-fold i) to investigate the reliability and sensitivity of the 6-s and 30-s WAnT ii) to measure the effects of W:R ratio and exercise modality during all-out training on physiological and performance changes. These aims were met by in part by undertaking the six studies reported on in the portfolio of published works. In addition, constructing this thesis allowed interconnection between these studies to be made more clearly thereby demonstrating a coherent body of work that is original and significantly contributes to the broader literature in this area. The nature of PhD by Published Works has meant that there was a non-linear process to this journey, but, despite this, each publication has interconnected originality, significance and rigour.

Publication 1 showed no significant differences in PPO and MPO across four trials of a 6- and 30-s WAnT in males and females. This suggests that both protocols are reliable and therefore researchers/practitioners can choose which test to use. However, when testing female participants, it is recommended to use at least two familiarisation sessions. Furthermore, test sensitivity of both Wingate tests was generally marginal in both sexes and only male MPO in the 30-s test displayed good test sensitivity.

Publication 2 was a 2-week cycling RST intervention, which found that the type and magnitude of adaptations is dependent on the prescribed W:R ratio. Specifically, greater improvements in endurance performance tests (3-km running TT, $\dot{V}O_{2peak}$ and TTE) were observed with shorter rest periods (1:3 W:R ratio), whereas improvements in MPO and PPO were higher with longer rest periods (1:8 and 1:12 W:R ratios). Therefore, the 1:8 W:R ratio during cycling RST appears to be optimal when targeting both aerobic and anaerobic adaptations.

Publication 3 demonstrated positive adaptations in laboratory tests requiring endurance intensive efforts (10-km cycling TT, TTE and CP) following four weeks of cycling SIT (4 x 30-s all-out sprints with 4-min rest) in female-only participants. However, twice weekly cycling SIT sessions did not provide adequate stimulus to significantly increase cardiorespiratory fitness ($\dot{V}O_{2peak}$) in healthy young females.

Publication 4 was the last of cycling-based interventions and used a longer RST programme in competitive adolescent male football players. A significant change in lactate kinetics following a 6-week cycling RST was associated with the improvements in different performance measures. Specifically, maximal blood lactate kinetics was shown to correlate with sprint and power performance, while endurance performance was related to maximal blood lactate clearance. The final two studies investigated the effects of exercise modality on performance changes.

Publication 5 directly compared early physiological adaptations following two weeks of cycling SIT and uphill sprint training (UST) in recreationally active males. The findings indicated that UST may offer an effective and ecologically valid alternative to laboratory-based SIT. There was a significant improvement in TTE in the UST group (+11%), with a smaller, non-significant change found in the SIT group (+3%). The ventilatory threshold was significantly enhanced in both training groups (SIT: +16%, UST: +15%), but no significant improvements in $\dot{V}O_{2peak}$ were observed either training modality. Improvements after two weeks of UST were attributed to the greater acute aerobic metabolic and cardiovascular responses (HR, $\dot{V}O_2$, and $\dot{V}CO_2$) when compared to the SIT.

Finally, Publication 6 measured effectiveness of a longer, 6-week UST to improve physical characteristics in semi-professional male footballers. Twice weekly UST performed alongside normal football training significantly enhanced endurance (YYIR1 distance +11.9%; estimated $\dot{V}O_{2peak}$ +2.9%; 3-km TT -4%), leg and back strength (+10%) and change of direction speed (-3.2%) measures.

Overall, the findings from the published works included in this portfolio have important implications for all-out testing and training prescription in research and practice. A visual framework outlining the main considerations for researchers/practitioners when using the all-out training and testing is presented in **Figure 4**. That said, several areas that warrant further investigation can be identified:

- Longer training interventions (>12 weeks) are required to better understand the chronic adaptations in response to the all-out training. Such studies should be carefully designed and controlled to ensure progressive overload through the systematic manipulation of training variables.
- The interaction effect between the training variables during all-out protocols is still largely unknown and therefore future research should consider investigating adaptations following different configurations of training variables.
- More research is still required to determine the exact dose-response relationship, especially when there may be the potential for diminishing performance returns with excess volumes of all-out training (Langan & Grosicki, 2021).
- Currently there are very few ‘real-world’ studies on the effects of all-out training (SIT/RST/UST) when used in combination with other training approaches (e.g., resistance training). Thus, future research should study all-out training as part of broader training programmes and not just in isolation.

- More empirical data using UST modality in different populations are required. Additionally, a systematic review using currently available studies in this area would further benefit training prescription and design of future research.
- Finally, all future studies on this topic should be planned with female participants in mind to help address gender imbalance in sampling.

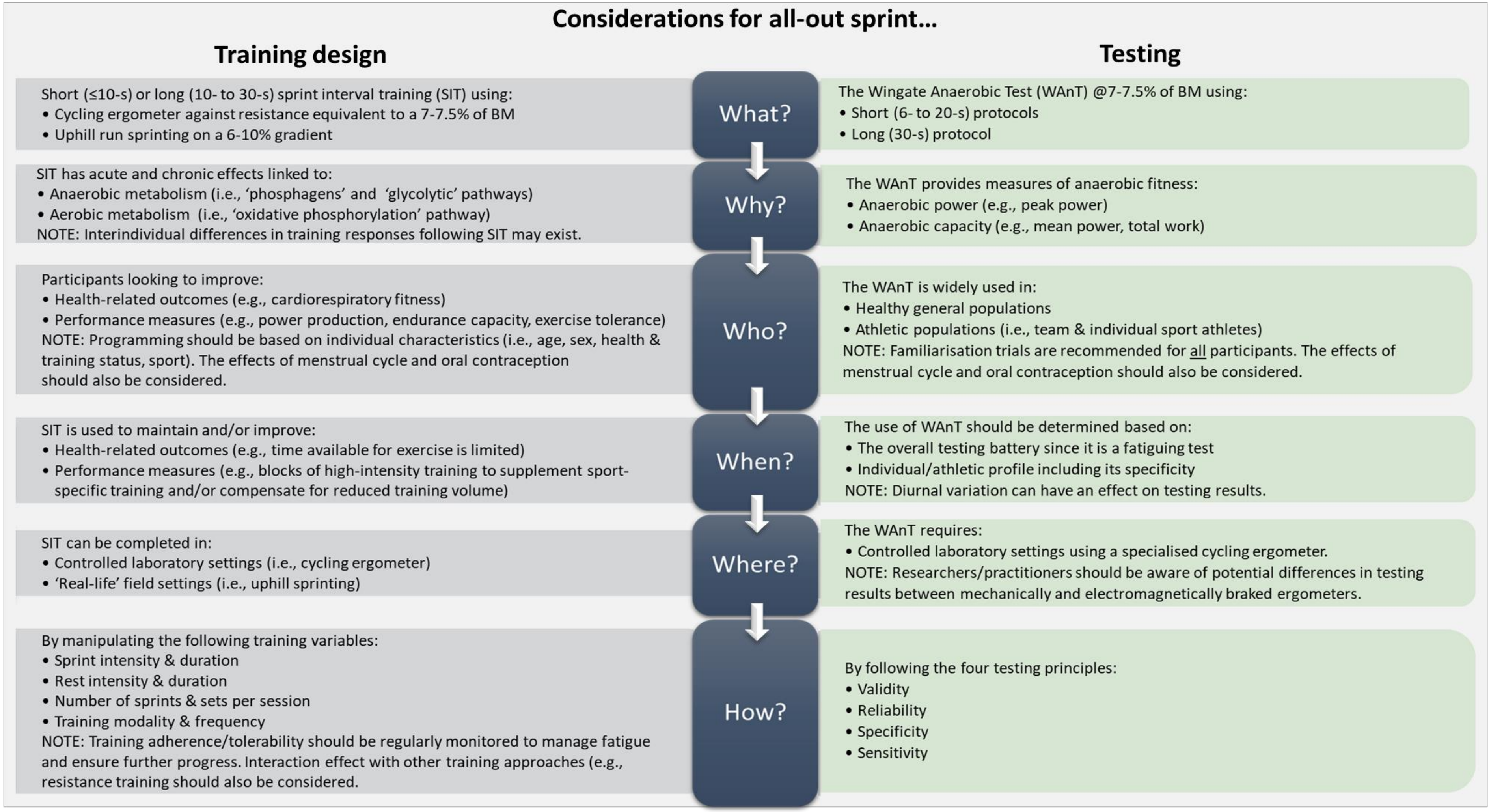

Figure 4. A visual framework highlighting the main considerations for the all-out sprint training and testing.

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