The Effect of High Intensity Intermittent Exercise on Local Tissue Oxygenation, Blood Pressure and Enjoyment in 18 - 30 Year Old Sedentary Men

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The Effect of High Intensity Intermittent Exercise on Local Tissue Oxygenation, Blood Pressure and Enjoyment in 18 - 30 Year Old Sedentary Men

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Abstract

Introduction

This thesis is comprised of a series of three independent, but related studies of sedentary individuals performing high intensity intermittent exercise of various formats and modes. The three studies resulted in four research articles.

High intensity interval training (HIIT) has been proposed as a format of exercise to improve exercise compliance in sedentary individuals, thereby providing positive health effects including improvements in cardiorespiratory fitness (CRF). The recovery format (active versus passive recovery) and mode (running versus cycling) of HIIT are expected to modulate the physiological responses and perceptual sensations that occur during HIIT. There has been no direct comparison, in sedentary individuals, of the effect of HIIT sessions of varying recovery format and exercise mode on local oxygen utilisation, a potential primary stimulus for increasing CRF. Furthermore, blood pressure (BP) and enjoyment, which have implications for safety and adherence to exercise, have not been compared under these experiment conditions. Additionally, HIIT can be as effective, or more effective, than continuous moderate intensity exercise (CMIE) at improving CRF. There has been no direct comparison, in sedentary individuals, of the effect of a session of HIIT to a work-matched session of CMIE on local oxygen utilisation, BP and enjoyment.

Article 1

Purpose: To compare the relative change in local tissue oxygen utilisation during HIIT conditions which included either passive or active recovery.

Methods: Twelve sedentary males (mean ± SD; age 23 ± 3 yr) completed: 1) four bouts of 30 s Wingate HIIT with passive recovery periods (HIITPASS), 2) four bouts of 30 s Wingate HIIT with active recovery periods (HIITACT) and 3) active recovery periods only (REC). Relative change in deoxygenated haemoglobin (ΔHHb) in the vastus lateralis (VL) and gastrocnemius (GN) muscles and the pre-frontal cortex (FH), oxygen consumption (VO_2) and heart rate (HR) were measured.

Results: There was an increase in HHb at VL during bouts 2 ($p = 0.017$), 3 ($p = 0.035$) and 4 ($p = 0.035$) in HIITACT, compared to HIITPASS. There was a main effect for anatomical site in HIITPASS ($p = 0.029$) and HIITACT ($p = 0.005$). There were no differences in VO_2 and HR between HIITPASS and HIITACT.

Conclusions: In young sedentary men**,** a higher level of local oxygen utilisation occurred during HIIT including passive recovery periods, compared to active recovery periods. The differences in HHb between anatomical sites indicates the location specificity of oxygen utilisation.

Article 2

Purpose: To compare exercise enjoyment and blood pressure response during HIIT conditions which included either passive or active recovery.

Methods: Twelve sedentary males (mean ± SD; age 23 ± 3 yr) completed: 1) HIITPASS, 2) HIITACT, and 3) REC. Blood pressure (BP) and physical activity enjoyment (PACES) were measured.

Results: There were no differences in PACES or systolic BP for HIITPASS, compared to HIITACT. Diastolic BP was lower during recovery in HIITACT ($p = 0.025$) and HIITPASS ($p = 0.027$), compared to resting BP. Diastolic BP was lower after 6 min of recovery following HIITPASS, compared to HIITACT ($p = 0.01$).

Conclusions: In young sedentary men, exercise enjoyment is independent of HIIT recovery format. The reductions in diastolic BP, coinciding with pre-syncopal symptoms, indicates that HIIT protocols including passive recovery periods post-exercise have negative safety and compliance implications in participants susceptible to symptomatic post-exercise hypotension (PEH).

Article 3

Purpose: To compare the change in local tissue oxygen utilisation and exercise enjoyment between and across bouts of HIIT conducted either running or cycling.

Methods: Twelve sedentary men (mean ± SD; age 24 ± 3 yr) completed: 1) free-paced cycling HIIT (HIITCYC) and 2) constant-paced running HIIT (HIITRUN). Relative change in deoxygenated haemoglobin (∆HHb) at FH, GN, LVL and RVL sites, VO_2, HR, RPE and PACES were measured.

Results: There was a higher HHb at FH ($p < 0.001$), LVL ($p = 0.001$) and RVL ($p = 0.002$) and a higher VO_2 ($p = 0.017$) and HR ($p < 0.001$) during HIITCYC, compared to HIITRUN. PACES was lower ($p = 0.032$) during HIITCYC, compared to HIITRUN.

Conclusions: In young sedentary men, free-paced cycling HIIT produced higher levels of physiological stress, but lower levels of enjoyment, compared to constant-paced running HIIT.

Article 4

Purpose: To compare the change in local tissue oxygen utilisation, blood pressure and exercise enjoyment during a session of HIIT and a session of work-matched CMIE.

Methods: Eleven sedentary men (mean ± SD; age 23 ± 4 yr) completed a session of: 1) high intensity interval training (HIIT) and 2) work-matched CMIE (MOD). Relative change in deoxygenated haemoglobin (∆HHb) at FH, GN, LVL and RVL sites, VO_2, HR, BP and PACES were measured.

Results: During HIIT, compared to MOD, ∆HHb in FH ($p = 0.016$) and GN ($p = 0.001$) was higher and PACES ($p = 0.032$) and diastolic BP ($p = 0.043$) were lower.

Conclusions: In young sedentary men, a session of HIIT induced higher levels of oxygen utilisation, but lower levels of post-exercise diastolic BP and enjoyment than a session of CMIE, for the same total work.

Discussion

In young sedentary men undertaking HIIT sessions including active and passive recovery periods, HIIT sessions performed running and cycling and during a work-matched session of CMIE, it was determined that:

Local tissue oxygen utilisation is increased during HIIT including active recovery periods, compared to passive recovery periods; during cycling HIIT, compared to running HIIT and during HIIT compared to a work-matched session of CMIE. A single bout of HIIT is sufficient to achieve maximal levels of local oxygen utilisation at locomotor muscle sites, irrespective of HIIT recovery format and mode. Reductions in diastolic BP occur post-HIIT and coincide with pre-syncopal symptoms in 51% of sedentary participants. Diastolic BP was lowest after cycling HIIT including passive recovery periods. Enjoyment of HIIT decreases with increasing exercise intensity.

These findings have implications for selection of exercise recovery format, mode and intensity in a sedentary population for physiological stress, safety, exercise enjoyment and compliance.

Declaration of originality

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, this thesis contains no material previously published or written by any person other than the candidate except where due and proper reference has been given in the text.

Mr Yuri Kriel

Signature:

Date: 26/10/2017

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Table of contents

List of tables

List of figures

List of original publications

1. Kriel, Y., H. A. Kerhervé, C. D. Askew and C. Solomon (2016). "The Effect of Active versus Passive Recovery Periods during High Intensity Intermittent Exercise on Local Tissue Oxygenation in 18 - 30 Year Old Sedentary Men." PLoS One 11(9): e0163733.

List of original publications (submitted)

1. Kriel, Y., H. A. Kerhervé, C. D. Askew and C. Solomon. "The Effect of Active versus Passive Recovery Periods during High Intensity Intermittent Exercise on Perceived Exertion, Enjoyment and Blood Pressure in 18 - 30 Year Old Sedentary Men." PLoS One

2. Kriel, Y., C. D. Askew and C. Solomon. "The Effect of Running versus Cycling High Intensity Intermittent Exercise on Local Tissue Oxygenation and Perceived Enjoyment in 18 - 30 Year Old Sedentary Men." PeerJ

3. Kriel, Y., C. D. Askew and C. Solomon. "High Intensity Intermittent Exercise versus Moderate Intensity Continuous Exercise: Acute Effects on Local Tissue Oxygenation, Blood Pressure and Enjoyment in 18 - 30 Year Old Sedentary Men." PLoS One

List of abbreviations

AIT	Aerobic interval training
ANOVA	Analysis of variance
AT	Anaerobic threshold
ATP	Adenosine triphosphate
ATT	Adipose tissue thickness
$a\text{-}vO_{2diff}$	Arteriovenous oxygen difference
BP	Blood pressure
CBF	Cerebral blood flow
CMIE	Continuous moderate intensity exercise
COPD	Chronic obstructive pulmonary disease
CRF	Cardiorespiratory fitness
CW	Continuous wave
DPF	Differential pathlength factor
FD	Frequency domain
FH	Forehead
fMRI	Functional magnetic resonance imaging
GN	Gastrocnemius muscle
Hb	Haemoglobin
Hb_{diff}	Haemoglobin difference
HHb	Deoxygenated haemoglobin
HIIT	High intensity interval training
HREC	Human Research Ethics Committee
HR	Heart rate
HR_{max}	Heart rate maximum

IC	Intercostal muscle
LVL	Left vastus lateralis muscle
MAP	Mean arterial pressure
Mb	Myoglobin
mmHg	Millimetres of mercury
Min	Minute
MIE	Moderate intensity exercise
NIRS	Near infrared spectroscopy
NIR	Near infrared
nm	Nanometer
O_2	Oxygen
OxyHb	Oxygenated haemoglobin
PA	Physical activity
PAR-Q	Physical Activity Readiness Questionnaire
PaO_2	Partial pressure of arterial oxygen
PCr	Phosphocreatine
PEH	Post exercise hypotension
P_{peak}	Peak power
$PredHR_{max}$	Predicted heart rate maximum
RPM	Revolutions per minute
RVL	Right vastus lateralis muscle
S	Second
SCD	Sudden cardiac death
SD	Standard deviation
SIT	Sprint interval training
SV	Stroke Volume

TD	Time domain
THb	Total haemoglobin
TOI	Tissue oxygenation index
TSI	Tissue saturation index
VO_2	Oxygen consumption
VO_{2max}	Maximal oxygen consumption
VO_{2peak}	Peak oxygen consumption
VT	Ventilation threshold
W	Watt

1. Introduction

High intensity interval training (HIIT) is broadly defined as repeated bouts of short to moderate duration exercise (10 s to 4 min) completed at a relatively high intensity, separated by recovery periods of low to moderate intensity exercise or passive rest (30 s to 4 min) [1-5]. The health benefits associated with HIIT participation are increasingly the focus of scientific investigation, specifically in individuals at risk of chronic diseases linked to sedentary behaviour [6-8]. HIIT is often compared with continuous moderate intensity exercise (CMIE) when examining these benefits [9-11]. Nine design variables (series, inter-series, bout and recovery: number, duration and intensity as well as exercise mode) can be altered when prescribing HIIT [2]. Altering these variables affects the physiological and perceptual responses to a HIIT session and therefore impacts on the health benefits associated with HIIT, in addition to the findings of any comparison of HIIT with CMIE.

Sedentary behaviour, defined as not meeting physical activity (PA) recommendations for the achievement of health benefits, is a risk factor for multiple chronic diseases [12-14] and is a global epidemic [12, 15-19]. Sedentary individuals will routinely be advised to accumulate 150 – 300 minutes of moderate intensity exercise (MIE) each week for the associated health benefits [20]. The most frequently cited reason for non-compliance with the PA recommendations is a lack of time [21]. Participation in HIIT improves health parameters in a time efficient manner [6, 7, 22-30]. Young sedentary individuals are likely proponents of HIIT [27], due to the reduced time commitment, the novelty of this intermittent form of exercise and younger individuals having a lower risk of adverse events when performing high intensity exercise [7, 21, 31-36].

HIIT has been shown to be as effective, or more effective, than CMIE at improving specific markers of risk, such as low cardiorespiratory fitness (CRF) [5, 6, 37, 38]. Increased CRF is associated with a decrease in all-cause mortality and morbidity [39] and contributes to the primary prevention of 35 chronic conditions [40]. Increased CRF is partly attributed to improvements in oxidative capacity, including increases in mitochondrial content and function [41, 42] and an increased ability to utilise energy from aerobic pathways [1]. Whilst the exact stimuli contributing to the increases in mitochondria are not completely understood, it is possible that the increase in demand for oxygen utilisation at the local muscle level during an acute session of HIIT provides a stimulus for these improvements [43, 44] and is potentially partly responsible for the effectiveness of HIIT at improving CRF, compared to CMIE [6, 33]. Conversely, increases in cerebral oxygen utilisation during HIIT may be a potential mechanism contributing to fatigue, increased perception of effort and exercise cessation [45]. Altering the design variables of HIIT effect the extent to which aerobic pathways, and therefore oxygen, is utilised at a local tissue and systemic level [2, 46-48]. The importance of time efficiency during HIIT, in a health-related context, necessitates that the duration of the exercise bouts and recovery periods are effectively curtailed. Additionally, inter-series design variables are surplus to requirements, as HIIT in sedentary populations routinely consists of a single series of exercise bouts and recovery periods [33]. The effect of altering the remaining design variables (recovery format or mode) of an acute session of HIIT, on locomotor muscle and cerebral tissue oxygen utilisation, is unknown in a sedentary population and may explain some of the variability in the results of studies examining CRF during HIIT and CMIE [33]. It is therefore important to investigate and quantify the oxidative physiological responses that occur during various formats of HIIT, and in comparison to CMIE, in the young sedentary proportion of the general population.

Near infrared spectroscopy (NIRS), the non-invasive evaluation of oxygenation based on near infrared light absorption and transmission through living tissue, allows for novel multi-site measurement and comparison of local tissue oxygen utilisation during acute sessions of exercise, including HIIT and CMIE. If HIIT is to be recommended for sedentary individuals, as an alternative to CMIE, it is important that this recommendation be based upon scientific evidence of which change in design variables stimulates the most advantageous physiological responses, including the largest change in oxygen utilisation. Furthermore, it is important to investigate the potential differences in physiological responses between HIIT and CMIE to gain an understanding of how HIIT potentially leads to improvements in CRF for a shorter time commitment than CMIE. This thesis will investigate oxygen utilisation in locomotor muscles and cerebral tissue during HIIT including active and passive recovery periods, during HIIT performed running and cycling and during HIIT compared to a session of work-matched CMIE.

The safety of HIIT is debated [5, 49-53]. High intensity exercise, compared to MIE, is associated with a transient increased risk of adverse cardiovascular events, especially in sedentary or infrequent exercisers [20, 54]. The mechanism(s) by which high intensity exercise triggers such adverse events is not fully understood, but proposed mechanisms include increases in blood pressure (BP) and associated increases in haemodynamic strain [55]. Furthermore, aversive symptomatic hypotensive responses following exercise have been linked to high intensity exercise [56, 57], sedentary status [58], situations in which the secondary muscle pump is not active, such as passive recovery [59], and occur after both running and cycling [59]. Young adults are extensively represented in the symptomatic post exercise hypotension (PEH) literature [60] and symptomatic PEH has been reported during HIIT in active individuals [57]. Therefore, it is plausible to expect hypertensive responses during HIIT, and hypotensive responses acutely post-HIIT, in young sedentary individuals unaccustomed to this level of exertion. Conversely, while large fluctuations in BP may be expected during a session of HIIT, the intermittent format of HIIT may mitigate the overall physiological response, particularly when the recovery periods are passive and / or exercise is non-weight bearing and therefore produce a BP response comparable to a session of CMIE. The effect of altering the recovery format or mode of an acute session of HIIT, on exercise and acute post-exercise BP is unknown in a sedentary population. This thesis will therefore evaluate BP responses in sedentary individuals during and after sessions of HIIT including active and passive recovery periods, during HIIT performed running and cycling and during HIIT compared to a session of work-matched CMIE.

HIIT consists of bouts of demanding, intense exercise requiring high levels of motivation to complete. The ability to sustain high levels of motivation during repeated maximal efforts has led researchers to question whether HIIT is a suitable exercise format and a realistic alternative to CMIE in sedentary populations [61], for whom the motivation to exercise is low [62, 63]. Motivation is inherently linked to enjoyment and enjoyment is inherently linked to habitual exercise participation [64]. Preliminary results on sedentary individual's enjoyment of HIIT are conflicting, finding HIIT to be more, equal or less enjoyable in comparison to CMIE [6, 37, 38, 65-67]. Results are also conflicting when comparing HIIT protocols of different length and / or duration [68, 69]. The effect of altering HIIT recovery format or mode on sedentary participants' enjoyment is unknown and is important to quantify in a population recommended to adopt this form of training (or be targeted for this training) [70, 71]. Additionally, overall workload is often not controlled when enjoyment during acute HIIT and CMIE sessions is compared. This thesis will therefore investigate enjoyment during HIIT including active and passive recovery periods, during HIIT performed running and cycling and during HIIT compared to a session of work-matched CMIE.

In summary, sedentary participants performing HIIT sessions of varying recovery format (active versus passive recovery), mode (running versus cycling) and intensity (HIIT versus CMIE) will allow for the examination of:

- multi-site locomotor muscle and cerebral oxygen utilisation, using NIRS, to provide novel information into local tissue oxygenation.
- blood pressure responses, to provide additional information relevant to the cardiovascular load and safety of HIIT.
- enjoyment during HIIT, to evaluate if this format of exercise is a realistic option in a sedentary population.

1.1. Thesis outline

This thesis consists of a series of three separate, but related studies involving sedentary individuals performing high intensity exercise. The three studies resulted in four research articles.

1.1.1. Chapter 4 and 5 (Study 1)

The first study was designed to enable the quantification and comparison of local and systemic oxygen utilisation, heart rate, mechanical power output (Article 1), blood pressure, perception of effort and exercise enjoyment (Article 2) in response to acute HIIT sessions which included active (HIITACT) and passive (HIITPASS) recovery periods. Identification of the recovery format that results in the largest oxygen utilisation, and / or an appropriate blood pressure response and / or is perceived to be the most enjoyable would support which format of HIIT is appropriate for adoption in a sedentary population.

1.1.2. Chapter 6 (Study 2)

The second study was designed to enable the quantification and comparison of local and systemic oxygen utilisation, heart rate, mechanical power output, blood pressure, perception of effort and exercise enjoyment in response to acute sessions of cycling HIIT (HIITCYC) and running HIIT (HIITRUN) (Article 3). The most common mode utilised during HIIT is a bicycle ergometer equipped with specialist instantaneous resistance mechanisms, due to protocols being based on the Wingate cycling test (16, 24) and anecdotal safety / injury concerns with high intensity running. However, if running HIIT can offer similar or increased physiological responses when compared to cycling HIIT, and / or an appropriate blood pressure response and / or be perceived as more enjoyable, these findings would support running HIIT as an alternative to cycling HIIT.

1.1.3. Chapter 7 (Study 3)

The third study was designed to enable quantification and comparison of local and systemic oxygen utilisation, heart rate, mechanical power output, oxygen utilisation, blood pressure, perception of effort and exercise enjoyment in response to a session of high intensity exercise (HIIT) and a work-matched session of CMIE (MOD) (Article 4). HIIT has been shown to be as effective, or more effective, than CMIE at increasing CRF [5, 6, 37]. Increased CRF has been linked to increases in mitochondrial content and function [14, 15]. This study provided insight into whether higher levels of oxygen utilisation at the local tissue level do occur during an acute session of HIIT, compared to a session of CMIE, and thereby provide proof of a potential mechanism to explain the CRF benefits of HIIT, compared to CMIE. Additionally, findings of an appropriate blood pressure response and / or a higher level of enjoyment would support which intensity of exercise is more appropriate in a sedentary population.

2. Literature review: High intensity interval training

This chapter will review literature on high intensity interval training. Chapters 4, 5, 6 and 7 of this document detail the independent experiments which constitute the thesis and include the specific literature relevant to each experiment. A review of the relevant near infrared spectroscopy (NIRS) methods is in Appendix A.

2.1. Introduction

High intensity interval training (HIIT) is broadly defined as repeated bouts of short to moderate duration exercise (i.e. 10 s to 4 min) completed at a relatively high intensity, separated by periods of low intensity exercise or passive rest (i.e. 30 s to 5 min) [1-4]. High intensity interval training can be subdivided into sprint interval training (SIT) and aerobic interval training (AIT). Sprint interval training typically represents protocols of 4 - 6 short (10 s to 40 s) bouts at near maximal, maximal or supramaximal exercise intensities (95 to 150% VO_{2max}) separated by recovery periods of 30 s to 5 min [1, 2, 4, 72]. Aerobic interval training represents protocols of 4 - 6 longer (2 min to 4 min) bouts at submaximal exercise intensities (65 - 90% VO_{2max} or HR_{max}), separated by recovery periods of 3 min to 4 min [1, 33, 73]. Both SIT and AIT routinely consist of exercise above the intensity associated with continuous moderate intensity exercise (CMIE) (50 – 75% VO_{2max}), the exercise intensity typically recommended for the accrual of health benefits through exercise participation in sedentary or infrequent exercisers [74].

Traditionally, SIT protocols have been utilised with healthy young populations to examine the effects of this format of HIIT on measures of performance [1]. However, recent investigation of SIT in at risk populations provides evidence of positive health outcomes [28]. Preliminary findings suggest that physiological mechanism(s) unique to this higher intensity form of HIIT have a role in the reduction of specific risk factors [27, 72, 75, 76]. Additionally, SIT protocols maximise the time-efficiency aspect of HIIT [77].

To date, AIT protocols have been utilised with healthy and / or young populations to examine the effects of this longer, but still high intensity format of HIIT on measures of performance and health [4, 78]. However, AIT has also been used in older and / or high risk clinical populations [6, 79] due to the lower absolute intensities of exercise involved, compared to SIT, thereby reducing the risk and the motivation and effort required to complete the protocol [61, 71, 80, 81].

2.2. Sedentary behaviour, cardiorespiratory fitness and other health benefits attributed to HIIT

Sedentary behaviour equates to low levels, or an absence, of physical activity (PA) [82]. A large proportion of first world populations are not complying with current health-related exercise guidelines [16, 83]. More than half of the Australian public were classed as either sedentary or achieving low levels of exercise in 2011 – 2012 [16] and in 2014 – 2015 [84]. Sedentary behaviours lead to deadaptations in physiology and a consequent decrease in PA tolerance [24]. These physiological changes can be of central origin, occur at a peripheral local muscle level, or consist of a combination of the two [11, 24, 65, 67]. The subsequent low cardiorespiratory fitness (CRF) of sedentary individuals, routinely evaluated by measuring systemic oxygen utilisation (VO_2) [33], is increasingly contributing to the growing ill health of communities [40, 83, 85, 86] and is an independent predictor of mortality and morbidity [13].

Increased levels of PA and the attendant increases in CRF reduce the incidence of chronic diseases associated with poor lifestyle choices, including sedentary behaviours [20, 85]. Consequently, it is important that novel methods are found to increase routine PA. Leisure-time activities, such as exercise, are the largest contributor to total PA in first world countries such as Australia [87]. It is therefore important that exercise levels increase. An often-cited barrier to exercise initiation and compliance is a lack of time [21, 88-90]. Therefore, HIIT has gained popularity, chiefly because HIIT conveys increases in CRF [6, 33], whilst requiring a reduced time commitment compared to the 150 min of CMIE per week routinely advocated by health authorities for the accrual of exercise related health benefits [20]. High intensity interval training protocols of different exercise intensities (range: 75% of VO_{2peak} – 'all-out effort') and exercise and recovery durations (range: 30 s – 4 min and 1 min – 4.5 min, respectively) have been shown, in sedentary and / or chronic disease populations, to improve CRF (range: 5.4 % - 46%) and other cardiometabolic risk factors [5, 6, 33, 91-93]. The large improvement in aerobic capacity that can occur after participation in HIIT is illustrated in a study in which six sessions of HIIT, completed over a two-week period, doubled the aerobic endurance capacity of participants [94]. Additionally, HIIT has been shown to result in similar changes in aerobic exercise performance and skeletal muscle oxidative capacity, compared to CMIE, also over a two-week period [95]. The study comparing HIIT to CMIE encapsulates the time saving argument surrounding HIIT, as

HIIT represented a 90% lower exercise volume and a 75% lower time commitment than CMIE, over the two-week period.

Improvement in CRF / systemic oxygen utilisation in response to HIIT interventions is variable (range: -0.6% - 46%) [5, 6, 33, 91, 94, 96, 97]. Systemic oxygen utilisation is routinely increased by HIIT participation [6, 33, 91]. However, infrequently, no change in VO_{2peak} pre- and post-HIIT [33, 94, 97] has been found. This variability is potentially due to differences in HIIT protocol design and hence the overall work performed by participants, leading to different acute physiological responses and hence varying degrees of longer term physiological adaptations and CRF increases [98]. It is therefore proposed that there may be a minimum threshold of HIIT, expressed as a measure of acute duration or intensity that enables increases in CRF. Additionally, this minimum threshold is potentially affected by participants training state / pre-intervention CRF [33]. Importantly, variables other than HIIT duration or intensity, such as recovery format and exercise mode, may contribute to the variance in the physiological responses, adaptations and CRF improvements, especially in sedentary individuals with low pre-intervention CRF.

The evidence is also mixed as to whether physiological mechanisms, responses and adaptations stimulated by HIIT reduce risk factors other than CRF, as well as the disease prevalence, that CMIE has been shown to achieve [6, 27, 28, 79, 99]. Conclusive evidence is not yet available to show whether HIIT is as effective as CMIE at reducing all risk factors linked to sedentary behaviour, or the prevalence and incidence of diseases of lifestyle. However, the lesser time commitment represented by HIIT, whilst conferring some health benefit (as shown by the available research) [6, 7, 31, 99], is potentially attractive to individuals looking for a time efficient solution to sedentary behaviour and / or associated disease mechanisms [66, 68, 100, 101].

The impressive improvements in some clinical markers of risk brought about by participation in HIIT is highlighted by a study in which 32 individuals diagnosed with metabolic syndrome were randomized to equal volumes of CMIE or AIT three times per week over a sixteen-week period or to a control group [37]: The HIIT group had greater increases in VO_{2max} than the CMIE group (35% vs. 16% increases; $P < 0.01$). The HIIT group was found to have greater beneficial changes in endothelial function, insulin signalling, skeletal muscle biogenesis, blood glucose levels and lipogenesis. The HIIT intervention was also found to be as effective as CMIE at lowering mean arterial BP and reducing body weight. Possibly the most striking result was that after the intervention, individuals improved diagnostic criteria to such an extent that they could no longer be classified as suffering from the metabolic syndrome. The HIIT group yielded a greater number of such individuals when compared to the CMIE group: 45.5 % versus 37.5%, respectively. The number of participants in this study was however small, with 9 individuals assigned to the control group, 8 to the CMIE group and 11 to the HIIT group.

Based on the current literature detailing the effect of HIIT on risk factors for cardiometabolic disease, it is evident that some positive effects occur acutely (insulin sensitivity) [28], whilst others occur after extended periods of HIIT participation (body composition) [102]. Even when no effect is found post intervention, it is suggested that perhaps the intervention was simply not long enough, implying either a much delayed response in some physiological areas or a need for multiple additional changes other than HIIT exposure to be instituted by the individual before measurable change in some health parameters occur [6]. These findings highlight the importance of investigating the entirety of the physiological effects of HIIT, from the acute responses to an individual bout / session to the longer-term physiological adaptations that are accrued after extended HIIT interventions, in order to optimise the impact of HIIT as a health intervention [91]. The physiological adaptations due to HIIT participation have been extensively studied [6, 33, 103], whilst the acute responses to HIIT bouts / sessions have received less scientific scrutiny [7, 104].

There is therefore a lack of consensus as to the optimal dose of HIIT needed to maximise health benefits and time efficiency, whilst minimising risk, in sedentary individuals. Potentially, the lack of consensus is due to the difficulty in collating the HIIT literature, due to confounding factors, the variability in protocol design and the lack of investigation into all variables of HIIT protocol design. The study by Tjønna et al. [37] provides an example of possible confounding factors that occur when HIIT leads to improvement in clinical variables in sedentary participants. Participants allocated to a HIIT protocol warmed up for 10 min at 70% of HR_{max} before completing four high intensity bouts of 4 min duration each. Between each bout of HIIT a 3-min active recovery was performed at 70% of HR_{max}. Each session finished with a 5-min cool down period. This equates to 24 min of moderate intensity exercise (MIE), in addition to 16 min of HIIT. In a sedentary population, it is conceivable that the warm up, inter-bout recovery periods and the cool down represent a substantial physiological stimulus. Therefore, the favourable outcomes demonstrated by participants in the HIIT group in this study, could have been brought about by the exercise session in its entirety, not solely the high intensity bouts, which are often the focus.

Psychological and perceptual factors (perception of effort, mood, motivation, enjoyment, coping ability) influence HIIT performance / tolerance / completion and hence physiological responses, adaptations and the health related benefits attributed to HIIT, including CRF [62]. These psychological and perceptual factors may also partly explain the variance in results to date [33]. Specifically, in sedentary populations, the lack of inherent motivation, previous exposure to and the mental tolerance for the discomfort associated with HIIT may confound HIIT completion [61], the stimulus inherent in the acute exercise dose and hence research findings. In contrast, whilst few scientific articles overtly mention how HIIT sessions were tolerated [53], those that do indicate that in obese, sedentary and / or clinical populations, HIIT was well tolerated with high completion rates [5, 11, 49]. However, the self-selection by participants could have biased these findings. Preliminary anecdotal evidence, documented during the comparison of HIIT to CMIE in a population diagnosed with metabolic syndrome, indicated that participants perceive HIIT favourably, finding the variable intensities of HIIT motivating whilst CMIE was found to be boring [105]. The limited number of studies which measure perceptual factors and the anecdotal reports of enjoyment need to be supplemented by further research in sedentary populations, specifically research examining these perceptual factors in response to SIT protocols, which maximise the time efficiency of HIIT.

In summary, whilst health benefits, including increases in CRF, can be attributed to HIIT participation [6-8], formalised, evidence-based guidance regarding HIIT protocol design, to maximise these health benefits in sedentary populations, is lacking. Based upon an analysis of the literature, this is proposed to be partly due to a lack of translational research examining the effect of HIIT protocol variations on beneficial physiological and perceptual acute responses, adaptations and health benefits.

2.3. HIIT protocol design variations used in health interventions

Populations at risk of chronic disease (sedentary and / or obese individuals) as well as populations with diagnosed chronic disease (diabetes, metabolic syndrome, hypertension, coronary artery disease, peripheral vascular disease and even heart transplant patients) are becoming the focus of investigations into the effects of HIIT on parameters of treatment and / or health [6, 22-24, 29, 79, 99, 105]. These diverse populations introduce the need for variety into the design of HIIT protocols, due to individual and disease specific considerations as well as the intended physiological responses, adaptations and exercise prescription targets to maximise the health benefits associated with HIIT [53]. Nine design variables can be altered when prescribing HIIT, as illustrated in figure 2.1.

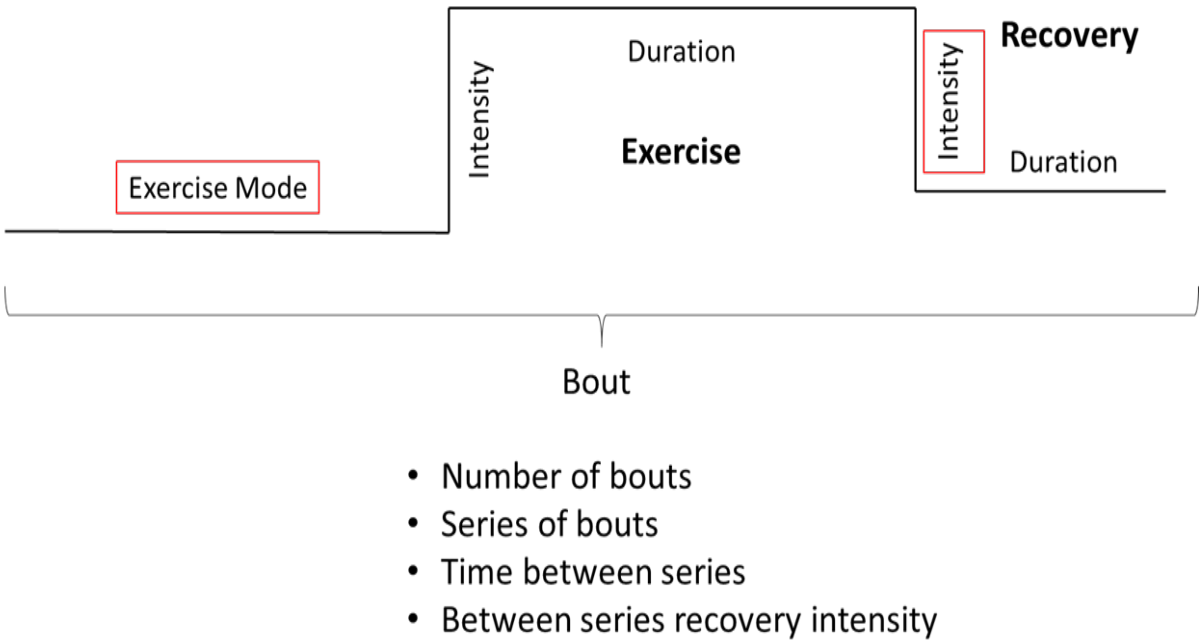

Figure 2.1. The nine design variables that can be altered during high intensity interval training (HIIT).
Adapted from [2].

The use of HIIT in health promotion and clinical exercise interventions focuses on HIIT being a time saving format of exercise, compared to CMIE, whilst conveying health benefits [31]. To achieve this time efficiency, the number of bouts and the duration of the exercise bouts and recovery periods are somewhat constrained. Furthermore, inter-series aspects of HIIT are often superfluous, as HIIT in sedentary and / or clinical populations routinely consists of a single series of exercise bouts and recovery periods [5, 53, 92, 106, 107]. Additionally, the exercise intensity of HIIT sessions has safety and compliance implications [53, 54, 108] and exercise intensity is often inversely related to exercise duration [74]. Therefore, researchers have predominantly investigated the physiological responses to HIIT protocols of different exercise intensity and / or exercise and recovery period duration and the associated measured health variables [5, 10, 53, 92, 109, 110]. The effect of altering the HIIT design variables of recovery intensity / format and exercise mode, on physiological responses, is yet to be fully elucidated in a health context.

Previous research examining the effects of HIIT has routinely been comprised of participants assigned to HIIT or CMIE (or a control group) over a period of weeks or months, allowing the magnitude of change in a health related variable or clinical risk indicator pre-and post-intervention to be quantified [6, 27, 37]. HIIT interventions have not routinely matched for mechanical work, when compared to CMIE interventions, during these studies [36, 67, 111]. No direct comparison of HIIT protocols has occurred, in which a design element other than the exercise intensity of the protocol is changed and the effect of this change on physiological and perceptual variables, in the same group of sedentary participants, is evaluated. Specifically, the design elements of recovery format and exercise mode have not been evaluated in this way. Unlike in the sporting literature [1], there has been minimal investigation into the optimisation of HIIT protocol design in a health context. Such optimisation (i.e. the format(s) of HIIT) most likely to reduce risk factors, prevalence and incidence of disease via various physiological responses, whilst maximising time-efficiency, enjoyment and minimising the risk of the exercise stimulus would allow targeted and effective clinical prescription of HIIT. Therefore, based upon the lack of information regarding the most beneficial format of HIIT available in the literature at present, standardisation via a series of studies evaluating physiological and perceptual responses of sedentary individuals to HIIT protocols with a single design variable alteration, are required.

2.3.1. Exercise bout intensity

Exercise bout intensity during HIIT interventions typically ranges from 75% - 150% of various physiological indices, including VO_2 and HR [33, 92]. Therefore, prescription of the intensity of HIIT bouts routinely requires prior maximal exercise testing. The VO_{2max}, HR_{max} or peak power output (P_{peak}) data is used to determine HIIT session intensity [33]. However, other methods of deriving a HIIT bout of sufficient intensity do not require pre-testing, via providing resistance against which an individual must cycle whilst giving a maximal effort, derived from the Wingate anaerobic test [98]. The Wingate test is accepted as a standardized, reliable and valid method of measuring high intensity power production [112]. Applying this logic in reverse, if a test is a valid measure of high intensity short term effort, then it must conversely be a suitable stimulus to provoke high intensity exercise when used as a HIIT protocol.

Importantly, factors governing the intensity of HIIT sessions in the health related / clinical area of exercise prescription often relate to the level of risk traditionally associated with the exercise intensity [5, 53]. High intensity exercise is associated with an increased risk of musculoskeletal injury and adverse cardiovascular events [54]. The risk of adverse cardiovascular events during exercise, while low in absolute terms, is highest in sedentary and / or high risk individuals performing unaccustomed or infrequent vigorous physical activity (PA) [20]. This cautionary statement is weighed against the fact that whilst there is a transient and elevated risk of sudden cardiac death (SCD) during and immediately after exercise, the cardiovascular benefits / protection of exercise participation, over time, outweighs the acute and transient risks associated with exercise [20]. Whether these statements apply to HIIT is yet to be fully elucidated, as the majority of research informing these position statements did not specifically evaluate HIIT [113, 114]. Preliminary data seems to indicate that HIIT may have an acceptable risk profile, even in populations suffering from cardiovascular disease [49]. However, interventions examining the benefit versus risk of HIIT have routinely taken place in supervised rehabilitation settings (which implies rigorous pre-screening, appropriate medical management and continued monitoring of participants) and studies have been underpowered to assess cardiac events during training [5, 53]. Additionally, in patients with cardiometabolic disease, who have an increased propensity for sedentary behaviour [115], whilst rates of adverse events during HIIT were low, rates of adverse events were five times higher, compared with adverse events rates during moderate intensity exercise (MIE) [53]. Future investigations examining the effects of various formats of HIIT, which may have inherent exercise intensity differences due to the recovery format or exercise mode [116], on the extent of cardiovascular perturbation and / or adverse events during participation will allow insight into the safety of different formats of HIIT in sedentary individuals, currently lacking in the literature [6, 117, 118].

Furthermore, in a health related context, during SIT bouts of high to maximal intensity, but short duration (10 – 30 s), the application of the exercise stimulus potentially does not allow time for cardiovascular parameters such as HR and BP to reach near maximal levels, before inter-bout recovery is initiated, especially in the early bouts of a HIIT session [119, 120]. Additionally, depending on the recovery format imposed (active versus passive), overall cardiovascular responses may be increased or attenuated [119]. Therefore, the actual intensity, and the associated cardiovascular load of the SIT session is uncertain. It is proposed that the descriptor of SIT being maximal or supramaximal in intensity may at times be inaccurate in terms of the physiological responses achieved during SIT bouts, by sedentary individuals. The accuracy of this proposal is yet to be fully elucidated.

2.3.2. Exercise bout and recovery period duration

Exercise bout duration during HIIT sessions ranges from 10 s to 4 min, whilst recovery period duration ranges from 30 s to 5 min [1, 2, 4, 72]. Researchers routinely use fixed work-recovery ratios when determining recovery period duration (i.e. 1:1, 1:2, 1:3. 1:4) or a fixed time frame [98]. As stated previously, to achieve the time efficiency aspect of HIIT, the duration of the exercise bouts and recovery periods are somewhat constrained and exercise intensity is often inversely related to exercise duration [74]. Longer duration (lower intensity) formats of HIIT are frequently evaluated in sub-clinical and clinical populations [92]. Preliminary evidence from longitudinal studies, including individuals with cardiometabolic disease, suggests that longer duration formats result in greater increases in CRF / VO_{2peak}, compared to shorter duration formats [5]. However, this finding is potentially premature, due to the small number of studies including shorter duration formats of HIIT, available for comparison [5, 6]. Therefore, further investigations into short duration HIIT are necessary in cardiometabolic and other clinical / sub-clinical populations [5, 28].

2.3.3. Recovery period format / intensity

There is little available literature on the acute or chronic effects of recovery format (active versus passive) during high intensity intermittent exercise [121-124]. The only investigation to examine the effect of recovery format during HIIT in sedentary populations, focused on acute responses, included only 6 participants, and found differences in mean power output, but no differences in peak power output and heart rate between active and passive recovery formats [120]. In active populations, results are mixed as to which recovery strategy (active versus passive) is deemed beneficial in a performance context, potentially due to differences in exercise bout and recovery period duration and differences in specific physiological measurements, both acutely and over time [125-131]. A longitudinal study found that after 7 weeks of HIIT including either passive or active 30 s recovery periods between 30 s bouts of high intensity running, participants in both groups significantly increased their time to exhaustion and maximal aerobic velocity [130]. The active recovery group were found to have significantly increased their VO_{2max}. The pre-intervention VO_{2max} values (59 and 58 ml.kg.min^{-1}, respectively) indicate that participants were well trained. Potentially the passive recovery protocol did not provide an adequate threshold of training to improve already high VO_2 values.

Additionally, the intensity and the physiological variable used to delineate intensity during active recovery protocols vary:

- 20 – 30% VO_{2max} [120, 132]
- 30 - 40% VO_{2max} [121, 124, 126, 129, 133]
- a running velocity or cycling resistance equivalent to ≈ 40% VO_{2max} [48, 125, 130, 132]
- 60% HR_{max} [134]
- 45% P_{peak} [123, 135]
- 20-40% of maximal aerobic power [104]
- Self-selected intensity [136]

Importantly, the effect of active versus passive recovery formats during HIIT on acute physiological responses with implications for improvements in systemic health variables such as CRF and cardiovascular load as well as issues such as enjoyment, safety and compliance have not been investigated in sedentary individuals.

2.3.4. Exercise mode

Exercise modality has received little attention in scientific investigations into HIIT [2]. No direct comparison of HIIT exercise mode has been undertaken in sedentary individuals. Running and cycling protocols are utilised during SIT [27, 48, 125], however there appears to be a bias towards cycling protocols [31]. This bias is potentially due to possible safety aspects associated with performing high intensity exercise on a treadmill (running at high speeds and gradients) and the fact that the majority of SIT protocols are based on the Wingate cycling test [46, 57, 94, 137, 138] which utilises specialised bicycle ergometers and specific software to facilitate the exercise stimulus inherent in the short duration, supramaximal protocols [27, 62, 94]. This constitutes a possible barrier to entry for this form of exercise, as sedentary individuals potentially do not have access or financial means to access a bicycle ergometer equipped with such software [139]. It is unknown if HIIT, from a physiological perspective, performed on a treadmill would equal or exceed the exercise stimulus associated with cycling, in sedentary individuals.

Importantly, the effect of mode (running versus cycling) during HIIT on acute physiological responses related to improvements in systemic health variables such as CRF as well as issues such as enjoyment, safety and compliance has not been examined in sedentary individuals.

2.4. Physiological responses and adaptations to HIIT

Whilst participation in HIIT results in various vascular, respiratory, metabolic and hormonal responses and adaptations [1, 27, 42, 91, 92, 140, 141], this section will focus on the review of physiological responses relevant to local oxygen utilisation, the related cardiovascular and oxidative processes and blood pressure.

In the context of this review, physiological responses are defined as changes in physiological variables during a single bout or session of HIIT. Physiological adaptations, defined as changes in physiological variables in response to multiple sessions of HIIT, are reviewed briefly, as this thesis did not examine physiological changes due to a training effect. However, as indicated in the literature [1, 27, 42, 91, 92, 140, 141], acute physiological responses form the basis of longer term adaptation which in turn potentially leads to the health benefits attributed to HIIT [6]. Additionally, acute physiological responses can themselves be beneficial [28] or a risk [142]. Finally, it is important to be aware of the potential confounding effects of adaptation, as acute responses to HIIT in a sedentary population may promote rapid (session-to-session) adaptations in physiological parameters, due to the participants' untrained state [33].

HIIT has been a training format in sport for decades [1, 4, 143]. Consequently, a substantial portion of research investigating physiological responses and adaptations to HIIT have occurred in active populations [4]. There is a relative paucity of research examining mechanistic physiology during HIIT in sedentary populations [120]. Therefore, this review includes relevant findings from investigations of HIIT in a performance context to provide a thorough summary of the literature.

Few studies have examined the physiological response to a single session of HIIT [9, 123, 144, 145]. The importance of examining the acute effects of HIIT is illustrated by improvements in metabolic and vascular parameters noted at 24 hr after a two week HIIT intervention, but not at 72 hr, making it unclear as to whether the improvements were due to the acute effects of the last bout of HIIT or due to cumulative, but transient physiological adaptations brought about by the training period in its entirety [27]. This issue led to a study by the same group, to examine the effects of a single session of HIIT, compared to an single extended sprint session and a non-exercise control [28]. Results from this experiment indicated that one HIIT session improves fat oxidation in sedentary men. The HIIT protocol consisted of 4 x 30 s maximal sprints, separated by 4.5 min of active recovery. Furthermore, the design of this study demonstrates that typically the physiological responses to a HIIT protocol are compared to another format of exercise and / or non-exercise control. Importantly, the direct comparison of the effect of two HIIT protocols of varying format on acute physiological responses, in the same participants, is rare [69, 122]. Specifically, the direct comparison of the effect of HIIT recovery format and mode on acute local oxidative responses, in sedentary participants, has not occurred.

2.4.1. Oxidative and glycolytic responses to HIIT

Physiological responses to exercise attempt to limit disturbances in homeostasis when physiological systems are exposed to a stressor [146]. This concept underlies the physiological stimulus inherent in short duration, supramaximal HIIT participation, due to the rapid and large homeostatic disturbance created by sudden, repeated, high intensity bouts of exercise [80, 147]. The improvement in oxidative and glycolytic responses, and therefore aerobic and anaerobic performance, due to HIIT participation is well documented [62, 94, 148]. However, the specific mechanism(s) behind these improvements is less clear. Physiological mechanisms put forward to explain these improvements include increased skeletal muscle oxidative and / or glycolytic enzyme activity [46, 62], increased skeletal muscle buffering capacity [4, 149, 150], improvement in ventilatory and / or anaerobic thresholds [151], an increased ability to oxidise fat relative to carbohydrates [96, 152] and the recruitment of a large muscle mass and increased stress to muscle fibres [62, 153].

During a session of HIIT, demand for and production of energy increases, due to the increased muscle fibre recruitment and the increase in work performed by the active musculature (under direction of the brain and neuromuscular recruitment pathways) [98], resulting in increases in HR [119, 134], VO_2 [121, 133] and lactate [28]. During high intensity exercise, contributions from both aerobic and anaerobic energy pathways occur in different concentrations, dependent on absolute exercise intensity, length of activity, training status and substrate availability [98]. A crossover point exists, at approximately 75 s of near maximal exercise, at which both systems contribute equally to this supply [154]. Before this point, more energy is contributed by anaerobic sources. After this point, more energy is contributed by from aerobic sources. The percentage contribution by each pathway during a 30 s bout of HIIT has been defined: Approximately 80% of energy metabolism comes from anaerobic sources and 20% from aerobic sources [98]. Therefore, after short duration supramaximal HIIT, increases in parameters of glycolytic and oxidative pathways occur [7, 46, 62, 148]. In comparison, MIE increases oxidative enzyme and mitochondrial activity, but has little or no effect on glycolytic enzyme activity [155]. The contribution of aerobic pathways during HIIT explains why favourable changes in CRF occur in response to HIIT which have traditionally been linked to lower intensity exercise formats. The findings above imply greater efficiencies during HIIT, compared to MIE, by stimulating acute responses (and longer-term adaptations) to both pathways of energy production, leading to the subsequent improvements in systemic oxygen utilisation / CRF for a reduced time commitment [7].

Additionally, it has been proposed that molecular signalling pathways such as adenosine monophosphate kinase and calcium-calmodulin kinase [62], associated with different intensities of exercise, can cause similar adaptations by activating molecular master switches such as peroxisome proliferator-activated receptor-y coactivator-1α [148, 156]. These signalling pathways, through activation of the master switch, have similar downstream effects, such as increasing mitochondrial mass or activity, that end with an increased ability to generate adenosine triphosphate (ATP) aerobically [148]. Therefore, as indicated in the literature, improvements in CRF occur after CMIE [157], after HIIT of varying intensity and duration [31, 33] or after a combination of HIIT and CMIE [103]. HIIT has been shown to effect local oxygen utilisation, substrate utilisation and blood flow responses [140, 158, 159], which are components of oxidative energy pathways and therefore play a role in the improvements in aerobic energy production, systemic oxygen utilisation and CRF [98]. However, the effect of short duration supramaximal HIIT recovery format and mode on the potential mechanisms of aerobic energy transfer / stimuli, which upregulate these signalling pathways, is unknown.

Via manipulation of the intensity and duration of the bouts and potentially the format of the recovery periods and mode of a HIIT session, changes in demand through the distinct oxidative and glycolytic metabolic pathways can be achieved [1, 148]. For example, the contribution of aerobic metabolism to energy production increases from bout one to bout two during repeat high intensity bouts [160], indicating that as the HIIT session progresses, aerobic sources contribute a greater percentage of the required energy. This increase in contribution from aerobic sources may have implications for the number of bouts included in a session of HIIT to drive aerobic responses, adaptations and hence increases in CRF, in sedentary individuals. Additionally, in a sedentary population with a low level of CRF, the inclusion of active recovery periods between bouts could increase aerobic contributions to the HIIT session and therefore result in increased local and systemic oxidative responses and adaptations [37]. However, the effect of HIIT recovery format and mode, on the aerobic energy pathways at a local tissue level, in sedentary individuals, is yet to be elucidated.

In addition to an increase in the number of bouts, when recovery time between high intensity exercise bouts decreases and as the length of individual bouts increases, the contribution from glycolytic pathways decrease and aerobic / oxidative contributions increase [46-48]. This altering of design variables theoretically allows for targeting of relevant energy systems and provides additional insight into how HIIT can improve health parameters linked to improvements in CRF [33]. The mechanism(s) and degree of perturbation attributable to changes in HIIT protocol design variables have yet to be fully elucidated. Quantification of the change in local oxygenation responses, a potential primary stimulus for increased mitochondrial function (and hence systemic oxygen utilisation / VO_2 / CRF), during HIIT of varying recovery formats and modes would provide information as to one potential primary mechanism.

2.4.2. Local oxygenation responses to HIIT

Near infrared spectroscopy

Technological advancements, represented by near infrared spectroscopy (NIRS) devices, allow for novel investigation into local tissue oxygen utilisation during HIIT [45, 161, 162], upon which systemic oxygen utilisation and CRF are inherently dependant. Whilst the physiological mechanisms, structures and substances involved in aerobic metabolism have been identified and extensively studied [98, 146], regional multi-site muscle oxygen utilisation collected in real time has not, potentially due to a lack of versatile non-invasive regional measurement options.

Near infrared spectroscopy was first reported in 1977 to be of value in assessing cerebral tissue oxygen saturation [163]. The evaluation of oxygenation via NIRS is based on near infrared light absorption and transmission through living tissue, using the modified Lambert-Beer law [164]. In human tissue, in the 700 – 1300nm range, NIR light penetrates several centimetres, allowing for evaluation of cerebral or muscle oxygenation. In this NIR range, the primary light absorbing chromophore of interest is haemoglobin (Hb), located in the small arterioles, capillaries and venules [165]. Haemoglobin is the dominant transportation method of oxygen in blood.

When measuring Hb via NIRS, both oxyhaemoglobin (O_2Hb) and deoxyhaemoglobin (HHb) are routinely measured [166-168]. Oxyhaemoglobin broadly represents the change in supply of oxygen and deoxyhaemoglobin the change in utilisation at a particular moment in time [169, 170].

In addition to measuring changes in O_2Hb and HHb, other indices can be derived. Total haemoglobin (THb), the sum of oxy and deoxyhaemoglobin, reflects changes in blood volume [171]. The difference between O_2Hb and HHb, termed Haemoglobin difference (Hb_{diff}), reflects a balance between delivery and removal of oxygen in the small blood vessels [171]. Tissue saturation index (TSI), alternatively know as tissue oxygenation index (TOI) and calculated as (O_2Hb/THb) x100, indicates the balance between tissue oxygen supply and consumption as a percentage [164].

The small number of studies which have utilised NIRS to study oxygenation during HIIT have routinely been performed using trained participants [167, 168, 172-176] and evaluate one or two tissue sites [172, 177, 178]. These sites have routinely been a cerebral site located on the forehead (FH) and / or a locomotor muscle site, the vastus lateralis (VL) [179]. Investigation of oxygen utilisation in multiple local muscle sites in response to HIIT is important as these local oxygen utilisation responses, when considered cumulatively, represent the mechanistic basis of whole-body physiological responses, integral to normal function in health and performance [180]. Therefore, novel insights into oxygen utilisation responses in muscle are of value to understand the improvements (and decrements) in a health-related variable such as CRF in response to exercise interventions such as HIIT and lifestyle behaviours such as sedentariness.

The majority of previous exercise studies using NIRS have utilised incremental exercise testing protocols and have shown that the general pattern of an increased oxygen utilisation with increasing exercise intensity, in individuals of varying CRF, is similar [179]. The exercise stimulus during HIIT is markedly different to that during incremental exercise, but a proportion of exercise during incremental testing is at a high intensity, and along with the small number of HIIT studies evaluating NIRS data, allows insight into the expected oxygenation responses.

Cerebral NIRS responses to exercise

Increases in cerebral activity and cerebral blood flow (CBF) have been shown to occur during incremental exercise [181]. Up to exercise intensities of 60% - 75% of maximal oxygen uptake, CBF and cerebral oxygenation has been shown to increase linearly with increases in exercise intensity [182, 183]. However, when nearing maximal exercise intensities, CBF and oxygenation has been shown to decrease [181, 183, 184], which it has been postulated is either in response to autoregulatory vasoconstriction of the cerebral arterial vasculature or a decrease in the neuronal activity of regions controlling motor function [185].

During incremental exercise, cerebral HHb has been shown to either remain stable during submaximal exercise and then exhibit a rapid increase at approximately 60% VO_{2max} or to increase from beginning to cessation of exercise [179], representing an increase in the rate of oxygen utilisation. O_2Hb also increases, but only until ventilatory threshold (VT), after which it decreases up to maximal exercise, indicating an increase in oxygen availability up to VT followed by a decrease in availability above VT. THb also increases until VT, after which it remains constant until cessation of exercise occurs [182], indicating an increase in blood volume up to VT, after which blood volume remains stable. These responses have been shown to occur in the pre-frontal, premotor and motor cortex [184].

Training status has an impact on cerebral oxygenation. Trained individuals exhibit lower cerebral oxygenation and blood volume variables at submaximal intensities, but at maximal intensities display higher levels of O_2Hb, HHb and THb, when compared to untrained individuals [185]. A plausible explanation for this difference is that exercise-training adaptations cause a down-regulation of sensory signalling to cortical areas at submaximal exercise intensities, thereby reducing cerebral blood flow and oxygenation [186]. Lowered peripheral chemo-sensitivity, as seen in aerobically trained individuals, may lead to less vasoconstriction and therefore higher levels of oxygenation during maximal exercise [185].

During repeated sprint exercise, cerebral oxygenation (defined as an increase in O_2Hb and THb) has been shown to increase during the first 2 of 10 sprints before fluctuating slightly thereafter [175]. Different results have occurred during 7 repeat sprints, showing an increase in cerebral oxygenation and THb during the first sprint, but a gradual decrease in both parameters during the remainder of the protocol (with no decreases in simultaneous arterial saturations) [45]. The differences could be explained by differences in protocol design as well as exercise and recovery durations, leading to differences in exercise intensity, metabolic load and oxygen demand, which in turn would necessitate different oxygen supply patterns [162]. It is important to acknowledge that tissue oxygenation is affected by arterial oxygen content, haematocrit and blood flow [171, 187]. Because NIRS devices do not measure blood flow, changes in O_2Hb and THb are not direct measures of oxygen supply.

A review article [185], in which a meta-analysis was performed to quantify the effects of exercise on cerebral oxygenation measured via continuous wave NIRS, highlights the paucity of information in this area. Only 25 articles were included in the review, highlighting the low absolute amount of NIRS exercise literature. This review describes the effects of incremental exercise on cerebral oxygenation, and results are in agreement with the responses described earlier in this section [185]. Importantly this review of exercise responses does not include any investigations into HIIT. Specifically, due to the lack of available literature, it is unknown whether cerebral oxygen utilisation differs during various recovery formats or modes of HIIT, in sedentary individuals. Additionally, it is unknown whether cerebral oxygen utilisation differs during a session of HIIT, compared to a session of work-matched CMIE.

Skeletal muscle NIRS responses to exercise

At the initiation of exercise, a hyperaemic response is typically observed in the active musculature [188, 189]. During incremental exercise to exhaustion, a decrease in O_2Hb is observed, matched by an increase in HHb whilst THb also increases [170, 190]. Occasionally a slowing or plateau occurs in muscle HHb towards maximal exercise [170, 179] and is purported to represent maximal O_2 utilisation. The increase in THb has occasionally been observed up to 60 – 65% of VO_{2peak} before plateauing [191, 192] potentially as a result of redistribution of blood flow within or among the locomotor muscles due to muscle activation patterns [179]. The TOI shows an accelerated decrease from 60 – 65% of VO_{2peak} until maximal exercise. The increased utilisation above 60 – 65% of VO_{2peak}, in the presence of a stable THb (representing a stable blood volume), may be due to a rightward shift of the O_2Hb dissociation curve brought about by the onset of metabolic acidosis. [191, 192]. During recovery, O_2Hb increases rapidly, THb remains higher than resting values whilst HHb rapidly returns to resting levels [193, 194]. However, a high level of heterogeneity in oxygenation responses has been observed among and within muscles, as well as between individual participants [179, 195, 196], therefore these generalised responses should be used as a reference with caution.

The majority of studies investigating skeletal muscle oxygenation via NIRS utilise the VL muscle of the quadriceps [176, 197-199], but similar patterns (increases in HHb and decreases in O_2Hb) have been confirmed at respiratory and arm muscle sites [200, 201].

After a period of training, greater increases in HHb are observed in skeletal muscle at maximal exercise intensities [179, 202], indicating a training effect. This increased level of HHb represents an increased ability to utilise oxygen during prolonged and / or high intensity activity. Importantly, studies which show increases in maximal HHb, also routinely show increases in VO_{2max} [170] providing a correlation between increased local oxygen utilisation and systemic increases in CRF. Additionally, at submaximal exercise intensities [203], a lesser degree of muscular desaturation was noted after training, independent of blood volume changes. After training, the relative intensity of the exercise was therefore reduced, leading to less demand on aerobic and anaerobic metabolic pathways. Similar trends in desaturation were noted in repeat sprint performance before and after eight weeks of endurance training [173].

During one of the few studies to examine regional oxygenation during HIIT, VL TOI decreased over successive 30 s high intensity bouts whilst HHb levels increased during each successive bout [174], indicating a greater oxygen utilisation in the working muscle, even though a decrease in external power production occurred across the repeat sprints. Furthermore, the rate of utilisation (HHb) was marked, reaching similar levels as those seen during exercise known to elicit near maximal oxygen utilisation. This study provides evidence that the length of the high intensity bout causes a variable change in oxygenation parameters, with a twofold greater increase in HHb observed during this study than in a study involving much shorter (4 s) sprint activity undertaken previously by the same authors. Furthermore, these changes in oxygenation variables provide NIRS derived evidence for the aerobic component of HIIT [193].

In summary, the findings presented above demonstrate that oxygenation responses during HIIT of varying intensity and duration have been described, but that oxygenation responses during HIIT protocols including different recovery formats or modes of exercise have not. Specifically, whilst there has been limited examination of oxygen utilisation at multiple locomotor muscle sites during incremental or steady-state exercise [204-207], it is unknown whether locomotor muscles have different oxygen utilisation profiles, timings and kinetics during various recovery formats or modes of HIIT, or if there are differences in oxygen utilisation between the same muscle located in different limbs during HIIT of varying recovery format or mode. Additionally, it is unknown whether locomotor muscles have different oxygen utilisation profiles, timings and kinetics / dynamics during HIIT, compared to work-matched CMIE.

2.4.3. Blood pressure responses to HIIT

The investigation of acute blood pressure responses during and immediately post-HIIT has been the subject of few scientific experiments [80, 120, 133, 208, 209]. Specifically, the acute BP response to sessions of HIIT has received little attention in sedentary individuals [120]. In habitually active participants BP responses to a single session of HIIT remain within normal limits [80, 133, 208] and therefore do not constitute a safety issue via a hypertensive response during exercise [74]. However, BP was not measured post-HIIT during these investigations and therefore does not give an insight into potential adverse hypotensive responses after exercise.

The only study to compare the acute post-exercise BP responses between SIT, AIT and continuous high intensity training, found that in young healthy participants, reductions in post–exercise blood pressure, termed post exercise hypotension (PEH), occurred in all three formats. However, only AIE resulted in sustained (> 2 hour) PEH, compared against a control group [57]. Furthermore, no symptomatic PEH responses were reported during this study. The occurrence of asymptomatic or symptomatic PEH after sessions of HIIT of varying recovery format and mode, in sedentary participants, is unknown.

2.4.4. Physiological adaptations to HIIT

Acute physiological responses form the basis of longer term physiological adaptation [1, 27, 42, 91, 92, 140, 141], which in turn possibly result in the health benefits attributed to HIIT [6]. Specifically, an acute oxidative response, such as local muscle oxygen utilisation, is potentially a primary stimulus resulting in the oxidative physiological adaptations reviewed in this section, as well as the health benefits linked to oxidative processes, such as increased CRF [98].

After repeated exposure to HIIT, training adaptations in oxidative metabolism occur, including [2, 3, 27, 30, 76, 77, 92, 140, 210]:

- an increased number, size and functioning of mitochondria.
- an increase in aerobic enzyme function.

- improved blood flow and distribution of blood flow during intense exercise
- muscle fibre changes that enhance aerobic energy transfer
- central cardiovascular adaptations including cardiac hypertrophy, increased vascularisation of the cardiac musculature, increased plasma volume, stroke volume, cardiac output and hence oxygen supply allowing an increased potential for oxygen utilisation from the circulating blood.
- enlargement of the cross-sectional area of vessels as well as the increased capillarisation of the muscle. This angiogenesis can occur rapidly, even after a single bout of exercise.
- increased maximal exercise ventilation, through increases in tidal volume, allowing increased gas exchange ability.
- increased rates of lactate clearance and utilisation during exercise

After repeated exposure to HIIT, adaptations also occur in anaerobic metabolism including increased levels of anaerobic substrates such as phosphocreatine (PCr) increased anaerobic enzyme function [211] and increased capacity to tolerate higher levels of anaerobic production by-product: H^+ ions [2, 3], which also contribute to the increases in VO_{2max} and hence CRF evidenced in the literature [33].

Two HIIT protocols of widely different design can produce similar adaptations in exercise capacity over a 3-week period [212]: The two protocols consisted of 8 x 4min @ 85% P_{peak} with 1.5 min active recovery (AIT) or 12 x 30 s @ 175% P_{peak} with 4.5 min active recovery (SIT). The authors proposed that the increases in 40km time trial performance were brought about by different physiological adaptations stimulated by the different intensities and durations of training, but that the mechanisms were at that stage unclear. As indicated in section 2.4.1 of this review, it has been proposed that a potential mechanism explaining the results described above involves molecular signalling pathways such as adenosine monophosphate kinase and calcium-calmodulin kinase [62]. These signalling pathways, associated with different intensities of exercise, have similar downstream effects relevant to oxidative physiology, such as increasing mitochondrial mass, that result in an increased ability to generate ATP aerobically [148]. This would explain why improvements in CRF occur with HIIT interventions of varying intensity and duration [31, 33]. Furthermore, the study described above [212] again highlights the predominant focus in the HIIT literature being the investigation of the effect of exercise intensity as well as exercise and recovery period duration on longer term physiological adaptations, not the acute responses to alterations in other HIIT design variables such recovery format or mode.

Few studies have examined BP adaptations to repeated HIIT sessions [5, 6, 92, 213, 214] and have provided contradictory findings, showing reductions in BP post-HIIT [5, 213] and no change in BP post-HIIT [6, 92, 214]. However, when no change in BP has been found comparing pre- and post-HIIT interventions, the participants were either individuals with normal BP or individuals with well controlled BP on anti-hypertensive medications [6, 214]. Therefore, the failure to facilitate further reductions in BP is not unexpected. Furthermore, a large degree of heterogeneity in individual BP responses and adaptations was noted across studies [91].

Lastly, psychological adaptations including increased motivation, improved mental fortitude and increased tolerance for the discomfort associated with high intensity exercise have been proposed to explain a proportion of the physiological adaptations associated with HIIT [62].

2.5. Acute physiological and perceptual responses to variations in HIIT recovery format and mode

Participation in HIIT protocols of varying intensity and duration have been shown to result in cardiovascular, respiratory, metabolic, hormonal and perceptual responses [1, 27, 42, 91, 92, 109, 140, 141, 215]. This section is a review of the literature on the known physiological responses relevant to local oxygen utilisation, related cardiovascular and oxidative processes as well as blood pressure and enjoyment in response to HIIT of varying recovery format and exercise mode.

2.5.1. Recovery format

There is a paucity of literature detailing the effect of recovery format (active versus passive) during high intensity intermittent exercise [121-124] and the majority of investigations involve active participants. Specifically, the effect of active versus passive recovery format on multi-site oxygen utilisation (with implications for improvements in systemic health variables such as CRF), during and post–exercise blood pressure responses (with implications for cardiovascular load and safety) and enjoyment (with implications for exercise initiation and compliance), have not been investigated in sedentary individuals.

Oxygen utilisation

The effect of HIIT recovery format on local and systemic oxygen utilisation during short duration (time-efficient) HIIT protocols, has been the subject of minimal investigation [48, 121]. HIIT exercise bouts routinely represent exercise intensity's above the anaerobic threshold (AT) [2] and therefore incorporates both oxidative and glycolytic energy pathways [98]. Above the AT, metabolites accumulate [98]. This increase in metabolite levels is associated with exercise cessation and increased perception of effort [216]. Therefore, due to the fact that clearance of H^+ ions in the exercising muscle is enhanced by active recovery [1, 125, 129, 136, 217], it is proposed that by including active recovery periods, latter bouts of HIIT would be able to be completed, with increased oxygen utilisation, reduced perception of effort (due to decreased general muscular discomfort associated with high levels of metabolic waste product accumulation) and therefore greater levels of enjoyment. In addition, it has been shown that active recovery enhances power output recovery during subsequent exercise bouts [133], an important variable during HIIT.

However, an alternate view proposes that competition for available oxygen may occur between the processes of PCr resynthesis, lactate oxidation and the oxygen cost of continued exercise during active recovery [125]; causing a decrease in performance and power generation when active recovery protocols are adopted. Additionally, in sedentary populations the improved clearance of metabolites associated with active recovery, compared to passive recovery, may not occur in an acute session of HIIT, as the improved clearance of metabolites is an adaptation that occurs with routine exercise training at higher intensities [1]. Therefore, due to the untrained state of sedentary participants and the possible heightened perception of effort during active recovery linked to higher minute ventilation [48] and / or continued muscular discomfort, passive rest periods may allow participants to recover to a greater extent, enabling increased effort, oxygen utilisation and motivation over the course of a session of HIIT, which in turn may translate into higher levels of enjoyment.

Active and passive recovery periods have been shown to affect central cardiovascular and peripheral tissue oxygenation parameters differently: Active recovery causes an increased HR response and VO_2 during HIIT sessions, compared to passive recovery [126, 133].The increased HR (and cardiac output) could equate to increased blood flow and potentially a heightened BP response during HIIT exercise in sedentary individuals. In addition to an increased HR, an increased VO_2 assumes an increased oxygen utilisation by the active musculature. However, in contrast to this theory, a slower decline in O_2Hb was found during intermittent exercise which included passive recovery periods, compared to active recovery periods [121]. Data were collected from one site, the right vastus lateralis (RVL). Therefore, no insight is available with regards to differences in oxygenation variables in different muscles due to recovery format. The slower decline in O_2Hb (indicating a relative increased availability / supply of oxygen) associated with passive recovery could allow a higher reoxygenation rate and higher PCr resynthesis, contributing to the longer time to exhaustion found [121]. This statement is supported by research in which lower levels of PCr were measured after 21 s of recovery during exercise sessions containing active recovery periods when compared to exercise sessions containing passive recovery periods [125]. Additionally, the participants were active soccer players [121] therefore, training adaptations could have effected oxygenation results [185].

Similar oxygenation findings occur during repeat maximal treadmill sprints and repeat Wingate bouts in active populations, with higher muscle HHb (indicating increased oxygen utilisation) found during protocols including active recovery periods [48, 104]. However, these studies included sprint and recovery periods of very short duration (4 and 15 s sprints and 21 and 15 s recovery periods). The shorter exercise and recovery timings would affect the degree of aerobic energy contribution and hence the changes in Hb chromophores observed, compared to longer exercise and recovery periods [154].

In summary, the effect of active versus passive recovery format during HIIT on the acute multi-site oxygen utilisation responses, with implications for the systemic health variable of CRF, has not been investigated in sedentary individuals.

Blood pressure

Comparison of the systolic and diastolic BP response of sedentary participants to sessions of HIIT including either active or passive recovery periods, has not occurred. However, in habitually active participants, blood pressure remained within normal limits during single HIIT sessions that included either passive or active recovery periods [80, 133, 208]. Habitual PA (and increased CRF as indicated by VO_{2max} values of participants in these studies) potentially had an impact on the relative intensity of the HIIT sessions, and therefore the BP responses. Additionally, habitual PA and higher levels of CRF have been linked to an improved ability to regulate BP responses during and after activity [218]. Three studies have compared BP responses between HIIT sessions including passive or active recovery periods, reporting no differences between recovery format in active [133, 209] and sedentary [120] participants. However, the study involving sedentary participants reported mean arterial pressure (MAP) at rest and after the last HIIT bout and did not report on longer-term post-exercise BP responses or the occurrence of post-exercise hypotension (PEH).

Comparison of the propensity for symptomatic PEH to manifest following sessions of HIIT including either active or passive recovery periods, in sedentary individuals, has not occurred. Previous research investigating the BP response of active participants to repeated Wingate bouts separated by active recovery periods found a significant decrease in DBP post-exercise, when compared to resting levels [57, 137]. It was not reported whether the reductions in DBP coincided with symptoms of pre-syncope in one of these studies [137]. However, 2 of 13 subjects withdrew from the other study after experiencing vasovagal PEH events during the HIIT protocol [57]. Furthermore, the investigation of symptomatic PEH, whilst recovering passively after a session of HIIT, represents a realistic situation in a sedentary population who will likely be fatigued post-HIIT and unable or unwilling to perform an active recovery (one of the recommendations to prevent symptomatic PEH) [60]. Conversely, the session of HIIT including either active or passive recovery periods which induces a greater degree of PEH, if asymptomatic, may have implications for improvements in blood pressure profiles (reductions) linked to cardiovascular health [213, 214].

Enjoyment

There has been no direct comparison of enjoyment between HIIT protocols including active and passive recovery periods. Individuals with coronary artery disease reported a higher level of enjoyment during a HIIT protocol which included 15 s exercise and passive recovery periods, compared to a HIIT protocol of the same durations including active recovery periods [122]. However, the differences in enjoyment were reported anecdotally. The only study to specifically compare exercise enjoyment between HIIT protocols found no differences in enjoyment between sessions of varying interval and active recovery duration (four 4 min intervals at 90-95% HR_{max}, separated by 3 min recovery at 50 W and sixteen 1 min intervals at 90-95% HR_{max}, separated by 1 min recovery at 50 W) [69].

2.5.2. Exercise mode

There are few experiments detailing the effect of exercise mode (running versus cycling) during short duration HIIT [219, 220]. Specifically, the effect of running versus cycling HIIT on multi-site local oxygen utilisation, during and post–exercise blood pressure responses and enjoyment have not been investigated in sedentary individuals. However, by examining research into physiological and perceptual responses when utilising a variety of exercise modalities and intensities, insight into the expected outcomes can possibly be predicted.

Oxygen utilisation

The effect of HIIT mode on local and systemic oxygen utilisation has been the subject of few scientific experiments, specifically during short duration (time-efficient) HIIT protocols [221]. However, comparisons of mode have occurred during incremental exercise [116, 222]. By examining these incremental exercise comparisons of mode as well as research into physiological responses relevant to oxidative processes when utilising a variety of exercise modalities and intensities, the expected local and systemic oxygen utilisation responses during a direct comparison of exercise modes can possibly be predicted.

During running, VO_2 and HR responses are higher, compared to cycling, due to running being weight bearing and the greater number of active muscle groups recruited, thereby eliciting a higher oxygen cost [116, 220, 223-226]. A higher stroke volume (SV) also occurs during maximal running when compared to maximal cycling, whilst arteriovenous oxygen difference ($a\text{-}vO_{2diff}$) has been reported to be similar between the two modes [227]. Due to the higher central cardiorespiratory responses during running, including higher cardiac outputs[228], greater blood pressure and blood flow would potentially eventuate and it is proposed that higher maximal levels of oxygen utilisation would occur at the active muscle sites throughout a running HIIT session, compared to a cycling HIIT session. This proposal is tenuously supported by a study in which HHb were shown to be higher in the RVL muscle during incremental cycling, than during knee extension exercise in active participants [197], providing evidence that exercise modality effects the degree of deoxygenation in active muscle. The finding of a higher oxygen utilisation in active participants during running, compared with cycling, as indicated in the literature, may however be offset by the inability to increase the intensity of exercise sufficiently when running, due to potential running inefficiency in the sedentary population [229]. Cycling against a resistance may therefore induce a greater exercise stress, a greater local and systemic oxygen utilisation and a greater BP response. Furthermore, the similarity of oxygen utilisation associated with different modes of exercise is illustrated by a study in which VO_2, HR, and lactate levels were not significantly different during progressive submaximal exercise on cycling or rowing ergometers [230]. Additionally, no significant differences in muscle oxygen utilisation were found when comparing cycling and arm crank incremental exercise in recreationally active men and women [188]. However, oxygen utilisation trends were measured in different muscles during the arm cranking and the cycling, indicating that across two different muscle sites, the same maximal change in oxygen utilisation was achieved during two non-weight bearing modes of exercise.

Blood flow directly effects oxygen availability, and hence indirectly, utilisation [231]. A mechanism that contributes to regional blood flow and oxygen availability in active muscles during exercise is the muscle pump [232]. The muscle pump aids venous return to the heart [146]. Direct comparison of the muscle pump during different modes of exercise has not occurred. It has however been postulated that the efficacy of the muscle pump would be affected by the mode and intensity of exercise, with the muscle pump being more effective during running than cycling, due to muscle pump efficiency being greater in the erect posture [227, 233, 234]. However, no significant differences were noted in mean increase or maximal brachial artery blood flow during a comparison of low intensity cycling and walking [235], implying that in the non-active musculature at least, lower limb exercise causes similar increases in blood flow irrespective of mode.

In highly trained triathletes, mode of exercise has been shown to effect arterial oxygenation levels (PaO_2), with PaO_2 levels decreasing significantly more during running than during cycling of matched submaximal intensity [223, 236, 237]. Possible explanations for this hypoxaemia include relative hypoventilation brought about by aerobic training or ventilation / perfusion mismatching [238]. These possible factors may affect regional oxygenation between modes of exercise, especially at the high exercise intensities inherent in HIIT, when ventilation / perfusion mismatching could conceivably occur.

Lactate levels, collected at the fingertip, have been shown to be higher during matched high intensity running when compared to cycling in recreationally active men [220], indicating an increased reliance on anaerobic processes during the running protocol. However, no differences in lactate levels have been found between these modes during submaximal and high intensity exercise in healthy populations [116, 239].

Additionally, when examining exercise test modalities for individuals diagnosed with chronic obstructive pulmonary disease (COPD), peak lactate levels were found to be higher during cycling than during treadmill incremental exercise, despite higher VO_{2peak} values being achieved during treadmill incremental exercise [226]. This finding could be explained by the fact that cycling would be an unaccustomed exercise format among the clinical participant population, whilst walking would be familiar and hence allow for some specificity of training. It is possible that a similar training effect, due to the principle of specificity, could be present in sedentary individuals during a comparison of cycling and running modes [227].

Muscle recruitment patterns, muscle contraction efficiency, type of contraction and strength deficits have been shown to differ between modes of exercise [222, 240]. Running consists of concentric and eccentric contractions, whilst cycling consists of concentric contractions only [222]. Eccentric contractions have a lower metabolic cost than concentric contractions [222]. Therefore, it is possible that in a sedentary population with no specificity of training, during 30 s exercise bouts, an increased level of oxygen utilisation (linked to metabolic demand) could exist for running HIIT when compared to cycling HIIT.

Blood pressure

The comparison of BP responses between running and cycling modes of HIIT has not occurred in sedentary individuals. However, when BP responses are measured during sessions of HIIT conducted either running or cycling, BP remained within normal limits and no adverse sensations associated with blood pressure reductions were reported [80, 133, 208]. However, participants were habitually active and BP was not measured post-HIIT in all conditions.

Enjoyment

There has been no direct comparison of enjoyment between short duration HIIT protocols performed running and cycling. However, exercise mode has been shown to have an acute effect on psychological mood state [241, 242], including enjoyment [64], with running eliciting a more positive mood profile than weightlifting [243].

2.6. Acute physiological and perceptual responses during comparisons of HIIT and CMIE

Participation in HIIT, compared to CMIE, result in differences in vascular, respiratory, metabolic, hormonal and perceptual responses [1, 27, 42, 91, 92, 109, 140, 141, 215]. This section is a review of the literature on the known physiological responses relevant to local oxygen utilisation, related cardiovascular and oxidative processes as well as blood pressure and enjoyment in response to a session of HIIT, compared to a session of work-matched CMIE.

The effect of a short duration HIIT protocol, compared to a session of CMIE matched for the mechanical work performed during the HIIT protocol, on multi-site local oxygen utilisation, during and post-exercise blood pressure and enjoyment has not been investigated in sedentary individuals.

Oxygen utilisation

Previous comparisons of locomotor muscle oxygenation in response to HIIT and CMIE have led to conflicting results: no difference in ΔHHb and O_2Hb levels have been shown [44, 177], however a greater ΔHHb was found during HIIT, compared to CMIE [44]. However, these investigations were conducted during steady state [177] or step transition [44, 177] exercise tests of different intensities in physically active individuals before and after a period of training, as opposed to determining the acute effects of the different exercise intensities on local oxygen utilisation, in the same participants.

Health related variables, including systemic oxygen utilisation have been compared in sedentary individuals between single sessions of HIIT and work or energy expenditure matched CMIE, showing increased systemic oxygen utilisation during HIIT, compared to CMIE [10, 11]. Oxygen utilisation at multiple locomotor muscles has not been compared between a single session of HIIT and CMIE matched for work, in sedentary individuals. It is expected that, similar to systemic measures of oxygenation [101], local oxygen utilisation will be higher during HIIT than in CMIE when mechanical work is controlled for.

Blood pressure

The acute effects of a single HIIT session versus a work-matched CMIE session on BP responses, in a sedentary population, are unknown. As detailed in section 2.4.4 of this review, the effect of 2 – 16 week HIIT versus CMIE interventions on BP have been evaluated and provide mixed results, with findings of no difference or improvements (reductions) in BP post-HIIT interventions [6, 11, 79, 92, 111]. During these longitudinal investigations, acute blood pressure measurements / responses were evaluated and no adverse acute blood pressure responses were reported at these specific time points. However, the majority of these investigations included lower intensity protocols of HIIT, not supramaximal short-duration SIT protocols. Symptomatic PEH responses have been linked to high intensity exercise [56, 57], sedentary / training status [58] and lower CRF [218]. However, no direct comparison of sessions of HIIT and CMIE exercise, with the aim of delineating potential differences in symptomatic PEH responses between these exercise formats, has occurred in sedentary individuals. The acute effects of a single HIIT session versus a work-matched CMIE session on the likelihood and magnitude of PEH, in a sedentary population, are therefore unknown.

Enjoyment

Active participants report HIIT to be more [36, 244, 245] or equally [246] enjoyable, compared to CMIE. The comparison of enjoyment during exercise of different intensities in sedentary participants has yielded contradictory results: Sedentary individuals are more likely to enjoy exercise that they perceive as moderate in intensity [64, 108, 242], however no difference in enjoyment levels have been found between a session of HIIT and CMIE in this population [66, 247, 248]. Additionally, HIIT was found to be less [38, 117], equal [101] and more [37, 65, 67] enjoyable than continuous lower (moderate to vigorous) intensity exercise during both single interventions and training studies. However, all but one [101] of the previous studies examining enjoyment have not controlled for the mechanical work performed during the exercise sessions. Different workloads across the sessions could influence exercise enjoyment, especially in untrained sedentary individuals, and therefore obscure findings. The only study to match HIIT and CMIE sessions for energy expenditure during the evaluation of enjoyment, found no difference between HIIT and CMIE over an eight week period [101]. However, the HIIT protocol was of 30 min duration, which does not fulfil the requirement of HIIT being time-efficient, compared to CMIE.

Finally, comparisons of HIIT and CMIE have routinely been designed as longitudinal cohort studies comprising a group assigned to a HIIT intervention and another group assigned to a CMIE intervention [65, 67, 101]. Future studies examining enjoyment (and other variables) during a session of HIIT compared to CMIE, featuring a repeated measures design, arguably have the advantage of eliminating differences between the groups of participants. A disadvantage of a repeated measure design, order effects, can be controlled, where possible.

2.7. Summary of the literature review

The health benefits associated with HIIT protocols have been investigated [6, 7, 23, 29, 31, 33-35, 67, 79, 91, 92, 103, 110, 249-253], including the increases in CRF due to HIIT training. However, the physiological mechanisms and responses contributing to these benefits have received less attention [7, 24-26, 30, 47, 140, 158, 159, 254]. Specifically, the acute multi-site local oxygen utilisation responses to single sessions of HIIT, a potential primary stimulus leading to the acute increases in systemic oxygen utilisation during HIIT sessions and the improvements in CRF after multiple exposures to HIIT, have not been investigated in sedentary individuals. Oxygen utilisation data, in the form of systemic arteriovenous oxygen difference, is used to calculate VO_2 (the surrogate measure of CRF). VO_2 has been measured during HIIT in sedentary populations, [33, 38, 103] showing an expected increase in VO_2 during a single HIIT session and after multiple HIIT sessions (constituting an increase in CRF due to a training effect). However, local tissue oxygen utilisation at multiple sites has not been measured simultaneously with systemic VO_2 during various HIIT protocols in sedentary individuals. The simultaneous measurement of multi-site local oxygen utilisation and systemic VO_2 will allow greater insight into how local oxygen utilisation influences systemic VO_2 in this population, and thereby provide information on the mechanisms of the increase in the important health marker of CRF [6, 33].

The physiological and perceptual responses of sedentary individuals to HIIT protocols of different intensities and durations have been investigated [27-29, 33, 42, 67, 76, 91, 107, 109, 110, 140, 144, 215, 255-259]. The majority of these investigations have been longitudinal in design [27, 29, 33, 42, 67, 76, 91, 107, 109, 110, 215, 255-259]. The effect of differences in recovery format (active versus passive) and mode (running versus cycling) on physiological and perceptual responses in sedentary individuals has not been investigated. Specifically, the effect of active versus passive recovery format and running versus cycling modes during short duration HIIT on multi-site local oxygen utilisation (with implications for improvements in systemic health variables such as CRF), during and post-exercise blood pressure responses (with implications for cardiovascular load and safety) and enjoyment (with implications for exercise compliance), is unknown in sedentary individuals.

Investigation of the health benefits and risks associated with HIIT participation and the related physiological and perceptual responses to HIIT routinely involve comparisons to CMIE [7, 29, 30, 37, 38, 65, 67, 92, 93, 103, 107, 215, 244, 250, 257, 260-265]. However, these comparisons are routinely longitudinal in design. The acute physiological responses to a single HIIT session, which are the basis of the health benefits and risks associated with HIIT participation, are largely unreported in these longitudinal comparisons. Additionally, these comparisons rarely control for the amount of work performed during the HIIT and CMIE conditions [6, 7, 44, 77, 245, 248, 266]. Specifically, the effect of a single short-duration HIIT protocol, compared to a work-matched session of CMIE, on multi-site local oxygen utilisation (which could potentially explain some of the variance in systemic oxygen utilisation / CRF results between HIIT and CMIE interventions to date), blood pressure (with implications for cardiovascular load and safety differences between these two exercise formats) and enjoyment (with implications for the feasibility of HIIT to replace CMIE as the recommended format of exercise) has not been investigated in sedentary individuals.

3. The aims and hypotheses of the research

3.1. Aims

The aims of this thesis were to enable the quantification and comparison of locomotor muscle and cerebral oxygen utilisation, blood pressure and exercise enjoyment in young sedentary participants in response to acute sessions of HIIT:

a) including active and passive recovery formats,
b) conducted running and cycling,
c) and in comparison to a work-matched session of CMIE.

3.2. Hypotheses

It was hypothesised that in young sedentary individuals:

Oxygen utilisation, BP and enjoyment would be higher during a HIIT session including active recovery periods, compared to a session including passive recovery periods.

Oxygen utilisation, BP and enjoyment would be higher during a running HIIT session, compared to a cycling HIIT session.

Oxygen utilisation and BP would be higher and enjoyment lower during a HIIT session, when compared to a work-matched CMIE session.

3.3. Significance of thesis

The acute physiological responses to a single HIIT session are ill-defined [122, 174]. It therefore follows that the quantification of local oxygen utilisation, BP and enjoyment responses to HIIT of varying format has largely not occurred, in sedentary populations.

The utilisation of NIRS to investigate oxygenation in human tissue is a relatively new practice, first described in 1977 [163, 267]. The majority of early exercise studies utilising NIRS to investigate regional muscle oxygenation focused on young, active healthy populations [166, 168, 190, 268-271], measurements from single muscle or brain sites [166, 168, 268, 271], isolated exercises such as plantar flexion or handgrip evaluations [269, 270, 272] and moderate intensity or incremental exercise training studies [166, 197, 203, 271]. There is a relative paucity of NIRS literature available regarding local oxygenation responses during high intensity exercise of any format, mode or design. The significance of this thesis includes that, for the first time, oxygenation will be examined across three locomotor muscle sites and a cerebral site, in response to HIIT sessions of varying format.

Growing interest in HIIT is evidenced by the rapidly increasing body of literature (both scientific and commercial) indicating that health benefits can be attributed to HIIT, particularly the reduction of cardiovascular and metabolic risk factors [6, 7, 28], the reduction in rates of clinical event occurrence and improvements in wellness [259, 273-277]. However, research has tended to focus on the effect of HIIT protocols (of numerous durations and designs) on specific health measures and / or risk factors reductions, such as changes in insulin sensitivity and CRF over time [6, 27], not on the acute physiological responses underlying changes in these variables. Acute changes in local muscle and brain oxygen utilisation during HIIT would provide evidence of the mechanism facilitating the improvements in aerobic function, systemic oxygen utilisation (VO_2) and CRF documented in training studies and reviews [6, 202] and quantify the effect of altering HIIT recovery format and mode on these mechanisms. Therefore, the novel quantification of local oxygen utilisation responses is essential, as a number of oxygen dependant health benefits occur in response to HIIT, with little insight as to the stimulus leading to said improvements [6].

Proposals to adopt HIIT in sedentary populations have met with concern [70]. High intensity exercise is associated with increased risk of injury, cardiovascular events and sudden cardiac death, particularly during infrequent or unaccustomed exercise [20]. The novel research included in this thesis will quantify the physiological responses of the cardiovascular parameters HR and BP to HIIT sessions of varying format and mode in sedentary individuals’ and define the actual exercise intensities achieved during these sessions. Quantifying the physiological responses and actual exercise intensities achieved during HIIT of varying recovery format, mode and in comparison to a session of work-matched CMIE is necessary, if the benefits of HIIT are to be maximised and the risks minimised.

The ability of sedentary individuals’ to maintain the high intensities of exercise required during HIIT, is ill-defined and has been questioned [62]. During this thesis, the physiological responses to self-paced HIIT were evaluated by instructing participants to ‘exercise as hard as they can’ during each bout of high intensity exercise, when practical to do so. This format of HIIT removed the need for sophisticated and often expensive equipment to formulate, monitor and benchmark effort / intensity during HIIT sessions. This distinction enabled evaluation of the physiological responses to this less complex and inherently self-moderated form of HIIT, representative of HIIT protocols adopted in real-world situations. In addition to physiological data collected, instructing each participant to exercise at a perceived maximal intensity (i.e. 'as hard as they can') during the high intensity bouts enabled unique insights into whether sedentary individuals would maintain the requisite intensities required during HIIT acutely, their perceptions of intensity compared to physiological markers of intensity and their enjoyment levels considering their physiological and perceptual responses. These acute responses potentially inform longer term compliance or avoidance behaviours.

Enjoyment during exercise predicts exercise compliance and adherence [66, 108, 278, 279]. If enjoyment during initial HIIT session(s) is low, longer-term adherence to HIIT will be negatively impacted, regardless of the time efficiency and risk reductions shown during laboratory based experiments and heavily promoted in favour of HIIT interventions. Previous researchers have highlighted the need for research into the efficacy of HIIT in sedentary at-risk populations [6, 27, 28]. However, HIIT consists of nine design variables, each of which may impact on the enjoyment of the session. There is no research directly comparing variations of the design variables of recovery format and mode on enjoyment in sedentary participants. Therefore, this thesis documents the novel investigation of sedentary individuals' enjoyment during HIIT sessions of varying recovery format, mode and in comparison to a session of work-matched CMIE.

4. The effect of recovery format during HIIT on local oxygen utilisation

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Statement of intellection contribution and relative role of the candidate, Mr Yuri Kriel, in the execution of the study and writing of the paper:

Conceived and designed the experiment: YK, CS

Performed the experiment: YK

Analysed the data: YK, HAK, CDA, CS

Wrote the first draft of the paper: YK

Edited the paper: YK, HAK, CDA, CS

Yuri Kriel

Hugo A. Kerhervé

Christopher D. Askew

Colin Solomon

Full Title: **The effect of active versus passive recovery periods during high intensity intermittent exercise on local tissue oxygenation in 18 – 30 year old sedentary men**

Short Title: **Effect of high intensity intermittent exercise on tissue oxygenation**

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4.1. Abstract

Purpose

High intensity interval training (HIIT) has been proposed as a time-efficient format of exercise to reduce the chronic disease burden associated with sedentary behaviour. Changes in oxygen utilisation at the local tissue level during an acute session of HIIT could be the primary stimulus for the health benefits associated with this format of exercise. The recovery periods of HIIT effect the physiological responses that occur during the session. It was hypothesised that in sedentary individuals, local and systemic oxygen utilisation would be higher during HIIT interspersed with active recovery periods, when compared to passive recovery periods.

Methods

Twelve sedentary males (mean ± SD; age 23 ± 3 yr) completed three conditions on a cycle ergometer: 1) HIIT with passive recovery periods between four bouts (HIITPASS) 2) HIIT with active recovery periods between four bouts (HIITACT) 3) HIITACT with four HIIT bouts replaced with passive periods (REC). Deoxygenated haemoglobin (HHb) in the vastus lateralis (VL) and gastrocnemius (GN) muscles and the pre-frontal cortex (FH), oxygen consumption (VO_2), power output and heart rate (HR) were measured continuously during the three conditions.

Results

There was a significant increase in HHb at VL during bouts 2 ($p = 0.017$), 3 ($p = 0.035$) and 4 ($p = 0.035$) in HIITACT, compared to HIITPASS. Mean power output was significantly lower in HIITACT, compared to HIITPASS ($p < 0.001$). There was a significant main effect for site in both HIITPASS ($p = 0.029$) and HIITACT ($p = 0.005$). There were no significant differences in VO_2 and HR between HIITPASS and HIITACT.

Conclusions

The increase in HHb at VL and the lower mean power output during HIITACT could indicate that a higher level of deoxygenation contributes to decreased mechanical power in sedentary participants. The significant differences in HHb between sites indicates the specificity of oxygen utilisation.

4.2. Introduction

Sedentary behaviour, defined as not meeting physical activity recommendations for the achievement of health benefits, is a risk factor for multiple chronic diseases [12, 13] and a global epidemic [12, 15-19]. Physical activity recommendations include accumulating 150 – 300 min of moderate intensity exercise each week [20]. The most frequently cited reason for non-compliance is a lack of time [21]. High intensity interval training (HIIT) of a low volume has been proposed as a time-efficient exercise format to improve exercise adherence, thereby reducing the chronic disease burden associated with sedentary behaviour [31]. The beneficial effect of HIIT interventions on markers of health risk has been well documented [6, 7, 259]. HIIT has been shown to be as effective or more effective than longer, moderate intensity exercise interventions at improving specific markers of risk, such as low cardiorespiratory fitness [5, 6, 37].

Benefits of regular HIIT exercise, such as increased cardiorespiratory fitness, have been linked to increases in mitochondrial content and function [41, 42]. Whilst the exact mechanisms underlying these increases are not completely understood, it is possible that the increase in oxygen utilisation at the local tissue level during an acute session of HIIT provides a stimulus for these improvements. The effects of a single HIIT intervention on systemic and locomotor muscle oxygenation have been evaluated previously [48, 172]. However, these investigations were conducted in active individuals, evaluated only one muscle site and used measures of oxygenation in a sports performance context [48, 174].

Site specific oxygen utilisation at the local tissue level can be measured using near infrared spectroscopy (NIRS). NIRS is a non-invasive method for the measurement of the change in concentration of oxyhaemoglobin (O_2Hb) (oxygen availability) and deoxyhaemoglobin (HHb) (oxygen utilisation), as measures of tissue level oxygenation. Oxygen utilisation during exercise has been described in active individuals at a single muscle site [280] and in component muscles of the quadriceps [195, 281]. In active individuals, at a single muscle site, oxygen utilisation (as indicated by increased HHb) is increased during HIIT bouts when compared to pre-exercise values [48, 104].However, oxygen utilisation during HIIT in sedentary individuals at the local tissue level has not been determined. Furthermore, it is unknown if oxygen utilisation differs between distinct locomotor muscles in a sedentary population during HIIT. Investigation of the oxygen utilisation responses in sedentary individuals will provide additional information on the extent to which oxygen utilisation increases during HIIT in distinct locomotor muscles, a potential stimulus for improved mitochondrial function.

Nine design components (series, inter-series, bout and recovery: number, duration and intensity as well as exercise mode) can be altered in HIIT [2]. The recovery periods of HIIT are an integral part of the exercise session, as these periods have an effect on the physiological responses that occur during the session [124].The two most frequently adopted HIIT recovery formats are passive and active recovery. The effect of recovery formats on local tissue oxygenation and markers of performance have yielded inconsistent findings to date, with active recovery leading to higher [48], lower [124] or an equivalent [104] degree of local muscle deoxygenation when compared with passive recovery. Similarly, inconsistent findings have been shown when mechanical power and heart rate were compared during HIIT that included either active or passive recovery [119-121, 124]. Variations in the HIIT protocols used during these projects may have contributed to the conflicting results. The effect of active versus passive recovery periods on oxygen utilisation during HIIT bouts at specific locomotor muscle and brain tissue sites, in sedentary populations, is unknown.

The primary aim of this project was to compare the local (Δ[HHb]) and systemic (VO_2) oxygen utilisation, mean power output and heart rate responses during HIIT conditions which included either passive or active recovery. A secondary aim was to compare the relative Δ[HHb] between local muscle and brain tissue sites during HIIT exercise.

It was hypothesised that in young sedentary individuals, during high intensity exercise bouts that are interspersed with active recovery periods, when compared to passive recovery periods, VO_2, Δ[HHb], mean power output and heart rate would be higher and that the increase in Δ[HHb] during HIIT exercise would be higher at the local muscle tissue sites when compared to the brain site.

4.3. Methods

4.3.1. Ethics statement

This research project was approved by the human research ethics committee of the University of the Sunshine Coast (S/13/472). All participants received a research project information sheet before providing written informed consent.

4.3.2. Experiment design

The project consisted of three testing sessions, one for each of the three conditions of the project. Exercise was performed using a cycling ergometer. All testing sessions were separated by three to seven days to prevent a potential carry-over effect between conditions and to minimise the effect of any potential confounding variables between testing sessions. In this article, each 30 s period of high intensity exercise is referred to as a bout. Each complete protocol consisting of four x 30 s bouts of high intensity exercise, separated by 2 min recovery periods, is referred to as a condition.

The three conditions were: 1) a protocol of high intensity interval exercise with passive recovery periods between each bout of HIIT (HIITPASS) 2) a protocol of high intensity interval exercise with active recovery periods between each bout of HIIT (HIITACT) 3) a protocol in which only the active recovery periods were completed and the bouts of HIIT were replaced with passive periods (REC), in order to quantify the effect of active recovery. The conditions were randomized and followed a Latin-squares cross-over design to control for a possible order effect. The conditions and the timing of measurements are illustrated in Fig 4.1.

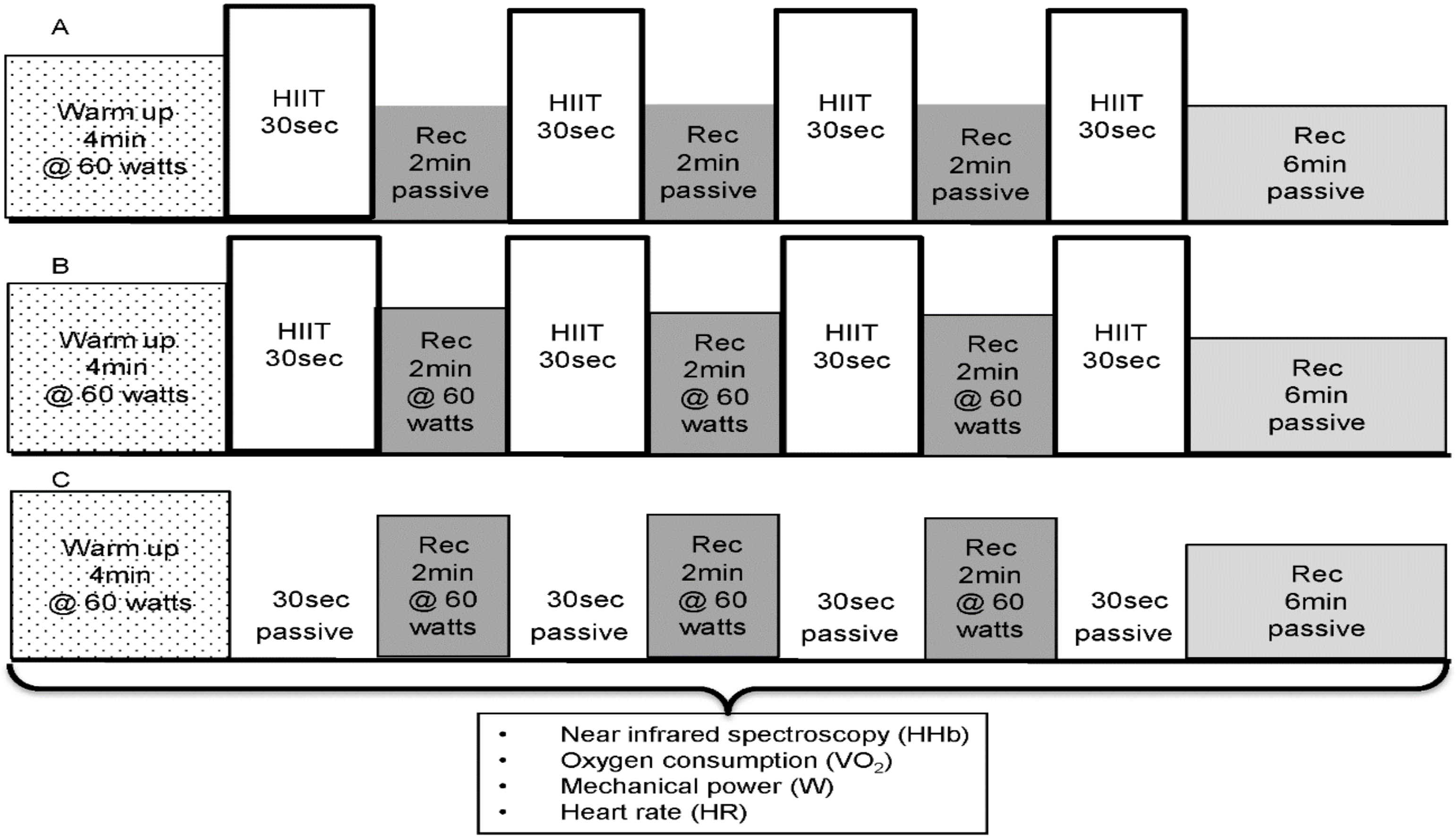

Figure 4.1. The structure and timing of measurements of the three conditions.

(A) HIITPASS. (B) HIITACT. (C) REC.

4.3.3. Participants

The participant group consisted of twelve males from the University community who met the inclusion criteria of being aged 18 – 30 yr.; currently completing less than 150 min of moderate intensity or 75 min of vigorous intensity activity per week; presenting with no cardiovascular and metabolic disease; taking no medications; having no known orthopaedic or other health related issues that would be made worse by participation in, or inhibit completion of the project. Descriptive physical characteristics of these participants are in Table 4.1.

Table 4.1. Participant characteristics.

Height (cm)	176.3 ± 8.3
Weight (kg)	78.19 ± 13.82
Age	23 ± 3
Vastus lateralis skinfold (mm)	12.75 ± 5.88
Gastrocnemius skinfold (mm)	11.00 ± 3.25
FVC (L)	5.40 ± 0.77
FVC % pred (%)	104.7 ± 10.2
FEV_1 (L)	4.54 ± 0.72
FEV_1 % pred (%)	104 ± 10.9

(FVC = Forced vital capacity; FEV_1 = Forced expiratory volume in 1 s).

Data are (mean ± SD) (n = 12).

4.3.4. Procedures and equipment

Screening procedures

At the first testing session, participants completed risk screening and medical history questionnaires and a physical activity log. For the physical activity log participants reported the duration, intensity and type of activity which they had completed over the preceding seven days as well as the daily activity undertaken during an average week over the last three months. This physical activity log was used to ensure that participants' recent activity levels were within the definition of sedentary for the purposes of this project (an individual not achieving the current minimal recommendations for exercise participation to gain health benefits) [282]. Participants were asked to refrain from performing any exercise in the 24 hours preceding each session and to not ingest any caffeine, alcohol or a large meal in the four hours preceding a session. Participants were asked to ensure that they were adequately fed and hydrated on the day of testing and this was confirmed at each testing session. To ensure normal resting pulmonary function, participants completed a pulmonary function test (Spirolab II, Medical International Research, Rome, Italy) following standard procedures [283] (Table 1). Participants were characterised by height, mass and adipose tissue thickness (ATT) (Table 4.1). ATT measurements, performed by the same researcher in each instance using skinfold callipers (Harpenden, British Indicators Ltd, Burgess Hill UK) and standard procedures, ensured that site-specific changes in oxygenation occurred within the muscle tissue rather than in the skin and adipose tissue.

Exercise conditions

Prior to the first exercise session, participants were familiarised with the Wingate testing protocol, the Velotron cycle ergometer (Racermate, Seattle WA, USA) and the process of holding a constant cadence. The cycle ergometer seat height and handlebar position were adjusted for each participant and replicated for subsequent exercise sessions.

The HIIT protocol utilised during two of the three conditions (HIITPASS and HIITACT) was adapted from protocols used in sporting, recreationally active and untrained populations. [62, 94-96, 104, 174, 284].

Each condition consisted of an initial baseline data collection period of 3 min when the participant remained stationary on the cycle ergometer. Exercise testing began with a 4 min warm up period. The warm up period consisted of each participant cycling against a fixed resistance of 60 Watts (W) at a cadence of 60 revolutions per minute (RPM). The warm up was followed by four 30 s bouts of high intensity exercise in the HIITPASS and HIITACT conditions, with 2 min recovery periods separating each of the high intensity bouts. During the REC condition, the four high intensity exercise bouts were replaced by periods of passive rest. Each participant was asked to increase cadence to a maximum during a five second period immediately preceding each bout of HIIT.

The resistance (0.075kg per kg body weight), automatically applied to the flywheel of the ergometer at the start of each bout of HIIT, was utilised during other HIIT Wingate protocols involving untrained adult populations [98]. Power output during the HIIT bouts was determined by participant effort. Participants were instructed to give a maximal effort from the beginning of each bout, using the prompt to ‘go as hard as you can’. Participants were then verbally encouraged using standardised phrases during all bouts of exercise in an attempt to ensure a maximal effort. During the passive recovery periods of the HIITPASS condition, participants were instructed to sit as still as possible with the bicycle cranks in a relaxed horizontal position. During the active recovery periods of the HIITACT and REC conditions, participants were instructed to pedal at a cadence of 60 RPM against a resistance of 60 W (approximately 30-40% VO_{2max}) [125], an intensity of active recovery shown to promote optimal clearance of metabolites [136, 217]). Upon completion of the fourth and final bout, there was a 6-min passive recovery period.

Participants were instructed to remain seated throughout each condition in an attempt to reduce movement artefact in the NIRS data and to allow for consistency in muscular recruitment patterns and hence power data.

Tissue oxygenation

Changes in local tissue oxygenation were measured continuously during rest, exercise and recovery. The terms oxygenated haemoglobin (O_2Hb), and deoxygenated haemoglobin (HHb) each include the combined signal of Hb and myoglobin (Mb). The changes in the relative concentration of O_2Hb ($\Delta[O_2Hb]$) and HHb ($\Delta[HHb]$) as a function of time were measured using a Near Infrared Spectroscopy (NIRS) system (2 x PortaMon and 2 x Portalite devices, Artinis Medical Systems BV, Zetten, Netherlands). This system allows for non-invasive and simultaneous measurement of these variables at multiple sites. The NIRS system uses a modified form of the Beer-Lambert law to calculate changes in O_2Hb and HHb using two continuous wavelengths of near infrared light (763 and 855nm). A fixed differential pathlength factor (DPF) of 4 was used for muscle tissue and an age dependant DPF was used for cerebral tissue based on manufacturer recommendations.

The NIRS devices (weighing 84 g with dimensions of 83 x 52 x 20 mm) were placed on the shaved skin overlying the muscle belly of two locomotor muscles of the left leg, the vastus lateralis (VL) and the gastrocnemius (GN), a muscle involved in respiration: the

7th external intercostal muscle (IC) and the area of the forehead overlying the pre-frontal cerebral cortex (FH) approximately 3 cm left from the forehead midline and immediately above the supra-orbital ridge (between Fp1 and F3, according to the modified international EEG 10 – 20 system). To ensure measurement consistency, the placement of the NIRS devices was referenced to accepted anatomical landmarks as detailed in previous experiments [48, 97, 104, 168, 175]. The location of devices was marked with a felt tip pen at the first testing session and participants were instructed to maintain these marks between sessions. Each device was secured using standardised procedures to shield against ambient light contamination and to prevent motion artefact due to device slippage. For all testing the same device was used at the same measurement site for each participant. The NIRS system was connected via Bluetooth to a computer for data acquisition and subsequent data analysis.

For this project, both Δ[O_2Hb] and Δ[HHb] were measured, however only Δ[HHb] values are presented. The Δ[HHb] data are potentially unaffected by changes in perfusion, blood volume or arterial Hb concentration [166, 285, 286]. The Δ[O_2Hb] data are affected by muscular compression and changes in blood flow and volume [287] , especially during the rapid and substantial changes in these variables that accompany HIIT bouts [48]. Using Δ[HHb] is consistent with other research utilising NIRS measurements to investigate HIIT and exercise in general [48, 104] thereby allowing for comparisons to be made between this project and previous research. NIRS data collected at the IC site included gross movement artefact throughout testing, obscuring the NIRS signal. Gross movement artefact was also present in NIRS data collected at the VL and GN sites during the passive recovery periods of the HIITPASS condition. Therefore, data collected at the IC site and recovery period data from other sites were not included in further analysis. The inter-individual variability noted in the Δ[HHb] data (range 0.73 – 32.56 μM) is presented for the VL in HIITACT (Fig 4.2.).

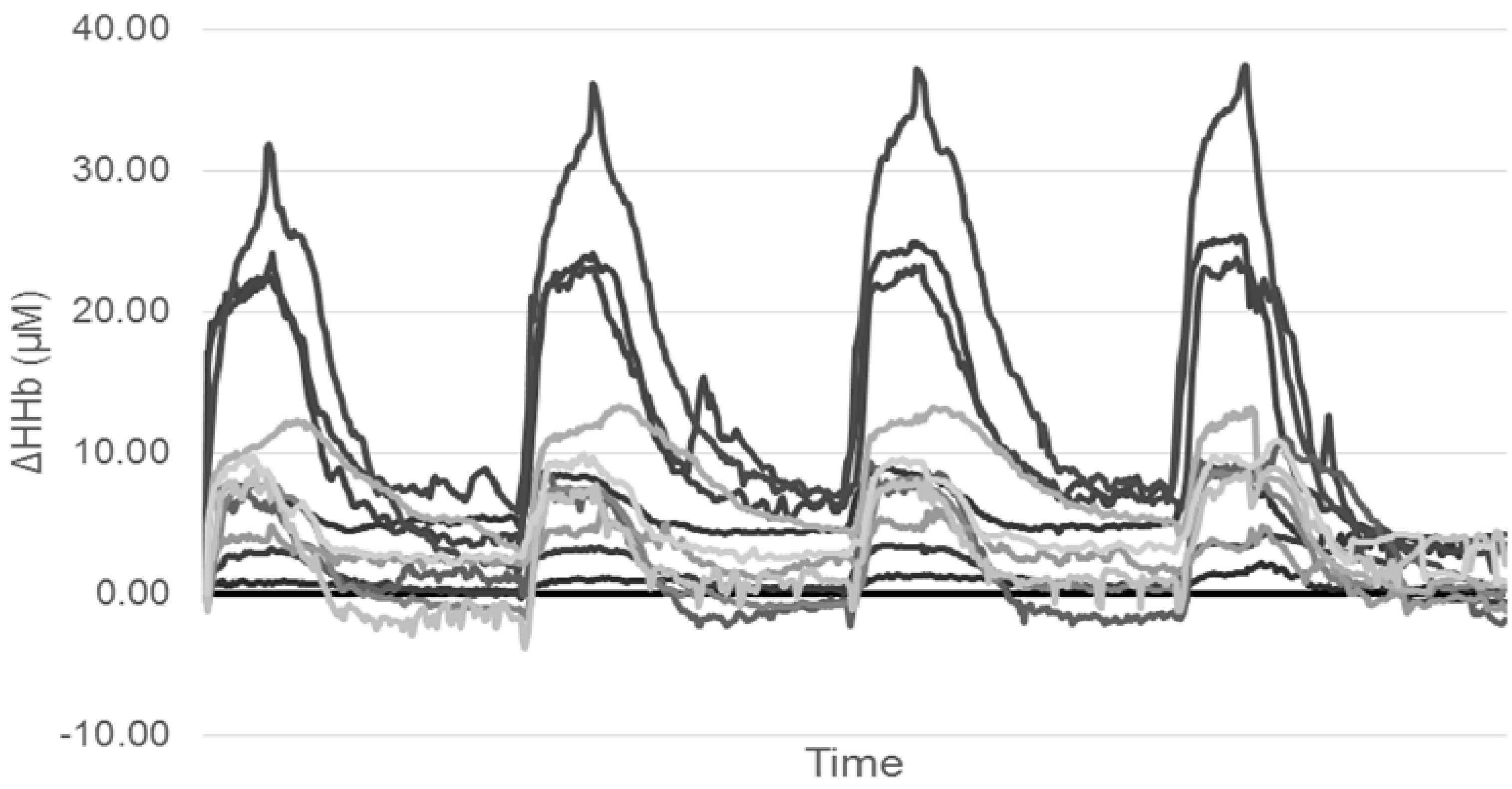

Figure 4.2. Individual relative change from baseline of deoxygenated haemoglobin (HHb) during the HIITACT condition.

(n=12).

Systemic oxygen consumption (VO_2)

In order to quantify the systemic oxygen utilisation in response to the three conditions, systemic oxygen consumption data were collected continuously during the rest, exercise and recovery periods using a respiratory gas analysis open circuit spirometer system (Parvo Medics, Sandy UT, USA) and a standard gas collection mouthpiece (Hans Rudolph, Kansas, United States of America). Standardised calibration and methods were used [288].

Mechanical power

Mechanical power was measured during the cycling portions of each condition using a SRM 'Science' power meter (SRM, Julich, Germany). Prior to each testing session the SRM unit was calibrated according to the manufacturer's specifications.

Heart rate (HR)

To quantify exercise intensity during all exercise conditions, a heart rate monitor (RS400, Polar Electro, Kempele, Finland) was used to measure heart rate data during rest, exercise and recovery periods.

4.3.5. Data calculation and statistical analysis

All NIRS data were collected at a frequency of 10 Hz and smoothed using a 10-point moving average before being averaged to 1 s periods. Due to the HHb data being a measure of change from an arbitrarily assigned baseline zero value, the NIRS data are expressed as units of change (μMol) from the mean value of the 30 s of baseline data preceding the start of exercise (Δ[HHb]). To determine the between test reliability of the HHb data from the NIRS system, absolute reliability (Typical Error: VL = 0.4, GN = 0.8, FH = 0.6) of the baseline data for each site was used. Furthermore, previous research has shown that the NIRS method provides acceptable reliability [205, 289]. VO_2 data were averaged over 5 s periods in preparation for further analysis whilst mechanical power and HR data were averaged at 1 s intervals. The NIRS, HR, VO_2 and power data were then time aligned and the time periods of data corresponding to the four 30 s bouts of HIIT identified. Mean 30 s values were then calculated for all dependant variables for each bout of HIIT, providing a single value per bout for statistical analysis.

Statistics

Statistical tests were performed using IBM SPSS Statistics (version 22, IBM Corporation, Armonk NY, USA). Data was initially screened for normality of distribution using a Shapiro-Wilk test. A two factor, repeated-measures analysis of variance (ANOVA) was used to analyse the effect of condition and bout on the dependant variables of VO_2, HR and mechanical power. A three factor, repeated-measures ANOVA was used to analyse the effect of condition, bout and site on the dependant variable Δ[HHb]. Mauchly's W test was used to evaluate sphericity for each dependant variable. For those variables that violated the assumption of sphericity, the degrees of freedom were adjusted using the Greenhouse-Geisser correction if the estimate of sphericity (ϵ) < 0.75. If ϵ >0.75 the Huynh-Feldt adjustment was used and significance re-evaluated. If a significant main effect was identified, a Bonferroni's post hoc test was used to make pair wise comparisons. All variables are presented as mean ± standard deviation (SD). For all statistical analyses, a p value of < 0.05 was accepted as the level of significance.

4.4. Results

4.4.1. Tissue oxygenation

For the mean Δ[HHb] from all conditions, sites and bouts combined, there was a main effect for site (p = 0.003, F = 7.493), with significant differences found between FH and VL sites (p = 0.025) and the difference between GN and VL sites approaching significance (p = 0.056). There was also a main effect for condition (p < 0.001, F = 20.899), however no significant differences were found between the two HIIT conditions. There were condition x site (p = 0.016) and site x bout (p = 0.002) interactions.

For the mean Δ[HHb] for each condition, there was a main effect for site for HIITPASS [(p = 0.029, F = 4.346) FH = 1.97 ± 2.69 μM, GN = 4 ± 4.46 μM, VL = 6.97 ± 5.42 μM] and HIITACT [(p = 0.005, F = 10.014) FH = 1.81 ± 2.65 μM, GN = 4.44 ± 3.75 μM, VL = 10.722 ± 8.48 μM] with significant differences found between FH and VL (p = 0.018) and GN and VL (p = 0.035) for HIITACT. There were site x bout interactions for HIITPASS (p = 0.001) and HIITACT (p = 0.042). No significant differences were found for REC [FH = -0.28 ± 1.16 μM, GN = -0.64 ± 2.39 μM, VL = 0.22 ± 3.38 μM].

Forehead (FH)

For the FH there was a main effect in the mean Δ[HHb] for condition, however no significant differences were found between the two HIIT conditions: [(p = 0.002, F = 8.513) HIITPASS 1.97 ± 2.69 μM; HIITACT 1.8 ± 2.65 μM; REC -0.27 ± 1.16 μM]. There was a condition x bout interaction (p = 0.003).

For the mean Δ[HHb] for each bout (Fig 4.3, panel A), differences were found between conditions for Bout 2 (p = 0.006, F = 6.504), Bout 3 (p = 0.003, F = 7.845) and Bout 4 (p < 0.001, F = 12.758), however no significant differences were found between the two HIIT conditions. For the mean Δ[HHb] within conditions, there were significant increases across bouts, with values increasing over time in the HIITPASS (p = 0.003, F = 9.733) and HIITACT (p = 0.007, F = 8.511) conditions.

Gastrocnemius (GN)

For the GN there was a main effect in the mean Δ[HHb] for condition, however no significant differences were found between the two HIIT conditions: [(p < 0.001, F = 11.911) HIITPASS 4.00 ± 4.46 μM; HIITACT 4.4 ± 3.75 μM; REC -0.06 ± 2.39 μM]. There was no significant condition x bout interaction.

For the mean Δ[HHb] for each bout (Fig 4.3, panel B), differences were found between conditions for Bout 1 (p = 0.006, F = 9.270), Bout 2 (p < 0.001, F = 11.339), Bout 3 (p = 0.001, F = 9.475) and Bout 4 (p < 0.001, F = 12.765), however no significant differences were found between the two HIIT conditions. For the mean Δ[HHb] within conditions, no significant differences were found across bouts.

Left vastus lateralis (VL)

For the VL, there was a main effect in the mean Δ[HHb] for condition: [(p = 0.003, F = 13.060) HIITPASS 6.97 ± 5.42 μM; HIITACT 10.72 ± 8.48 μM; REC 0.22 ± 3.38 μM]. There was no significant condition x bout interaction.

For the mean Δ[HHb] for each bout (Fig 4.3, panel C), differences were found between conditions for Bout 1 (p = 0.002, F = 14.835), Bout 2 (p = 0.003, F = 12.968), Bout 3 (p = 0.006, F = 10.587) and Bout 4 (p = 0.004, F = 12.575) with significant differences found between the two HIIT conditions. For the mean Δ[HHb] within conditions, there were no significant differences found across bouts.

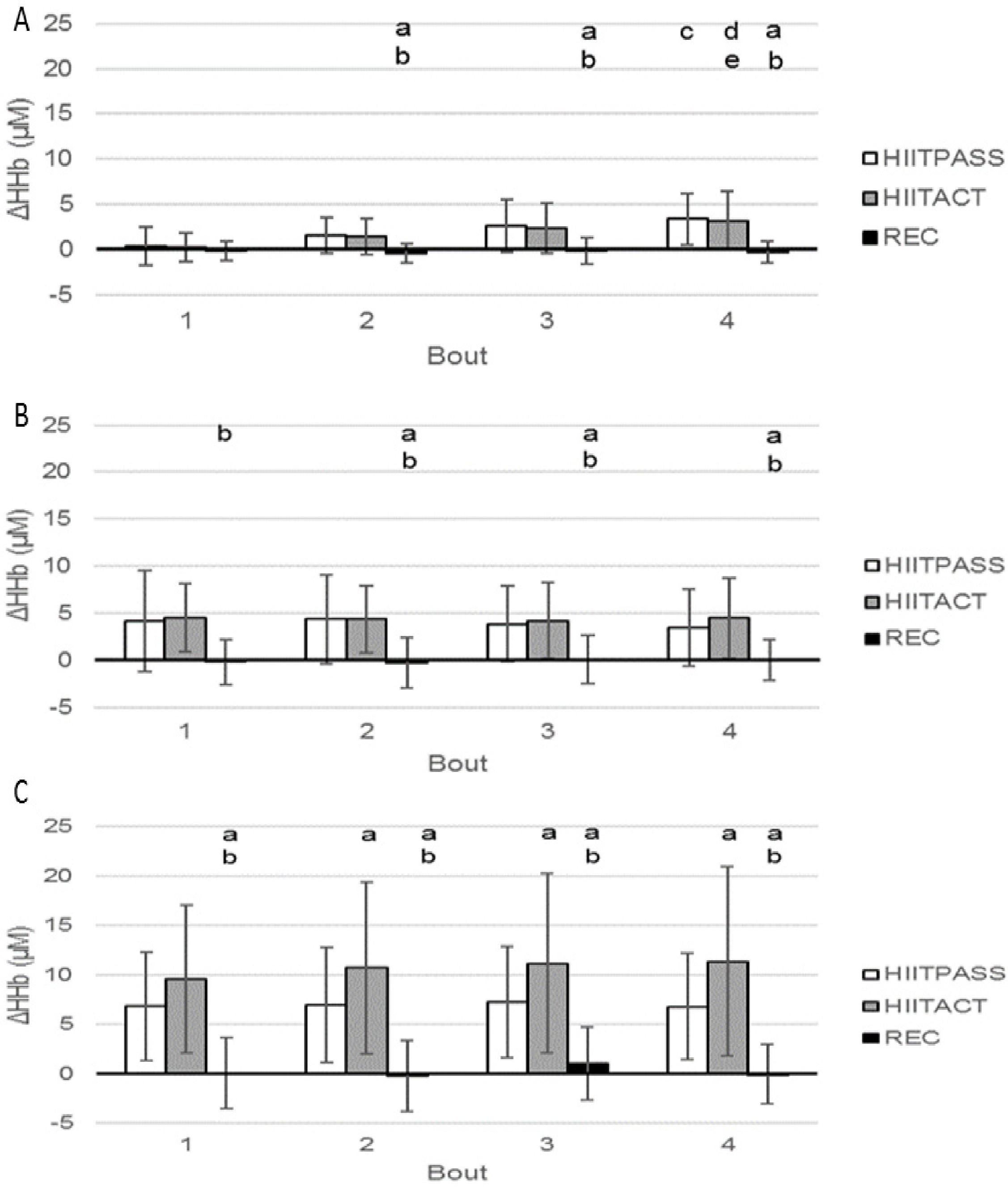

Figure 4.3. Relative change from baseline of deoxygenated haemoglobin (HHb) concentration during the four bouts of the three conditions.

(A) Forehead (FH). (B) Gastrocnemius (GN). (C) Left vastus lateralis (LVL). a = different to HIITPASS at same Bout; b = different to HIITACT at same Bout; c = different to HIITPASS Bout 1; d = different to HIITACT Bout 1; e = different to HIITACT Bout 2. Data are mean ± SD. Letters (‘a’, ‘b’, etc.) denote significant differences at $p \leq 0.05$.

4.4.2. Systemic oxygen consumption

For the mean VO_2, there was a main effect for condition [($p < 0.001$, $F = 161.601$), however no significant differences were found between the two HIIT conditions [HIITPASS 29.6 ± 3.26 $ml.kg.min^{-1}$; HIITACT 31.4 ± 4.53 $ml.kg.min^{-1}$; REC 12.3 ± 1.61 $ml.kg.min^{-1}$].There was no significant condition x bout interaction.

For the mean VO_2 for each bout (Fig 4.4, panel A), differences were found between conditions for Bout 1 ($p < 0.001$, $F = 491.444$), Bout 2 ($p < 0.001$, $F = 161.961$), Bout 3 ($p < 0.001$, $F = 77.016$) and Bout 4 ($p < 0.001$, $F = 72.269$), however no significant differences were found between the two HIIT conditions. For the mean VO_2 within conditions, no significant differences were found across bouts, with values remaining relatively similar over time.

Mean VO_{2peak} within conditions and across bouts had the same statistical differences as mean VO_2.The differences in VO_2 when comparing the REC condition to the HIITPASS and HIITACT conditions were as expected (Fig 4.4 panel A).

When total oxygen consumption was compared across the three conditions, differences were found [($p < 0.001$, $F = 78.562$) HITTPASS 12.7 ± 2.06 litres; HIITACT 16.0 ± 3.02 litres; REC 8.4 ± 0.79 litres] with significant differences between all conditions.

4.4.3. Mechanical power

For the mean power output, there was a main effect for condition [($p < 0.001$, $F = 57.636$). HIITPASS 374.3 ± 70 W; HIITACT 339.9 ± 72.7 W]. There was no significant condition x bout interaction.

For the mean power output for each bout (Fig 4.4, panel B), differences were found between conditions for Bout 1 ($p = 0.026$, $F = 6.612$), Bout 2 ($p < 0.001$, $F = 87.513$), Bout 3 ($p < 0.001$, $F = 24.144$) and Bout 4 ($p = 0.045$, $F = 5.118$). For the mean power output within conditions, decreases were found across bouts over time (HIITPASS $p < 0.001$, $F = 25.281$; HIITACT $p < 0.001$, $F = 22.923$).

4.4.4. Heart rate

For the mean HR there was a main effect for condition [($p < 0.001$, $F = 395.034$), however no significant differences were found between the two HIIT conditions: HIITPASS 165 ± 7.6 bpm. HIITACT 166 ± 11.5 bpm. REC 99 ± 11.3 bpm]. There was a condition x bout interaction ($p = 0.022$).

For the mean HR for each bout (Fig 4.4, panel C), differences were found between conditions for Bout 1 ($p < 0.001$, $F = 224.796$), Bout 2 ($p < 0.001$, $F = 375.081$), Bout 3 ($p < 0.001$ $F = 417.149$) and Bout 4 ($p < 0.001$, $F = 289.073$) however no significant differences were found between the two HIIT conditions. For the mean HR within conditions, increases were found across bouts over time. HIITPASS ($p < 0.001$, $F = 20.234$); HIITACT ($p < 0.001$, $F = 16.574$); REC ($p < 0.001$, $F = 14.227$).

Average HR_{peak} within conditions and across bouts provided the same statistical differences as mean HR. The differences in HR when comparing the REC condition to the HIITPASS and HIITACT conditions were as expected (Fig 4.4, panel C).

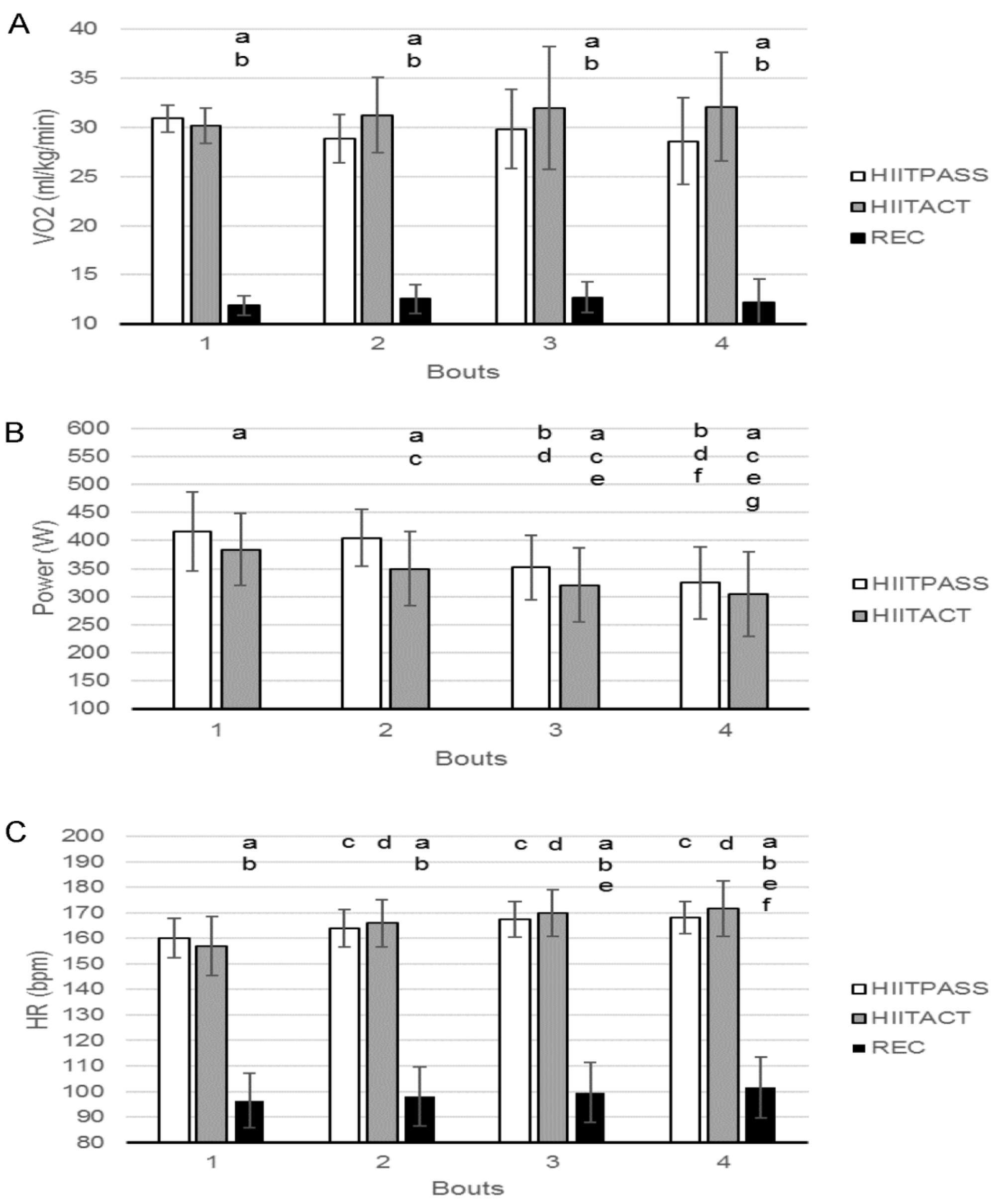

Figure 4.4. Oxygen consumption, mechanical power and heart rate during the four bouts of the three conditions.

(A) Oxygen consumption (VO_2). a = different to HIITPASS at same Bout; b = different to HIITACT at same Bout. (B) Mechanical power. a = different to HIITPASS at same Bout ; b = different to HIITPASS, Bout 1; c = different to HIITACT, Bout 1; d = different to HIITPASS, Bout 2; e = different to HIITACT, bout 2; f = different to HIITPASS, bout 3; g = different to HIITACT, bout 3. (C) Heart rate (HR). a = different to HIITPASS at same bout; b = different to HIITACT at same Bout; c = different to HIITPASS, bout 1; d = different to HIITACT bout 1; e = different to REC, bout 1; f = different to REC, bout 2. Data are mean ± SD. Letters (‘a’, ‘b’, etc.) denote significant differences at $p \leq 0.05$.

4.5. Discussion

The primary aim of this project was to compare the local (Δ[HHb]) and systemic (VO_2) oxygen utilisation, mean power output and heart rate responses during HIIT conditions which included either passive or active recovery. A secondary aim was to compare the relative Δ[HHb] between local muscle and brain tissue sites during HIIT exercise. In support of our hypotheses, there was a significant increase in HHb at the VL site during the 2nd, 3rd and 4th high intensity exercise bouts interspersed with active recovery periods (HIITACT) when compared to bouts interspersed with passive recovery periods (HIITPASS). Also supporting our hypotheses, when including the exercise performed during the active recovery periods, the total VO_2 was significantly higher during the HIITACT condition when compared to both the HIITPASS and REC conditions. In opposition to our hypotheses, mean power output during the exercise bouts was significantly higher in the HIITPASS condition when compared to the HIITACT condition. No significant differences were found in Δ[HHb] at the (FH) and (GN) sites, in mean VO_2 and in mean HR during the high intensity exercise bouts when comparing HIITPASS and HIITACT. There were significant differences for all dependant variables when comparing the bouts in REC to HIITPASS and HIITACT. These results were expected and validate the use of the REC protocol as a control condition.

4.5.1. Tissue oxygenation

The significantly higher Δ[HHb], indicating increased oxygen utilisation, at the VL site during the second, third and fourth bouts of the HIITACT condition, when compared to the HIITPASS condition could indicate a response to the reduced reoxygenation of the muscle during the active recovery portions, leading to a higher deoxygenation of the muscle tissue during subsequent bouts. This would explain the significantly decreased mean power outputs that occur during the HIITACT bouts, as increased deoxygenation would impair subsequent performance in this large locomotor muscle, potentially due to impaired phosphocreatine (PCr) resynthesis linked to competition for limited oxygen resources [125] or via centralised neuromuscular downregulation in response to the increased rate of biochemical changes [290]. In intermittent sprints [48, 104] the same pattern of reduced performance measures and higher levels of deoxygenation during active recovery conditions has occurred, if insufficient time is provided for a complete physiological recovery [121, 124]. To the contrary, Calbet et al. [161] suggest that there may be a functional reserve in oxygen diffusing capacity during exercise, in which situation the higher level of deoxygenation observed during the HIITACT condition would not be considered limiting. Due to differences in the design of the experiments it is difficult to compare the findings of these projects, however it is possible that the oxygen utilisation at the VL site, which is the primary locomotor muscle for cycling [222], is likely to be underestimated by the assessment of whole leg oxygen utilisation via femoral blood samples by Calbet et al. [161].

Additionally, the significantly higher Δ[HHb] in the VL during the bouts of the HIITACT condition cannot be accounted for by the effect of active recovery as a simple additive process (i.e. HIITPASS + REC = HIITACT), as the differences in the Δ[HHb] between the bouts of the two HIIT conditions are higher than the Δ[HHb] during the bouts of the REC condition (Fig. 4.3C).

In the smaller GN muscle of the same leg, which has a lesser role in power production during cycling [222] and a greater percentage of oxidative muscle fibres [291, 292], there were no significant differences in Δ[HHb] between conditions. During exercise, the muscle with a greater percentage of oxidative fibres (GN) would be able to meet the increasing energy requirements, creating little change in HHb values, compared to pre-exercise values. The reasons provided above could also explain why the magnitude of mean Δ[HHb] in the VL muscle was greater than that in the GN muscle in both the HIITPASS and HIITACT conditions.

When comparing Δ[HHB] within conditions, there was no progressive muscle deoxygenation observed in VL and GN from bouts one to four irrespective of recovery type. If exercise effort was maximal, in line with participant instructions to give a maximal effort during each bout, an upper oxygen utilisation limit was reached during each effort at both muscle sites. This has occurred in previous research involving repeat Wingate testing [104]. When the significant reductions in mechanical power are taken into account, this indicates that declining muscle performance is associated with repeated maximal levels of oxygen utilisation, providing evidence that maximal oxygen utilisation may not be a limiting factor during HIIT, in sedentary participants. Assessment of the rate of muscle deoxygenation and reoxygenation could yield important information to further delineate differences between HIIT conditions and provide additional information into potential mechanisms involved in site specific oxygen utilisation. Whilst an important future research direction, this assessment was not possible during the current project due to artefact present in the NIRS data during recovery portions of the PASSHIIT condition and the impracticality of cuff occlusion (a common practice when examining deoxygenation and reoxygenation rates [173]) during supramaximal intermittent exercise whilst measuring HHb in multiple limb segments.

The inter individual variability in the VL Δ[HHb] response during the HIITACT condition (Fig. 4.2) was unrelated to the participants power output (i.e. the participants with the highest power outputs did not show the greatest increases in HHb). Additionally, mean Δ[HHb] remained unchanged over time whilst mean power decreases significantly, hence the variability cannot be explained by a simple demand-driven system. A similar degree of variability in the Δ[HHb] response can be seen in the one project to publish individual results [167] or by noting the standard deviation of the Δ[HHb] signal if the method of data calculation and analysis is similar [293]. Currently there is no standard for NIRS instruments or for the method of calculating, analysing and presenting NIRS data [165]. This makes comparison of Δ[HHb] data between projects difficult, even when projects have been performed in similar populations, performing similar HIIT interventions. This in turn limits the ability of researchers to gain a comprehensive understanding of what constitutes a normal NIRS response (or range) during exercise in sedentary populations.

When comparing the FH Δ[HHb] from bout one to bout four, HHb concentrations did not rise significantly until the last bout of both HIIT conditions. This response could be due to the brain being protected from homeostatic disturbances and therefore adequately perfused during the majority of exercise bouts [290]. Late in maximal exercise cerebral vasoconstriction, diminished cerebral blood flow and an increase in cerebral oxygen uptake occur [181, 185]. These factors would explain the late rise in HHb. A similar response is noted in previous intermittent sprint research [45, 175].

Interpretation of differences in the Δ[HHb] data between sites should be made with caution. A significant main effect for site was found, however the NIRS devices measure relative Δ[HHb] from an arbitrary baseline. Parameters that potentially affect NIRS measures, such as blood flow and muscle tension, are not routinely measured in conjunction with HHb. Therefore, a lack of significant differences in the Δ[HHb] between the FH and GN sites does not necessarily indicate that the oxygen utilisation responses to the exercise stimulus are the same at these two sites.

4.5.2. Systemic oxygen consumption

Previous research [133] has indicated that active recovery is associated with increased oxygen consumption during exercise bouts when compared to passive recovery. However, no significant differences were found for the HIITPASS and HIITACT conditions when comparing mean VO_2 between conditions and across bouts. Our findings are in agreement with other research [121], although that study incorporated open ended intermittent exercise. Potential mechanisms for no difference between conditions could include compensatory decreased oxygen utilisation at non-exercise associated tissue.

The lack of differences across bouts was unexpected, since the response in each subsequent exercise bout is not an isolated exercise period, but would be expected to be, in part, a function of the previous bouts. Therefore, an increase in VO_2 and HR as a function of time was predicted due to incomplete physiological recovery in the 2 min available to the sedentary individuals between supramaximal exercise bouts. A potential explanation for no difference across bouts could be, if oxygen utilisation is maximised at the muscle (as indicated by the relatively stable Δ[HHb] over time in both VL and GN) a similar pattern would be expected in systemic oxygen utilisation measured at the mouth, and any differences in work across bouts would be met anaerobically. Other potential contributing factors to the results obtained include the significant decrease in mechanical power output across bouts, effectively requiring less aerobic contribution over time, in effect counteracting the increased VO_2 due to the cumulative load of the protocol. Furthermore, whilst we did not measure maximal VO_2 in this group of participants, it is conceivable that VO_2 values in excess of 30 $ml.kg.min^{-1}$ were maximal in these sedentary individuals, effectively creating a ceiling effect in each and every bout.

4.5.3. Mechanical power

The mean mechanical power achieved during the exercise bouts was lower than that achieved by active individuals performing repeat Wingate tests [294]. Mean mechanical power declined significantly from the first to the fourth bout in both the HIITPASS and HIITACT conditions. This was expected, due to the cumulative fatigue and incomplete ATP repletion and PCr resynthesis that occur during repeat Wingate exercise that include recovery periods that do not allow for complete recovery [104, 119, 123].

The HIITACT bouts were all performed at a lower mean power output when compared to the HIITPASS bouts. To the best of our knowledge no similar HIIT research has been done in sedentary individuals. However, in active populations when comparing the effect of active and passive recovery on mean power output during intermittent sprints, contradictory results have been published. Some researchers found no significant differences [123, 126, 295], whilst others have found that passive recovery protocols yielded greater mean power values [104]. Lopez et al [119] found that an active recovery condition resulted in a significantly greater mean power output in later (5^{th} and 6^{th}) Wingate bouts. This finding could be explained by the fact that the longer the exercise session, the greater the contribution of active recovery to metabolite clearance, the correction of a cellular acidosis and resynthesis of PCr, which enabled a lower magnitude decline in mean power production in the later Wingate bouts.

The contradictory findings above could also be explained by differences in the intensity of active recovery utilised in different projects, highlighting the difficulty in comparing HIIT research due to the variety available when designing exercise protocols.

Current evidence suggests that passive recovery can improve subsequent performance when recovery duration is short (15 – 120 s) and / or exercise intensity is high [124]. Our findings in sedentary individuals support this. Choosing an appropriate recovery format (and duration) is an important consideration when considering prescription of HIIT to time poor sedentary individuals, as recovery periods would be of relatively short duration to ensure that the entire HIIT session is in fact shorter than the current moderate intensity exercise recommendations.

The lower mean power output in the HIITACT condition occurred from the first bout. In a sedentary population with no previous experience of repeat Wingate testing, participants potentially adopted a subconscious feedforward pacing strategy to minimise the ‘additional’ discomfort associated with a condition including an active recovery.

In each subsequent bout, mean power output was significantly lower in the HIITACT condition compared to the HIITPASS condition. The local muscle recovery includes the resynthesis of PCr, which relies on oxygen dependant pathways and is strongly correlated with repeat sprint ability [296]. Competition for available oxygen supplies may occur between the processes of PCr resynthesis, lactate oxidation and the oxygen cost of continued exercise itself during active recovery [119, 124, 125, 132, 297]; causing a decrease in performance and power generation when active recovery protocols are adopted. Additionally, in sedentary populations the improved active recovery clearance of metabolites may not occur in an acute session of HIIT due to the fact that the improved clearance of metabolites is an adaptation that occurs with routine exercise training at higher intensities [1]. Due to the untrained state of participants, passive rest periods may allow participants to recover to a greater extent, enabling a lesser reduction in power output over the entirety of the HIIT session.

4.5.4. Heart rate

In both HIIT conditions mean HR rose significantly when comparing bout one to later bouts, in line with findings from previous research [119].

In opposition to previous research [119, 123, 126] showing an active recovery condition is associated with a greater HR response when compared to a passive recovery condition, no significant differences were found between the HIITPASS and HIITACT conditions for mean HR overall and during each bout. This response is however in agreement with other research [121]. The lack of difference found in our project could be explained by the significantly lower power output generated by the sedentary participants during the HIITACT condition. The lower power output could be responsible for a lesser HR response during the HIITACT bouts even though the active recovery portions of the condition kept HR higher during active recovery. During the HIITPASS condition, a higher power output would cause a greater rise in HR, but from a lower starting point due to a greater HR recovery during the passive recovery portions, in effect providing no difference in mean HR during each bout when comparing across conditions.

4.6. Limitations

The participants within this group, whilst relatively homogenous in their sedentary behaviour during the project, were heterogeneous in their past exercise behaviours. This variability could potentially have confounded results. Participants needed to maintain a high level of motivation during the repeated maximal HIIT bouts. Individuals with extensive past exercise experience, even if currently sedentary, could rely on past exercise experience to better cope with the inherent discomfort of HIIT. Those with little or no previous exercise experience would potentially adopt either conscious or subconscious pacing strategies in an attempt to reduce the discomfort associated with repeated all-out efforts, despite instructions to perform maximally.

A number of participants reported feelings of dizziness and nausea during the recovery period of the HIITPASS condition. Although these symptoms were sub-clinical in severity, the negative sensations could have impacted on the participant's exercise behaviours within the study.

Cycling was chosen for the current project due to practical and safety considerations. However, choosing a mode of exercise with a high degree of specificity may have limited the performance of sedentary individuals who would be more accustomed to weight-bearing forms of ambulation. The effect of mode on performance during HIIT in sedentary individuals requires further investigation.

4.7. Conclusions

During the HIITACT condition a higher level of deoxygenation in the VL muscle and a lower mean power output occurred, when compared to the HIITPASS condition. This suggests that the higher level of deoxygenation could have contributed to an impaired performance during the HIITACT condition.

However, when compared across bouts within each condition, the level of deoxygenation did not change significantly at either the VL and GN sites from bout one to bout four, when participants were instructed to give a maximal effort. This indicates that oxygen utilisation reached maximal (but different) values at the two sites in each bout. Mean power output decreased over the course of both conditions. It can therefore be concluded that maximal oxygen utilisation is not a limiting factor in sedentary individuals over the course of a HIIT condition, irrespective of the inclusion of active or passive recovery periods.

The level of deoxygenation at the FH site did not increase significantly from pre-exercise values until the fourth bout in both HIIT conditions. This suggests that cerebral oxygenation was adequate until late in supramaximal exercise, possibly due to the importance of maintaining adequate cerebral perfusion.

To our knowledge this is the first research to show that in sedentary participants, the Δ[HHb] levels attained during HIIT exercise varies in different locomotor muscles of the same leg, indicating the specificity of individual muscle oxygen utilisation.

4.8. Acknowledgements

The authors would like to thank the participants of this research project, without whom this project would not have been possible.

4.9. Supplementary information

In agreement with suggested revisions by the thesis examiners, the abstract of the research publication, detailed in Chapter 4, has been revised to include additional detail of the HIIT protocol design and the addition of the word ‘anatomical’ prior to the word ‘site’. These changes have been made in the initial Abstract section of the thesis (page i).

In agreement with suggested revisions by the thesis examiners, the methods section of the research publication, detailed in Chapter 4, has been revised to clarify that a higher physical activity enjoyment scale (PACES) score indicates a higher level of enjoyment. This change has been made in the initial Abstract section of the thesis (page i).

5. The effect of recovery format during HIIT on perceived exertion, exercise enjoyment and blood pressure

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Statement of intellection contribution and relative role of the candidate, Mr Yuri Kriel, in the execution of the study and writing of the paper:

Conceived and designed the experiment: YK, CS

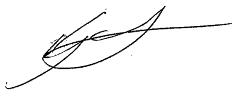
Performed the experiment: YK

Analysed the data: YK, HAK, CDA, CS

Wrote the first draft of the paper: YK

Edited the paper: YK, HAK, CDA, CS

Yuri Kriel



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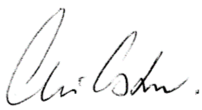

Colin Solomon

Full Title: **The effect of active versus passive recovery periods during high intensity intermittent exercise on perceived exertion, exercise enjoyment and blood pressure in 18 – 30 year old sedentary men**

Short Title: **HIIT recovery format: perceived exertion, enjoyment and blood pressure**

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5.1. Abstract

Purpose

High intensity interval training (HIIT) has been proposed as a format of exercise to improve exercise compliance and provide positive health effects in sedentary individuals. Whilst the efficacy of HIIT is well established, feasibility is dependent upon the perception, enjoyment and safety of this format of exercise. The recovery periods of HIIT will likely modulate the physiological responses and perceptual sensations that occur during and after a session. It was hypothesised that in sedentary participants, perception of effort would be lower, and enjoyment and blood pressure higher during a session of HIIT interspersed with active recovery periods, compared to passive recovery periods.

Methods

Twelve sedentary males (mean ± SD; age 23 ± 3 yr) completed three exercise sessions on a cycle ergometer: 1) HIIT with passive recovery periods between four bouts (HIITPASS), 2) HIIT with active recovery periods between four bouts (HIITACT), and 3) HIITACT with the four HIIT bouts replaced with passive periods (REC). Ratings of perceived exertion (RPE) and blood pressure (BP) were measured immediately after each bout. Physical activity enjoyment (PACES) and BP were measured during post-exercise recovery.

Results

There were no significant differences in RPE, PACES or systolic BP for HIITPASS, compared to HIITACT. Diastolic BP was lower during recovery in HIITACT ($p = 0.025$) and HIITPASS ($p = 0.027$), compared to resting BP. Furthermore, diastolic BP was lower after 6 min of recovery following HIITPASS, compared to HIITACT ($p = 0.01$).

Conclusions

Perception of exertion and exercise enjoyment are independent of HIIT recovery format among young sedentary men. Due to reductions in diastolic BP coinciding with pre-syncopal symptoms, HIIT protocols including passive recovery periods post-exercise have negative safety and compliance implications in participants susceptible to symptomatic post-exercise hypotension (PEH).

5.2. Introduction

High intensity interval training (HIIT) of a low volume has been proposed as a time-efficient format of exercise to improve exercise compliance and provide positive health effects in sedentary individuals [31]. Whilst the efficacy of HIIT is well established [6, 7, 31], feasibility is dependent upon the enjoyment and safety of this exercise format. Enjoyment and safety of exercise is largely dependent on intensity, and the sensations resulting from the exercise stimulus, both physiological and perceived. HIIT is often associated with aversive sensations such as discomfort [247, 298]. Aversive exercise experiences have a direct effect on perception of exertion, exercise enjoyment, perceived safety and therefore adherence [108, 299] in a population which often has low intrinsic motivation to exercise [63, 139]. Therefore, whilst the physiological benefits of HIIT [6, 7] provide the basis of recommending this format of exercise to sedentary individuals, it is necessary to use perceptual data to evaluate the response of sedentary individuals' to HIIT, if HIIT is to be effective as a primary prevention strategy [6, 27, 32, 106].

Nine design components (series, inter-series, bout and recovery: number, duration and intensity as well as exercise mode) can be altered in HIIT [2]. The recovery periods are an integral part of the HIIT session, as these periods modulate the physiological responses and perceptual sensations that occur during, and after, HIIT. The two most frequently adopted recovery formats are active and passive recovery. The performance benefits of active and passive recovery in trained populations have previously been investigated [104, 119, 123, 130]. However, there have been no comparisons of the effect of active versus passive recovery on perception of effort, exercise enjoyment and the cardiovascular responses that influence safety during a session of HIIT in sedentary individuals. The investigation of these factors will contribute valuable information to the understanding of supramaximal exercise prescription, safety, and compliance.

The investigation of sedentary individuals' enjoyment during exercise has yielded inconsistent results: Sedentary individuals are more likely to enjoy and be compliant with exercise that they perceive as moderate in intensity [108], however HIIT has been shown to be enjoyable and is associated with a degree of positive affect (mood state) [68]. No difference in enjoyment was found when comparing a single session of HIIT to CMIE, using the physical activity enjoyment scale (PACES) [66, 247, 248]. However, it is proposed that factors other than intensity of an exercise session contribute to enjoyment [278, 279]. One such factor during HIIT is the recovery format. The effect of active versus passive recovery periods on sedentary individuals' enjoyment levels during HIIT is unknown. By comparing enjoyment levels between these two recovery formats it will be possible to identify which format is more likely to promote exercise initiation and ongoing compliance.

Ratings of perceived exertion (RPE) is used as a marker of intensity during exercise prescription and evaluation [20]. Comparison of RPE in trained individuals during HIIT including active versus passive recovery periods has found no difference [123, 126]. However, it is proposed that active recovery, compared to passive recovery, could assist in providing optimal clearance of metabolites during a HIIT session [136, 217], thereby decreasing local muscle discomfort and contributing to decreased RPE and increased PACES scores. As perceived exercise intensity has been shown to influence sedentary individuals' mood state, exercise enjoyment levels and potential compliance [66], a better understanding of the RPE responses to active versus passive recovery formats would assist in evaluating whether HIIT is a viable exercise option in this population.

The safety of HIIT is debated [5, 49-52], due to the absence of research detailing the adverse physiological responses experienced by participants [5] and because high intensity exercise is associated with a transient higher risk of adverse cardiovascular events and adverse symptoms, especially in sedentary individuals attempting unaccustomed exercise [20, 54]. The mechanism(s) by which high intensity exercise produce adverse cardiovascular events is unclear, but proposed triggering mechanisms include increased wall stress from increases in blood pressure (BP) and flow, leading to atherosclerotic plaque disruption [55]. It is plausible to expect hypertensive responses during HIIT. However, passive recovery periods during a HIIT session, compared to active recovery periods, would potentially allow for a reduction in systolic blood pressure (SBP) and therefore lower the overall blood pressure response. Furthermore, adverse symptoms associated with post exercise hypotension (PEH) have been linked to high intensity exercise [56], HIIT [57], sedentary status [58] and young adults are heavily represented in the symptomatic PEH literature [60]. Symptomatic PEH is potentially more likely after HIIT which includes passive recovery periods, as the secondary muscle pump is not active throughout the session [59]. However, the incidence of symptomatic PEH after an acute session of HIIT and the effect of active versus passive recovery format, in sedentary individuals, is unknown. In addition to symptomatic PEH having safety implications due to the increased risk of falls and injury, symptomatic PEH is associated with aversive sensations of dizziness, nausea, near syncope or syncope [59, 300]. Experiencing aversive symptoms could negatively affect enjoyment levels. It is therefore necessary to quantify the blood pressure responses and associated sensations to a session of HIIT including either active or passive recovery periods.

For this experiment, it was hypothesised that in young sedentary participants, during a session of HIIT including active recovery periods, compared to a session of HIIT including passive recovery periods, RPE would be lower, while PACES and BP would be higher.

5.3. Methods

5.3.1. Ethics statement

This research study was approved by the human research ethics committee of the University of the Sunshine Coast (S/13/472). All participants received a research study information sheet before providing written informed consent.

5.3.2. Experiment design

The experiment consisted of three experiment conditions conducted on a bicycle ergometer: 1) HIIT with passive recovery periods between each bout (HIITPASS), 2) HIIT with active recovery periods between each bout (HIITACT) and 3) a protocol in which only the active recovery periods were completed and the bouts of HIIT were replaced with passive periods (REC), in order to provide an indication of sedentary individuals' perceptual responses to a low intensity interval exercise session. The conditions followed a Latin-squares cross-over design to control for a possible order effect. All testing sessions were separated by three to seven days to minimise the influence of any potential carry-over effects or confounding variables between testing sessions. The conditions and the timing of measurements are illustrated in Fig 5.1.

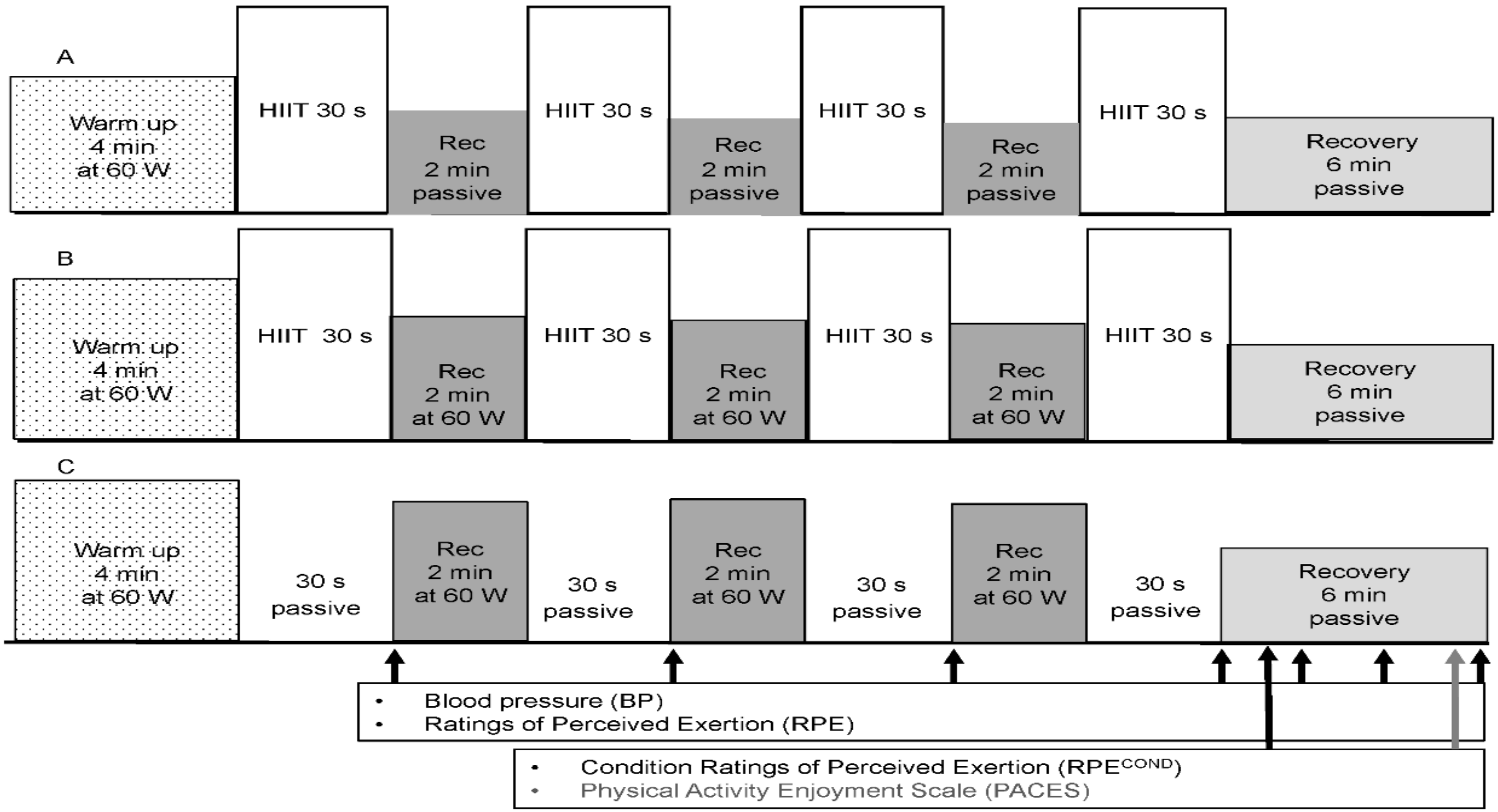

Figure 5.1. The structure and timing of measurements of the three conditions.

(A) HIITPASS. (B) HIITACT. (C) REC.

5.3.3. Participants

The participant group consisted of twelve men who met the inclusion criteria of being aged 18 – 30 years; currently completing less than 150 min of moderate intensity or 75 min of vigorous intensity activity per week; reporting no cardiovascular and metabolic disease; taking no medications; having no known health related issues that would be made worse by, or inhibit participation in the sessions. Descriptive physical characteristics of the participants are presented in Table 5.1. The same participants took part in: Kriel et al. (2016), where local tissue oxygenation was compared during sessions of HIIT incorporating active and passive recovery periods. Thus, the heart rate data, included in the present study to describe the intensity of the sessions, has been published previously [301].

Table 5.1. Participant characteristics.

Height (cm)	176 ± 8.36
Weight (kg)	78.2 ± 13.8
Body Mass Index (kg/m^2)	25.0 ± 3.97
Age (yr)	22.5 ± 3.21
FVC (L)	5.40 ± 0.77
FVC % pred (%)	105 ± 10.2
FEV_1 (L)	4.54 ± 0.72
FEV_1 % pred (%)	104 ± 10.9

(FVC = Forced vital capacity; FEV_1 = Forced expiratory volume in 1 s).

Data are (mean ± SD) (n = 12).

5.3.4. Procedures and equipment

Screening procedures

At the initial session, participants completed risk screening questionnaires, a physical activity log and physical characteristics of height, mass and resting pulmonary function were measured (Table 1), as previously described [301]. Briefly, the physical activity log was used to ensure that participants' activity levels during the previous three months were within the definition of sedentary for the purposes of this experiment (i.e. not achieving the minimal exercise recommendations to gain health benefits) [282]. Participants were asked to not perform any exercise in the 24 hr preceding each session and to not consume any caffeine, alcohol or a large meal in the four hours preceding a session. It was confirmed at each testing session that participants were adequately fed and hydrated in line with pre-exercise guidelines [302-304].

Exercise conditions

The format of the experiment conditions, as illustrated in Figure 5.1, have been described previously [301]. Briefly, prior to the first exercise session, participants were familiarised with the cycle ergometer (Veletron, Racermate, Seattle WA, USA) and the testing protocol.

Participants were instructed to remain seated throughout each condition to allow for consistency in muscular recruitment patterns. Each experiment condition began with a 4 min warm up period, which consisted of each participant cycling against a fixed resistance of 60 Watts (W).

The warm up was followed by four 30 s bouts of high intensity exercise in the HIITPASS and HIITACT conditions, with 2 min recovery periods separating each high intensity bout.

During the HIIT bouts, power output was determined by participant effort against resistance (0.075kg per kilogram body weight),applied to the flywheel of the ergometer at the start of each bout [98]. The HIIT format and timings were adapted from protocols used in trained and untrained populations [62, 94-96, 104, 174, 284]. Participants were instructed to give a maximal effort from the beginning of each bout. During the passive recovery periods of the HIITPASS condition, participants were instructed to sit as still as possible. During the active recovery periods of the HIITACT and REC conditions, participants were instructed to pedal against a resistance of 60 W (approximately 30-40% VO_{2max}) [125], an intensity shown to promote optimal clearance of metabolites [136, 217].During the REC condition, the four high intensity exercise bouts were replaced by periods of passive rest. At the completion of all exercise conditions, a 6-min passive recovery period took place.

Heart rate (HR) was used to describe the exercise intensity during the three conditions. A heart rate monitor (RS400, Polar Electro, Kempele, Finland) was used. No differences in HR were found between the two HIIT conditions: HIITPASS 165 ± 7.6

bpm. HIITACT 166 ± 11.5 bpm. REC 99 ± 11.3 bpm, indicating that exercise intensity was well matched between HIITPASS and HIITACT. Within each HIIT condition, HR increased from Bout 1 to Bout 2 before remaining relatively stable.

Ratings of perceived exertion (RPE)

To determine perceived exertion, participants were provided with a standardised description of the ten point category-ratio (CR10) RPE scale [305] and the scales purpose, including memory anchoring of the scale (an explanation of the sensations associated with the high and low scale categories) [306]. Participants were asked to provide an RPE score immediately after each bout of HIIT as well as give a ‘Condition’ RPE score (RPE^{COND}) 1 min after the final (fourth) bout. This RPE^{COND} score was used to compare the overall perception of exertion between the three experimental conditions.

Physical activity enjoyment scale (PACES)

To determine enjoyment to each condition, participants completed the PACES questionnaire within 5 min of completing each condition. PACES was used to compare enjoyment levels between the three experimental conditions. The PACES consists of 18 items on a 7-point bipolar scale. A minimum total score of 18 and a maximal total score of 126 is possible, and a higher score indicates a higher level of enjoyment.

Blood pressure (BP)

To quantify systolic (SBP) and diastolic (DBP) blood pressure responses during the three experimental conditions, a manual blood pressure cuff, aneroid and stethoscope (Welch Allyn, New York, U.S.A.) were used. The measurements were taken at rest, immediately after each bout of high intensity exercise (and equivalent timings during the REC condition) and every 2 min during the 6-min recovery period (Rec 2, Rec 4, and Rec 6).

5.3.5. Data calculation

Group mean values were calculated for RPE, PACES, SBP and DBP data at each measurement time, providing a single value per measurement time for statistical analysis.

5.3.6. Statistics

Statistical tests were performed using IBM SPSS Statistics (version 22, IBM Corporation, Armonk NY, USA). Data was initially screened for normality of distribution using a Shapiro-Wilk test. A two factor repeated-measures analysis of variance (ANOVA) was used to analyse the effect of condition and bout on the dependant variables of RPE, SBP and DBP. If a significant main effect or interaction was identified, a Bonferroni's post hoc test was used to make pair wise comparisons. The effect of condition on RPE^{COND} and PACES scores was analysed using a one-way ANOVA. Mauchly's W test was used to evaluate sphericity for each dependant variable. Where applicable either the Greenhouse-Geisser correction or the Huynh-Feldt adjustment was used to address violation of sphericity. All variables are presented as mean ± standard deviation (SD). For all statistical analyses, a p value of < 0.05 was accepted as the level of significance.

5.4. Results

5.4.1. Ratings of perceived exertion

For the mean RPE for all conditions, there was a main effect for bout ($p < 0.001$, $F = 43.677$). There was no significant condition x bout interaction.

For the mean RPE within conditions, increases were found across bouts in the HIITPASS ($p < 0.001$, $F = 28.839$) and HIITACT ($p < 0.001$, $F = 34.553$) conditions (Fig 5.2A). For the mean RPE for each bout, no differences were found between the two HIIT conditions.

For RPE^{COND}, there was a main effect ($p < 0.001$, $F = 110.968$) for condition, however no differences were found between the two HIIT conditions (Fig 5.2B.)

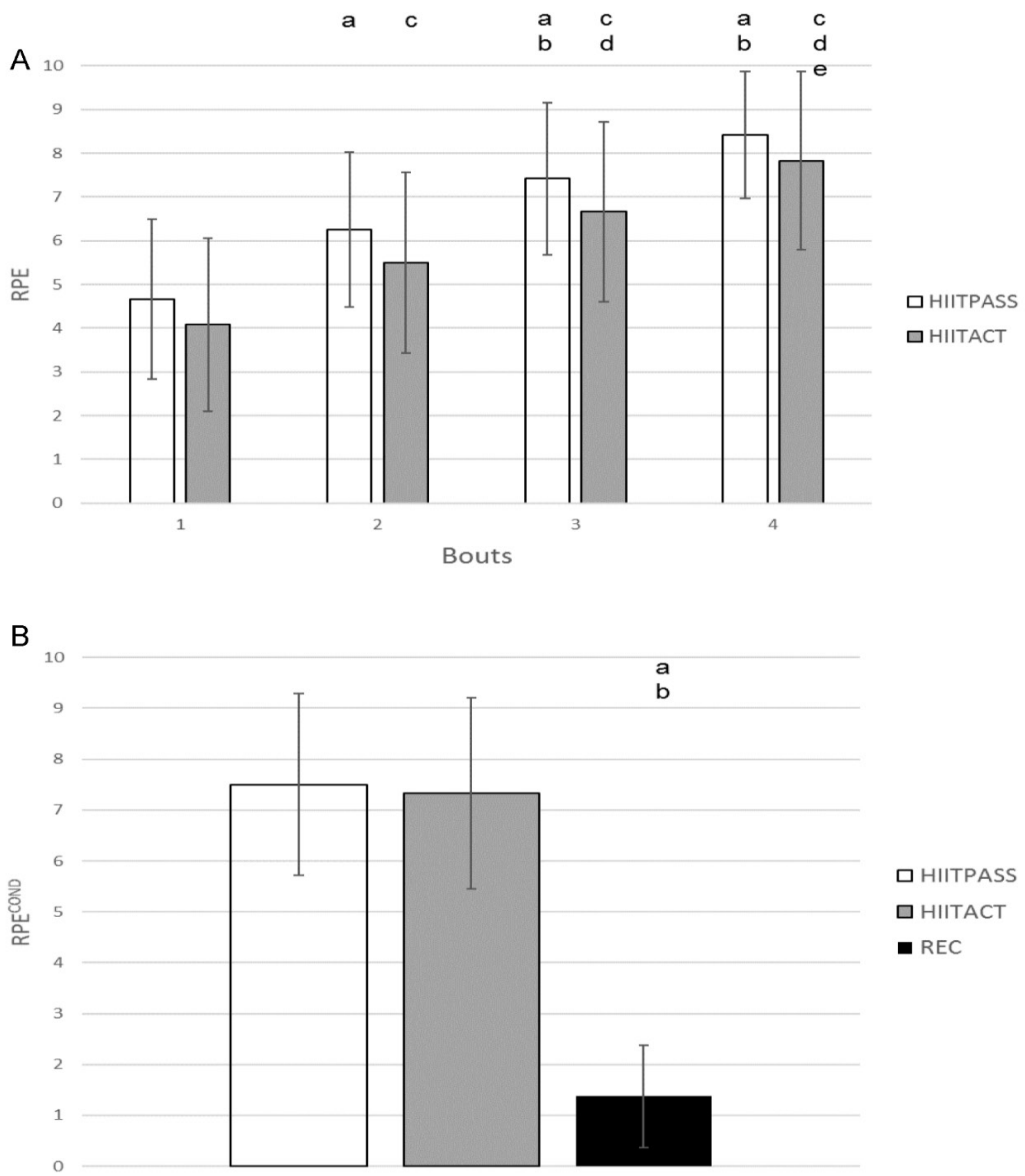

Figure 5.2. Ratings of Perceived exertion and Condition Ratings of Perceived Exertion for the three conditions

(A) Ratings of Perceived Exertion (RPE). a = different to HIITPASS, Bout 1; b = different to HIITPASS, Bout 2; c = different to HIITACT, Bout 1; d = different to HIITACT, Bout 2; e = different to HIITACT, Bout 3.

(B) Condition Ratings of Perceived Exertion (RPE^{COND}). a = different to HIITPASS; b = different to HIITACT. Data are mean ± SD. Letters ('a', 'b', etc.) denote significant differences at $p \leq 0.05$.

5.4.2. Physical activity enjoyment scale

For the mean PACES score, no differences were found between the three conditions (Fig 5.3).

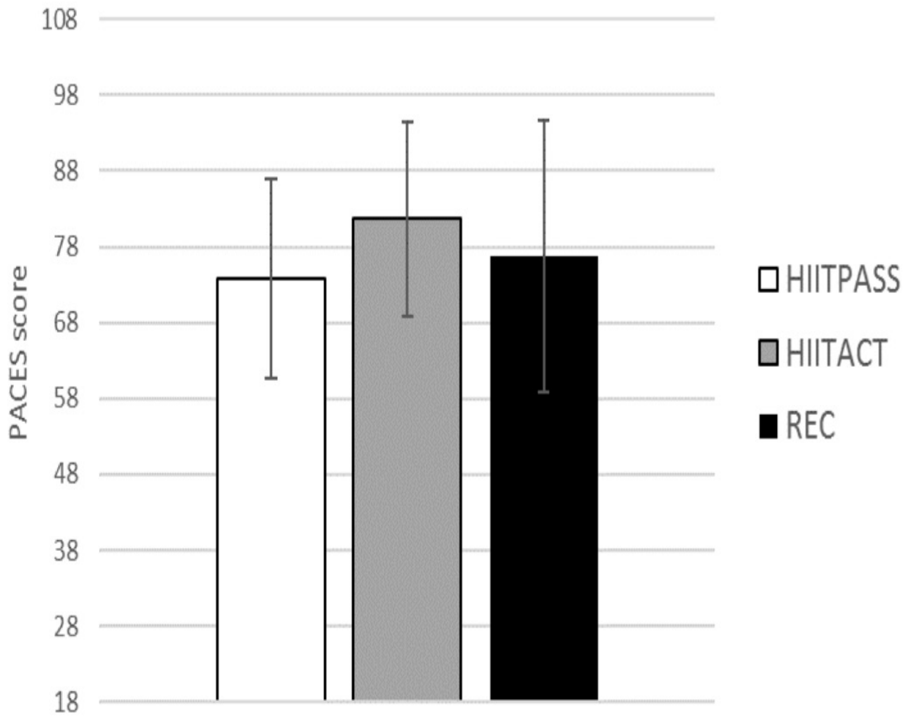

Figure 5.3. Physical activity enjoyment scale (PACES) for the three conditions

Data are mean ± SD.

5.4.3. Blood pressure

Systolic blood pressure

For the mean SBP, there was a main effect for condition ($p < 0.001$, $F = 11.781$) and time ($p < 0.001$, $F = 70.829$). There was a condition x time interaction ($p < 0.001$, $F = 10.345$)

For the mean SBP within conditions (Fig 5.4A), differences were found over time, as expected: HIITPASS ($p < 0.001$, $F = 32.331$), HIITACT ($p < 0.001$, $F = 51.117$), REC ($p = 0.001$, $F = 53.117$), with SBP increasing during exercise, compared to resting levels, and returning to near baseline by Rec 6. For the mean SBP for each measurement time, differences were found between conditions for Bout 1 ($p = 0.007$, $F = 6.251$), Bout 2 ($p < 0.001$, $F = 14.142$), Bout 3 ($p < 0.001$, $F = 13.484$), Bout 4 ($p = 0.000$ $F = 25.797$) and Rec 2 ($p < 0.001$, $F = 14.122$), however no differences were found between the two HIIT conditions.

Diastolic Blood pressure

For the mean DBP, there was a main effect for condition ($p < 0.001$, $F = 16.948$) and time ($p = 0.003$, $F = 5.940$). There was a significant condition x time interaction ($p < 0.001$, $F = 5.011$).

For the mean DBP within conditions (Fig 5.4B), differences were found over time in HIITPASS ($p = 0.001$, $F = 6.665$) and HIITACT ($p = 0.001$, $F = 6.958$), with DBP lower during the recovery portions of both conditions, compared to resting levels. For the mean DBP for each measurement time, differences were found between conditions for Bout 2 ($p =0.009$, $F = 5.872$), Bout 3 ($p = 0.004$, $F = 7.169$), Bout 4 ($p = 0.007$, $F = 6.384$), Rec 2 ($p < 0.001$, $F = 29.390$), Rec 4 ($p < 0.001$, $F = 25.428$) and Rec 6 ($p < 0.001$, $F = 28.176$) with differences found between the two HIIT conditions for Rec 6 only in which DBP was lower in HIITPASS, compared to HIITACT

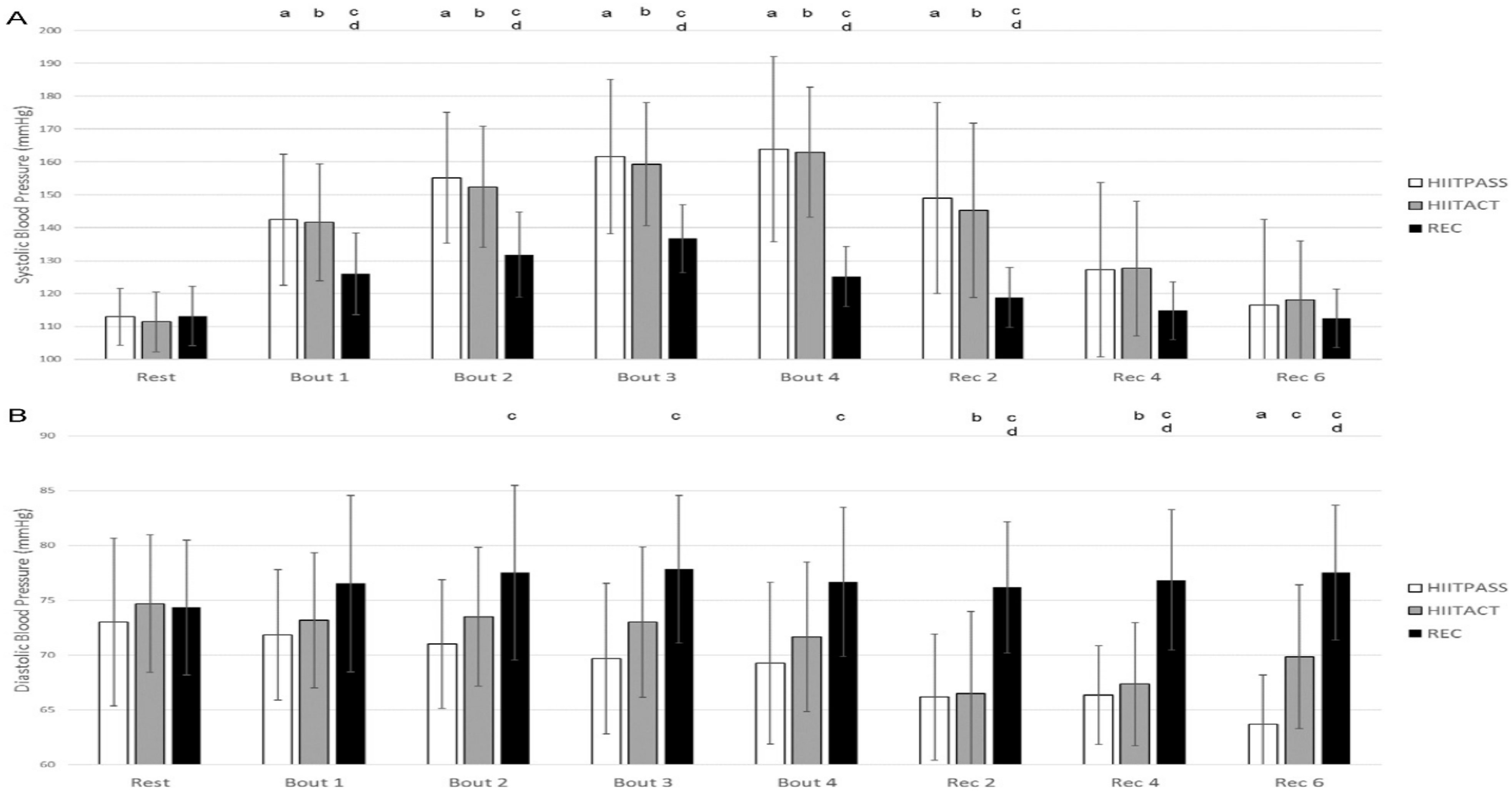

Figure 5.4. Blood pressure responses during the three conditions

(A) Systolic blood pressure (SBP). a = different to HIITPASS Rest; b = different to HIITACT Rest; c = different to REC Rest; d = different to HIIT conditions at same Time. (B) Diastolic blood pressure (DBP). a = different to HIITPASS Rest; b = different to HIITACT Rest; c = different to HIITPASS at same Time; d = different to HITACT at same Time. Data are mean ± SD. Letters ('a', 'b', etc.) denote significant differences at $p \leq 0.05$.

5.5. Discussion

The aim of this experiment was to compare the effect of a session of HIIT, which included either passive or active recovery periods, on RPE, PACES, SBP and DBP responses of sedentary participants. There were no differences in RPE, PACES or SBP during HIITPASS, compared to HIITACT. Diastolic BP was lower after 6 min of recovery following HIITPASS, compared to HIITACT.

5.5.1. Ratings of perceived exertion

Perception of exertion is defined as the subjective intensity of effort, strain, discomfort and / or fatigue that is experienced during physical exercise [307]. A higher perceived exertion (exercise intensity) can negatively influence sedentary individuals' mood state, exercise enjoyment levels and potential compliance [66, 108]. No differences in RPE were found when comparing HIITPASS and HIITACT, indicating that in the sedentary participants, perception of exertion during HIIT was independent of recovery format. The RPE score integrates information from various physiological and psychological signals [305, 307], including oxygen uptake, exercise experience, motivation and discomfort, and therefore may be insensitive to the small but important physiological or perceptual differences between recovery formats.

The RPE increased from Bout 1 to Bout 3 during HIITPASS before remaining stable, indicating that a plateau in RPE was reached, perhaps due to cumulative fatigue. The RPE increased during each successive bout of HIITACT. This continued rise in RPE during HIITACT, not seen in HIITPASS, could be attributed to the (small) additional exercise load represented by the active recovery portions, in the sedentary cohort.

Although participants were instructed to give a maximal effort in each of the four bouts, RPE scores for each bout do not indicate a perception of maximal effort, with a rating of 4 reported in Bout 1 of HIITACT and a rating of 8 reported in Bout 4 of HIITPASS. This is in contrast to research involving trained individuals, in which participants reported near maximal RPE scores from the first bout of all-out effort [294, 308]. The submaximal RPE scores in the current experiment could be due to a protective feedforward subconscious pacing strategy or due to an inability of sedentary individuals to link RPE to actual exercise intensity, perhaps due to poor memory anchoring of the scale. The apparent discrepancy in perception of effort in sedentary versus trained participants requires future investigation

5.5.2. Physical activity enjoyment scale

The PACES has been shown to be a reliable and valid measure of exercise participant enjoyment [309] and has been used to determine differences in the enjoyment levels of participants during various formats of exercise, including HIIT [68, 101, 244, 247]. The two studies to compare enjoyment between HIIT sessions of varying exercise bout and recovery period duration found no difference in enjoyment [69, 109]. Our finding of no difference in PACES between HIITPASS, HIITACT and REC is unexpected, as REC represented low intensity exercise whilst the HIIT conditions represented high intensity exercise. However, no difference in enjoyment has been found between HIIT and moderate intensity exercise [66]. Additionally, the mean PACES scores for all three conditions (HIITPASS = 74; HIITACT = 82 and REC = 77) were substantially lower than those reported in other HIIT research in sedentary populations (≥ 91) [65, 68, 101]. The young sedentary individuals participating in this experiment expressed low levels of exercise enjoyment, regardless of the exercise intensity or recovery format, indicating a potential contributing factor to their current sedentary status. The finding of no significant differences in the PACES score between the three conditions, in association with significantly lower RPE scores in REC when compared to the two HIIT conditions, contradicts research that has found that exercise that elicits a lower RPE score is seen as more enjoyable [310] . This indicates that exercise enjoyment in a sedentary population is influenced by more than the perception of exertion and / or actual exercise intensity and that recovery format during HIIT is not likely a key determinant of enjoyment in this population.

5.5.3. Blood pressure

Systolic blood pressure

Resting SBP was within normal ranges. As expected, SBP increased over the course of the exercise conditions and then decreased to near resting levels during the 6 min post-exercise recovery period [20]. During HIIT, the mean SBP did not reach exercise testing termination criteria (SBP >250 mmHg), indicating that the SBP response to this supramaximal format of exercise was appropriate, consistent with previous high intensity interval research in young participants [80]. The only study to compare BP responses to HIIT including either active or passive recovery periods in sedentary participants, found no differences in mean arterial pressure between recovery type after the last bout of HIIT, however did not report blood pressure responses during post-exercise recovery periods [120]. No differences were found for SBP when comparing HIITPASS and HIITACT. The SBP responses were therefore unaffected by recovery format, possibly due to the integratory physiological control mechanisms which ensured that SBP remained within normal ranges throughout exercise and recovery [59]. Furthermore, the similar SBP responses between HIITPASS and HIITACT likely reflect similar levels of cardiovascular strain during exercise and that any differences between the recovery formats were abolished at the onset of each bout of exercise.

Diastolic blood pressure

Resting DBP was within normal ranges. The accepted DBP response to continuous exercise is a slight decrease or no change [20]. Our findings during the HIIT conditions indicate a similar response during intermittent exercise, with no statistically significant decrease in DBP occurring during the exercise component of the HIIT conditions, compared to resting DBP. However, during the 6 min passive recovery period post-exercise, a decline in DBP was observed during both HIIT protocols, possibly due to peripheral vasodilation (and hence a decrease in total peripheral resistance) [311] [312] and / or post-exercise hyperaemia in response to the high intensity exercise conditions [313]. The DBP during HIITACT reached a minimum after 2 min of recovery, before returning to near resting levels by 6 min. The minimum DBP during HIITPASS was reached 6 min after exercised cessation. The continued reduction in DBP post-exercise following HIITPASS is consistent with the DBP response noted after a single Wingate bout [311], two Wingate bouts [296] and four Wingate bouts [137]. At 6 min post-exercise, DBP was significantly lower in HIITPASS, compared to resting levels, and compared to HIITACT and REC. The reduction in DBP during the recovery portion of HIITPASS could be attributed to the combination of an upright posture, the absence of the secondary muscle pump, blunted reflex vasoconstrictor responses and the dilation of the peripheral vasculature resulting in a centrally mediated signal for additional vasodilation and hypotension [60, 313]. In comparison, the active recovery portions of HIITACT (via muscle pump contributions to venous return and cardiac output) potentially compensated for the persistent decrease in peripheral vascular resistance during recovery, allowing a relatively rapid return to pre-exercise DBP levels.

Adverse reactions to HIIT are rarely reported [5]. The significant decrease in DBP post-exercise coincided with pre-syncopal symptoms of dizziness and nausea in six participants (three after HIITPASS, two after HIITACT and 1 after both conditions), which resolved with extended recovery time. It is of interest to note that the mean reduction in DBP (resting DBP compared to DBP 6 min post-exercise) was larger in the symptomatic participants (mean = 11 mmHg) than in the asymptomatic participants (mean = 6 mm Hg), regardless of the inclusion of passive or active recovery. Rates of pre-syncope can be over 50% during high intensity exercise interventions investigating post-exercise syncope [313], participation in HIIT can increase the risk of falls [142] and HIIT is becoming increasingly popular [7].Therefore, the reductions in DBP post-exercise and the pre-syncopal symptoms reported by participants have implications for the safety and practicality of conducting HIIT sessions. It therefore seems prudent to suggest an increased surveillance of post-exercise BP and signs and symptoms, especially if passive recovery periods are included post-exercise or if individuals cannot perform active recovery due to fatigue or discomfort. However, in those individuals not prone to symptomatic PEH, the larger decrease in DBP after HIITPASS, compared to HIITACT, could have positive implications for the prevention or treatment of hypertension [57]. Therefore, the effect of HIIT recovery format on the occurrence of longer term PEH requires further investigation. Furthermore, although all participants felt well upon leaving the laboratory (no more than 30 min post-exercise), these adverse sensations could have contributed to the relatively low levels of enjoyment reflected in the mean PACES scoring of the two HIIT conditions, however fails to explain the lack of differences between the HIIT conditions and REC.

5.6. Limitations

The participants in this experiment, whilst homogenous in their sedentary behaviour during the study, were noted anecdotally to be heterogeneous in their exercise history. The degree of discomfort experienced during HIIT, interpreted in reference to previous exposure to high intensity exercise, could lead to differences in RPE and PACES scores, as current perceptions could be informed by a combination of present and past experiences [221]. Therefore, the evaluation of exercise history on the variables of RPE and PACES during HIIT is suggested as a future research direction.

Participants were verbally encouraged during all bouts of exercise in an attempt to ensure a maximal effort. It is questionable if this extrinsic motivation would occur outside of the laboratory environment, therefore the encouragement could limit the applicability of experiment results to unsupported HIIT interventions.

Experiments that examine the effect of exercise on the participants' perceptions and enjoyment have limitations to their validity, as the exercise sessions are prescribed by the researcher and therefore do not allow participants to make many exercise related choices during the session, which in turn may affect their perceptions and enjoyment of the sessions and responses. By not including a moderate intensity exercise condition, researchers were unable to evaluate the participants' perceptual attitudes and exercise enjoyment towards the entire spectrum of exercise intensity. Therefore, conclusions that the participants' lack of enjoyment of the low intensity REC condition and the two HIIT sessions indicates a lack of enjoyment of all exercise could be erroneous.

5.7. Conclusions

It is concluded that, in sedentary participants, perception of exertion and exercise enjoyment are independent of HIIT recovery format. HIIT, as conducted in this experiment, is described as maximal exercise. However, sedentary participants do not perceive the conditions as such, irrespective of recovery format (indicated by RPE scores between 4 and 8) and possibly self-limit their exertion. Due to reductions in post-exercise DBP and associated pre-syncopal symptoms, HIIT protocols including passive recovery periods post-exercise have negative safety and compliance implications in participants susceptible to symptomatic PEH.

5.8. Acknowledgements

The authors would like to thank the participants of this experiment without whom this experiment would not have been possible.

6. The effect of HIIT mode on local tissue oxygenation and enjoyment

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Statement of intellection contribution and relative role of the candidate, Mr Yuri Kriel, in the execution of the study and writing of the paper:

Conceived and designed the experiment: YK, CS

Performed the experiment: YK

Analysed the data: YK, CDA, CS

Wrote the first draft of the paper: YK

Edited the paper: YK, CDA, CS

Yuri Kriel

Christopher D. Askew

Colin Solomon

Full Title**: The effect of running versus cycling high intensity intermittent exercise on local tissue oxygenation and perceived enjoyment in 18 – 30 year old sedentary men**

Short Title**: HIIT: a comparison of modes**

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6.1. Abstract

Purpose

High intensity interval training (HIIT) has been proposed as a time-efficient exercise format to improve exercise adherence, thereby targeting the chronic disease burden associated with sedentary behaviour. Exercise mode (cycling, running), if self-selected will likely affect the physiological and enjoyment responses to HIIT and therefore the efficacy of HIIT exercise in sedentary individuals. It was hypothesised that in young sedentary men, local and systemic oxygen utilisation and enjoyment would be higher during a session of running HIIT, compared to a session of cycling HIIT.

Methods

Twelve sedentary men (mean ± SD; age 24 ± 3 yr) completed three exercise sessions: a maximal incremental exercise test on a treadmill (MAX) followed by two experiment conditions, 1) free-paced cycling HIIT on a bicycle ergometer (HIITCYC) and 2) constant-paced running HIIT on a treadmill ergometer (HIITRUN). Deoxygenated haemoglobin (HHb) in the pre-frontal cortex (FH), gastrocnemius (GN), the left vastus lateralis (LVL) and the right vastus lateralis (RVL) muscles, oxygen consumption (VO_2), heart rate (HR), ratings of perceived exertion (RPE) and physical activity enjoyment (PACES) were measured during HIITCYC and HIITRUN.

Results

There was a higher HHb in the FH ($p < 0.001$), LVL ($p = 0.001$) and RVL ($p = 0.002$) sites and a higher VO_2 ($p = 0.017$) and HR ($p < 0.001$) during HIITCYC, compared to HIITRUN. RPE was higher ($p < 0.001$) and PACES lower ($p = 0.032$) during HIITCYC compared to HIITRUN.

Conclusions

In sedentary individuals, free-paced cycling HIIT produces higher levels of physiological stress when compared to constant-paced running HIIT. Participants perceived running HIIT to be more enjoyable than cycling HIIT. These findings have implications for selection of mode of HIIT for physical stress, exercise enjoyment and compliance.

6.2. Introduction

High intensity interval training (HIIT) of a short duration has been proposed as a time-efficient exercise format to improve exercise adherence, thereby helping to address the chronic disease burden associated with sedentary behaviour [31]. However, there is the relative and absolute scarcity of clinical exercise professionals to provide formalised exercise guidance to sedentary individuals [314] looking to initiate HIIT. Given the extensive coverage of the beneficial health effects of HIIT in previous literature [6, 91] and 'go as hard as you can' formats of HIIT via media outlets, it is expected that a proportion of sedentary individuals wanting to increase their physical activity levels will attempt HIIT in recreational settings unsupervised and self-select the modes of exercise (running and cycling) available to them.

Running elicits a greater cardiorespiratory response (VO_2 and HR) than cycling during incremental and submaximal exercise, at matched relative and absolute workloads above and below the anaerobic threshold [116, 315]. However, the selection of running versus cycling to perform a session of HIIT is associated with inherent differences in workloads between these two modes of exercise. This difference is due, in part, to how running and cycling ergometers are utilised to induce the requisite physiological stress inherent in the HIIT protocols [33, 130]. It is not known whether running or cycling elicits a greater cardiorespiratory response than cycling in sedentary individuals during short duration HIIT protocols. Additionally, while acute physiological responses linked to positive health and performance benefits are induced by bouts of either running and cycling HIIT [5, 6, 27, 28, 79, 106], there is no scientific literature comparing the effects of these exercise modes on physiological responses during HIIT in the same cohort of sedentary individuals [3]. The physiological responses, and therefore benefits, elicited by running and cycling HIIT protocols, as conducted in recreational exercise settings by unsupervised sedentary individuals, are expected to differ due to differences in the absolute workload able to be achieved [116], cardiorespiratory responses [116, 315, 316], muscle activation [222] and systemic oxygen utilisation [317] between these two modes of exercise. Therefore, it is necessary to describe the potential differences in physiological responses during protocols of HIIT utilising running and cycling modes to determine which mode will potentially provide the largest physiological perturbation and acute training response in unsupervised exercise scenarios.

A benefit of HIIT exercise, increased cardiorespiratory fitness, has been attributed partly to increases in mitochondrial content and function [41, 42]. Whilst the exact mechanisms underlying the increases in mitochondrial content and function are not completely understood, it is possible that the demand for increased oxygen utilisation at the local tissue level during an acute session of HIIT contributes to the stimulus for these adaptations. Near infrared spectroscopy (NIRS) is a non-invasive method for the measurement of the change in concentration of oxyhaemoglobin (ΔO_2Hb) (oxygen availability) and deoxyhaemoglobin (ΔHHb) (oxygen utilisation) at the local tissue level. Oxygen utilisation, measured via NIRS, has been described during running HIIT in component muscles of the quadriceps and hamstring [172] and during cycling HIIT at a single muscle site [318], in component muscles of the quadriceps [195, 281] and in the pre-frontal cortex [175]. The HHb in the locomotor muscles is increased during cycling and running HIIT bouts, compared to pre-exercise values [48, 104]. The HHb in the pre-frontal cortex is increased during high intensity cycling exercise [175, 301], compared to pre-exercise values and could be a potential mechanism contributing to fatigue and exercise cessation [45] and therefore influence the physiological responses to HIIT exercise. It is probable that, similar to systemic measures of oxygenation in other formats of exercise, running HIIT will elicit a greater local oxygen utilisation response than cycling HIIT. However, this is yet to be demonstrated. Investigation of the local oxygen utilisation responses in sedentary individuals will provide specific information as to which mode causes the largest increase in oxygen utilisation, a potential stimulus for improved mitochondrial function in muscle fibres, and therefore an important consideration when evaluating HIIT in a health-related context.

HIIT is often associated with discomfort [247, 298]. Aversive exercise experiences have a direct effect on perception of exertion, exercise enjoyment and therefore adherence [108, 299] in sedentary individuals, a population which often has low intrinsic motivation to exercise [63]. Whilst the physiological benefits of HIIT [6, 7] provide the basis for recommending this format of exercise to sedentary individuals, it is necessary to use perceptual data to determine the factors that may facilitate or impede the commencement or continuation of HIIT, if HIIT is to be an effective preventative health initiative [6, 27, 32, 106]. Perceived exercise intensity affects sedentary individuals' exercise enjoyment levels and ongoing compliance [66], with lower intensity exercise associated with higher levels of enjoyment [108] and improved adherence rates in novice exercisers [20]. However, this inverse relationship is not always strong [319] and is complicated by various factors, including exercise mode. At a fixed submaximal intensity [320] and during incremental exercise [116], cycling elicits a higher perception of effort than running. If, during the formats of HIIT likely to be adopted by sedentary individuals, cycling also elicits a higher perception of effort than running (and hence a lower level of enjoyment) exercise mode potentially has implications for the practical uptake of, and continued compliance with HIIT in a sedentary population.

The aim of this study was to compare the local (Δ[HHb]) and systemic (VO_2) oxygen utilisation, heart rate (HR), ratings of perceived exertion (RPE) and enjoyment (Physical Activity Enjoyment Scale: PACES) between and across bouts of HIIT conducted either running or cycling. It was hypothesised that in young sedentary individuals Δ[HHb], VO_2, HR and PACES would be higher and RPE lower during running HIIT bouts, compared to cycling HIIT bouts.

6.3. Methods

6.3.1. Ethics statement

This research study was approved by the human research ethics committee of the University of the Sunshine Coast (S/13/472). All participants received a research study information sheet before providing written informed consent.

6.3.2. Experiment design

The study consisted of three testing sessions: a maximal incremental exercise test conducted on a treadmill ergometer (MAX) followed by two experiment conditions; 1) a protocol of free-paced HIIT conducted on a bicycle ergometer (HIITCYC); and 2) a protocol of constant-paced HIIT conducted on a treadmill ergometer (HIITRUN). The HIIT conditions were randomised to control for any possible order effect. All testing sessions were separated by three to seven days to minimise the influence of any potential carry-over effects between testing sessions. The ΔHHb in the pre-frontal cortex (FH), gastrocnemius (GN), the left vastus lateralis (LVL) and the right vastus lateralis (RVL) muscles, VO_2, HR, RPE and the PACES were measured during the HIIT sessions. The format of the HIIT testing sessions and the timing of measurements are illustrated in Figure 6.1.

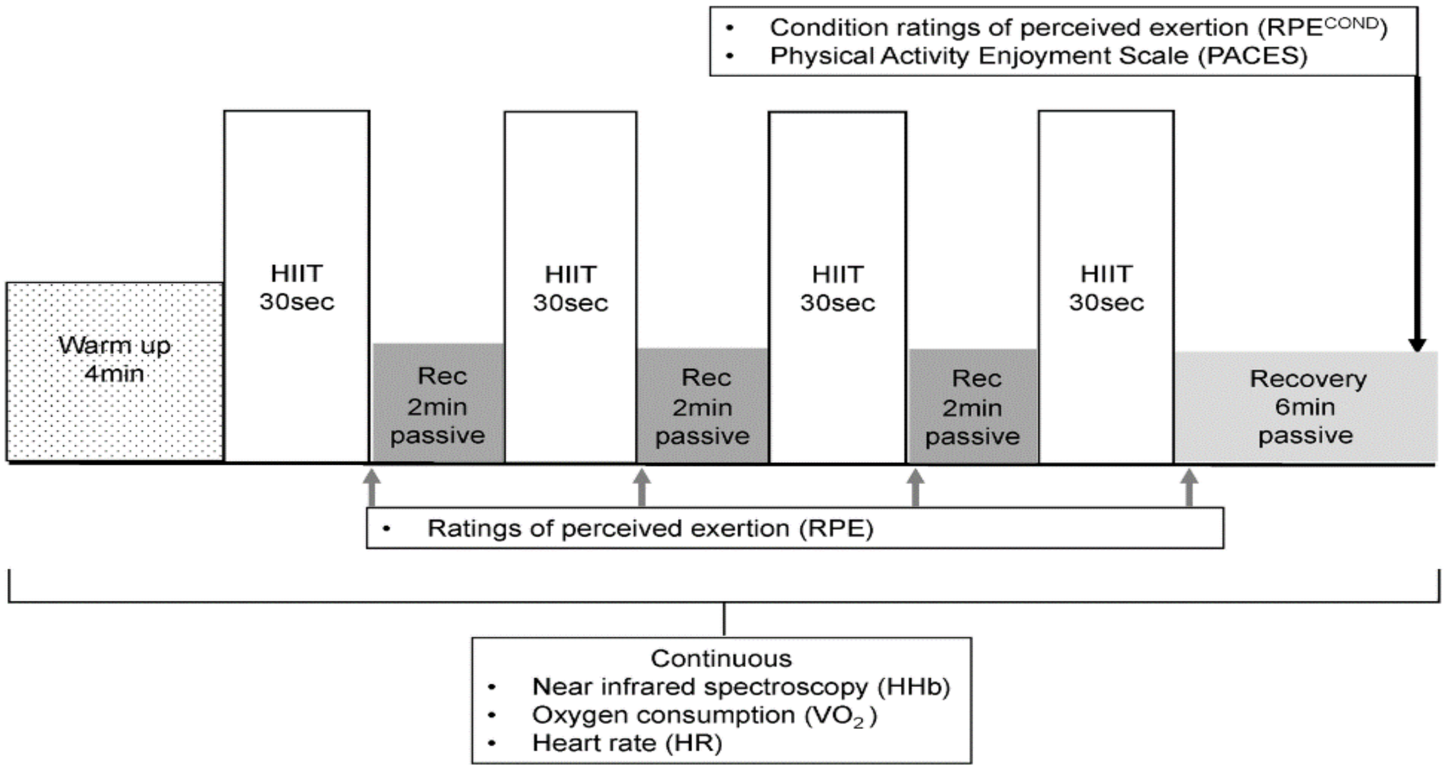

Figure 6.1. The format and timing of measurements of the HIIT sessions.

6.3.3. Participants

The participant group consisted of twelve men who met the inclusion criteria of being aged 18 – 30 years; currently completing less than 150 min of moderate intensity or 75 min of vigorous intensity activity per week; reporting no cardiovascular and metabolic disease; taking no medications; having no known health related issues that would be made worse by, or inhibit participation in the study. Descriptive physical characteristics of participants are presented in Table 6.1.

Table 6.1. Participant characteristics.

Height (cm)	176 ± 7.07
Weight (kg)	78.9 ± 13.9
Body Mass Index (kg/m^2)	25.4 ± 4.34
Age (yr)	24 ± 3
VO_{2peak} during MAX ($ml.kg.^{-1}min^{-1}$)	43.5 ± 4.30
Heart rate max (bpm)	189 ± 9
Peak treadmill running speed during MAX ($km.h^{-1}$)	12.2 ± 0.94
Peak RPE^{COND} value during MAX	8 ± 1
Left vastus lateralis skinfold (mm)	10.4 ± 4.48
Right vastus lateralis skinfold (mm)	11.0 ± 4.97
Gastrocnemius skinfold (mm)	10.9 ± 3.87
FVC (L)	5.46 ± 0.75
FVC % pred (%)	106 ± 11
FEV_1 (L)	4.56 ± 0.80
FEV_1 % pred (%)	105 ± 16

VO_{2peak} = Peak oxygen uptake; RPE^{COND} = Rating of perceived exertion for each condition; FVC = Forced vital capacity; FEV_1 = Forced expiratory volume in 1 s. Data are (mean ± SD) (n = 12).

6.3.4. Procedures and equipment

Screening procedures

At the initial session, participants completed risk screening questionnaires, a physical activity log and physical characteristics of height, mass, resting pulmonary function and adipose tissue thickness (ATT) were measured (Table 6.1), as previously described [301]. Briefly, the physical activity log was used to ensure that participants' activity levels over the previous three months met the definition of sedentary for the purposes of this study (i.e. not achieving the current minimal recommendations for exercise participation to obtain health benefits) [282]. Participants were asked to not perform exercise in the 24 hours prior to each session and to not consume any caffeine, alcohol or a large meal in the four hours preceding each session [321]. It was confirmed at each testing session that participants were appropriately fed and hydrated, in line with existing pre-exercise nutrition and hydration guidelines [302-304].

Exercise sessions

Prior to the initial exercise session, participants were familiarised with the testing protocols, the cycle ergometer (Veletron, Racermate, Seattle, WA, USA) and the treadmill (T200, Cosmed, Rome, Italy). A safety harness was worn during all treadmill sessions.

Each exercise session began with a 3-min baseline data collection period during which the participant either sat on the cycle ergometer or stood on the treadmill. The baseline period was followed by a 4-min warm up period, consisting of either cycling against a constant resistance of 60 Watts (W) (HIITCYC) or walking at a 10% gradient and an individually determined speed calculated to produce approximately 60W of resistance (HIITRUN), calculated from the rate of vertical displacement (running speed and gradient) and body mass.

During the maximal incremental exercise test, the warm up was followed by an incremental speed protocol at a fixed 10% gradient, with an initial running speed of 8 $km.h^{-1}$, increasing by 1 $km.h^{-1}$ every 30 s until volitional cessation. The peak treadmill running speed achieved during MAX was used as the participants' running speed during the HIITRUN bouts. The 10% grade was chosen to simulate individuals performing HIIT by running up a steep incline, to enable mechanical power to be calculated and to provide an intensity of exercise that would produce a maximal sprint effort without relying primarily on running speed. It was necessary to determine a realistic maximal running speed for the 30 s HIITRUN bouts, which would potentially not have been achieved with longer stage durations in untrained sedentary participants during the maximal incremental test, due to fatigue inducing exercise cessation prior to the attainment of maximal running speed [322, 323].

The format of the HIIT experiment conditions, as illustrated in Figure 6.1, have been described previously [301]. Briefly, the warm up was followed by four 30 s bouts of HIIT, with 2 min passive recovery periods separating each of the HIIT bouts. During the passive recovery periods, participants were instructed to sit (HIITCYC) or stand (HIITRUN) as still as possible to reduce movement artefact in the NIRS data. Following the final bout, there was a 6-min passive recovery period. The HIIT protocol format was based upon protocols used in trained and untrained populations. [62, 94-96, 104, 174, 284].

Tissue oxygenation

Changes in local tissue oxygenation were measured continuously, as illustrated in Figure 6.1, and as described previously [301]. Briefly, the changes in the relative concentration of HHb (Δ[HHb]) were measured using a Near Infrared Spectroscopy (NIRS) system (three x PortaMon and one x Portalite devices, Artinis Medical Systems BV, Zetten, Netherlands). The PortaMon devices were placed on the skin directly over the muscle belly of three locomotor muscles: the left vastus lateralis (LVL), the right vastus lateralis (RVL) and the left gastrocnemius (GN) and the Portalite optode was placed on the area of the forehead above the pre-frontal cerebral cortex (FH). Test-retest reliability of the HHb data from the NIRS system was examined prior to this study, providing acceptable absolute reliability values of the baseline data for each site (Typical Error: VL = 0.4 μM, GN = 0.8 μM, FH = 0.6 μM) [301]. For all testing, the same device was used at the same measurement site. To ensure placement consistency, positioning of the individually labelled NIRS devices was referenced to anatomical landmarks as detailed previously [48, 97, 104, 168, 175]. The location of devices was marked with an ink pen at the first session and participants were required to maintain the marks between subsequent sessions.

For this study, only Δ[HHb] values are presented, as discussed previously [301]. Briefly, the Δ[HHb] data are potentially unaffected by changes in perfusion, blood volume or arterial haemoglobin concentration [166, 285, 286]. Movement artefact was present in NIRS data collected at the LVL, RVL and GN sites during the passive recovery periods of the HIIT sessions, attributed to a low signal to noise ratio.

Therefore, recovery period data were not included in further analysis. Similar technical difficulties in NIRS data collection, leading to data exclusion, have been reported [324].

Systemic oxygen consumption (VO2), heart rate (HR) and mechanical power

Systemic oxygen consumption data were collected continuously, as illustrated in Figure 6.1, using a respiratory gas analysis open circuit spirometry system (Parvo Medics, Sandy UT, USA). Standardised calibration and methods were used [288]. A heart rate monitor (RS400, Polar Electro, Kempele, Finland) was used to measure and record heart rate, as illustrated in Figure 6.1. A crank-based power meter (SRM Science, Schoberer Rad Meßtechnik, Julich, Germany) was used during HIITCYC to measure and record mechanical power output. The power output during the HIITRUN bouts was a product of the constant speed, the fixed 10% gradient and the participant's body weight using the equations: Power = work / time; work = body weight x total vertical distance (speed x gradient x time), used previously when comparing high intensity bouts of uphill running to non-steady state cycling [315].

Ratings of perceived exertion (RPE)

To determine perceived exertion, participants were provided with a standardised description of the CR10 RPE scale [305] and the purpose of the scale, including memory anchoring of the scale (an explanation of the sensations associated with the high and low scale categories) [306]. Participants were asked to provide an RPE score immediately after each bout of HIIT as well as give a 'Condition' RPE score (RPE^{COND}) 1 min after the final (fourth) bout. This RPE^{COND} score was used to compare the overall perception of exertion between the HIIT conditions.

Physical activity enjoyment scale (PACES)

To determine enjoyment levels in response to each condition, participants completed the Physical Activity Enjoyment Scale (PACES) questionnaire within 5 min of completing each condition. The PACES was used to compare enjoyment levels between the HIIT conditions. The PACES consists of eighteen items on a 7-point bipolar scale. A minimum total score of 18 and a maximal total score of 126 is possible, and a higher score indicates a higher level of enjoyment. The PACES is a reliable and valid measure of enjoyment during HIIT [247, 325].

6.3.5. Data calculation

All NIRS data were collected at 10 Hz, smoothed using a 10-point moving average and then averaged to 1 s periods for statistical analysis. The NIRS data were expressed as units of change (µM) from the mean value of the 30 s of baseline data preceding the start of exercise (Δ[HHb]). VO_2 data were averaged over 5 s periods whilst HR and HIITCYC power data were averaged at 1 s intervals initially. The NIRS, HR, VO_2 and HIITCYC power data were then time aligned. The time periods of data corresponding to the four 30 s bouts of HIIT were then identified. Mean 30 s values were then calculated for all dependant variables for each bout of HIIT, providing a single value per bout for statistical analysis. RPE and PACES data provided a single value per measurement time for statistical analysis.

6.3.6. Statistics

Statistical tests were performed using the IBM SPSS Statistics (version 22, IBM Corporation, Armonk NY, USA) program. Data were initially tested for normality of distribution using the Shapiro-Wilk test. A three factor, repeated-measures analysis of variance (ANOVA) was used to analyse the effect of condition, bout and site on the dependant variable: Δ[HHb]. A two factor, repeated-measures ANOVA was used to analyse the effect of condition and bout on the dependant variables of VO_2, HR, mechanical power and RPE. If a significant main effect or interaction effect was identified, a Bonferroni's post hoc test was used to make pair wise comparisons. A paired samples T-test was used to analyse the effect of condition on PACES scores. All variables are presented as mean ± standard deviation (SD). For all statistical analyses, a P value of < 0.05 was used as the level of significance.

6.4. Results

6.4.1. Tissue oxygenation

For the mean Δ[HHb] for all sites, conditions and bouts combined, there was a main effect for site ($p = 0.002$, $F = 6.057$), condition ($p < 0.001$, $F = 43.392$) and bout ($p = 0.022$, $F = 5.641$). There were condition x site ($p <0.001$, $F = 8.031$), condition x bout ($p = 0.002$, $F = 9.643$) and site x bout ($p < 0.001$, $F = 7.615$) interactions. For the mean Δ[HHb] for each condition, there was a main effect for site for HIITCYC ($p = 0.001$, $F = 6.846$) and HIITRUN [($p < 0.001$, $F = 8.981$) with differences found between FH and

RVL ($p = 0.020$) for HIITCYC and between FH and GN ($p = 0.036$) and GN and LVL ($p = 0.041$) for HIITRUN. There was a main effect for bout ($p < 0.001$, $F = 15.849$) and site x bout interactions ($p = 0.003$) for HIITCYC.

Forehead (FH)

For the FH there was a main effect in the mean Δ[HHb] for condition: [($p < 0.001$, $F = 28.465$) HIITCYC 3.53 ± 2.89 μM; HIITRUN 0.77 ± 1.65 μM] and bout ($p < 0.001$, $F = 15.950$). There was a condition x bout interaction ($p = 0.005$).

For the mean Δ[HHb] for each bout (Fig 6.2A), differences were found between conditions for Bout 2 ($p < 0.001$, $F = 46.087$), Bout 3 ($p = 0.001$, $F = 23.138$) and Bout 4 ($p = 0.004$, $F = 14.270$), with Δ[HHb] higher during HIITCYC, compared to HIITRUN. For the mean Δ[HHb] within conditions, values increased over time when comparing Bout 1 to Bout 2, 3 and 4, in the HIITCYC condition only ($p = 0.001$, $F = 12.629$).

Gastrocnemius (GN)

For the GN no significant differences were found for condition ($p = 0.685$) or bout ($p = 0.057$) (Fig 6.2B).

Left vastus lateralis (LVL)

For the LVL, there was a main effect in the mean Δ[HHb] for condition: [($p = 0.001$, $F = 17.647$) HIITCYC 10.74 ± 8.53 μM; HIITRUN 1.87 ± 3.43 μM]. There was no significant condition x bout interaction.

For the mean Δ[HHb] for each bout (Fig 6.2C), differences were found between conditions for Bout 1 ($p = 0.002$, $F = 17.344$), Bout 2 ($p = 0.003$, $F = 14.593$), Bout 3 ($p = 0.001$, $F = 17.897$) and Bout 4 ($p = 0.001$, $F = 18.087$) with Δ[HHb] higher during HIITCYC, compared to HIITRUN. For the mean Δ[HHb] within conditions, a significant increase was found when comparing Bout 1 to Bout 3 in the HIITCYC condition only ($p = 0.006$, $F = 7.994$).

Right vastus lateralis (RVL)

For the RVL, there was a main effect in the mean Δ[HHb] for condition: [($p = 0.002$, $F = 16.347$) HIITCYC 11.16 ± 7.99 μM; HIITRUN 3.51 ± 4.88 μM]. There was a condition x bout interaction ($p = 0.045$)

For the mean Δ[HHb] for each bout (Fig 6.2D), differences were found between conditions for Bout 1 ($p = 0.002$, $F = 15.371$), Bout 2 ($p = 0.003$, $F = 13.762$), Bout 3 ($p = 0.002$, $F = 16.362$) and Bout 4 ($p = 0.001$, $F = 18.134$) with Δ[HHb] higher during HIITCYC, compared to HIITRUN. For the mean Δ[HHb] within conditions, there were no significant differences found across bouts.

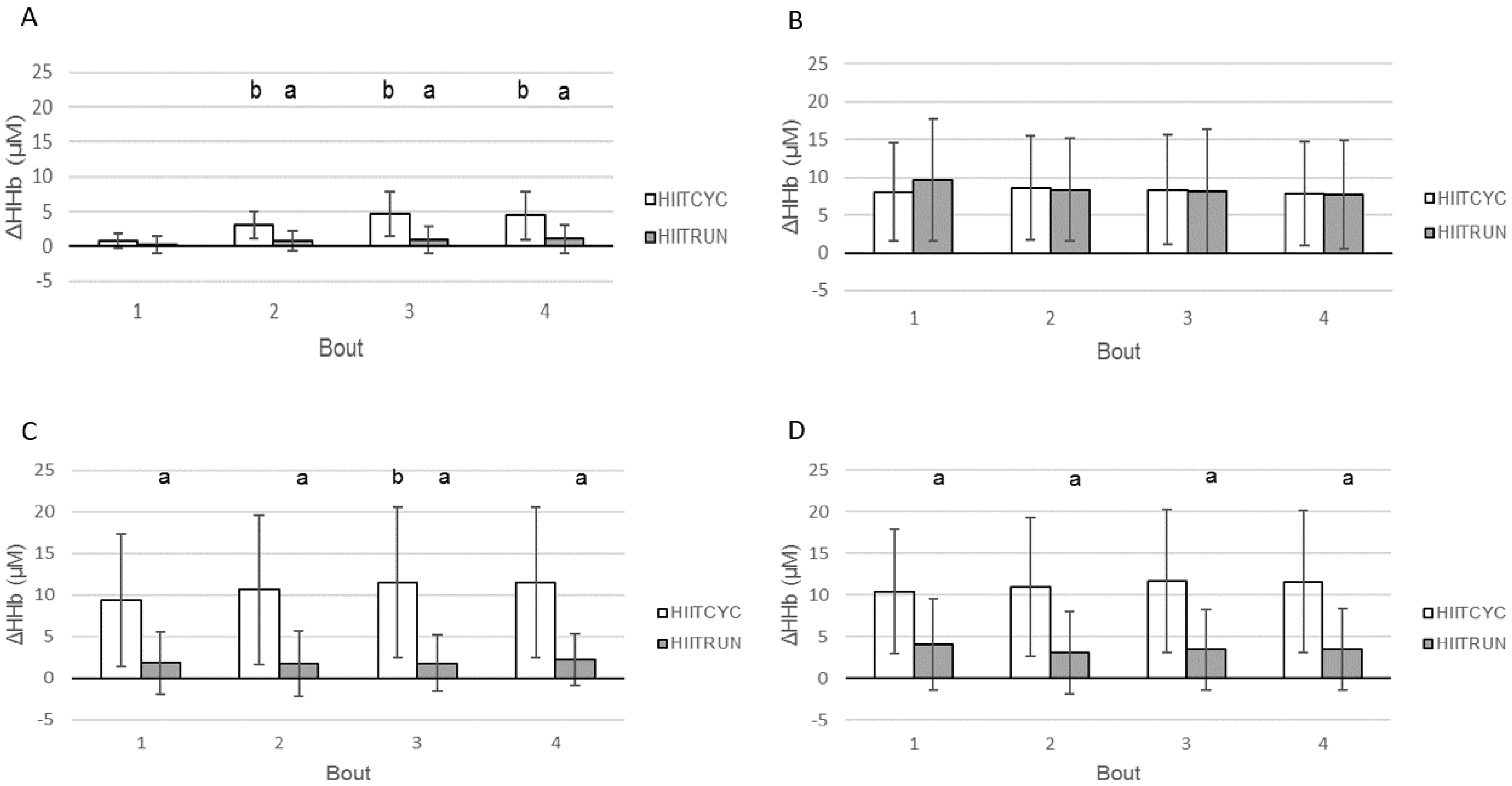

Figure 6.2. Deoxygenated haemoglobin (HHb) concentration during the four bouts in cycling (HIITCYC) and running (HIITRUN) HIIT. (A) Forehead (FH). (B) Gastrocnemius (GN). (C) Left vastus lateralis (LVL). (D) Right vastus lateralis (RVL). a = different to HIITCYC during the same Bout; b = different to HIITCYC Bout 1. Data are mean ± SD. Letters (‘a’, ‘b’, etc.) denote significant differences at $p \leq 0.05$.

6.4.2. Systemic oxygen consumption

For the VO_2, there was a main effect for condition ($p = 0.017$, $F = 9.118$) and bout ($p = 0.008$, $F = 5.016$). There was a condition x bout interaction ($p = 0.021$, $F = 3.885$).

For the mean VO_2 for each bout (Fig 6.3A), differences were found between conditions for Bout 2 ($p = 0.003$, $F = 14.807$) and Bout 3 ($p = 0.012$, $F = 9.317$) with VO_2 higher during HIITCYC, compared to HIITRUN. For the mean VO_2 within conditions, values increased over time in HIITCYC ($p = 0.016$, $F = 6.347$) when comparing Bout 1 to Bout 2 and Bout 3.

6.4.3. Heart rate

For the HR, there was a main effect for condition ($p < 0.001$, $F = 31.126$). There was a condition x bout interaction ($p = 0.014$)

For the mean HR for each bout (Fig 6.3B), differences were found between conditions for Bout 2 ($p < 0.001$, $F = 26.002$), Bout 3 ($p < 0.001$ $F = 53.022$) and Bout 4 ($p < 0.001$, $F = 37.521$) with HR higher during HIITCYC, compared to HIITRUN. For the mean HR within conditions, values increased over time in HIITCYC ($p < 0.002$, $F = 12.316$) when comparing Bout 1 to Bout 3 and 4.

6.4.4. Mechanical power

For the power output, there was a main effect for bout ($p = 0.001$, $F = 11.205$). There was a condition x bout interaction ($p = 0.001$).

For the mean power output for each bout (Fig 6.3C), differences were found between conditions for Bout 4 ($p = 0.008$, $F = 10.728$) with mechanical power lower during HIITCYC, compared to HIITRUN. For the mean power output within conditions, values decreased over time in HIITCYC ($p = 0.001$, $F = 11.205$) when comparing Bout 1 and 2 to Bout 3 and 4.

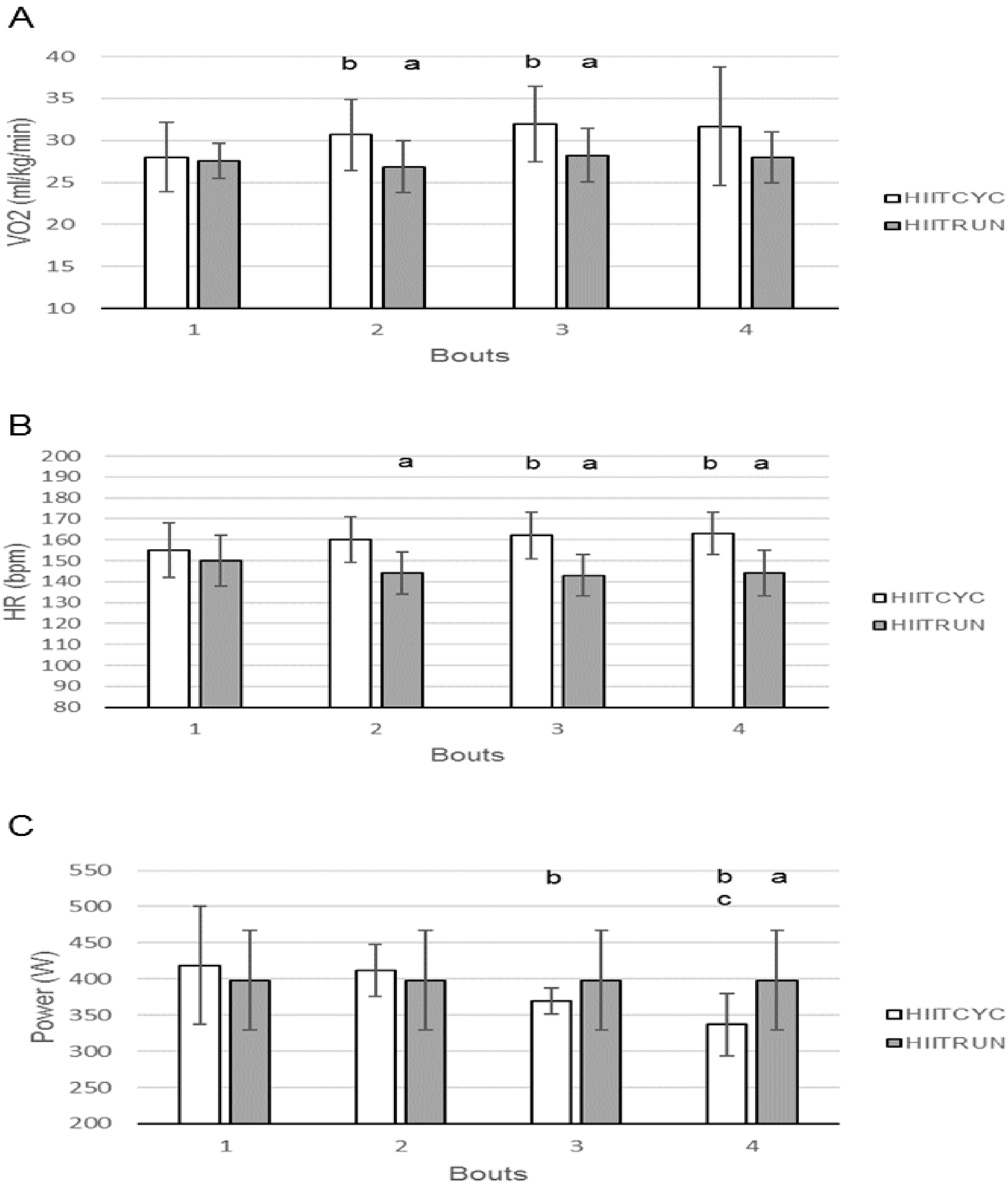

Figure 6.3. Oxygen consumption, heart rate and mechanical power during the four bouts in cycling (HIITCYC) and running (HIITRUN) HIIT.

(A) Oxygen consumption (VO_2). a = different to HIITCYC during the same Bout; b = different to HIITCYC during Bout 1. (B) Heart rate (HR). a = different to HIITCYC during the same Bout; b = different to HIITCYC during Bout 1. (C) Mechanical power. a = different to HIITCYC during the same Bout; b = different to HIITCYC during Bout 1; c = different to HIIITCYC during Bout 2. Data are mean ± SD. Letters ('a', 'b', etc.) denote significant differences at $p \leq 0.05$.

6.4.5. Ratings of perceived exertion

For the mean RPE, there was a main effect for condition ($p < 0.001$, $F = 79.976$) and bout ($p = 0.001$, $F = 14.259$). There was no significant condition x bout interaction.

For the mean RPE for each bout (Fig. 6.4A), differences were found for Bout 1 ($p = 0.001$, $F = 20.477$), Bout 2 ($p < 0.001$, $F = 95.703$), Bout 3 ($p < 0.001$, $F = 70.304$) and Bout 4 ($p < 0.001$, $F = 85.105$) with RPE higher during HIITCYC, compared to HIITRUN. For the mean RPE within conditions, values increased over time in the HIITCYC ($p < 0.001$, $F = 44.704$) and HIITRUN ($p < 0.017$, $F = 6.251$) conditions when comparing Bout 1 to Bout 2, 3 and 4 during HIITCYC and Bout 1, 2 and 3 to Bout 4 during HIITRUN.

The RPE^{COND} score was higher for HIITCYC, compared to HIITRUN, ($p < 0.001$, $F = 37.027$) (Fig. 6.4B).

6.4.6. Physical activity enjoyment scale

The PACES score was found to be higher for HIITRUN when compared to HIITCYC; $t(11) = -2.460$, $p = 0.032$ (Fig 6.4C).

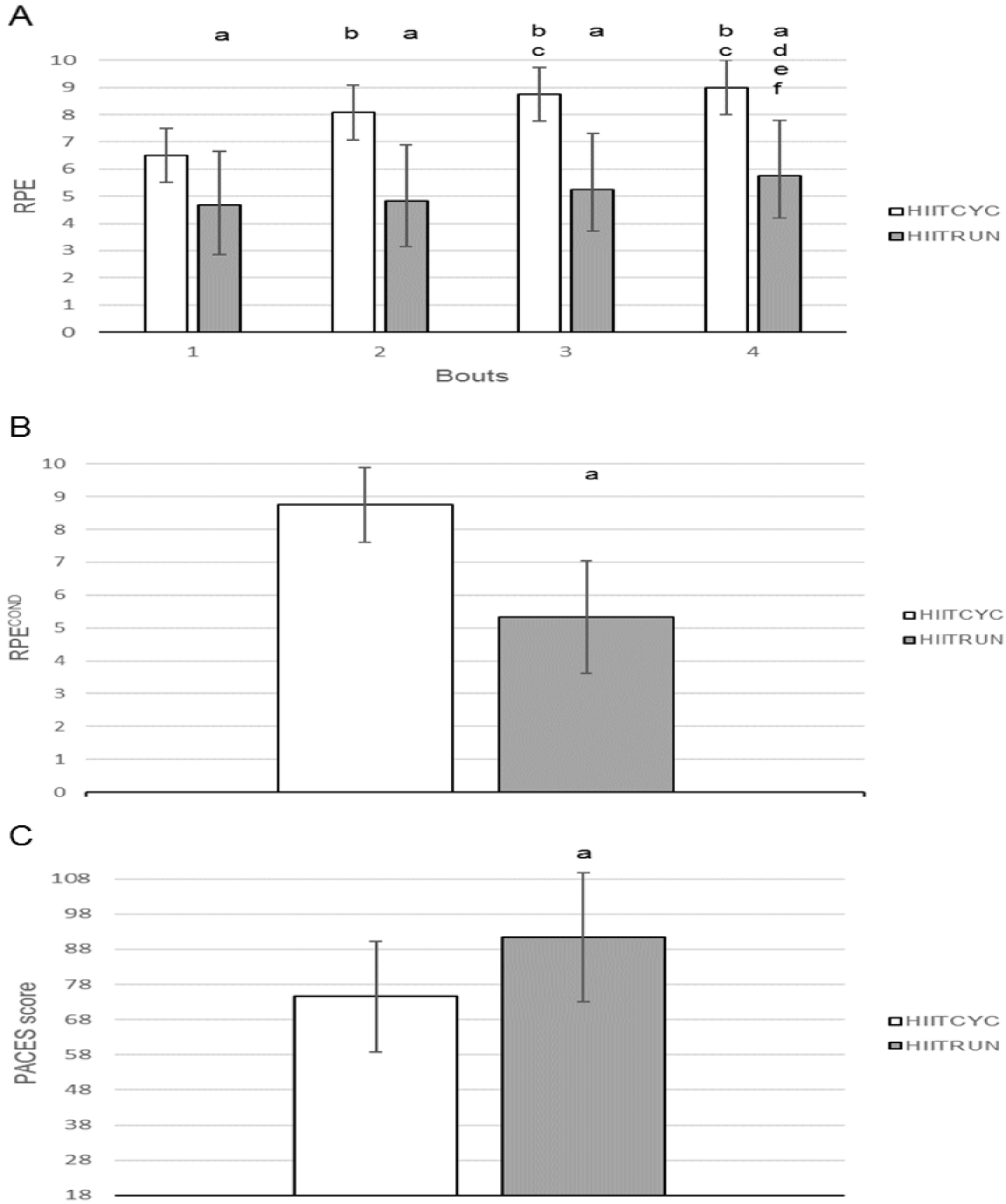

Figure 6.4. Ratings of perceived exertion, condition ratings of perceived exertion and Physical Activity Enjoyment Scale for cycling (HIITCYC) and running (HIITRUN) HIIT.

(A) Ratings of Perceived Exertion (RPE). a = different to HIITCYC during the same Bout; b = different to HIITCYC Bout 1; c = different to HIIITCYC Bout 2; d = different to HIITRUN Bout 1; e = different to HIITRUN Bout 2; f = different to HIITRUN Bout 3. (B) RPE^{COND}. a = different to HIITCYC. (C) Physical Activity Enjoyment Scale (PACES). a = different to HIITCYC. Data are mean ± SD. Letters ('a', 'b', etc.) denote significant differences at $p \leq 0.05$.

6.5. Discussion

The aim of this study was to compare the local (Δ[HHb]) and systemic (VO_2) oxygen utilisation, HR, RPE and enjoyment responses during time-efficient HIIT protocols that potentially represents the format of HIIT that sedentary individuals would perform utilising running and cycling ergometers in unsupervised recreational exercise settings.

In support of our hypotheses, RPE was lower and PACES was higher for the HIITRUN condition, compared to the HIITCYC condition. In contrast to our hypotheses, Δ[HHb] at the FH, LVL and RVL sites, VO_2, and HR were higher during HIITCYC, compared to HIITRUN. No significant differences were found in Δ[HHb] at the GN site when comparing HIITCYC and HIITRUN.

When exercise is performed incrementally to a definitive maximal endpoint, the influence of exercise mode on physiological variables is clearly delineated. When exercise is performed at matched submaximal intensities or intermittently (HIIT), the effect of mode is less clear, due to the potential masking effect of inherent exercise intensity differences between modes when an incremental maximal stimulus is not applied. For example, a protocol matched for intensity relative to VO_{2max} would result in different absolute workloads during running and cycling protocols, and therefore would not provide an equitable comparison of modes. This issue applies equally to other systemic physiological and perceptual measures such as HR and RPE, and potentially to local physiological measures such as Δ[HHb], due to differences in muscle activation patterns between modes [222]. These discrepancies indicate that the assumption that intensity is similar between exercise modes is debateable [116]. Therefore, whilst the effect of mode may, in part, be dependent on the intensity of the session, it is important to quantify the magnitude of this effect on physiological and perceptual variables during typical running versus cycling HIIT protocols, due to the potential prescription of HIIT in health-related exercise interventions.

6.5.1. Tissue oxygenation

A significantly higher Δ[HHb] at the LVL and RVL sites occurred during all bouts of HIITCYC, compared to HIITRUN. This is indicative of increased local oxygen utilisation in the large locomotor muscles during HIITCYC, which is consistent with a higher systemic oxygen utilisation, as indicated by higher VO_2 during HIITCYC. It is conceivable that in a population with no specificity of training in cycling, during high intensity exercise, a higher local oxygen utilisation (linked to metabolic demand) will exist during HIITCYC, compared to HIITRUN irrespective of previous findings of vastus lateralis muscle activity being greater or equal during running, compared to cycling [222, 240, 326]. Additionally, running consists of concentric and eccentric contractions, whilst cycling consists of concentric contractions only. Eccentric contractions have a lower metabolic cost than concentric contractions [222] and this may have contributed to the lower apparent local oxygen utilisation during HIITRUN.

In the smaller GN muscle of the leg, which generally has a greater percentage of oxidative muscle fibres [291, 292] and greater citrate synthase activity [292] than the vastus lateralis muscle, there were no significant differences in Δ[HHb] between conditions or bouts. In muscles comprised of oxidative fibres, an improved matching of oxygen supply and demand has been shown, when compared to muscles comprised of glycolytic fibres [179]. This indicates that during exercise, GN was able to meet the local increased energy requirements, creating little change in HHb values over time, irrespective of the mode specific differences in systemic and vastus lateralis oxygen utilisation. Additionally, whilst GN muscle activation is generally higher during cycling than running [326], running on an incline leads to a greater activation of the GN than during running on a level gradient [227]. Therefore, it is conceivable that the greater activation of GN during the incline running protocol of HIITRUN resulted in a similar level of oxygen utilisation in GN as the cycling protocol during HIITCYC, irrespective of the differences in exercise intensity.

A significantly higher Δ[HHb] occurred at the FH site during Bout 2, 3 and 4 of HIITCYC, when compared to HIITRUN. This may be indicative of increased oxygen utilisation in the pre-frontal cerebral cortex during HIITCYC which could be due to cerebral vasoconstriction, diminished cerebral blood flow and an increase in cerebral oxygen uptake due to the higher exercise intensity of the HIITCYC condition [181, 185].

When comparing Δ[HHB] within conditions, there was no overall progressive increase in muscle oxygen utilisation in GN, LVL and RVL from Bout 1 to Bout 4 irrespective of exercise mode. Exercise effort was submaximal (as indicated by VO_2, HR and RPE data) and if the 2 min passive recovery periods allowed adequate reoxygenation and recovery in the vasculature of the working muscles, the muscles would be able to meet the energy requirements of each bout with existing oxygen supply, creating little change in HHb values across bouts. The lack of significant change in Δ[HHb] at the locomotor muscle sites from Bout 1 to 4 indicates that the level of maximal oxygen utilisation achieved during the conditions was not increased by the addition of multiple exercise bouts, irrespective of the mode of exercise adopted. This suggests that a single bout may be sufficient to induce maximal levels of oxygen utilisation, and this has implications for identifying the smallest dose of HIIT needed to convey the health benefits attributed to this format of exercise.

When evaluating the FH ∆[HHb] from Bout 1 to Bout 4, HHb concentrations did not rise significantly in the HIITRUN condition. In the HIITCYC condition, ∆[HHb] rose from Bout 1 to Bout 2 and then did not change. These responses could both be due to the brain being capable of responding to homeostatic disturbances to provide adequate perfusion during the majority of exercise bouts, irrespective of exercise mode [290].

To our knowledge, this is the first research study to show that in sedentary participants, the ∆[HHb] levels attained during HIIT varies in multiple locomotor muscles of the lower limb and the cerebral cortex, due to the mode of exercise. This finding indicates the specificity of muscle oxygen utilisation in the sedentary population.

6.5.2. Systemic oxygen consumption

Higher peak VO_2 and HR values are frequently reported during incremental running exercise, compared to incremental cycling exercise, due to the increased metabolic cost of weight bearing ambulation [116, 315, 316, 327].

In contrast, in the current study the VO_2 and HR responses were not different at Bout 1 between HIITCYC and HIITRUN, indicating an increased intensity of exercise during HIITCYC, compared to HIITRUN. The significantly higher VO_2 during Bout 2 and Bout 3 of HIITCYC, compared to HIITRUN, further indicates an increased exercise intensity and integrated physiological demand during the non-weight bearing cycling condition, contributed to by an increased local oxygen utilisation, as evidenced by the higher Δ[HHb] discussed previously. These findings could be explained by the fact that workload during the cycling protocol of HIITCYC was able to be adjusted by the participants, allowing 'all out efforts'. This was not an option during the treadmill protocol of HIITRUN. Therefore, the relative intensity of HIITCYC was greater than HIITRUN. Lastly, in a sedentary population, it is assumed that at least a partial application of the specificity of training principle will exist for walking / running (due to everyday ambulation) whilst no such training effect would be present for cycling (no participants reported routine cycling activity when completing their physical activity log). This lack of adaptation, both centrally and peripherally, could have contributed to the increased intensity and physiological demand during HIITCYC.

When examining VO_2 changes within each condition, a potential explanation for no difference in VO_2 being found between Bout 2, 3 and 4 of HIITCYC could be the significant decrease in mechanical power output across bouts, effectively requiring less aerobic contribution over time, in effect counteracting the expected continued increase in VO_2 in later bouts due to the cumulative load of the protocol. Furthermore, whilst VO_{2max}, measured during maximal incremental treadmill exercise, was 43.5 ± 4.3 $ml.kg.min^{-1}$, it is conceivable that VO_2 values in excess of 31 $ml.kg.min^{-1}$ achieved by the sedentary individuals during HIITCYC were maximal for this mode and format of exercise, due to the recognised potential 5-25% reduction in VO_{2max} values elicited during cycling exercise compared to treadmill exercise [20], effectively creating an upper limit in each subsequent bout.

Exercise effort was submaximal during HIITRUN (as indicated by VO_2, HR and RPE data) and it is conceivable that the 2 min passive recovery periods allowed adequate recovery from this submaximal exercise. Therefore, VO_2 remained relatively stable over time.

The sedentary participants were potentially limited in their ability to achieve true maximal running speeds during the incremental treadmill test due to possible slower VO_2 kinetics, poor running efficiency, and lack of familiarity with running at rapidly increasing speeds at a 10% gradient. This is however an important observation: it appears that the (in)ability to run at speeds and gradients associated with maximal / supramaximal exercise may limit the exercise intensity able to be achieved by sedentary individuals during short duration treadmill running HIIT, when compared to short duration cycling HIIT. A potential future research direction may be to compare the beneficial effects of less time-efficient, but submaximal HIIT protocols performed on the treadmill at lower gradients, such as the 4 x 4 min protocol popular in clinical research [261], to Wingate cycling HIIT in sedentary participants.

6.5.3. Heart rate

The significantly higher mean HR during Bout 2, 3 and 4 of HIITCYC, compared to HIITRUN, are further indications of an increased exercise intensity and physiological demand during the cycling condition.

The relatively static heart rate response over time, when comparing Bout 2, 3 and 4 of HIITCYC, supports similar findings in which a passive recovery HIIT protocol was used [119]. In the HIITRUN condition, similar to VO_2 values, exercise effort was submaximal and the 2 min recovery periods allowed adequate recovery, it is conceivable that heart rates would also remain relatively stable over time.

6.5.4. Mechanical power

The most frequently used modes of HIIT are running and cycling, utilising ergometers [6, 33, 106]. During short duration supramaximal HIIT, there are differences in how running and cycling ergometers are utilised to induce the requisite physiological stress. Cycle ergometer HIIT, during which participants do not support their own body weight, safely lends itself to all out efforts, and this is typically achieved [33]. During treadmill ergometer HIIT, utilising motorised treadmills, the ability to safely produce short duration all-out efforts is limited. Typically, a prior indication of maximal running speed is required so that the speed (and gradient) of the HIIT session can be set, in order to produce a high intensity effort [130, 328]. Therefore, the mechanical power produced during HIITRUN and HIITCYC were not directly matched. However, when comparing mechanical power between conditions, no difference in mechanical power output occurred until Bout 4, when the mechanical power in HIITCYC was lower than in HIITRUN. This finding indicates that the approach adopted by the authors did reasonably match intensity between the two modes. The late reduction in mechanical power during HIITCYC, compared to HIITRUN, could be attributed to a greater cumulative fatigue due to the all-out format of the cycling bouts.

Power output (and exercise intensity) remained stable and submaximal for HIITRUN from Bout 1 to Bout 4. The submaximal intensity potentially enabled a more consistent effort during exercise, and enhanced recovery, during HIITRUN, hence potentially less cumulative fatigue developed. The higher relative intensity of the all-out cycling bouts during HIITCYC potentially lead to the significant decline in power output from Bout 1 to Bout 4 and the higher Δ[HHb], VO_2 and HR responses [104, 119, 123]. This is further evidence of cumulative fatigue during the cycling condition and was expected due to the incomplete ATP repletion and phosphocreatine resynthesis that occur during repeat Wingate exercise that do not allow time for complete recovery [104, 119, 123]. The differences in mechanical power output and relative intensity between HIITRUN and HIITCYC is an important finding, demonstrating that when utilising typical HIIT protocols available to sedentary individuals looking to initiate physical activity in recreational exercise settings utilising either running or cycling modes, cycling is likely to result in greater perturbations in physiological responses, compared to running.

However, this greater physiological stress may potentially compromise enjoyment of the exercise session, (discussed in the relevant section).

While the aim of this study was not to compare physiological and perceptual responses during matched intensity running and cycling HIIT, future research in which absolute workload of the HIIT session is matched would assist in determining to what extent the differences in responses observed in this study were the result of mode and / or intensity.

6.5.5. Ratings of perceived exertion

RPE was higher during the first bout of HIITCYC, compared to HIITRUN, despite no difference in markers of physiological intensity (VO_2 and HR) or mechanical power. This finding is consistent with previous research indicating that exercise performed at the same absolute intensity corresponds to a higher relative intensity in cycling [116]. RPE was also higher during Bouts 2 - 4 of HIITCYC, compared to HIITRUN. This finding is consistent with previous research which incorporated incremental [116] or steady state [320] exercise. RPE is a subjective indicator of intensity during exercise [20] and taken together with the higher Δ[HHb], VO_2 and HR response during Bouts 2 – 4 of HIITCYC provide further evidence of a higher physiological strain, a higher level of cumulative fatigue during HIITCYC and a potential lack of habitual adaptation to cycling.

RPE was found to increase over time in both conditions, but followed a different pattern in the two conditions. In HIITCYC the lack of difference between Bout 3 and 4, at an RPE value of 9, taken together with the reduced but similar mechanical power outputs during these bouts when compared to earlier bouts, provides yet further evidence of cumulative fatigue. The late rise in RPE during HIITRUN, with a final RPE value of 6, taking into account the constant speed and gradient in each of the HIITRUN bouts, was potentially due to the absolute duration of exercise against a 10% gradient providing the stimulus for an increased RPE score in the last bout.

Whilst RPE^{COND} was found to be higher for HIITCYC than HIITRUN, no differences in RPE^{COND} were found between HIITCYC and MAX, indicating that participants perceived HIITCYC to be of a similar level of exertion as a maximal incremental exercise test. This finding is interesting given that a comparison of the physiological data (VO_2 and HR) from the HIITCYC and MAX conditions does not support this perception of a similar exercise intensity and suggests that in a sedentary population both formats of high intensity exercise are perceived as 'maximal', perhaps due to the inherent discomfort associated with high intensity exercise.

6.5.6. Physical activity enjoyment scale

The examination of sedentary individuals' enjoyment during exercise has provided inconsistent results: Sedentary individuals are more likely to enjoy and be compliant with exercise that they perceive as moderate in intensity [108], however HIIT has also been shown to be enjoyable and elicit a degree of positive affect [68]. Exercise mode has been shown to have an acute effect on psychological mood state, including enjoyment, with running eliciting a more positive mood profile than weightlifting [243]. However, the effect of mode on sedentary individuals' enjoyment levels during HIIT is unknown.

A higher PACES score for HIITRUN, when compared to HIITCYC, indicates that participants enjoyed the HIITRUN session more. When taking into account the significantly lower RPE scores in HIITRUN when compared to HIITCYC, this finding is in agreement with research that has found that exercise that elicits a lower RPE score is more enjoyable [310].

Adverse reactions to HIIT exercise are rarely reported [5]. During the current study, seven participants reported either leg muscle discomfort / cramping (n = 3) or dizziness and nausea (n = 4) during the recovery period of the HIITCYC condition. Although all participants felt well upon leaving the laboratory (no more than 30 min post-exercise), these physiological responses could have contributed to the lower levels of enjoyment during HIITCYC.

6.6. Limitations

Nine design variables can be adjusted when designing HIIT protocols [2], leading to large variability in HIIT protocol composition within the literature. The 30 s bouts and 2 min recovery periods (a 1:4 work to recovery ratio) limits the generalisability and comparison of the research findings to the broader HIIT literature.

It is routine to wait ≈15 min to collect an 'overall RPE' after HIIT, due to the discomfort of the last bout potentially affecting the overall figure. However, adverse reactions experienced by 7 participants during this study were noted in previous studies and generally occurred during the latter half of the 6 min post-exercise recovery period. Collecting the RPE^{COND} score earlier in recovery, whilst potentially introducing an exercise related bias, avoided a potential bias due to adverse sensations experienced later in recovery.

The PACES data were collected retrospectively, following exercise. The PACES score was likely to be influenced by the participants' physiological and psychological state at that time. This study would perhaps have been improved by assessing enjoyment during exercise, however this was deemed impractical due to experimental design and physiological data collection methods.

It is acknowledged that sedentary participants can exhibit slower VO_2 kinetics, hence VO_{2max} values may have been underestimated by using stages of 30 s duration during the maximal incremental exercise test, compared to standard stages of 3 min duration. However, no difference in VO_{2max} has been shown with short versus traditional length protocols [322, 329]. Furthermore, a VO_{2max} of 43.5 ± 4.3 $ml.kg.min^{-1}$, classified as the 35^{th} percentile in terms of fitness [74, 330], is relatively high for sedentary participants, making underestimation of VO_{2max} unlikely given that the reported mean physical activity time of a moderate intensity for this group was 31 ± 33 $min.week^{-1}$.

6.7. Conclusions

It is concluded that, in sedentary individuals, free-paced cycling HIIT produces higher levels of physiological stress when compared to constant-paced running HIIT. A single bout of HIIT may be sufficient to induce maximal levels of muscle oxygen utilisation, irrespective of the mode of exercise. Participants perceived running HIIT to be more enjoyable than cycling HIIT. These findings have implications for selection of mode of HIIT for physical stress, exercise enjoyment and compliance.

6.8. Acknowledgements

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7. A session of HIIT, compared to a session of work-matched CMIE

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Statement of intellection contribution and relative role of the candidate, Mr Yuri Kriel, in the execution of the study and writing of the paper:

Conceived and designed the experiment: YK, CS

Performed the experiment: YK

Analysed the data: YK, CDA, CS

Wrote the first draft of the paper: YK

Edited the paper: YK, CDA, CS

Yuri Kriel

Christopher D. Askew

Colin Solomon

Full Title: **High intensity intermittent exercise versus moderate intensity continuous exercise: acute effects on local tissue oxygenation, blood pressure and enjoyment in 18 – 30 year old sedentary men**

Short Title: **High intensity intermittent versus moderate intensity continuous exercise**

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7.1. Abstract

Purpose

High intensity interval training (HIIT) can be as effective, or more effective, than continuous moderate intensity exercise (CMIE) at improving a primary risk factor for cardiometabolic disease, low cardiorespiratory fitness (CRF). There has been no direct comparison in sedentary individuals, of the acute effects of a session of HIIT to a work-matched session of CMIE on local oxygen utilisation, a primary stimulus for increasing CRF. Furthermore, blood pressure (BP) and enjoyment, which have implications for safety and adherence to exercise, have not been compared under these exact experimental conditions. It was hypothesised that in sedentary men, local oxygen utilisation and BP would be higher and enjoyment lower during a session of HIIT, when compared to a session of CMIE.

Methods

Eleven sedentary men (mean ± SD; age 23 ± 4 yr) completed three exercise sessions on a bicycle ergometer; 1) a maximal ramp-incremental exercise test (MAX), followed by two experimental sessions, 2) high intensity interval training (HIIT), 3) work-matched continuous moderate intensity exercise (MOD). Deoxygenated haemoglobin (ΔHHb) in the pre-frontal cortex (FH), gastrocnemius (GN), left vastus lateralis (LVL) and the right vastus lateralis (RVL) muscles, systemic oxygen utilisation (VO_2), systolic (SBP) and diastolic (DBP) blood pressure and physical activity enjoyment (PACES) were measured during the two experiment conditions.

Results

During HIIT, compared to MOD, mean ΔHHb in FH ($p = 0.016$) and GN ($p = 0.001$) was higher and PACES ($p = 0.032$) and DBP ($p = 0.043$) were lower.

Conclusions

In young sedentary individuals, a session of HIIT induced higher levels of oxygen utilisation, but lower levels of post-exercise diastolic blood pressure and enjoyment than a session of CMIE, for the same amount of work. These findings have implications for selection of exercise format and intensity in a sedentary population for physiological stress, safety, exercise enjoyment and adherence.

7.2. Introduction

Physical activity recommendations include accumulating 150 – 300 min of moderate intensity exercise each week [20]. A frequently cited reason for non-compliance with these recommendations, in the general population [21] and in young men [139] is insufficient time. High intensity interval training (HIIT) of a low volume has been proposed as a time-efficient exercise format to improve exercise initiation and adherence, thereby reducing the chronic disease burden associated with sedentary behaviour [31]. HIIT has been shown to be as effective [75] or more effective [37] than longer duration continuous moderate intensity exercise (CMIE) at improving specific cardiovascular disease risk factors, such as low cardiorespiratory fitness (CRF) [5, 6].

Increased CRF, as a result of HIIT and CMIE, has been attributed partly to increases in mitochondrial content and function [41, 42]. Whilst the exact mechanisms underlying the increases in mitochondria are unknown, it is possible that a larger increase in tissue oxygen utilisation during an acute session of HIIT, when compared to a session of CMIE [44], provides the stimulus for the enhanced mitochondrial and aerobic adaptations. Previous comparisons of locomotor muscle oxygenation have found no difference during HIIT and CMIE [44, 177]. However, these investigations utilised steady state or step transition exercise tests before and after a period of training and only assessed oxygen utilisation at a single site, in active individuals. There has been no direct comparison of local oxygen utilisation at multiple sites during sessions of HIIT and CMIE matched for work, in sedentary individuals. Given that HIIT is proposed as an exercise training format to engage sedentary, ‘time-poor’ individuals, there is a need to better understand the local oxygen utilisation responses to HIIT versus CMIE in this population.

Site specific oxygen utilisation at the local tissue level can be measured using near infrared spectroscopy (NIRS). NIRS is a non-invasive method for the measurement of the change in concentration of oxyhaemoglobin (ΔO_2Hb) (oxygen availability) and deoxyhaemoglobin (ΔHHb) (oxygen utilisation). Oxygen utilisation (ΔHHb) has been described during HIIT in active individuals at a single muscle site [318], in component muscles of the quadriceps [195, 281] in the pre-frontal cortex [175], and is increased when compared to pre-exercise values [104]. It is expected that, similar to systemic measures of oxygenation in sedentary individuals, during HIIT local oxygen utilisation will be higher than during CMIE. By investigating the oxygen utilisation responses in sedentary individuals at multiples sites, this project aims to define the extent of the disparity in oxygen utilisation between HIIT and CMIE, and thereby provide an insight into the role of tissue oxygen utilisation as a stimulus for training adaptation.

The safety of HIIT is debated [5, 49-52], partly due to the fact that high intensity exercise is associated with a transient increased risk of adverse cardiovascular events, especially in sedentary or infrequent exercisers [54]. The mechanism(s) by which high intensity exercise produce these events is unclear, but proposed triggering mechanisms include increased wall stress from increases in transmural blood pressure (BP) and blood flow, leading to atherosclerotic plaque disruption [55]. Furthermore, symptomatic post exercise hypotension (PEH) has been linked to high intensity exercise [56], sedentary status [58] and low cardiovascular fitness [218]. Young adults are heavily represented in the symptomatic PEH literature [60]. Therefore, it is plausible to expect hypertensive responses during HIIT, and hypotensive responses post-HIIT, in young sedentary individuals unaccustomed to this level of exertion. Conversely, while large fluctuations in BP may be expected during a session of HIIT, the intermittent format of HIIT may mitigate the overall haemodynamic response to the session. It is therefore necessary to compare BP responses between a session of HIIT and a session of CMIE to determine if HIIT elicits greater perturbations in exercise and post-exercise blood pressure.

While HIIT has the potential advantage of being a time efficient mode of exercise, its adoption may be limited by the extent to which it is enjoyed. The comparison of enjoyment during exercise of different intensities has yielded contradictory results in sedentary participants. Sedentary individuals are more likely to enjoy exercise that they perceive as moderate in intensity [108], however no difference in enjoyment levels has been found between a session of HIIT and a session of CMIE [66, 247, 248]. These previous comparisons have not controlled for the total work performed during the exercise sessions. Differing workloads across the sessions could influence the physiological demands and enjoyment of the exercise format, especially in untrained sedentary individuals, and therefore obscure findings. Comparing enjoyment levels between a session of HIIT and a session of work-matched CMIE will provide an insight into the acceptability and likely adherence to these different exercise formats. This information is necessary to determine if HIIT can effectively take the place of CMIE as a primary strategy for improving CRF and the prevention of chronic disease [6, 27, 32, 106] in a population with low intrinsic motivation to exercise [63, 139].

It was hypothesised that in young sedentary men, Δ[HHb] and exercise BP would be higher while enjoyment and post-exercise BP would be lower during a session of HIIT, compared to a work-matched session of CMIE.

7.3. Methods

7.3.1. Ethics statement

This research project was approved by the human research ethics committee of the University of the Sunshine Coast (S/13/472). All participants received a research project information sheet before providing written informed consent.

7.3.2. Experiment design

The project consisted of three testing sessions conducted on a bicycle ergometer: 1) a maximal ramp-incremental exercise test (MAX) followed by two experimental sessions, 2) a protocol of high intensity interval exercise (HIIT) and 3) a protocol of continuous moderate intensity exercise (MOD) matched for the mechanical work performed during HIIT. All testing sessions were separated by three to seven days to minimise the influence of any potential carry-over effects or confounding variables between testing sessions. The ∆HHb in the pre-frontal cortex (FH), gastrocnemius (GN), left vastus lateralis (LVL) and the right vastus lateralis (RVL) muscles, VO_2, heart rate (HR), BP, ratings of perceived exertion (RPE) and enjoyment via the Physical Activity Enjoyment Scale (PACES) were measured during the two experiment sessions. The format of the experimental conditions and the timing of measurements are illustrated in Figure 7.1.

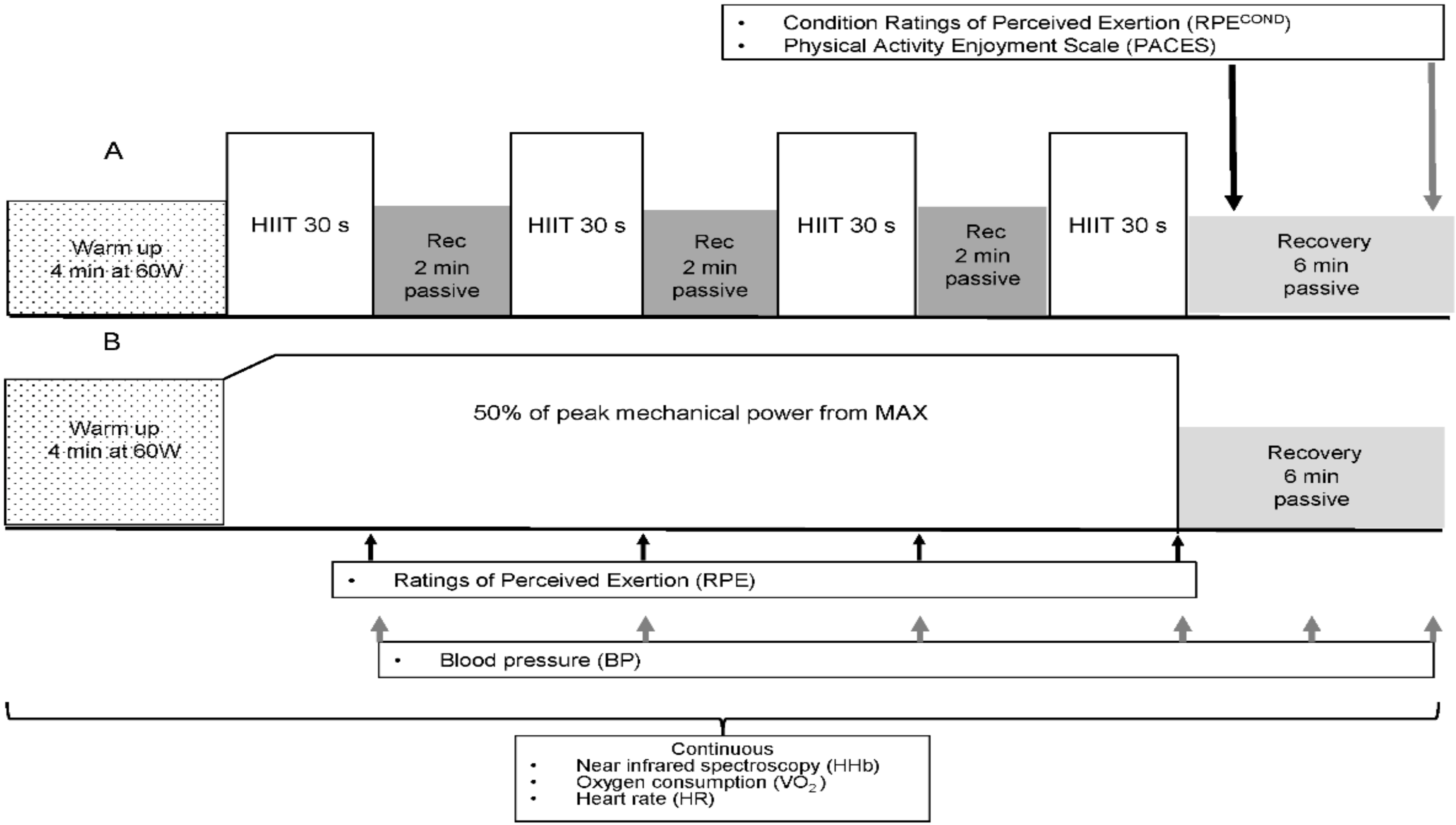

Figure 7.1. The format and timing of measurements of the two experimental conditions

(A) HIIT. (B) MOD.

7.3.3. Participants

The participant group consisted of eleven men who met the inclusion criteria of being aged 18 – 30 years.; currently completing less than 150 min of moderate intensity or 75 min of vigorous intensity activity per week; reporting no cardiovascular and metabolic disease; taking no medications; having no known orthopaedic or other health related issues that would be made worse by participation in, or inhibit completion of, the project. Descriptive physical characteristics of the participants are in Table 7.1.

Table 7.1. Participant characteristics

Height (cm)	179 ± 8.09
Weight (kg)	78.1 ± 7.10
Body Mass Index (kg/m^2)	24.3 ± 3.13
Age (yr)	23.1 ± 4.30
VO_{2peak} (ml.kg.min^{-1}) during MAX	40.7 ± 4.30
Peak heart rate (bpm) during MAX	182 ± 14.5
Peak mechanical power (W) during MAX	255 ± 30.2
Peak Systolic blood pressure (mmHg) during MAX	187 ± 20.9
Peak Diastolic blood pressure (mmHg) during MAX	79.6 ± 6.86
Peak RPE^{COND} during MAX	9 ± 1
Left vastus lateralis skinfold (mm)	10.4 ± 2.87
Right vastus lateralis skinfold (mm)	11.8 ± 2.75
Gastrocnemius skinfold (mm)	11.3 ± 2.90
FVC (L)	5.74 ± 0.86
FVC % pred (%)	108 ± 12
FEV_1 (L)	4.82 ± 0.78
FEV_1 % pred (%)	107 ± 11

(VO_{2peak} = Peak oxygen uptake; RPE^{COND} = Rating of perceived exertion for the condition; FVC = Forced vital capacity; FEV_1 = Forced expiratory volume in 1 s). Data are (mean ± SD) (n = 11).

7.3.4. Procedures and equipment

Screening procedures

At the initial session, participants completed risk screening questionnaires, a physical activity log and physical characteristics of height, mass, resting pulmonary function and adipose tissue thickness (ATT) were measured (Table 7.1), as previously described [301]. The physical activity log was used to ensure that participants' activity levels during the previous three months were within the definition of sedentary for the purposes of this project (an individual not achieving the current minimal recommendations for exercise participation to gain health benefits) [282]. Participants were asked to refrain from performing any exercise in the 24 hr preceding each session and to not ingest any caffeine, alcohol or a large meal in the four hours preceding each session [321]. It was confirmed at each testing session that participants were appropriately fed and hydrated, in line with existing pre-exercise nutrition / hydration guidelines [302-304].

Exercise conditions

Prior to the first exercise session, participants were familiarised with the testing protocols, the Velotron cycle ergometer (Racermate, Seattle WA, USA) and the process of maintaining a constant cadence. Each exercise session began with an initial 3-min baseline data collection period during which the participant remained stationary on the cycle ergometer. The baseline period was followed by a 4-min warm up period, which consisted of cycling against a fixed resistance of 60 Watts (W) at a cadence of 60 revolutions per minute. Participants were instructed to remain seated throughout each session to reduce movement artefact in the NIRS signal and to allow for consistency in muscular recruitment patterns and hence power data.

During MAX, the warm up was followed by a ramp-incremental protocol, during which the resistance was increased by 20 W every minute until volitional cessation. During HIIT, the warm up was followed by four 30 s bouts of high intensity exercise, with 2 min passive recovery periods separating each bout. Each participant was asked to increase cadence to a maximum during a 5 s period immediately preceding each high intensity bout. Power output during the Wingate style HIIT bouts was determined by participant effort against the resistance (0.075kg per kilogram body weight) applied to the flywheel of the ergometer. The HIIT format and timings were adapted from protocols used previously in active and untrained populations [62, 94-96, 104, 174, 284]. Participants were instructed to give a maximal effort from the beginning of each bout, using the prompt to ‘go as hard as you can’. Participants were verbally encouraged using standardised phrases during all bouts of exercise to promote a maximal effort. During the 2 min passive recovery periods between bouts, participants were instructed to sit as still as possible to reduce movement artefact in the NIRS data and to ensure that no mechanical work was performed.

During MOD, the warm up was followed by a session of CMIE. Resistance during MOD was fixed at 50% of the peak power output achieved during MAX. The MOD condition was matched to the mechanical work performed during the HIIT condition. Therefore, the length of the MOD session was specific to each participant (range 5:33 - 7:38 min). No significant differences in mechanical work were found between the experimental conditions (HIIT 47.09 ± 5 kJ, MOD 45.4 ± 5kJ). The slight differences in mechanical work between conditions were due to sedentary participants having difficulty holding constant power outputs and cadences during the MOD session. At the completion of all exercise sessions, there was a 6-min passive recovery period.

Tissue oxygenation

Changes in local tissue oxygenation were measured continuously during rest, exercise and recovery, as described previously [301]. Briefly, the changes in the relative concentration of O_2Hb ($\Delta[O_2Hb]$) and HHb (Δ[HHb]) were measured using a Near Infrared Spectroscopy (NIRS) system (3 x PortaMon and 1 x Portalite devices, Artinis Medical Systems BV, Zetten, Netherlands). The PortaMon devices were placed over the muscle belly of three locomotor muscles: the left vastus lateralis (LVL), the right vastus lateralis (RVL) and the left gastrocnemius (GN) and the Portalite optode was placed on the area of the forehead over the pre-frontal cerebral cortex (FH). Between test reliability of the HHb data from the NIRS system was examined prior to this project, providing acceptable absolute reliability values of the baseline data for each site (Typical Error: LVL = 0.4 μM, GN = 0.8 μM, FH = 0.6 μM) [301]. For all testing the same device was used at the same measurement site for all participants.

For this project only Δ[HHb] values are presented, as discussed previously [301]. Briefly, the Δ[HHb] data are potentially unaffected by changes in perfusion, blood volume or arterial haemoglobin concentration [166, 285, 286]. The $\Delta[O_2Hb]$ data are affected by muscular compression and changes in blood flow and volume [287] , especially during the rapid and substantial changes in these variables associated with HIIT bouts [48]. Gross movement artefact was present in NIRS data collected at the

LVL, RVL and GN sites during the passive recovery periods of the HIIT sessions. Therefore, the passive recovery period data were not included in further analysis. Similar technical difficulties in NIRS data collection, leading to data exclusion, have occurred in other research projects [324].

Systemic oxygen consumption (VO_2)

To quantify the systemic oxygen utilisation during all exercise sessions, systemic oxygen consumption data were collected continuously during the rest, exercise and recovery periods using a respiratory gas analysis open circuit spirometry system (Parvo Medics, Sandy, UT, USA) and a standard gas collection mouthpiece (Hans Rudolph, Kansas, United States of America). Standardised calibration and methods were used [288].

Heart rate

To quantify heart rate response during all exercise sessions a heart rate monitor (RS400, Polar Electro, Kempele, Finland) was used to measure heart rate continuously during rest, exercise and recovery periods.

Mechanical power

To quantify mechanical power continuously during all exercise sessions a crank-based power meter (SRM Science, Schoberer Rad Meßtechnik, Julich, Germany) was used. Prior to each testing session the power meter was calibrated according to the manufacturer's specifications.

Blood pressure

To quantify systolic (SBP) and diastolic (DBP) blood pressure responses during the three sessions, a manual blood pressure cuff, aneroid and stethoscope (Welch Allyn, New York, U.S.A.) were used. The measurements were taken at rest, immediately after each bout of high intensity exercise, at equivalent times during the MOD condition and every 2 min during the 6-min recovery period (Rec 2, Rec 4, and Rec 6).

Ratings of perceived exertion (RPE)

To determine perceived exertion, participants were provided with a standardised description of the CR10 RPE scale [305] and the purpose of the scale, including memory anchoring of the scale (an explanation of the sensations associated with the high and low scale categories) [306]. Participants were asked to provide an RPE score immediately after each bout of HIIT and at equivalent times during the MOD condition as well as give a 'Condition' RPE score (RPE^{COND}) 1 min after the final (fourth) bout. This RPE^{COND} score was used to compare the overall perception of exertion between the experimental conditions.

Physical activity enjoyment scale (PACES)

To determine enjoyment level in response to each condition, participants completed the Physical Activity Enjoyment Scale (PACES) questionnaire within 5 min of completing each condition. The PACES was used to compare enjoyment between the experimental conditions. The PACES consists of 18 items on a 7-point bipolar scale. A minimum total score of 18 and a maximal total score of 126 is possible, and a higher score indicates a higher level of enjoyment.

7.3.5. Data calculation

All NIRS data were collected at a frequency of 10 Hz and smoothed using a 10-point moving average before being averaged to 1 s periods. Due to the HHb data being a measure of change from an assigned baseline zero value, the NIRS data were expressed as units of change (µM) from the mean value of the 30 s of baseline data preceding the start of exercise (Δ[HHb]). The VO_2 data were averaged over 5 s periods and HR and power data were averaged at 1 s intervals initially. The NIRS, HR, VO_2 and power data were then time aligned and the time periods of data corresponding to the exercise periods of each condition identified. Mean values for each exercise period were then calculated for all dependant variables for each condition, providing a single value per condition for statistical analysis. The passive recovery periods during the HIIT session were not included in the calculation of mean values. The SBP, DBP, RPE and PACES data provided a single value per measurement time for statistical analysis.

7.3.6. Statistics

Statistical tests were performed using IBM SPSS Statistics (version 22, IBM Corporation, Armonk NY, USA) program. Data were initially tested for normality of distribution using the Shapiro-Wilk test. A two factor, repeated-measures analysis of variance (ANOVA) was used to analyse the effect of condition (HIIT versus MOD) and site (FH, GN, LVL and RVL) on the dependant variable Δ[HHb] and the effect of condition and time on RPE, SBP and DBP. If a significant main effect was identified, a Bonferroni's post hoc test was used to make pair wise comparisons. A paired samples T-test was used to analyse the effect of condition on VO_2, HR, mechanical power, RPE^{COND} and PACES scores. All data are presented as mean ± standard deviation (SD). For all statistical analyses, a P value of < 0.05 was used as the level of significance.

7.4. Results

7.4.1. Tissue oxygenation

For the mean Δ[HHb] for all sites and conditions, there was a main effect for site (p = 0.032, F = 3.387) and condition (p = 0.001, F = 24.135). For the mean Δ[HHb] for each condition, there was no main effect for site. For the FH and GN, mean Δ[HHb] was higher during HIIT compared to MOD (p = 0.016, F = 8.783) and (p = 0.001, F = 18.76), respectively (Fig 7.2A and 7.2B). For the LVL and RVL, no significant differences were found for the mean Δ[HHb] between conditions (Fig 7.2C and 7.2D).

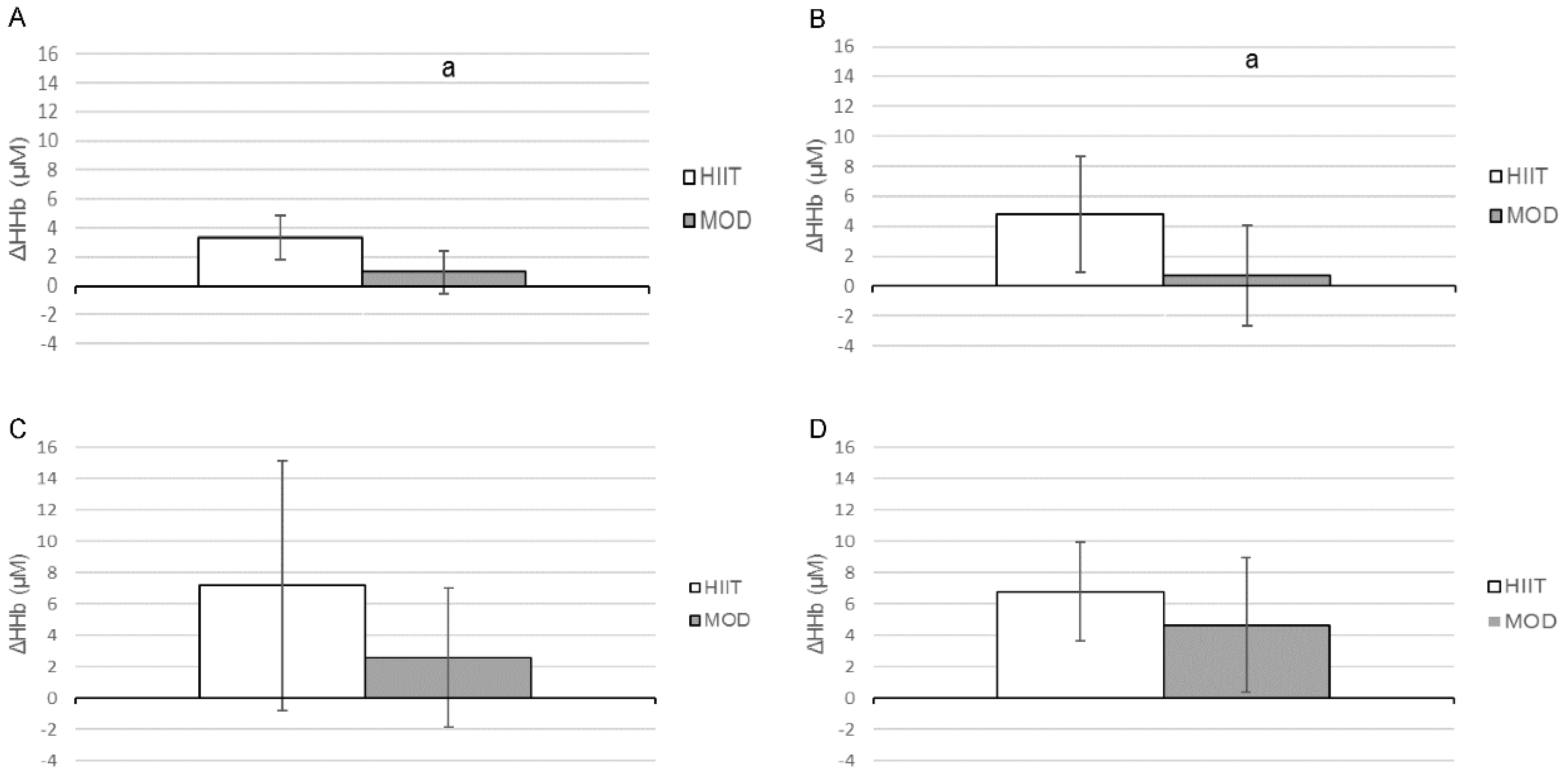

Figure 7.2. Change in deoxygenated haemoglobin (HHb) concentration during HIIT and MOD.

(A) Forehead (FH). (B) Gastrocnemius (GN). (C) Left vastus lateralis (LVL). (D) Right vastus lateralis (RVL). a = different to HIIT. Data are mean ± SD. Letter ‘a’ denotes significant differences at $p \leq 0.05$.

7.4.2. Systemic oxygen consumption, heart rate and mechanical power

The VO_2 and HR were higher; $t(9) = 11.243$, $p < 0.001$; $t(10) = 9.718$, $p < 0.001$, respectively during HIIT compared to MOD. (Fig 7.3A and 7.3B). Mean mechanical power was higher; $t(10) = 21.811$, $p < 0.001$ during HIIT (392 ± 48 W) compared to MOD (130 ± 15 W), as expected due to the study design (i.e. the inherent differences in exercise intensity between the two conditions).

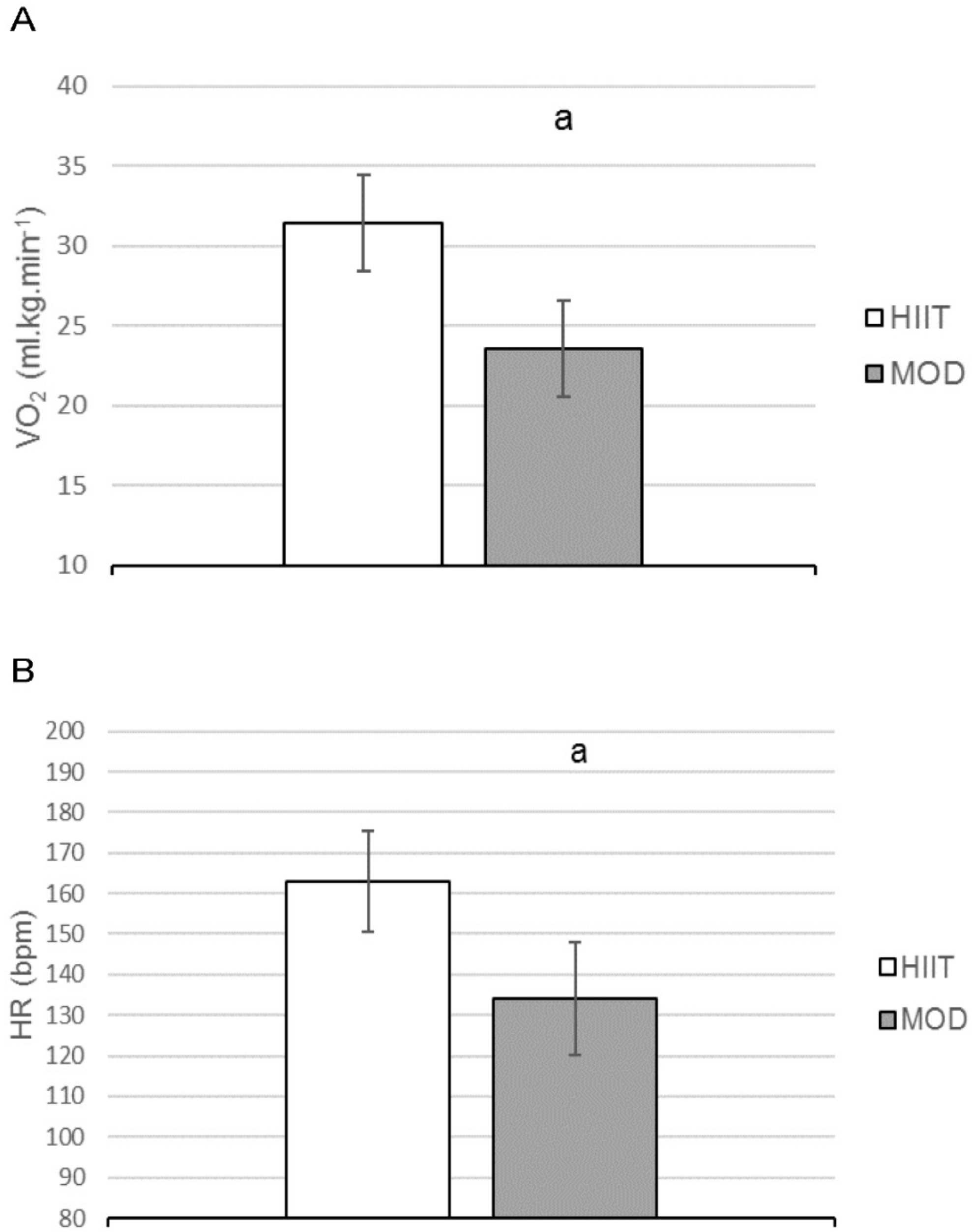

Figure 7.3. Oxygen consumption and heart rate during HIIT and MOD.

(A) Oxygen consumption (VO_2). (B) Heart rate (HR). a = different to HIIT. Data are mean ± SD. Letter 'a' denotes significant differences at $p \leq 0.05$.

7.4.3. Blood pressure

Systolic blood pressure

For the mean SBP, there was a main effect for time ($p < 0.001$, $F = 78, 564$). For the mean SBP within conditions (Fig. 7.4A), differences were found over time in HIIT ($p < 0.001$, $F = 47.6143$) and MOD ($p < 0.001$, $F = 68.055$), with SBP increasing significantly during exercise, when compared to resting levels, and returning to baseline during recovery. No significant differences were found between conditions.

Diastolic blood pressure

For the mean DBP, there was a main effect for condition ($p = 0.043$, $F = 7.231$) and time ($p < 0.001$, $F = 8.348$). There was a significant condition x time interaction ($p = 0.042$, $F = 2.386$).

For the mean DBP within conditions, differences were found over time in HIIT, between Rest and Time 3 ($p = 0.001$, $F = 4.098$). For the mean DBP for each measurement time (Fig. 7.4B), differences were found between conditions for Time 1 ($p = 0.042$, $F = 5.44$), Time 3 ($p =0.012$, $F = 9.302$), Rec 2 ($p = 0.038$, $F = 5.682$), Rec 4 ($p = 0.017$, $F = 8.091$) and Rec 6 ($p = 0.031$, $F = 6.328$).

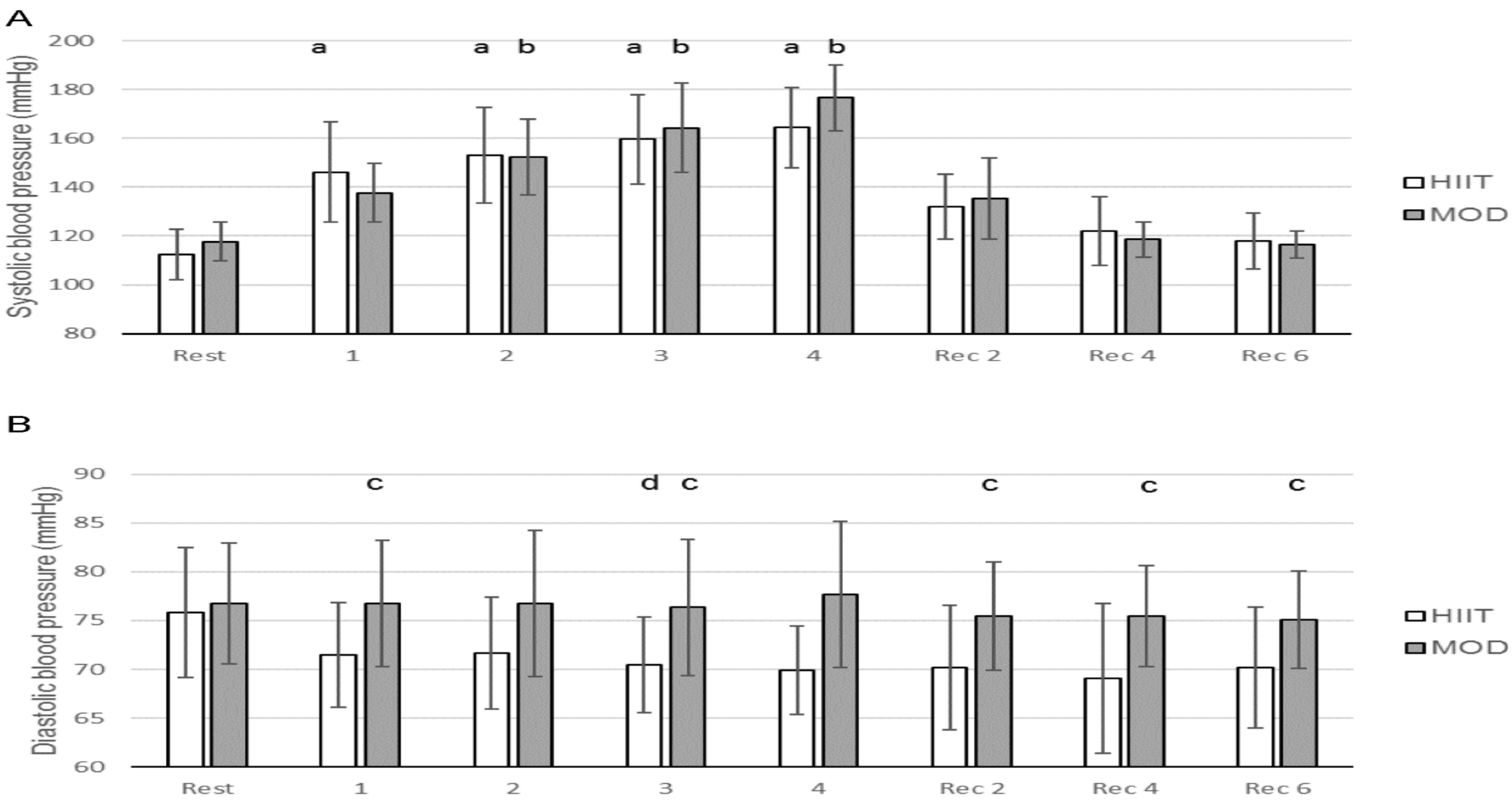

Figure 7.4. Blood pressure responses during HIIT and MOD.

(A) Systolic blood pressure (SBP). a = different to HIIT Rest; b = different to MOD Rest. (B) Diastolic blood pressure (DBP). c = different to HIIT at same Time; d = different to HIIT Rest. Data are mean ± SD. Letters (‘a’, ‘b’, etc.) denote significant differences at $p \leq 0.05$.

7.4.4. Ratings of perceived exertion

For the mean RPE, there was a main effect for condition ($p < 0.007$, $F = 26.94$) and time ($p = 0.022$, $F = 9.502$). There was no significant condition x bout interaction.

For the mean RPE within conditions, differences were found in HIIT ($p < 0.001$, $F = 24.402$) and MOD ($p < 0.017$, $F = 16$) with values increasing over time. For the mean RPE for each measurement time, differences were found between conditions for Time 1 ($p = 0.001$, $F = 19.322$), Time 2 ($p < 0.001$, $F= 30.613$), Time 3 ($p < 0.001$, $F = 92.401$) and Time 4 ($p = 0.001$, $F = 63.391$) (Fig. 7.5A). RPE^{COND} was found to be higher during HIIT, compared to MOD; $t(10) = 11.726$, $p < 0.001$ (Fig. 7.55B).

7.4.5. Physical activity enjoyment scale

The PACES score was higher for MOD compared to HIIT; $t(10) = -2.482$, $p = 0.032$ (Fig 7.5C).

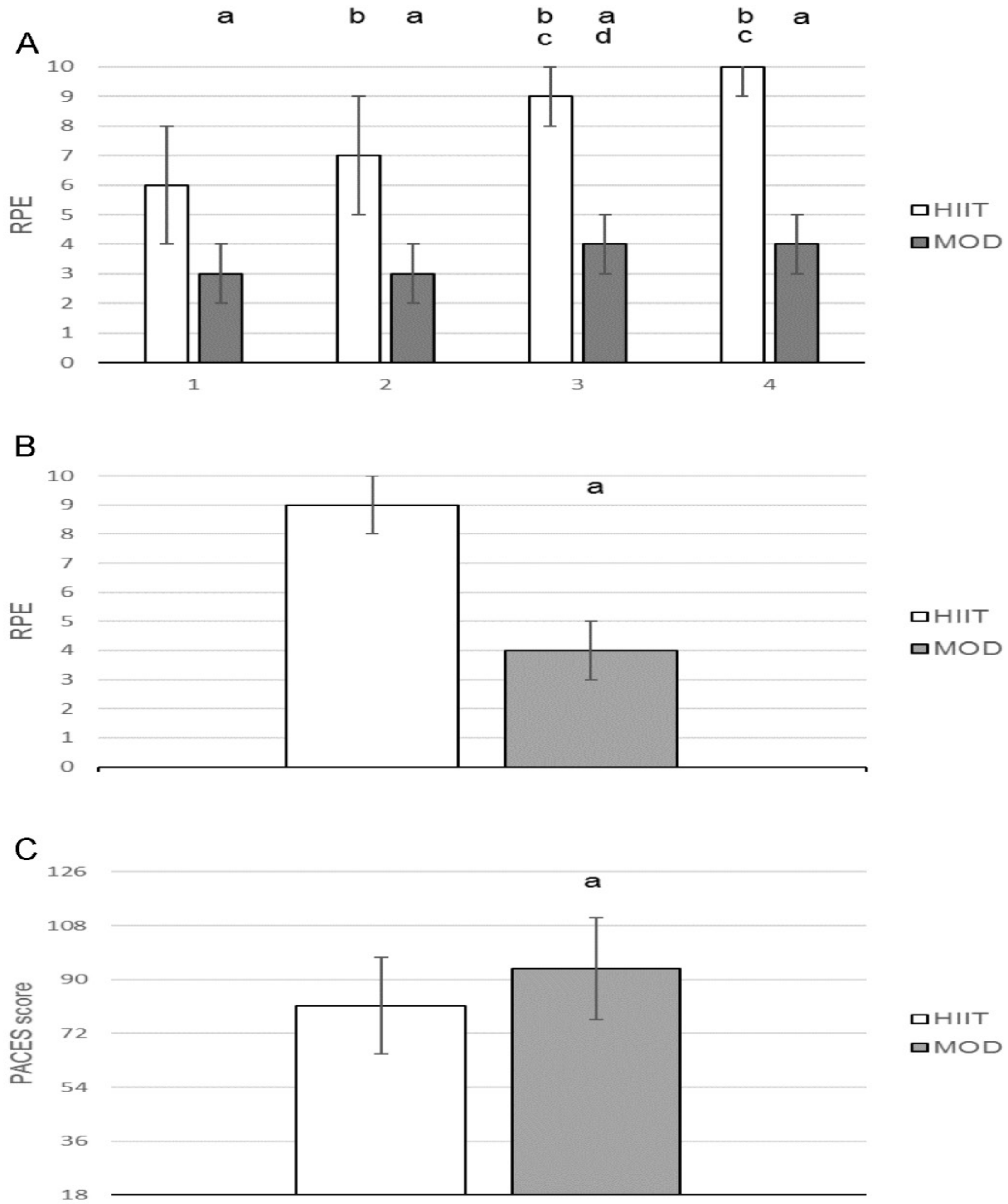

Figure 7.5. Ratings of Perceived Exertion, Condition Ratings of Perceived Exertion and Physical Activity Enjoyment Scale for HIIT and MOD.

(A) Ratings of perceived exertion (RPE). a = different to HIIIT during same time; b = different to HIIT Time 1; c = different to HIIT Time 2; d = different to MOD Time 1. (B) Condition Ratings of Perceived Exertion (RPE^{COND}). a = different to HIIT. (C) Physical Activity Enjoyment Scale (PACES). a = different to HIIT. Data are mean ± SD. Letters (‘a’, ‘b’, etc.) denote significant differences at $p \leq 0.05$.

7.5. Discussion

The aim of this project was to compare the local oxygen utilisation (Δ[HHb]), BP responses and exercise enjoyment (PACES) between a session of HIIT and a work-matched session of CMIE, in young sedentary men.

In support of our hypotheses, a higher Δ[HHb] at the FH and GN sites and a lower PACES score was found during HIIT, and a lower DBP was found post-exercise, compared to MOD. In contrast to our hypotheses, no significant differences were found in Δ[HHb] at the LVL and RVL sites and in SBP when comparing HIIT to MOD.

7.5.1. Tissue oxygenation

This project was novel in that Δ[HHb] was measured simultaneously in three skeletal muscle sites and the pre-frontal cortex in sedentary men during a session of HIIT and a work-matched session of CMIE.

The finding of no difference between conditions in Δ[HHb] at the LVL and RVL sites was contrary to the hypothesis of an increased oxygen utilisation during HIIT in these large locomotor muscles, when compared to MOD. This finding is inconsistent with the significantly higher systemic oxygen utilisation (indicated by the higher VO_2 and HR during HIIT when compared to MOD). However, at higher exercise intensities, increases in oxygen supply (due to increased demand) are not wholly distributed to larger locomotor muscles such as the VL. The distribution of the increased systemic oxygen supply to areas other than the locomotor muscles is proposed, due to factors including the mechanical constraints of heavy contractions in the locomotor muscles during HIIT and the need for the respiratory muscles to meet the increased work of breathing [331, 332], potentially limiting the increase in oxygen supply to the LVL and RVL. Therefore, a higher VO_2 and HR would not necessarily indicate an increased local oxygen utilisation at the site(s) of measurement. Another potential contributing factor for this finding is the intermittent format of HIIT and the typical Δ[HHb] response patterns at these large locomotor muscles: During 30 s bouts of HIIT, Δ[HHb] increases from baseline. During the recovery periods of HIIT, Δ[HHb] levels routinely decrease (recover) to baseline values [301]. During CMIE, Δ[HHb] typically increases continuously or increases and then plateaus until exercise cessation [177] at a lower absolute level than those achieved during HIIT. The responses during the HIIT and MOD sessions of this project conform to this pattern. These transient responses also confirm there was no evidence of a ceiling effect, as the maximal Δ[HHb] values achieved during MOD were less than the maximal Δ[HHb] values achieved during HIIT. Therefore, it is possible that, due to the different patterns of increase, similar mean responses were found between HIIT and MOD. The finding of no difference between HIIT and MOD is relevant when examining the physiological effect of the sessions in their entirety, as it indicates that in these large locomotor muscles, the oxygen utilisation during a session of HIIT is similar to that achieved during a work-matched session of CMIE. Finally, the large degree of inter individual variability in the Δ[HHb] response, indicated by the large standard deviation (Fig. 7.2C and 7.2D) could have contributed to a misrepresentative non-significant statistical difference between HIIT and MOD at the LVL and RVL sites. Variable individual responses in HHb have been documented previously in research utilising NIRS [179]. However, statistically significant differences were found at the FH and GN sites during this project and in two previous studies to publish individual results with a similar sample size and / or a similar degree of variability in the Δ[HHb] response to the current research project [167, 301].

In the smaller GN muscle, the increased oxygen utilisation during HIIT, when compared to MOD, was unexpected due to no difference in oxygen utilisation between the two experimental conditions at the VL sites. However, when considered in isolation, increased oxygen utilisation at the GN site during HIIT, when compared to MOD, is consistent with the increased power output, muscle fibre recruitment, and oxygen demand during high intensity exercise [233]. No previous studies have published Δ[HHb] data from the GN when comparing HIIT to CMIE. The GN muscle usually has a lesser role in power production during cycling than the larger VL muscles [222]. However, in a sedentary cohort with no cycling specific training adaptation (no routine cycling activity was reported), it is possible that the smaller GN was recruited to a greater extent than in trained participants [333], played an increased contributory role in power production during HIIT and therefore exhibited an increased local oxygen utilisation when compared to MOD. Additionally, the GN muscle has a greater percentage of oxidative muscle fibres [291, 292] and greater citrate synthase activity than the VL muscles [292]. It would be expected that, under conditions demanding increased mechanical force production such as HIIT, that a smaller muscle (GN) with a greater oxygen dependant muscle composition would have an increased oxygen utilisation response than larger muscles (LVL and RVL) with a greater glycolytic capacity [265].

The increased oxygen utilisation in the pre-frontal cerebral cortex during HIIT, when compared to MOD is consistent with previous findings [324]. The higher Δ[HHb] in this area of the brain could be due to cerebral vasoconstriction, diminished cerebral blood flow and an increase in cerebral oxygen uptake due to the higher exercise intensity of the HIIT condition [181, 185] and could potentially have contributed to the higher perception of exertion expressed by participants during HIIT [45, 175].

7.5.2. Systemic oxygen consumption, heart rate and mechanical power

The significantly higher VO_2, HR and mechanical power during HIIT, when compared to MOD, indicates an increased exercise intensity and integrated physiological demand during HIIT. Additionally, these findings supports previous research [248] and were expected due to the study design [177]. The constant power output during MOD, fixed at 50% of the peak power output achieved during MAX, produced physiological (VO_2 and HR) and perceptual (RPE) responses consistent with moderate intensity exercise [20].

7.5.3. Blood pressure

Systolic blood pressure

Resting SBP was within normal ranges and no differences were found between conditions for resting SBP. As expected, SBP increased over the course of the exercise conditions and then decreased to near resting levels during the 6 min recovery period [20]. During HIIT, the mean SBP did not reach established exercise testing termination criteria (SBP > 250 mmHg) in any individual [20]. Therefore, the SBP response to this supramaximal format of exercise was appropriate and consistent with previous high intensity interval exercise research in young participants [80]. A higher SBP response was expected during HIIT, when compared to MOD, due to the higher exercise intensity. However, no significant differences were found for SBP between HIIT and MOD. The finding of no difference was likely due to the intermittent format of HIIT allowing a reduction in BP during the recovery periods, thereby mitigating the overall rise in cardiac output and SBP during HIIT while the longer continuous period of exercise during MOD potentially allowed for a more complete rise in cardiac output and SBP.

Diastolic blood pressure

Resting DBP was within normal ranges and no differences were found between conditions for resting DBP. The accepted DBP response to continuous exercise is a slight decrease or no change from rest [20] and our findings during HIIT and MOD support this response with no substantial decreases in DBP occurring. The lower DBP noted during the exercise portion of HIIT, when compared to MOD, could be attributed to the absence of the secondary muscle pump during the passive recovery portions of HIIT, potentially combined with the dilation of the peripheral vasculature in skeletal muscle [311]. Consistent with previous research [334], no significant decrease in DBP occurred during the 6-min passive recovery period in both conditions, when compared to resting DBP. However, during the 6-min passive recovery period, a significantly lower DBP was observed during HIIT when compared to MOD at Rec 2, Rec 4 and Rec 6. This could possibly be due to peripheral vasodilation (and hence decrease in total peripheral resistance) [311] [312] and / or post-exercise peripheral hyperaemia in response to the high intensity exercise condition [313].

Some participants reported adverse sensations of dizziness and / or nausea (n = 7) during the recovery period of HIIT. Symptoms were reported in the absence of statistically significant decreases in DBP during recovery, when compared to resting levels. This would suggest that the mechanism(s) causing these symptoms remains to be elucidated. However, this assumption is made with caution, as a lack of a statistically significant decrease in group mean BP does not necessarily equate to no clinically significant effect on an individual basis, especially as the specific reduction in BP which triggers symptomatic post exercise hypotension (PEH) and its sequalae after high intensity exercise is unclear and probably highly individual [59]. It is of interest to note that the mean reduction in DBP (resting DBP compared to lowest post-exercise DBP), whilst variable in both groups, was larger in the symptomatic individuals (mean = 11 mmHg) than in the asymptomatic individuals (mean = 7 mmHg). This finding leads authors to suggest the investigation of the effect of HIIT versus CMIE on post-exercise BP in participants with previous documentation of symptomatic PEH, as a future research direction.

7.5.4. Ratings of perceived exertion

RPE was higher at all measurement points during HIIT when compared to MOD, consistent with previous research [248] and in keeping with the higher VO_2 and HR response during HIIT, which indicate a higher physiological strain.

RPE was found to increase over time in both conditions. In a sedentary population, fatigue would be expected to be, in part, a function of the exercise completed and therefore cumulative, even during the MOD condition [244].

The RPE^{COND} was found to be higher for HIIT than MOD, as expected, and no differences in RPE^{COND} were found between HIIT and MAX, indicating that participants perceived HIIT to be of a similar level of exertion as a maximal incremental exercise test. This suggests, in sedentary individuals, that high intensity exercise (and the associated physical and psychological discomfort that accompanies such exercise) influences RPE independent of the structure of the exercise session.

7.5.5. Physical activity enjoyment scale

The physical activity enjoyment scale (PACES) is a reliable and valid measure of enjoyment during HIIT and CMIE [244, 247, 325]. However, contradictory findings have been reported: Active individuals report HIIT to be more enjoyable than CMIE [36, 244], but no significant differences in enjoyment have been found between high and moderate intensity exercise [247, 248, 335] and sedentary individuals are more likely to enjoy exercise that they perceive as moderate in intensity [108]. The lack of control for mechanical work and differences in protocol design and participant fitness during previous research could explain the contradictory findings.

Our results are in agreement with the finding of a higher level of enjoyment during moderate intensity exercise in sedentary individuals, compared to HIIT. When taking into account the significantly lower RPE scores during MOD, compared to HIIT, our findings are also in agreement with research stating that exercise associated with a lower RPE score is more enjoyable [310].

Adverse reactions to HIIT exercise are rarely reported [5]. During the current project, participants reported adverse sensations of either leg muscle discomfort / cramping (n = 3) or dizziness and nausea (n = 7) during the recovery period of HIIT. Although all participants felt well upon leaving the laboratory (no more than 30 min post-exercise), these adverse sensations could have contributed to the relatively low levels of enjoyment during HIIT.

7.6. Limitations

The physiological and perceptual responses during this project could have been influenced by the continuous versus intermittent nature of the MOD and HIIT conditions respectively, obscuring the analysis of the variable: exercise intensity. It has been suggested that the intermittent format may be responsible for some of the positive physiological and perceptual responses found during HIIT and that intermittent moderate intensity exercise may provide similar positive responses without the compliance and safety issues of HIIT [336]. Therefore, the comparison of high and moderate intensity intermittent exercise formats, matched for mechanical work, is suggested as a future research direction.

While BP measurements were taken within 10 s of the end of each 30 s bout of the HIIT condition, BP measurements were taken during exercise at the corresponding time point of the continuous MOD condition. The 10 s delay in measurement during the HIIT condition could have underestimated the true maximal SBP and DBP levels during the 30 s HIIT bouts due to a potential fall in BP during the passive recovery portions of testing. This limitation leads authors to suggest monitoring of continuous BP during HIIT and CMIE interventions as a future research direction.

7.7. Conclusions

It is concluded that, in young sedentary individuals a session of HIIT consisting of four 30 s bouts induced higher average levels of oxygen utilisation during exercise, but lower levels of enjoyment than a work-matched session of CMIE.

Furthermore, in an apparently healthy sedentary cohort there was no evidence of an excessive hypertensive response during HIIT. However, DBP was lower during the post-exercise period of HIIT, compared to MOD. The lower DBP during HIIT coincided with pre-syncopal symptoms in some participants.

Therefore, these findings have implications for selection of exercise format and intensity for a sedentary population for physiological stress, safety, exercise enjoyment and adherence. Whilst HIIT induced higher levels of physiological stress, compared to MOD, the pre-syncopal symptoms and lower levels of enjoyment associated with HIIT sessions could preclude general use of this exercise format in young sedentary men.

7.8. Acknowledgements

The authors would like to thank the participants of this research project, without whom this project would not have been possible. Thank you to Dr Hugo Kerhervé for his technical assistance.

8. General discussion and conclusions

8.1. Discussion

This thesis reported five specific novel findings for HIIT in sedentary individuals:

- A HIIT session including passive recovery periods resulted in a lower level of local tissue oxygen utilisation and diastolic blood pressure, but no difference in exercise enjoyment, compared to a HIIT session including active recovery periods.
- A running HIIT session resulted in a lower level of local tissue oxygen utilisation and exercise enjoyment, compared to a cycling HIIT session.
- No progressive increases in oxygen utilisation occurred at locomotor muscle sites during successive bouts of HIIT, irrespective of recovery format or mode.
- Local tissue oxygen utilisation levels differed at locomotor muscle and cerebral sites during HIIT sessions of varying recovery format and mode, and a session of CMIE.
- A session of HIIT resulted in a higher level of local tissue oxygen utilisation and a lower level of diastolic blood pressure and exercise enjoyment, compared to a session of work-matched CMIE.

8.1.1. Tissue oxygenation

Local muscle oxygen utilisation differed due to HIIT recovery format, mode and exercise session intensity (indicated by the greater Δ[HHb] at the VL site during the HIITACT protocol of Study 1, the greater Δ[HHb] at the LVL and RVL sites during the HIITCYC protocol of Study 2 and the greater Δ[HHb] at the GN site during the HIIT protocol of Study 3). The acute stimulus of increased local muscle oxygen utilisation, along with acute increases in systemic variables such as VO_2 and HR during the HIIT protocols, would possibly result in increased mitochondrial function [42, 43, 337] and an increased ability to utilise energy from aerobic pathways after HIIT training [42], which would lead to the improvements in CRF evidenced in the literature [6, 33, 37, 38]. The three studies together provide the novel finding that cycling HIIT including active recovery periods resulted in higher levels of local muscle and systemic oxygen utilisation than cycling HIIT including passive recovery periods, running HIIT including passive recovery periods or cycling CMIE, in sedentary participants. Therefore, if the primary objective of a HIIT protocol is to stimulate the highest local muscle oxygen utilisation response, thereby providing an acute primary stimulus for longer term increases in systemic oxygen utilisation / CRF in sedentary participants, it would be reasonable to suggest cycling HIIT including active recovery periods as the preferred exercise mode and format. The combination of cycling mode and active recovery recommended above indicates a potential key interaction between design variables, examined in isolation during this thesis. Therefore, the cumulative effect of the design variables of recovery format and mode, in the same participants, requires further investigation.

Pre-frontal cerebral cortex Δ[HHb] increased during all HIIT and CMIE exercise sessions, compared to pre-exercise values, and this is consistent with cerebral Δ[HHb] responses described previously [185]. Increases in pre-frontal cortex oxygen utilisation were associated with increased exercise intensity and were higher during protocols which elicited higher levels of variables associated with systemic oxygenation, including VO_2 and HR (HIITCYC, compared to HIITRUN during Study 2 and HIIT, compared to MOD during Study 3), possibly due to cerebral vasoconstriction, diminished cerebral blood flow and an increase in cerebral oxygen uptake during higher intensity exercise [181, 185]. Evidence of the proposed association between pre-frontal cerebral cortex oxygen utilisation response, systemic oxygen utilisation response and exercise intensity is further indicated by there being no differences in pre-frontal cerebral cortex Δ[HHb], VO_2 and HR between HIITPASS and HIITACT during Study 1. Furthermore, exercise intensity affects perception of effort, with an increasing intensity associated with an increasing perception of effort [305]. It therefore possibly follows that if increases in exercise intensity are associated with increases in pre-frontal cortex Δ[HHb], increased pre-frontal cortex oxygen utilisation is potentially a variable contributing to increased perception of effort [45]. Results of the experiments conducted for this thesis support this proposal, with higher RPE scores coinciding with increases in pre-frontal cortex Δ[HHb] in HIITCYC, compared to HIITRUN during Study 2 and HIIT compared to MOD during Study 3 and no difference in RPE scores and pre-frontal cerebral cortex Δ[HHb] values found between HIITPASS and HIITACT during Study 1.

In an effort to maximise the time efficiency and health impact of HIIT, attempts have been made to define the lowest ‘dose’ of HIIT an individual must perform (and therefore the lowest time commitment) while still achieving health benefits [7, 92]. No progressive increase in local oxygen utilisation was noted at any muscle site during the four bouts of the HIITPASS, HIITACT, HIITCYC and HIITRUN protocols of Study 1 and 2. The lack of increase indicates that a single bout of HIIT is sufficient to achieve maximal levels of oxygen utilisation, irrespective of the recovery format or mode of exercise and thereby supports previous findings that a single bout of HIIT provides the necessary stimulus for beneficial physiological change [262]. However, it is acknowledged that the magnitude of the muscle oxygen utilisation response is potentially not the only factor to stimulate beneficial physiological change and that the duration / volume of time spent at a maximal level of oxygen utilisation may also be an important stimulus [76] and requires further investigation.

The majority of exercise studies utilising NIRS to investigate local tissue oxygenation include active populations [166, 168, 190, 268-271] and routinely take measurements from single muscle or brain sites [166, 168, 268, 271]. To my knowledge, this is the first research to show that in sedentary participants, the Δ[HHb] levels attained during HIIT sessions including passive and active recovery periods, HIIT performed running and cycling and a session of work-matched CMIE varies in different locomotor muscles and a cerebral site, indicating the specificity of oxygen utilisation to the site of measurement.

When interpreting the Δ[HHb] data, it must be acknowledged that NIRS responses may be affected by various factors, including blood flow and muscle tension [165]. Blood flow and muscle tension are not routinely measured concomitant with Δ[HHb] data [165] Therefore, in an effort to standardise NIRS responses, the majority of exercise studies using NIRS have used the kinetic / dynamic responses of muscle oxygenation [168, 179, 281]. Typically, the NIRS responses are therefore normalised relative to the total amplitude of the response (peak values of the response = 100% or to the amplitude of the NIRS signal during a complete arterial occlusion = 100%). However, the amplitude of the 'non-normalised' NIRS responses might include important information into the relationship between local muscle oxygen utilisation and functional indices such as systemic oxygen utilisation (VO_2) and mechanical power output [179]. A recent study examining the amplitude of HHb in active participants with heterogeneous VO_{2peak} results showed that HHb amplitudes were positively correlated to VO_{2peak} [170]. It is suggested that this association may be especially evident during acute sessions of HIIT of varying format or in response to habitual HIIT exposure in sedentary or clinical populations (in which these relationships may be underdeveloped or detrimentally affected by pathology). By displaying the HHb data without normalisation in the current experiments, preliminary comparisons based on amplitude of the HHb response were made. However, due to the rapidly changing magnitude of response over 30 s of HIIT, the author felt that using the mean response for the duration of each bout provided a better indication of the overall bout response / change than the maximal amplitude.

8.1.2. Blood pressure

Systolic blood pressure (SBP) responses during HIIT sessions including active and passive recovery periods and a session of work-matched CMIE indicated that, irrespective of the recovery format or intensity of exercise, no excessive hypertensive responses occurred in healthy, young sedentary men. Furthermore, no differences in SBP were noted between conditions during Study 1 and Study 3, demonstrating that SBP responses during HIIT sessions are relatively insensitive to recovery format or exercise intensity, possibly due to the similar levels of cardiovascular strain achieved during HIITPASS and HIITACT of Study 1 and the intermittent format of HIIT mitigating the rise in SBP during Study 3, respectively.

Diastolic blood pressure (DBP) was lowest following cycling HIIT protocols which included passive recovery periods, possibly due to widespread peripheral vasodilation and the cessation of secondary muscle pump contributions to venous return [311]. During the 6-min passive post-exercise recovery period, 18 participants (Study 1 = 6, Study 2 = 4 and Study 3 = 7) of 35 participants across all studies reported adverse sensations of nausea and dizziness post-HIIT. In all studies, the mean decrease in DBP post-HIIT was greater in the symptomatic individuals, compared to the asymptomatic individuals. These findings support previous research which indicates that symptomatic PEH is linked to high intensity exercise [56], sedentary status [58], post-exercise situations in which the secondary muscle pump is not active [59] and that young adults are susceptible [60]. Therefore, it is reasonable based upon the findings detailed in this thesis to urge caution when prescribing HIIT protocols including passive recovery periods between HIIT bouts and passive post-exercise recovery periods and to recommend close monitoring of post-HIIT BP and associated signs and symptoms. An active recovery post-exercise or other simple physical movements such as squatting have been found to be beneficial in preventing symptomatic PEH [59]. However, it is questionable whether active recovery is possible, or practical, in sedentary individuals after multiple bouts of supramaximal HIIT, due to the cumulative fatigue and localised muscle discomfort reported by some participants.

Additionally, the adverse sensations during the passive post–exercise recovery period resulted in a longer recovery period (up to 30 min) in 51% of participants, before activities of daily living could resume. The time efficiency of HIIT must consider the entirety of a session. This increased time commitment decreases any time saving argument routinely associated with HIIT, in those individuals susceptible to symptomatic PEH. However, in those individuals who do not develop symptomatic

PEH, the reductions in DBP 6 min post-HIIT, compared to low intensity exercise (REC protocol of Study 1) and CMIE (MOD protocol of Study 3), indicate a potential cardiovascular benefit post-HIIT and an acute example of the BP reductions evidenced in longitudinal HIIT training studies [6]. Uniquely, the combined results of the experiments in this thesis indicates that these acute reductions in DBP, which could contribute to cardiovascular protection, are greatest after cycling HIIT which includes passive recovery periods. The translation of this finding to the therapeutic prescription of HIIT for hypertensive individuals to reduce BP is however viewed with caution, due to the high percentage of individuals across the three studies who developed symptomatic PEH, and the fact that the likelihood and magnitude of PEH is increased in hypertensive individuals [58, 60].

It was beyond the scope of this thesis to assess the magnitude of longer term (30 min – 24 h) BP responses post-HIIT sessions of varying recovery format and mode. Therefore, extended periods of post-exercise BP measurement to quantify the positive (asymptomatic PEH linked to cardiovascular health benefits) and negative (symptomatic PEH associated with adverse sensations) BP responses to acute HIIT sessions of varying recovery format and mode is suggested as a possible future research direction. Furthermore, habitual exercise training can affect the degree and putative mechanisms leading to PEH [338, 339]. Therefore, investigation of whether habituation to HIIT sessions of varying recovery format and mode leads to a reduction in severity or a complete cessation of symptomatic PEH during a longitudinal training study is suggested as a related future research direction. It is important to quantify the degree of reduction or cessation of PEH following HIIT sessions, as the likelihood and severity of symptomatic PEH post-HIIT has implications for the safety, enjoyment, time-efficiency and feasibility of HIIT to improve exercise compliance in sedentary individuals.

8.1.3. Enjoyment

During Study 1, HIITPASS and HIITACT evoked the same (low) level of enjoyment for the same level of exercise intensity (no difference in HR, VO_2 and RPE). During Study 2, the higher intensity HIITCYC was less enjoyable than the lower intensity HIITRUN. During Study 3, the HIIT session was less enjoyable than the MOD session. These findings, together, support previous research identifying that sedentary individuals enjoy moderate intensity exercise more than high intensity exercise [38, 108] and indicate that sedentary individuals' enjoyment of HIIT sessions of varying recovery format and mode is inversely related to the physiological and perceived intensity of the session. This inverse relationship between HIIT intensity and enjoyment has been proposed previously, based upon affective responses [36]. The finding of an inverse relationship between HIIT intensity and enjoyment represents a challenge with regards to HIIT exercise prescription in a health context, as some of the positive health effects of HIIT may be due to the near maximal intensities achieved during higher intensity SIT protocols [6, 336].

The finding of an inverse relationship between HIIT intensity and enjoyment provides a further challenge with regards to HIIT prescription in a health context. As the intensity of a HIIT session is reduced, the duration of the session is routinely increased [33], thereby decreasing the time-efficiency aspect of HIIT, in comparison with CMIE physical activity recommendations. However, given the importance of enjoyment in facilitating exercise uptake and continued exercise participation [66, 118], prioritising enjoyment during HIIT over maximal time-efficiency may be warranted. Furthermore, whilst the VO_{2peak} of the current participants classified them as 'poor' in terms of CRF [74] and participants reported weekly PA levels well below the recommended totals for health benefit accrual (Study 1 = 37 ± 47 min; Study 2 = 33 ± 37 min; Study 3 = 31 ± 33 min), it is conceivable that a proportion of sedentary individuals would have even lower levels of CRF and PA than the current research participants [65]. These very low levels of CRF and PA would increase the relative exercise intensity of any HIIT intervention [81]. Therefore, given the inverse relationship found between intensity and enjoyment, and the propensity for sedentary individuals to have a low level of CRF, it seems reasonable to recommend a reduction in intensity of HIIT sessions, which may be more enjoyable and better tolerated by severely deconditioned individuals, even if the time-efficiency aspect of the session is somewhat compromised.

An additional factor which may contribute to enjoyment during HIIT, even if the duration of a session is increased, is the interval format of HIIT. Whilst the investigation of enjoyment and the health benefits associated with HIIT have largely focused on intensity [31, 92] most comparisons of HIIT and CMIE, including Study 3 of this thesis, involve not only a different exercise intensity, but also interval versus continuous exercise. Despite the HIIT session being found to be less enjoyable than the CMIE session of Study 3, it has recently been proposed that some of the physiological responses, health benefits and enjoyment associated with HIIT participation may be due to the intermittent format of HIIT [336], and that moderate intensity intermittent training (MIIT) may lead to similar physiological responses, health benefits as well as greater enjoyment and a lower risk of adverse events, compared to HIIT and be more enjoyable than CMIE [37, 336]. Therefore, the investigation of HIIT versus MIIIT protocols of various recovery format and modes on enjoyment, risk and physiological benefit is suggested as a future research direction.

Exercise enjoyment effects and potentially predicts the uptake, compliance and adherence to longer-term HIIT participation [66, 118]. This thesis provides evidence for a low level of enjoyment during acute sessions of short duration HIIT, regardless of the fact that the HIIT sessions took 12 min to complete and therefore represents a substantial time saving, compared to MIE recommendations. Investigation into whether enjoyment levels would remain static or change on repeated exposures to HIIT warrants further research. Investigations detailing the change in levels of enjoyment upon multiple exposures to HIIT and CMIE have recently been published [38, 65], indicating that enjoyment of HIIT can increase over time, whilst enjoyment of CMIE remains relatively static (and lower than HIIT) or that enjoyment of both decrease over time. The investigation of the recovery format and mode of HIIT that promotes the greatest level (or increase) in enjoyment over time is therefore suggested as a future research direction.

The novel finding of this thesis suggests that, on the basis that enjoyment of acute exercise is a predictor of exercise adherence [252, 340], short duration HIIT sessions, irrespective of recovery format or mode, should not be viewed as a replacement for CMIE as a primary prevention strategy to increase exercise uptake in young sedentary men. However, as previously indicted, nine design variables can be adjusted when designing HIIT protocols. Whilst the HIIT protocols within this thesis were designed to investigate the effect of recovery format and exercise mode on enjoyment (as well as local tissue oxygenation and BP), other design variables such as bout and recovery number and duration were fixed, due to necessity and to maximise the time-efficiency aspect of HIIT, purported to be integral to the appeal of HIIT to enhance exercise initiation and compliance in the sedentary population [70]. The HIIT protocols in this thesis were therefore 12 min in duration, including a 4-min warm-up period, compared with the 30 min of MIE recommended in PA guidelines. It is acknowledged that the 30 s bouts and 2 min recovery periods (a 1:4 work to recovery ratio) and the subsequent physiological and perceptual responses to these protocols does limit the generalisability of the research findings to the broader HIIT literature.

In summary, the quantification of the Δ[HHb] at multiple local tissue sites, BP and enjoyment during HIIT sessions of varying formats, and in comparison to a session of CMIE, has facilitated an improved understanding of the ill-defined acute physiological responses to single HIIT sessions in sedentary populations and indicates the contribution of this thesis.

8.2. Conclusions

It is concluded that, in young sedentary men undertaking acute HIIT sessions including active and passive recovery periods, HIIT sessions performed running and cycling and during a work-matched session of CMIE:

- Local tissue oxygen utilisation was higher during a HIIT session including active recovery periods, compared to passive recovery periods, during cycling HIIT, compared to running HIIT and during a session of HIIT compared to a session of work-matched CMIE.
- A single bout of HIIT was sufficient to achieve maximal levels of local oxygen utilisation at locomotor muscle sites.
- Reductions in DBP occurred post-HIIT and coincided with pre-syncopal symptoms in 51% of sedentary participants.
- Enjoyment of HIIT of varying recovery format and mode was a function of exercise intensity, with enjoyment decreasing with increasing exercise intensity.

Cycling HIIT including active recovery periods produced higher levels of local and systemic physiological stress than cycling HIIT including passive recovery periods, running HIIT including passive recovery periods or cycling CMIE.

Local muscle oxygen utilisation remained constant from Bout 1 to Bout 4 during all HIIT protocols. Therefore, a single bout of HIIT may be sufficient to induce maximal levels of oxygen utilisation, irrespective of recovery format or mode.

Diastolic blood pressure was lowest following cycling HIIT protocols, which included passive recovery periods. Additionally, pre-syncopal symptoms were reported by 51% of participants during the 6-min post–HIIT recovery period and reductions in DBP were greater in symptomatic individuals, compared to asymptomatic individuals.

Exercise enjoyment was relatively low during HIIT, with an inverse relationship found between exercise intensity and enjoyment. Higher levels of enjoyment were reported for the exercise protocols which produced lower levels of physiological stress and perceived exertion.

These findings have implications for the selection of HIIT protocols in sedentary populations, for physiological stress, post-exercise BP response, enjoyment and practicality.

8.3. Limitations and observations

The main limitations to this thesis were technological or physiological issues, and included artefact present during NIRS data collection and the heterogeneity of sedentary participants' past exercise experience. Observations, made by the author, whilst not being limitations to the production of this thesis, are included to inform subsequent research programmes.

8.3.1. Technical limitations

Recommendations have been made to standardise the collection and presentation of NIRS data [165]. However, the treatment, analysis and presentation of the limited NIRS data in the literature addressing HIIT is not consistent or standardised and the presentation of individual participant data almost non-existent [167]. During this thesis, unexpectedly high inter-individual variability in tissue oxygenation was measured. Furthermore, O_2Hb and recovery portions of HHb data were excluded from analysis due to high levels of artefact. Without previous research findings with which to compare the high inter-individual variability and acceptable noise-to-signal ratios, the statistical sensitivity of results and scope of analysis able to be performed was curtailed.

During Study 1, the examination of the possibility of selective distribution for oxygenation of the muscles of respiration versus the active locomotor muscles was planned, by placing a NIRS device on an intercostal (IC) muscle site in addition to the VL and GN muscle sites. However due to a large degree of artefact in the NIRS data at the IC site during data collection, the IC data was excluded from further analysis. The degree of artefact present in the sedentary participant data at the IC site (and other sites) was not present during preliminary pilot testing in habitually trained and recreationally active individuals. It is theorised that, potentially due to a) the increased adiposity, b) the increased ventilatory requirement, c) the increased discomfort in the musculature associated with exercise and d) the reduced ability to hold a stable cycling posture, the amount of movement artefact in the sedentary participants of this thesis was increased.

The mechanical work performed during the running and cycling HIIT protocols during Study 2 was not explicitly controlled or matched. Therefore, it is acknowledged that the physiological differences cannot be exclusively attributed to mode of exercise, but are also a function of intensity. However, as discussed in Chapter 6, the free-paced 'all-out' model of HIITCYC and the constant-paced 'maximal speed' model of HIITRUN represent practical utilisations of these two modes of exercise in the delivery of HIIT. Therefore, the investigation of physiological and perceptual responses to these modes / designs and the research findings are transferable and relevant to realistic exercise applications.

8.3.2. Physiological limitations

The group of participants in the experiments were homogenous in their sedentary behaviours in the three months prior to and during the research programme, but were heterogeneous in their exercise history. Differences in previous exercise experience potentially affected physiological performance and perceptual responses during HIIT. Furthermore, sedentary individuals self-selecting to participate in research involving multiple HIIT sessions may not be representative of the broader sedentary community and therefore introduce bias. Recruitment of habitually sedentary individuals, with no or less previous exercise experience, may have allowed for more homogenous group responses. However, as detailed in the observations section below, the selective recruitment of a participant population with a long term sedentary profile was impractical due to time constraints.

Participants in the experiments were exclusively men, allowing for potential sex differences in respiratory, hormonal and energy substrate utilisation to be controlled. The exclusion of women from the participant group limits the generalisability of the research findings and does not allow commentary on the mediating effects of sex on local tissue oxygen utilisation, blood pressure and enjoyment during HIIT of varying recovery format and mode and in comparison to a work-matched session of CMIE. The influence of sex, in sedentary individuals, on the physiological and perceptual responses to HIIT of varying recovery formats and modes is unknown [144]. Taking into consideration that 61% of Australian women are insufficiently active for the achievement of health benefits, compared with 47.5 % of men [84], it is important to investigate sex specific responses to HIIT [33], if HIIT is to be recommended for all sedentary individuals, as an alternative to CMIE.

Blood pressure data was collected during Study 2 (the effect of running HIIT versus cycling HIIT). However, some BP values obtained during HIITRUN were non-physiological: (a rise in SBP of less than 30mmHg was noted for several participants directly after the HIIT bouts, when compared to resting SBP). Therefore, the BP response of sedentary individuals to running versus cycling HIIT was excluded from further analysis. A search of the HIIT literature failed to find information to inform this issue. It is acknowledged that BP measurements during treadmill exercise are difficult to obtain and measurement error is an issue [341-343], however the author has extensive experience (13+ years) measuring manual BP during maximal clinical exercise testing. Alternative methods of non-invasive BP measurement, considered during research programme design to exclude human error, such as automated sphygmomanometery and plethysmography, have reduced measurement accuracy during exercise, especially at higher intensities [343].

8.3.3. Observations

Initial participant recruitment and subsequent data collection presented a challenge, taking two calendar years. Therefore, recruiting for a more homogenous sample of past sedentary behaviours would have been impractical, given Ph.D. completion timeframes. Recruitment strategies included multiple rounds of face-to-face, print and electronic communication platforms over the two year period. However, once recruited, participant retention was high with only 3 of a total of 38 participants across all studies withdrawing prior to completing required sessions (1 due to academic pressures, 1 lost to follow-up and 1 due to unrelated injury). Future research projects, planning to recruit sedentary individuals to perform multiple sessions of HIIT (and additional sessions of maximal incremental exercise testing), should take the potential difficulty in initial recruitment and the subsequent longer than anticipated data collection period into consideration when forecasting project timelines.

High intensity interval training (HIIT) is routinely used as an umbrella term describing any high intensity interval effort. Sprint interval training (SIT) is used to describe short duration maximal or supramaximal efforts. Aerobic interval training (AIT) is used to describe longer duration efforts that are of a high intensity, but are predominantly aerobic / submaximal. Whilst this thesis included HIIT bouts based on the Wingate test and therefore the HIIT sessions would be expected to be maximal or supramaximal in intensity, results from the interventions show the actual intensity of exercise sessions in this sedentary cohort to be submaximal (comparing HR and VO_2 responses during HIIT to predicted or actual HR_{max} and VO_{2max} values). The protocols could therefore be argued to fulfil the criteria of both SIT and AIT, hence the umbrella term of HIIT has been retained in all instances. Potentially, during HIIT involving sedentary / untrained individuals in a clinical context, the acronym SIT should, where applicable, be substituted for SDIT (short duration interval training) to more accurately describe time efficient formats of HIIT and avoid discrepancies between the expected versus actual exercise intensity achieved.

8.4. Future research directions

Future research directions, the rationale for which are provided in section 8.1 of this chapter, are listed below:

- The examination of the maximal amplitudes of oxygenation responses to HIIT protocols including active and passive recovery periods and conducted running and cycling in sedentary and / or clinical populations.
- The quantification of the maximal level (and longevity) of PEH post-HIIT sessions including active and passive recovery periods and conducted running and cycling.
- The evaluation of whether habituation to HIIT including passive post-exercise recovery periods leads to a reduction in severity or a complete cessation of symptomatic PEH in susceptible sedentary individuals.
- The investigation of the recovery format and mode of HIIT that promotes the greatest level (or increase) in enjoyment over time.
- The comparison of physiological and perceptual responses during HIIT and MIIT protocols including active and passive recovery periods and conducted running and cycling.
- The influence of gender, in sedentary individuals, on the physiological and perceptual responses to HIIT including active and passive recovery periods and conducted running and cycling.

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Appendices

Appendix A: Near infrared spectroscopy (NIRS)

Introduction

Near infrared spectroscopy (NIRS) was first reported by Jobsis in 1977 [163] to be of value in assessing cerebral tissue oxygen saturation. Living tissues are relatively transparent to wavelengths of light in the near infrared spectrum. It is therefore possible to transmit light through organs to provide real time, in situ monitoring.

Since the initial publication by Jobsis, NIRS has been used as a non-invasive, continuous method of assessing oxygenation in regional muscle, connective and cerebral tissue. Prior to utilising NIRS to evaluate site-specific oxygenation, research relied on large blood vessel or whole limb oxygenation data to infer regional changes, which compromised the specificity and regional accuracy of findings. Alternate regional oxygenation measurement options do exist, but are invasive, cumbersome, costly and do not allow for the freedom of movement associated with realistic, dynamic exercise. These alternate methods, such as functional magnetic resonance imaging (fMRI), have however allowed comparison and evaluation of NIRS as a scientific measurement apparatus. The results of such comparisons have shown NIRS to be a valid and accurate measurement tool for oxygenation research at rest and during exercise [205, 344-348].

NIRS has been utilised by clinical and sporting disciplines [180, 345] to investigate oxygenation variables in various areas of interest. Investigations utilising NIRS technology include the role of cerebral, central and peripheral mechanisms in fatigue; training methodology influence on regional oxygenation and blood flow; intensive care and peri-operative management of cerebral oxygen saturation; evaluation of blood flow and oxygenation parameters in health, exercise and disease and changes in cerebral oxygenation in response to micro and hypergravity periods of time during parabolic flight [173, 180, 345, 349].

NIRS measurement devices and types

The evaluation of oxygenation via NIRS is based on near infrared light absorption and transmission through living tissue, using the modified Lambert-Beer law. The Lambert-Beer law was initially intended for use in a non-scattering medium. Since biological tissue causes scattering of light a differential pathlength factor (DPF), which accounts for the increase in optical pathlength due to this scattering in tissue, is utilised during NIRS measurements.

In human tissue, in the 700 – 1300nm range, NIR light penetrates several centimetres, allowing for evaluation of cerebral or muscle oxygenation. In this NIR range, the primary light absorbing chromophore of interest is Hb, located in the small arterioles, capillaries and venules. Haemoglobin is the dominant transportation method of oxygen in blood.

The vascular specificity of the signal is because, in small vessels, light absorption is minimal whilst in larger vessels light is almost completely absorbed by water. Whilst other chromophores (cytochrome, bilirubin and myoglobin) do contribute to the NIRS measurement, their contribution has been shown to be negligible [169, 180].

When measuring Hb via NIRS, both oxyhaemoglobin (O_2Hb) and deoxyhaemoglobin (HHb) are routinely measured. There is scientific debate over what changes in measured NIRS variables represents and which physiological parameters can be linked to or affect these changes. At this time, the consensus appears to indicate that O_2Hb broadly represents the change in supply or availability of oxygen and HHb the change in utilisation or extraction of oxygen, at a particular moment in time. The absorption spectrum for deoxyhaemoglobin ranges between 650 and 1000nm and for oxyhaemoglobin between 700 and 1150nm. Peak absorbency for HHb occurs at 760nm and for O_2Hb at 850nm. The wavelengths employed by commercially available NIRS devices are set to maximise measurement and separation of these important chromophores, therefore wavelengths between 700 and 850nm are used.

In addition to measuring changes in O_2Hb and HHb, other indices can be derived. Total haemoglobin (THb), the sum of oxy and deoxyhaemoglobin, reflects changes in blood volume. The difference between O_2Hb and HHb, termed Haemoglobin difference (Hb_{diff}), reflects a balance between delivery and removal of oxygen in the small blood vessels. Tissue saturation index (TSI), alternatively know as tissue oxygenation index (TOI) and calculated as (O_2Hb/THb) x100, indicates the balance between tissue oxygen supply and consumption as a percentage.

Time domain and frequency domain spectroscopy

Time domain (TD) NIRS illuminates tissue under the area of inspection with short pulses of light and detects the shape of the pulse after propagation through tissues. Frequency domain (FD) NIRS illuminates tissue with intensity-modulated light, measuring both attenuation and phase delay of emerging light [345]. Whilst these types of NIRS devices allow for absolute measurements of HHb and O_2Hb to be made, by quantifying scattering and absorption coefficients, the units themselves are routinely large, cumbersome and difficult to operate via telemetry. From a financial standpoint, FD and TD units are prohibitively expensive. TD units also require stabilisation to operate effectively.

Continuous wave spectroscopy

Continuous wave (CW) spectroscopy allows for changes in concentration of O_2Hb and HHb to be detected due to differences in the chromophores' absorption spectrum [350]. The changes are measured in relation to an initial baseline value assigned to zero. Measurements made with this type of device are relative, as the optical pathlength of the NIR light is derived via a DPF, not measured absolutely. CW NIRS units, such as those used in this thesis, have the advantages of:

- providing site specific instead of 'averaged' whole limb insights into regional oxygenation
- allowing continuous real time measurements
- monitoring a number of distinct sites simultaneously, due to recent design improvements and size reductions
- being highly portable and low-cost
- being telemetry enabled devices, allowing for investigation of oxygenation in response to dynamic realistic movement and exercise.

The improvements in unit design allow researchers to evaluate oxygenation responses in different regions of the same muscle over time, changes in different muscles in response to the same stimulus as well as investigation of oxygenation responses of muscle and cerebral tissue to 'real world' exercise modalities and protocols.

NIRS usage in exercise science

NIRS was initially utilised in the area of neural oxidative research [345]. The use of NIRS in sport and exercise has been limited, partly due to the fact that this scientific technique is in its infancy in terms of technological development, with the use of NIRS in human subjects first described in 1977 [163]. However, in the last decade NIRS usage in exercise and PA research has increased. Reasons for this include:

- NIRS facilitates investigation and differentiation of the increased supply and utilisation of oxygen at a local muscle level, inherent in most exercise types and formats
- Derailments in oxygen transport or utilisation are inherent in many chronic diseases and / or exercise intolerance
- NIRS allows insight into central versus peripheral contributions to fatigue due to comparison of responses between brain and muscle tissue.

Early experiments utilised highly controlled, simplistic, single joint movements in a laboratory setting [269, 347, 351]. The units utilised in these studies lacked portability and general ease of use with regards to more dynamic exercise and field-testing. Advances in technology, including the use of wireless networks, telemetry, decreasing unit size and portable computer systems have allowed more realistic and field based exercise testing to take place. This in turn has allowed NIRS based exercise research to become an area of rapidly growing investigation and scientific publication. However, as far as the researcher is aware, no group has attempted to monitor and compare oxygenation across four distinct muscle and cerebral sites, as detailed in this thesis.

NIRS in health and disease

Jobsis first described the use of NIRS to evaluate oxygenation in neural tissue in 1977 [163]. Since this initial publication, the use of NIRS in the areas of medicine, health and disease has grown, not least of all due to the non-invasive nature of these devices. As NIRS technology has advanced, study into the application of NIRS device in a number of medical areas including intensive care and surgical monitoring [352], peripheral vascular disease research and diagnostics [353], diagnosis and investigation of muscle oxidative pathology [169], tissue oxygenation during exercise rehabilitation in multiple pathological populations [354] and neural oxygen research has been undertaken. NIRS has also been utilised in the areas of ergonomics and workplace rehabilitation to evaluate workplace performance [355] and fatigue levels in spinal support muscles [356]. Researchers utilising NIRS technology still have much to contribute to scientific and medical knowledge in the areas of ‘normal’ regional oxygen kinetics, pathological processes that compromise oxygen supply and utilisation and the evaluation of various exercise and pharmacological treatment regimens on regional oxygenation variables.

Limitations of NIRS

Technical limitations

Scattering of light and measurement of relative changes

During CW spectroscopy measurement, in a tissue which causes scattering of light, the actual pathlength of the light from transmitter to receiver is unknown, affecting the ability to calculate chromophore concentrations. Therefore, a DPF is utilised in continuous wave spectroscopy calculations. The attenuation of light in the tissue, via this measurement, therefore reflects relative oxy and deoxyhaemoglobin concentration changes from an arbitrary baseline, not absolute measures.

Radiant light

Exposure of the NIRS unit optodes to radiant light can disrupt the measurement. Whilst there have been recent advances in this area, making units more robust to radiant light contamination, during this research programme all NIRS units were fixed securely to the area of investigation and covered in a dark material ‘sleave’ for shielding purposes. This was effective in laboratory conditions, allowing a robust signal to be obtained. Our research group has found that even with shielding protection in place, along with additional precautions, measurements conducted outdoors were subject to radiant light contamination. Therefore, all measurements occurred indoors.

Physiological limitations

Skin and adipose tissue thickness

Some NIR light is absorbed and scattered by the skin and underlying subcutaneous adipose tissue, but with adequate optode separation distance (named the inter-optode distance or source-detector distance) this loss constitutes less than 5% of the signal measured in lean subjects [169, 346]. Light penetration is approximately half the distance between optodes. Adipose tissue thickness (ATT) was measured in participants to account for the contribution to signal loss due to lower blood flow rates and metabolic activity in the adipose tissue in a population that is expected to have increased ATT [348]. One prospective participant was excluded from the research programme due to having an ATT that exceeded half the inter-optode distance. In all other participants, the inter-optode distance allowed for adequate light penetration depth, therefore the principle measurement site was the small vasculature in the muscle itself rather than the subcutaneous adipose tissue.

Skin blood flow and heating

There is some contention as to whether the contribution of skin blood flow and the related process of skin heating and vasodilation contribute to the overall NIRS signal to any important degree [346]. As with ATT, the consensus is that if the optode distance is sufficient, the majority of the signal measured originates in the muscle and therefore skin blood flow and heating contributions to the signal obtained are minimal.

Melanin

High levels of melanin pigmentation has been shown to significantly affect light transmission and impair NIRS measurements [352]. Therefore, NIRS measurement units investigating cerebral oxygenation are generally placed on the forehead, avoiding the presence of excessive hair, 2-3 cm's above the orbital ridge, thereby also avoiding the frontal sinuses. Melanin in skin is confined to the very superficial layers and as such does not seem to attenuate the NIRS signal [352]. Skin sites were shaved prior to placement of NIRS units to further minimise absorption and contact issues. Following the manufacturer's recommendations, the NIRS unit cannot obtain accurate measurements in people with very dark skin pigmentation; therefore, such individuals were excluded from participation on this basis.

Myoglobin

In muscle tissue, myoglobin (Mb) is a chromophore that contributes approximately 10% of the NIRS signal. Because the Mb and Hb absorption spectra overlap, they cannot be distinguished with NIRS [231, 346]. However, as this programme of research was concerned with the relative changes in oxygen utilisation in the muscles under investigation, the contribution attributed to Hb versus Mb was not a confounding factor.

Arterial and venous occlusion

Early work utilising NIRS in exercise research made use of arterial and venous occlusions to study oxygenation and deoxygenation variables in limbs at rest and 'during' exercise. The process involved a blood pressure cuff being inflated to a pressure that would either prevent venous outflow (approx. 50mmHg) or all flow (approx. 250mmHg) in a limb. Measurements were then taken both whilst the flow was prohibited (representing an environment independent of flow mediated oxygenation) and after resumption of flow. These arterial and venous occlusions allowed the calculation of variables such as limb blood flow, rates of oxygen consumption by muscle tissue and resaturation recovery times. However, the limitations of the process are that it is moderately to highly uncomfortable for the participants, logistically and practically impossible to perform real time NIRS measurements during dynamic exercise / activity and is not reflective of normal physiological conditions

These factors have led to the conclusion that this method was inappropriate for the studies included in this thesis.

Appendix B: Research participant information sheet, Study 1

RESEARCH PROJECT INFORMATION SHEET	University of the Sunshine Coast

Muscle oxygenation during high intensity exercise with active versus passive recovery periods

Research Team Contacts	
Principal Researcher: Mr Yuri Kriel Email: ykriel@usc.edu.au Telephone: (07) 54565732	Research Supervisor: Dr. Colin Solomon Email: csolomon@usc.edu.au Telephone: (07) 54301128

Description

This research project is being conducted by Mr. Yuri Kriel as part of his Ph.D. research, at the University of the Sunshine Coast (USC). The purpose of this project is to investigate oxygenation in skeletal muscles and the brain, and the perception of effort during high intensity exercise in sedentary individuals. You are being invited to participate, as you are a healthy male and sedentary (not meeting current physical activity guidelines by participating in less than 150 minutes of moderate or 75 minutes of vigorous intensity physical activity or exercise). Please take your time to think about whether you wish to participate.

Eligibility criteria for this study include:

- Aged 18 – 30
- Sedentary (less than 150 minutes of moderate or 75 minutes of vigorous physical activity / exercise per week)
- Free from cardiovascular or metabolic disease
- No medications taken at present
- No orthopaedic or other health related issues that would be made worse by participation in, or inhibit completion of the study.

Participation

Your participation in this project is voluntary. If you do agree to participate, you can withdraw from participation at any time during the project without comment or penalty. If you decide to withdraw during the research project, you will be asked if you also wish to withdraw your data. In this case, data will be stored securely, but not utilised in the final data analysis or any publication resulting from this study

Your participation will involve three testing sessions each lasting two hours at USC. These testing sessions will be separated by 3-7 days over a 9 - 21 day period. Prior to each of the three testing sessions you will need to abstain from exercise for 24 hours, and food and caffeine for 4 hours. During the period of time that you are involved in this research project it is asked that you continue your normal, sedentary routine as well as your normal dietary habits.
You will be required to complete:
Questionnaires: To determine your medical health status, you will complete a Medical Health Questionnaire, Physical Activity Readiness Questionnaire, Pre-Exercise Screening Tool, and Activity / Training Log prior to completing any other components of the project. This is also the ideal time to ask any questions you may still have with regards to this document or any other queries you have.
Physical Measurements: During your first testing session, to measure your height you will stand against a wall, and to measure your weight you will stand on a scale.

Breathing Tests: During your first testing session, to measure the flow and volume of air in your lungs, you will inhale and exhale forcefully through a tube.
Skin Folds: During your first testing session, to measure fat tissue at the sites at which muscle oxygenation will be measured (the left calf muscle, the lower third of the left and right thigh, and on the left side of the chest midway down the rib cage), the tissue will gently be pushed together and measured using calipers.
Exercise Tests: You will complete three exercise sessions on a bicycle ergometer (one exercise session per visit). The tests will commence with measuring resting values, followed by a short bout of exercise. The exercise tests consist of a warm up period, a period of exercise and lastly a recovery period. During two of the three exercise tests, the warm up will be followed by four 30 second bouts of cycling as hard as you can against a pre-determined resistance. The four high intensity bouts will be interspersed with either passive recovery (sitting still on the bicycle) or active recovery (cycling at a low resistance) for 2 minutes. During the third exercise test, you will sit passively during the thirty-second periods and exercise only during the warm up and the 2-minute active recovery portions of testing.

You will have these measurements taken before, during or after the exercise sessions:
Measurements of Oxygenation: To measure your skeletal muscle and brain oxygenation, non-invasively through the skin, you will have monitors placed on your muscles and head.
Breathing and Gas Analysis: To measure your breathing (volume and rate) and exhaled gases (oxygen and carbon dioxide), you will breath into a mouth piece.
Heart Rate: To measure your heart rate, you will wear a heart rate monitor across your chest.
Blood Pressure: To measure your blood pressure, you will be fitted with a blood pressure cuff above your elbow.
Ratings of Perceived Exertion: During each exercise test, you will be asked to rate your perception of effort after each bout of high intensity exercise on a scale of 1 to 10 by pointing at a chart.

Risks

Breathing Tests: You could feel light-headed during or after the breathing test. For your safety, you will be seated during the test.
Exercise Tests: You will feel some physical responses typically associated with exercise, including having tired muscles, sweating, being breathless, being light-headed and general fatigue, during and/or after the exercise tests. There is the risk of nausea, musculoskeletal discomfort/ injury and the risk of death from performing high intensity exercise. In addition, you may have sore muscles for a number of days after testing. For your safety, the responses of your body will be continuously monitored during the exercise test. An investigator trained in CPR and defibrillation will be present during the exercise testing sessions, and there is a defibrillator and other resuscitation equipment in the laboratory.

For all the procedures, you will be monitored by a researcher, and the test stopped if there are any concerns. You will be asked during testing to report any symptoms which you may be experiencing. If you do experience any signs or symptoms please notify the researcher immediately.

Expected Benefits

You will receive information about your individual physiological response to exercise (including oxygen utilisation and heart rate responses), which could be of use to you in an exercise programme. You will receive a $50 gift voucher for your participation in this project.

It is expected the results of the project will add to the understanding of muscle and brain oxygenation in sedentary participants during high intensity exercise of short duration. This in turn will allow for real world recommendations to be made regarding effective methods for increasing exercise participation and related health benefits. Data from this project will be stored indefinitely. De-identified data obtained during this research project may be re-analysed at a later date or used in future research.

Results of the Project

The results of this project will potentially be utilised within or made available in the following formats:

- As part of a doctoral thesis
- As published research articles in applicable scientific research journals.

Your data will be utilised and published in de-identified format.
If you would like a summary of the results of the project sent to you, please indicate this to the researchers.

Confidentiality

The information and data obtained during this project will be kept confidential, unless required for legal reasons.

Consent to Participate

We request you sign a written consent form (enclosed) to confirm your agreement to participate.

Questions / Further Information about the Project

Please contact the researchers named above to have any questions answered, or if you require further information about the project.

Concerns / Complaints Regarding the Conduct of the Project

This study has been reviewed and approved by the USC Human Research Ethics Committee. The ethics approval number for this project is HREC: S/13/472. USC is committed to researcher integrity and the ethical conduct of research projects. However, if you have any complaints about the way this re**Error! Bookmark not defined.**search project is being conducted you can raise them with the Principal Researcher. If you prefer an independent person, contact the Chairperson of the Human Research Ethics Committee at the University: (c/- the Research Ethics Officer, Office of Research, University of the Sunshine Coast, Maroochydore DC 4558; telephone (07) 5459 4574; email humanethics@usc.edu.au). The USC Human Research Ethics Committee is not connected with the research project and can facilitate a resolution to your concern in an impartial manner.

Appreciation

The researchers and USC greatly appreciate your participation in this project, and thank you for your time and effort.

Appendix C: Research participant consent form

CONSENT FORM for USC RESEARCH PROJECT

University of the Sunshine Coast

Muscle oxygenation during high intensity training with active versus passive recovery periods

Statement of consent

By signing below, I am indicating that I:

- Have read, understood, and kept the information document regarding this project
- Have had any questions answered to my satisfaction
- Understand that if I have any additional questions I can contact the research team
- Understand that I am free to withdraw from this research project at any time, without comment or penalty
- Understand that I can contact the USC Human Research Ethics Committee by telephone (07) 5459 4574 if I have concerns about the ethical conduct of the project
- Agree to participate in the research project
- Understand and consent for research data arising from my participation to be utilised as outlined within the research information document.
- Understand that the results of this study will be produced as a doctoral thesis and may be published in research journals, but that no persons will be identified.

Name ....

Signature ....

Date .... / .... / ....

Appendix D: Research participant questionnaires

1. Exercise and Sports Science Australia / Sports Medicine Australia / Fitness Australia Adult Pre-Exercise Screening Tool

ADULT PRE-EXERCISE SCREENING TOOL

This screening tool does not provide advice on a particular matter, nor does it substitute for advice from an appropriately qualified medical professional. No warranty of safety should result from its use. The screening system in no way guarantees against injury or death. No responsibility or liability whatsoever can be accepted by Exercise and Sports Science Australia, Fitness Australia or Sports Medicine Australia for any loss, damage or injury that may arise from any person acting on any statement or information contained in this tool.

Name: ______________________________

Date of Birth: ______________ Male ☐ Female ☐ Date: ______________

STAGE 1 (COMPULSORY)

AIM: to identify those individuals with a known disease, or signs or symptoms of disease, who may be at a higher risk of an adverse event during physical activity/exercise. This stage is self administered and self evaluated.

Please circle response

1.	Has your doctor ever told you that you have a heart condition or have you ever suffered a stroke?	Yes	No
2.	Do you ever experience unexplained pains in your chest at rest or during physical activity/exercise?	Yes	No
3.	Do you ever feel faint or have spells of dizziness during physical activity/exercise that causes you to lose balance?	Yes	No
4.	Have you had an asthma attack requiring immediate medical attention at any time over the last 12 months?	Yes	No
5.	If you have diabetes (type I or type II) have you had trouble controlling your blood glucose in the last 3 months?	Yes	No
6.	Do you have any diagnosed muscle, bone or joint problems that you have been told could be made worse by participating in physical activity/exercise?	Yes	No
7.	Do you have any other medical condition(s) that may make it dangerous for you to participate in physical activity/exercise?	Yes	No

IF YOU ANSWERED 'YES' to any of the 7 questions, please seek guidance from your GP or appropriate allied health professional prior to undertaking physical activity/exercise

IF YOU ANSWERED 'NO' to all of the 7 questions, and you have no other concerns about your health, you may proceed to undertake light-moderate intensity physical activity/exercise

I believe that to the best of my knowledge, all of the information I have supplied within this tool is correct.

Signature ______________________ Date ______________

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V1 (2011) PAGE 1

EXERCISE INTENSITY GUIDELINES

INTENSITY CATEGORY	HEART RATE MEASURES	PERCEIVED EXERTION MEASURES	DESCRIPTIVE MEASURES
SEDENTARY	< 40% HRmax	Very, very light RPE# < 1	• Activities that usually involve sitting or lying and that have little additional movement and a low energy requirement
LIGHT	40 to <55% HRmax	Very light to light RPE# 1-2	• An aerobic activity that does not cause a noticeable change in breathing rate • An intensity that can be sustained for at least 60 minutes
MODERATE	55 to <70% HRmax	Moderate to somewhat hard RPE# 3-4	• An aerobic activity that is able to be conducted whilst maintaining a conversation uninterrupted • An intensity that may last between 30 and 60 minutes
VIGOROUS	70 to <90% HRmax	Hard RPE# 5-6	• An aerobic activity in which a conversation generally cannot be maintained uninterrupted • An intensity that may last up to about 30 minutes
HIGH	≥ 90% HRmax	Very hard RPE# ≥ 7	• An intensity that generally cannot be sustained for longer than about 10 minutes

= Borg's Rating of Perceived Exertion (RPE) scale, category scale 0-10

ADULT PRE-EXERCISE SCREENING TOOL

STAGE 2 (OPTIONAL)

Name: ______________________________

Date of Birth: ____________________ Date: ____________________

AIM: To identify those individuals with risk factors or other conditions to assist with appropriate exercise prescription. This stage is to be administered by a qualified exercise professional.

Question		RISK FACTORS
1. Age ______ Gender ______	≥ 45yrs Males or ≥ 55yrs Females +1 risk factor	
2. Family history of heart disease (eg: stroke, heart attack) Relative / Age / Relative / Age ☐ Father ___ ☐ Mother ___ ☐ Brother ___ ☐ Sister ___ ☐ Son ___ ☐ Daughter ___	If male < 55yrs = +1 risk factor If female < 65yrs = +1 risk factor Maximum of 1 risk factor for this question	
3. Do you smoke cigarettes on a daily or weekly basis or have you quit smoking in the last 6 months? Yes No If currently smoking, how many per day or week? ______	If yes, (smoke regularly or given up within the past 6 months) = +1 risk factor	
4. Describe your current physical activity/exercise levels: Sedentary ☐ Light ☐ Moderate ☐ Vigorous ☐ Frequency (sessions per week) ___ ___ ___ Duration (minutes per week) ___ ___ ___	If physical activity level < 150 min/ week = +1 risk factor If physical activity level ≥ 150 min/ week = -1 risk factor (vigorous physical activity/ exercise weighted x 2)	
5. Please state your height (cm) ______ weight (kg) ______	BMI = ____________ BMI ≥ 30 kg/m² = +1 risk factor	
6. Have you been told that you have high blood pressure? Yes No	If yes, = +1 risk factor	
7. Have you been told that you have high cholesterol? Yes No	If yes, = +1 risk factor	
8. Have you been told that you have high blood sugar? Yes No	If yes, = +1 risk factor	

Note: Refer over page for risk stratification.

STAGE 2 Total Risk Factors = ______

9.	Have you spent time in hospital (including day admission) for any medical condition/illness/injury during the last 12 months? Yes No	If yes, provide details
10.	Are you currently taking a prescribed medication(s) for any medical conditions(s)? Yes No	If yes, what is the medical condition(s)?
11.	Are you pregnant or have you given birth within the last 12 months? Yes No	If yes, provide details. I am ________ months pregnant or postnatal (circle).
12.	Do you have any muscle, bone or joint pain or soreness that is made worse by particular types of activity? Yes No	If yes, provide details

STAGE 3 (OPTIONAL)

AIM: To obtain pre-exercise baseline measurements of other recognised cardiovascular and metabolic risk factors. This stage is to be administered by a qualified exercise professional. (Measures 1, 2 & 3 – minimum qualification, Certificate III in Fitness; Measures 4 and 5 minimum level, Exercise Physiologist*).

	RESULTS		RISK FACTORS
1. BMI (kg/m²)		BMI ≥ 30 kg/m² = +1 risk factor	
2. Waist girth (cm)		Waist > 94 cm for men and > 80 cm for women = +1 risk factor	
3. Resting BP (mmHg)		SBP ≥140 mmHg or DBP ≥90 mmHg = +1 risk factor	
4. Fasting lipid profile*		Total cholesterol ≥ 5.20 mmol/L = +1 risk factor	
Total cholesterol		HDL cholesterol >1.55 mmol/L = -1 risk factor	
HDL		HDL cholesterol < 1.00 mmol/L = +1 risk factor	
Triglycerides		Triglycerides ≥ 1.70 mmol/L = +1 risk factor	
LDL		LDL cholesterol ≥ 3.40 mmol/L = +1 risk factor	
5 Fasting blood glucose*		Fasting glucose ≥ 5.50 mmol = +1 risk factor	
		STAGE 3 Total Risk Factors =	

RISK STRATIFICATION

Total stage 2
or
Total stage 3
Plus stage 2 (Q1 - Q4)

≥ 2 RISK FACTORS – MODERATE RISK CLIENTS

Individuals at moderate risk may participate in aerobic physical activity/exercise at a light or moderate intensity (Refer to the exercise intensity table on page 2)

< 2 RISK FACTORS – LOW RISK CLIENTS

Individuals at low risk may participate in aerobic physical activity/exercise up to a vigorous or high intensity (Refer to the exercise intensity table on page 2)

Note: If stage 3 is completed, identified risk factors from stage 2 (Q1-4) and stage 3 should be combined to indicate risk. If there are extreme or multiple risk factors, the exercise professional should use professional judgement to decide whether further medical advice is required.

2. Research Programme Medical Health Questionnaire

MEDICAL HEALTH QUESTIONNAIRE

University of the Sunshine Coast
Queensland, Australia

PARTICIPANT CODE: ____________

DATE OF SESSION: __ __ - __ __ - __ __ __ __

PERSONAL INFORMATION:

NAME: ______________________ **DATE OF BIRTH:** __ __-__ __-__ __ __ __ **AGE:** ____

GENDER: **Female** **Male**

ADDRESS: ______________________________
(Number and Street)

____
(City) (State) (Postcode)

TELEPHONE: **Home:** (__ __) __ __ __ __ __ __ __

Mobile: __ __ __ __ __ __ __ __ __ __

EMERGENCY CONTACT:

NAME: ______________________

ADDRESS: ______________________________
(Number and Street)

____
(City) (State) (Postcode)

TELEPHONE: **Home:** (__ __) __ __ __ __ __ __ __

Mobile: __ __ __ __ __ __ __ __ __ __

Medical Doctor who manages your health:

Name: ______________________ Telephone: ____________

GENERAL:

Are you currently ill?	YES	NO

IF YES: Provide details:

____

____

Have you lost or gained weight recently?	YES	NO
Are you currently well hydrated?	YES	NO
Are you currently more tired than usual?	YES	NO

FAMILY MEDICAL CONDITIONS:

Does any member of your immediate family have or had?

Heart problems	YES	NO	UNKNOWN
Blood pressure problems	YES	NO	UNKNOWN
Cholesterol problems	YES	NO	UNKNOWN
Stroke	YES	NO	UNKNOWN
Diabetes	YES	NO	UNKNOWN
Cancer	YES	NO	UNKNOWN
Breathing problems	YES	NO	UNKNOWN

IF YES: Provide details:

____

____

____

____

MUSCULOSKELETAL:

Do you have any bone or muscle conditions?	YES	NO

IF YES: Provide details:

____

____

CARDIOVASCULAR:

Do you have any heart conditions?	YES	NO
Do you have any blood pressure conditions?	YES	NO
Do you have any cholesterol conditions?	YES	NO
Do you have pain in the chest at rest or during exercise?	YES	NO

IF YES: Provide details:

____

____

Do you have any other heart or blood conditions?	YES	NO

IF YES: Provide details:

____

____

RESPIRATORY:

When was the last time you had a respiratory infection (cold, flu, other)? __________________

Do you have asthma?	YES	NO
Do you have allergic rhinitis?	YES	NO
Do you ever have episodes of:		
Chest tightness	YES	NO
Wheezing	YES	NO
Difficulty breathing	YES	NO
Excessive mucus production from your airways	YES	NO

IF YES: Provide details:

____

____

Do you have any other breathing conditions? YES NO

IF YES: Provide details:

____

____

ALLERGIES:

Have you ever had eczema?	YES	NO
Are you allergic to things in the environment (dust, pollen, grass, trees)?	YES	NO
Are you allergic to any animals?	YES	NO
Are you allergic to any medications?	YES	NO

IF YES: Provide details:

____

____

Are you allergic to anything else? YES NO

IF YES: Provide details:

____

____

REPRODUCTIVE:

<u>MEN:</u>
Do you have any reproductive conditions? YES NO

IF YES: Provide details:

____

____

URINARY:

Do you have any bleeding from your urinary tract? YES NO

IF YES: Provide details:

____

____

Do you have any other urinary system conditions? YES NO

IF YES: Provide details:

____

____

GASTROINTESTIONAL:

Do you have any bleeding from your digestive tract? YES NO

IF YES: Provide details:

____

____

Do you have any other digestive system conditions? YES NO

IF YES: Provide details:

____

____

NERVOUS:

Do you have any nervous systems conditions? YES NO

IF YES: Provide details:

____

____

HORMONAL:

Do you have diabetes? YES NO

IF YES: Provide details:

____

____

Do you have any other hormone conditions? YES NO

IF YES: Provide details:

____

____

PSYCHOLOGICAL:

Do you have any psychological conditions that will negatively affect your ability to exercise, your responses to exercise or your safety during exercise?? YES NO

IF YES: Provide details:

____

____

PHYSICAL EXERCISE:

List your current physical activities

____

____

Do you have any problems during or after performing exercise? YES NO

IF YES: Provide details:

____

____

MEDICATIONS

Are you currently taking any medications (prescription or non-prescription)? YES NO

IF YES: List all the medications and dosages and periods:

Name__________ Dose________ Started______ Stopped_____

Name__________ Dose________ Started______ Stopped_____

Have you ever taken any medication on an ongoing or long-term basis? YES NO

IF YES: List all the medications and dosages and periods:

Name__________ Dose________ Started______ Stopped_____

Name__________ Dose________ Started______ Stopped_____

Name__________ Dose________ Started______ Stopped_____

SMOKING (Any substance):

Do you currently smoke anything? YES NO

Have you ever smoked anything? YES NO

IF YES:

When did you start smoking? __________

When did you stop smoking? __________

On average how much did you smoke? ______________

Do you currently live with anyone who smokes anything? YES NO

IF YES:

How many people who you live with smoke? ___________

How long have you lived with the people who smoke? ___________

Are you exposed to the smoke? YES NO

Have you ever lived with anyone who smoked anything, whilst you lived with them? YES NO

IF YES:

How many people who you lived with smoked? _________

How long did you live with the people who smoked? ___________

Were you exposed to the smoke? YES NO

Are you exposed to smoke in any other situations? YES NO

IF YES: Provide details:

____

____

AIR POLLUTION:

Are you exposed to air pollution in any situation? YES NO

IF YES: Provide details:

____

____

OTHER MEDICAL CONDITIONS

Do you have any past or current medical conditions that would stop you from participating in this project, or make it dangerous for you to participate in this project? YES NO

IF YES: Provide details:

____

____

Do you have any other past or current medical conditions not listed? YES NO

IF YES: Provide details:

____

____

3. Physical Activity Readiness Questionnaire (PAR-Q)

Physical Activity Readiness
Questionnaire - PAR-Q
(revised 2002)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO		
☐	☐	1.	**Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?**
☐	☐	2.	**Do you feel pain in your chest when you do physical activity?**
☐	☐	3.	**In the past month, have you had chest pain when you were not doing physical activity?**
☐	☐	4.	**Do you lose your balance because of dizziness or do you ever lose consciousness?**
☐	☐	5.	**Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?**
☐	☐	6.	**Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?**
☐	☐	7.	**Do you know of any other reason why you should not do physical activity?**

If you answered

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or
- if you are or may be pregnant – talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME ____

SIGNATURE ________________________________ DATE ________________________

SIGNATURE OF PARENT ________________________ WITNESS ________________________
or GUARDIAN (for participants under the age of majority)

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.

4. Research Programme Physical Activity Log

University of the Sunshine Coast
Queensland, Australia

Participants Physical Activity Log

Name ____________________

Age / DOB ____________________

Occupation ____________________

Daily Activity Information

Type = Walk, gym, bike ride, sport (golf, team sport etc)
Duration = Number of minutes
Intensity = Easy, Moderate, Hard.
(As a guide, moderate intensity approximately equates to walking between 4.8 – 6.5 km/h or just being able to hold a conversation whilst performing exercise)

Last Week

AM	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Type							
Duration							
Intensity							
PM							
Type							
Duration							
Intensity							

Example of Typical Week

AM	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Type							
Duration							
Intensity							
PM							
Type							
Duration							
Intensity							

Any additional information regarding any physical activity you are involved in:

Have you ever been involved in sport? YES NO

If YES please specify activity, the number of years since you were last involved and the level at which you were involved:

5. Physical Activity Enjoyment Scale

Physical Activity Enjoyment Scale

University of the Sunshine Coast
Queensland, Australia

Please rate how you feel *at the moment* about the physical activity you have been doing.

*1)	1	2	3	4	5	6	7	
I enjoy it								I hate it
2)	1	2	3	4	5	6	7	
I feel bored								I feel interested
3)	1	2	3	4	5	6	7	
I dislike it								I like it
4)	1	2	3	4	5	6	7	
*I find it pleasureable								I find it unpleasurable
5)	1	2	3	4	5	6	7	
*I am very absorbed in this activity								I am not at all absorbed in this activity
6)	1	2	3	4	5	6	7	
It's no fun at all								It's a lot of fun
7)	1	2	3	4	5	6	7	
*I find it energising								I find it tiring
8)	1	2	3	4	5	6	7	
It makes me depressed								It makes me happy
9)	1	2	3	4	5	6	7	
*It's very pleasant								It's very unpleasant
10)	1	2	3	4	5	6	7	
*I feel good physically while doing it								I feel bad physically while doing it

11)	1	2	3	4	5	6	7	
*It's very invigorating								It's not at all invigorating
12)	1	2	3	4	5	6	7	
I am very frustrated by it								I am not at all frustrated by it
13)	1	2	3	4	5	6	7	
*It's very gratifying								It's not at all gratifying
14)	1	2	3	4	5	6	7	
*It's very exhilarating								It's not at all exhilarating
15)	1	2	3	4	5	6	7	
It's not at all stimulating								It's very stimulating
16)	1	2	3	4	5	6	7	
*It gives me a strong sense of accomplishment								It does not give me any sense of accomplishment at all
17)	1	2	3	4	5	6	7	
*It's very refreshing								It's not at all refreshing
18)	1	2	3	4	5	6	7	
I felt as though I would rather be doing something else								I felt as though there was nothing else I would rather be doing

*Item is reverse scored (1=7 2=6……… 6=2, 7=1)