The moderating role of recovery durations in high intensity interval training protocols of runners, cyclists and team sport athletes

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‘Why should I practice running slow?

I already know how to run slow. I want to learn to run fast.’

Emil Zatopek

Summary

High intensity interval training (HIIT) is often regarded the most effective training modality to improve cardiorespiratory and metabolic functioning, and, in turn endurance performance. HIIT incorporating repeated long work intervals (up to 16 min) can be described as 'aerobic interval training' (AIT), as work intensities are undeniably high - but ultimately submaximal. Collating the results of ~80 unique AIT interventions, significant small to moderate improvements were evident in both $\dot{V}O_2$max and performance. The of results our meta-analysis further suggested that AIT improved $\dot{V}O_2$max and performance significantly more than moderate intensity continuous training, and to a similar extent as sprint interval training.

It was suggested that the time athletes spent at high percentages of $\dot{V}O_2$max ($\geq$ 90% $\dot{V}O_2$max ($t90\dot{V}O_2$max) could serve as a good criterion to judge the effectiveness of AIT protocols. Even though AIT is common practice in training regimes of (traditionally) endurance athletes, surprisingly little research has explored the overall impact and potential moderating role of recovery durations on the overall effectiveness of AIT protocols. In both runners and cyclists, we show that in a six 4 min self-paced AIT protocol (performed under *'isoeffort'* conditions), longer recovery intervals facilitated higher external training loads (higher running velocities / higher power outputs), whilst the internal training load in these sessions ($t90\dot{V}O_2$max) was not moderated by an increased recovery duration.

In the context of a pre-season conditioning period of collegiate rugby players, we show that in AIT protocols of matched work intensities and training volume, the use of short recovery intervals (1 min) did not offer any advantage over the use of longer recovery intervals (3 min). The results of this thesis indicate, that when athletes incorporate self-paced AIT sessions in their training programs, long recovery intervals will allow athletes to train on higher external loads, which potentially triggers greater training adaptations.

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No man is an Island – John Donne

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Abbreviations

1MIN : 1 min recovery

(Experimental condition in **Chapter 6** and **Chapter** 7, Training group in **Chapter 8**)

1MTrun : 6 min run on 2.78 $m\cdot s^{-1}$, MT grade 1%

2MIN : 2 min recovery

3MIN : 3 min recovery

(Experimental condition in **Chapter 6** and **Chapter** 7, Training group in **Chapter 8**)

4MTrun : 6 min run on 2.78 $m\cdot s^{-1}$, MT grade 4%

6MTrun : 6 min run on 2.78 $m\cdot s^{-1}$, MT grade 6%

8MTrun : 6 min run on 2.78 $m\cdot s^{-1}$, MT grade 8%

AIT : Aerobic interval training

ANOVA : Analysis of variance

ADP : Adenosine diphosphate

ATP : Adenosine triphosphate

$A\dot{V}O_2$: Amplitude of $\dot{V}O_2$ response

BLa : Blood lactate concentration

BMI : Body mass index

CI : 95% Confidence interval

CO_2 : Carbon dioxide

CON : Non-exercising control group

cNMT : Curved non-motorized treadmill

cNMTfam : Familiarisation run on cNMT

cNMTrun : Experimental run on cNMT

(**Chapter 4**: 4 min run on 40 – 80% MAV, **Chapter 5**: 6 min run on 2.78 $m\cdot s^{-1}$)

CV : Coefficient of variation

ES : Effect size

(**Chapter 3**: Hedges' *g*, **Chapter 4**, **Chapter 5** and **Chapter 8**: Cohens' d)

GET : Gas exchange threshold

GRF : Ground reaction force

HIIT : High intensity interval training

HR : Heart rate

HRmax : Maximum heart rate

LT : Lactate threshold

MAV : Maximum aerobic velocity

MICT : Moderate intensity continuous training

MRT	:	Mean response time
MT	:	Motorized treadmill
MTrun	:	Experimental run on MT
NMT	:	Non-motorized treadmill
O_2	:	Oxygen
$p\dot{V}O_2$max	:	Power output associated with $\dot{V}O_2$max
PCr	:	Phosphocreatine
PL 1 – 4	:	Performance level 1 - 4
PO	:	Power output
PPO	:	Peak power output
PR	:	Perceived readiness
RER	:	Respiratory exchange ratio
RPE	:	Ratings of perceived exertion
RST	:	Repeated sprint training
SD	:	Standard deviation
SD_{diff}	:	SD of the difference between duplicate measurements
SEM	:	Standard errors of mean
SIT	:	Sprint interval training
SMD	:	Standardized mean difference
sRPE	:	Session RPE
SS	:	Self-selected
SSGs	:	Small sided games
ssMIN	:	Self-selected recovery
t	:	Time
τ	:	Time constant
t90HRmax	:	Time ≥ 90% HRmax per HIIT session
$t90\dot{V}O_2$max	:	Time ≥ 90% $\dot{V}O_2$max per HIIT session
t95HRmax	:	Time ≥ 95% HRmax per HIIT session
$t95\dot{V}O_2$max	:	Time ≥ 95% $\dot{V}O_2$max per HIIT session
tLim	:	Time to exhaustion on $v\dot{V}O_2$max
TTE	:	Time to exhaustion
$\dot{V}CO_2$	:	Amount of carbon dioxide produced
Vcomp	:	Velocity of last completed stage
$\dot{V}O_2$	:	Oxygen uptake
$\dot{V}O_2$baseline	:	$\dot{V}O_2$ before start subsequent work interval
$\dot{V}O_2$max	:	Maximum oxygen uptake
$\dot{V}O_2$(t)	:	$\dot{V}O_2$ at any given time

$\dot{V}O_2$peak : Peak oxygen uptake

v$\dot{V}O_2$max : Velocity associated with $\dot{V}O_2$max

WMD : Weighted mean difference

W:R ratio : Work : recovery ratio

Chapter 1:

General Introduction

1.1 Introduction

Understanding optimal training to maximize physiological adaptations and improve performance is important for coaches and athletes to gain a competitive advantage over opponents. Training can be defined as the systematic and regular participation in exercise, which aims to overload the human body and therewith deliberately disturbs the body's homeostasis (1–3). As a consequence of a single intense training session or training period, an athlete may experience acute feelings of fatigue, but after adequate rest these feelings can be followed by positive cardiovascular and metabolic adaptations that can result in improvements in performance. The process known as supercompensation, the positive adaptations after a training stimulus, deviating the athletes' physiological capacity from prior resting homeostasis during subsequent exercise sessions, is the basis of effective training programs (4)

Although world class athletes undoubtedly possess genotypes and demonstrate training responses that are uncharacteristic of most other athletes (5), training regimes of these successful athletes can be considered as optimal. Substantial retrospective studies assessing the training intensity distribution of elite and well-trained endurance athletes showed that most adopt a 'polarized' training distribution (6,7). In this distribution, 80 to 85% of the total training volume is performed at low-to-moderate intensities (Zone 1). The remaining 15 to 20% comprises high intensity training (Zone 3), at exercise intensities close to those that elicit a maximum oxygen uptake ($\dot{V}O_2$max; see **Figure 1.1 A**). These retrospective studies show that elite endurance athletes perform large volumes of Zone 1 training (6,7), however, it is also evident that an additional increase in the volume of just Zone 1 training did not further enhanced endurance performance or associated physiological variables in trained endurance athletes (8–10), and many, if not most elite endurance athletes have already reached the threshold of maximal feasible injury-free training volumes.

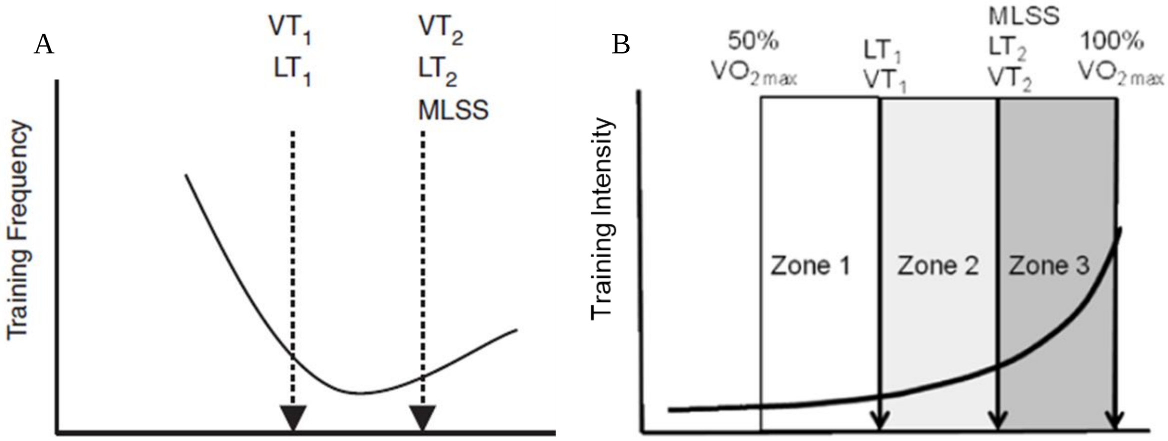


Figure 1.1: A) Conceptual training intensity distribution of the polarized training model and B) the three-intensity-zone model The model presented in figure 1.1 A emphasizes the large training volume endurance athletes perform in Zone 1, combined with significant doses of training in Zone 3 - aimed to elicit 90 - 100% $\dot{V}O_2$max. Figures adapted from Seiler & Kjerland (11) and Seiler (6)

Zone 1 training, typically performed as moderate intensity continuous training (MICT), is an indispensable constitutes of successful endurance training programmes. However, Zone 3 training, performed as high intensity interval training (HIIT), is regarded the most effective training modality to further improve cardiorespiratory and metabolic functioning (12–14). In HIIT, repeated periods of vigorous exercise are interspersed with recovery periods (15), and a complex interplay between the number of intervals, the exercise intensities and the duration of both the work and recovery intervals determine the workload of a HIIT session (16,17). The rationale behind such programmes is that the total accumulated time of vigorous exercise is higher than could be achieved during a single bout of continuous exercise at the same intensity until exhaustion (17,18). By maximizing the total accumulated time at exercise intensities at or near $\dot{V}O_2$max and the athletes' maximum heart rate (HRmax), the metabolic overload is greater than possible with traditional continuous training.

When it comes to the programming of HIIT sessions, the duration and the exercise intensities of both the work and recovery intervals are important determinants that need consideration to create a successful training session (19). Previously, interventions to optimize the intensity and duration of work intervals have received considerable scientific interest (e.g. (20–23)), however, little research has explored the overall impact of recovery intervals, and a better understanding of optimum exercise intensities and recovery durations in HIIT protocols is therefore timely.

The main metabolic processes that take place during recovery from intense exercise bouts are the repletion of phosphocreatine stores (PCr), the removal of hydrogen ions (H+) and restitution of the acid-base balance of the exercising muscles (14,24,25). These processes proceed at different rates (24,25), with PCr having a much faster half-life (~30 sec) and complete restoration time (~3 min), compared with the blood lactate concentration [BLa] and pH recovery (6 - 10 min). In order to work at the required exercise intensity during subsequent work intervals, recovery intervals need to be long enough to accomodate the return to metabolic homeostasis, or at least partially buffer intramuscular acidosis (26,27). The paradox is, that recovery intervals are ideally as short as possible to to maintain a minimal $\dot{V}O_2$, to reduce the time needed to reach $\dot{V}O_2$max (i.e. starting from an elevated 'baseline' (28)).An imbalance between the demands of the work intervals and the recovery potential of the recovery intervals can lead to premature fatigue, which potentially reduces the number of planned intervals, or lowers the work intensity during subsequent intervals. An example of an inadequate recovery duration is seen in the study by Laursen et al. (21), who reported that two groups of well trained cyclists completed only 64% of the total prescribed number of work bouts over a 4 week training cycle. Participants were 'pushed to exhaustion' in each session, as inadequate recovery had been prescribed given the intensity of the work interval, resulting in failure to complete the session. While this particular training intervention still improved time trial performance, peak power output (PPO) and $\dot{V}O_2$max (21), a protocol involving a longer recovery interval may have evoked even greater improvements.

1.2 Aims of the research

In two recent meta-analysis, both Weston et al. (29) and Milanovic et al. (30) reported equivocal effects on changes in $\dot{V}O_2$max with an increase in work:recovery ratio (W:R ratio) in sprint interval training sessions (SIT; e.g. greater recovery between subsequent 30-sec sprint intervals). For HIIT sessions incorporating long work intervals (up to 16 min), which can be described as 'aerobic interval training' (AIT), no clear scientific evidence is available to determine the optimal duration of recovery intervals. Previously, studies have evaluated manipulations in W:R ratio (or similar terminology) in a variety of HIIT protocols (e.g. (31,32)). While the W:R ratio is a term often used in the description of HIIT protocols, the construct holds limited information on the adequacy of the duration of recovery intervals, as it fails to incorporate the demands of the work intervals. For example; 1-min recovery between repeated 1-min work intervals performed at 75% PPO (W:R ratio = 1:1) is likely sufficient to complete numerous intervals, however, a similar W:R ratio in repeated 30-sec sprints at 130% PPO will most likely only allow for two / three repeats. Diverting from the use of the term W:R ratio, the main aim of this research is to assess the potential moderating role of the recovery interval duration in AIT sessions.

In a series of studies in runners and cyclists, we aim to provide new empirical data on the acute physiological and perceptual responses to AIT sessions – only differing in the recovery duration between work intervals. Theoretically, an AIT session in which athletes maximize their total accumulated time at exercise intensities at or near $\dot{V}O_2$max and HRmax is expected to yield larger improvements in both the oxygen consumption and oxygen utilization capacity of individuals, however, how this can be achieved is an ongoing question across sports science departments worldwide. Many studies have tried to optimize the work intervals of AIT protocols by manipulating work intensities (33,34) and work durations (20,35–37), where others examined different recovery intensities (38), pacing strategies (39), and even the use of additional aids like muscle vibration (40). Surprisingly little research has explored the overall impact of recovery intervals, and a better understanding of optimum exercise intensities and recovery durations in HIIT protocols is therefore timely.

Understanding the acute response to manipulating recovery durations is important when designing HIIT sessions. Smilios et al. (41) noted that an increased recovery duration (2, 3 or 4 min) did not affect the percentage of $\dot{V}O_2$max attained and the total time spend ≥ 80%, 90% and 95% of $\dot{V}O_2$max or HRmax during four 4 min intervals, ran at 90% maximal aerobic velocity (MAV). Although the data from the above study is informative (41), it also is a prime example of most published data, as acute physiological responses are evaluated to predefined fixed work intensities. In contrast to standardized exercise protocols, it was recently proposed that athletes measure and pace their work in training sessions on ratings of perceived exertion (RPE) and accumulated fatigue (42). In this so called *'isoeffort'* or self-paced HIIT, the actual work intensity per interval therewith is not a stable function of power or velocity over time, but rather the integrative outcome of feedback from external and internal receptors, and knowledge of the session demands (43,44). In the current thesis we expand on the findings of Smilios et al. (41), using a similar framework of manipulating only the recovery duration between work intervals, and examine if similar conclusions will be drawn in self-paced AIT sessions. This self-paced approach further allows for the evaluation of the potential trade-off between the internal and external training load (physiological and psychological strain vs work intensities). Longer recovery intervals might facilitate higher exercise intensities in AIT sessions, which in turn might alter the athletes' performance capacity.

Modern day cycling ergometers reproduce the power-speed relationship flat road cycling. This characteristic, and the typical highly reliable measures of power output by ergometers enable a valid assessment of self-paced cycling performance in lab setting. To assess running performance, motorized treadmills are an indispensable piece of laboratory equipment, however, they do not allow to study the quick, unconscious and frequent adjustments in running velocities that occur during self-paced exercise (45). Besides the main aim of this thesis specified above, we evaluated if a commercially available curved non-motorized treadmill would enable self-paced HIIT running in a lab setting.

Lastly, a tertiary aim of this thesis was to evaluate the long term training adaptations to AIT interventions, again, only differing in the recovery duration received between subsequent work intervals. In highly trained male cyclists (21) and recreationally active female team sport players (46), previous studies demonstrated a limited effect of the recovey duration between work intervals, when AIT protocols were matched for total training volume and work intensities. Whilst insightfull, both these studies administered a cycling intervention to their participants (21,46), and how these results generalize to running based AIT interventions is questionable. Diverting from the self-paced approach that is adopted throughout the remainder of this thesis, it was important to further fix all other variables to establish a better understanding of this relationship in runners.

1.3 Thesis structure

A schematic overview of the scheduled studies is presented in **Figure 1.2**. The experimental studies in the present thesis (presented in **Chapter4 – Chapter 8**), are designed based on the outcomes of a critical evaluation of the scientific literature (**Chapter 2**), and the results of the meta-analysis presented in **Chapter 3**.

In **Chapter 6** and **Chapter 7**, we evaluate the effect of recovery interval durations in self-paced HIIT protocols. Self-paced cycling in laboratory settings is possible with modern day cycling ergometers (**Chapter 7**), however, to study the potential trade-off between the internal and external training load (physiological and psychological strain vs work intensities) in runners (**Chapter 6**), the validation of a curved non-motorized treadmill was needed (**Chapter 4** and **Chapter 5**).

Concluding this thesis, we evaluated the moderating role of the recovery interval duration in HIIT protocols, in the context of a three-week pre-season conditioning period of collegiate rugby players (**Chapter 8**). To isolate, and solely study the role of the recovery interval duration, it was important to further match the protocols of two training groups.

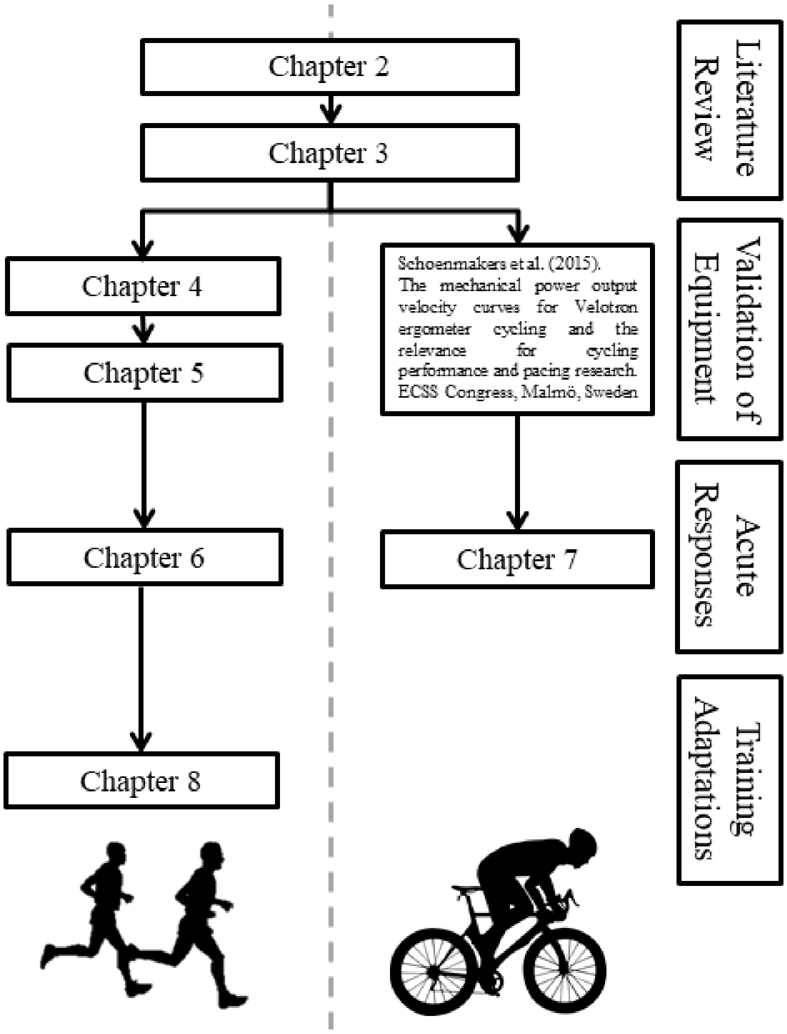


Figure 1.2: Schematic overview of thesis structure

1.4 Overview experimental studies

1.4.1 Chapter 3: The effects of aerobic interval training on $\dot{V}O_2$max and performance in runners and cyclists: A systematic review and meta-analysis

This study was carried out to provide a systematic review of running or cycling based AIT interventions and meta-analyse their effects on changes in $\dot{V}O_2$max and / or performance outcomes. Pooled estimates of effect sizes (ES, Hedges' *g*) for change in $\dot{V}O_2$max (n = 57) and performance (n = 20) across studies, were calculated using an inverse-variance random effects model for meta-analyses. Standardised mean differences, showed a significant increase of a small to moderate magnitude in $\dot{V}O_2$max (ES = 0.54, 95% confidence intervals (CI): [0.38 to 0.69]), which corresponds to a mean increase of 3.07 $mL\cdot kg\cdot min^{-1}$. Improvements in $\dot{V}O_2$max were similar between cycling and running interventions. Performance improved on average by 4.0% after AIT, which was of a small to moderate magnitude (ES = -0.49, CI: [-0.75 to -0.23]). Compared with different training modalities, the results suggest that AIT improves $\dot{V}O_2$max and performance significantly more than MICT interventions and non-training control groups (CON), and to a similar extent compared to SIT.

1.4.2 Chapter 4: The physiological and perceptual demands of running on a curved non-motorised treadmill: Implications for self-paced training

The aim of this study was to compare the physiological and perceptual response of running on a curved non-motorized treadmill (cNMT) with running on a motorized treadmill (MT). A secondary aim was to determine the running velocity at which a physiological response ≥ 90% $\dot{V}O_2$max was elicited on both treadmills. Thirteen trained male runners performed an incremental running test on a MT to determine $\dot{V}O_2$max and the accompanying MAV. After a familiarization session on the cNMT, participants ran for 4-min at five/six progressively higher velocities (40 - 90% MAV) on the cNMT and MT in two separate visits in a randomized and counterbalanced order. Our results show that running on the cNMT has higher physiological and perceptual demands than running on a MT, and running cadence is influenced. When using the cNMT, it is advised to lower the running velocity by 20% compared to MT runs, to generate a comparable physiological stimulus.

1.4.3 Chapter 5: The physiological and perceptual responses while running on a curved non-motorized treadmill compare to a 6 - 8% motorized treadmill grade

The current study compared the physiological and perceptual demands of running on a commercially available curved non-motorized treadmill (cNMT) to different incline grades on a motorized treadmill (MT). Ten male team-sport athletes completed, after a familiarization session, a 6-min run at a target velocity of 2.78 $m \cdot s^{-1}$ on the cNMT (cNMTrun). Mean individual running velocity of cNMTrun was then used as warm-up and experimental running velocity in three subsequent visits, in which participants ran for 6-min on the MT set at different grades (4%, 6% or 8%). The relationship between $\dot{V}O_2$ and MT grade was highly linear, and using linear interpolation, the concave curved design of the cNMT was estimated to mimic a 6.9 ± 3% MT grade. This was further evidenced by similar RPE responses between cNMTrun and the 6 - 8% MT grade trials. These findings can be used as reference value by athletes and coaches in the planning of cNMT training sessions, and amend running velocities accordingly.

1.4.4 Chapter 6: The effects of recovery duration on physiological and perceptual responses of trained runners during four self-paced HIIT sessions

This study examined the effects of different recovery durations on self-selected running velocities, physiological responses, and ratings of perceived exertion (RPE) in a commonly used high intensity interval training (HIIT) protocol. Twelve trained runners performed an incremental running test to determine maximum oxygen uptake ($\dot{V}O_2$max) and heart rate (HRmax). In four subsequent visits, participants performed a HIIT session comprising six 4-min work intervals, in which the recovery duration between work intervals equalled either a fixed (1MIN, 2MIN, 3MIN) or a self-selected duration (ssMIN). The results indicated that in a self-paced HIIT session, the length of recovery durations had a limited effect on the total physiological strain endured in the training, however, running velocities were higher when participants received the longest recovery period (3MIN). Longer recovery durations may facilitate a higher external training load (faster running), whilst maintaining a similar internal training load (physiological stimulus), and may therefore allow for greater training adaptations.

1.4.5 Chapter 7: The moderating role of recovery interval duration in simulated high intensity interval training sessions of trained cyclists

The total time spent at high percentages of $\dot{V}O_2$max ($\geq$ 90% ($t90\dot{V}O_2$max)) per high intensity interval training (HIIT) could serve as a good criterion to judge the effectiveness of HIIT protocols. This study compared the physiological and perceptual responses and accompanying exercise intensities to changes in the recovery interval durations. After completing an incremental cycling test, eleven male cyclists performed four HIIT sessions comprising six 4 min work intervals. Work intervals were separated by either 1, 2, 3 min or a self-selected recovery duration (1MIN, 2MIN, 3MIN, ssMIN respectively), and were performed under *'isoeffort'* conditions. No statistical differences were found in $t90\dot{V}O_2$max between protocols, however, participants spent a notable ~200 sec extra in $t90\dot{V}O_2$max in 1MIN compared to 2MIN, 3MIN and ssMIN. Power output (PO) across work intervals was higher in 3MIN and ssMIN than in 1MIN, and the decrease in PO between the first and final interval in 1MIN was greater compared to all other protocols. This study demonstrates a trade-off between the physiological stimulus and the external workload of a simulated HIIT session in cyclists.

1.4.6 Chapter 8: The moderating role of the recovery interval duration in predefined HIIT protocols is limited in team sport athletes – an intervention study

In the pre-season of contact team sports like rugby, a further increase in game-based conditioning might be undesirable considering potential injuries, and generic running HIIT might be beneficial to improve aerobic fitness. Prior to and immediately after a three week pre-season conditioning period, 25 collegiate rugby players performed 1) an incremental run test and 2) a time to exhaustion test. All participants completed a training program prescribed by the club, with no additional HIIT (CON), or an extra five HIIT sessions. These sessions comprised six 4-min work intervals, separated by either 1-min (1MIN) or 3-min (3MIN). The physiological load in the HIIT sessions of 1MIN and 3MIN was similar when expressed as time $\geq$ 90% HRmax. The addition of 2-hr generic HIIT resulted in improvements in $\dot{V}O_2$max and increased time to exhaustion in 1MIN and 3MIN, but not significantly different between training groups. These results indicate that the duration of the recovery intervals in HIIT sessions, run on predefined exercise intensities, did not attenuate the magnitude of changes in these outcome variables.

Chapter 2:

Literature Review

Citation:

Schoenmakers, P. Hettinga, F. Reed, K. (2019). The Moderating Role of Recovery Durations in High-Intensity Interval-Training Protocols. *International journal of sports physiology and performance*, (00), 1-9.

Summary

High intensity interval training (HIIT) is by no means a new phenomenon, but instead a training concept long appreciated by endurance athletes to improve cardiorespiratory and metabolic functioning, and, in turn endurance performance. Over recent years, many studies have tried to optimize the work intervals of HIIT protocols. A demanding ‘work interval’ is needed to facilitate training adaptations, but a successful HIIT protocol can only be achieved when work bouts are separated by an adequate recovery interval. In order to work at the required exercise intensity during subsequent intervals, recovery intervals need to be long enough to accommodate the return to metabolic homeostasis. An imbalance between the demands of the work intervals and the recovery potential of the recovery intervals can lead to premature fatigue, which potentially reduces the number of planned intervals, or lowers the work intensity during subsequent intervals. Surprisingly little research is available, evaluating the moderating role of recovery durations in HIIT protocols. Manipulations in the recovery duration in repeated sprint training (RST), and sprint interval training (SIT) protocols results in different acute physiological and perceptual responses, and most likely in different training adaptations. In aerobic interval training (AIT), the physiological strain endured per training protocol appears not to be moderated by the recovery intervals, unless the recovery interval is too short and causes premature fatigue. Longer recovery durations in RST, SIT and AIT protocols facilitate a higher external training load (higher exercise intensities in work intervals), and may therefore allow for greater training adaptations.

2.1 A brief history of high intensity interval training in endurance sports

High intensity interval training (HIIT) is regarded a highly effective training modality to improve cardiorespiratory and metabolic functioning, and is common practice in training regimes of many athletes, particularly those involved in endurance events (14). HIIT sessions aimed at improving endurance performance have been used for almost a century. In a detailed historical review by Billat (47), training schedules of successful middle- and long distance runners were analysed. It was found that, for example, the training programs of Hannes Kolehmainen (3-time Olympic champion) and Pavoo Nurmi (9-time Olympic champion) included interval training close to, or above, their race pace (47). Interval training was further popularized by Emil Zatopek (3-time Olympic champion), who used interval training sessions that included running up to 100 x 400 m bouts interspersed by 200 m recovery. HIIT received its first scientific attention in the early 1920s when Hill invented the concept of athletes' 'maximum oxygen uptake' ($\dot{V}O_2$max) and oxygen deficit (48). It was in the 1960s when Åstrand and colleagues published their pioneering work on the acute physiological responses to HIIT, which created the scientific basis for long (16) and short duration (49) interval training.

2.2 HIIT terminology and subcategories

Since the early days of scientific research, the use of HIIT has evolved and multiple new training methods have emerged from both the applied field and the laboratory. Recently, Buchheit & Laursen (14) published a comprehensive review, detailing nine key components that influence the effectiveness of HIIT sessions. The work intensity, the duration of work intervals, the recovery intensity, and the duration of recovery intervals are the key factors of an interval training session, and, depending on the number of intervals performed, form the total workload of a HIIT session (16,17). Based on the duration and exercise intensities of work intervals, HIIT can be divided into multiple training forms or subcategories, for which many terms exist. In this thesis we will use and discuss the terms repeated sprint training (RST), sprint interval training (SIT) and aerobic interval training (AIT) as the three main subcategories of HIIT, each targeting different physiological, neuromuscular and mechanical adaptations (14).

2.2.1 Repeated sprint training & Sprint interval training

Repeated all-out (or sometimes labelled ‘supramaximal’(50)) sprint training has received a growing research interest, as it replicates the demands of maximal-intensity sprint efforts typically performed in field-based team sports and endurance sports (51,52). In practical terms, based on the duration of the sprints and the subsequent recovery duration, sprint training can be divided into either short (3 to 10-sec; RST) or long (15 to 30 s; SIT) sprints. Whilst not exclusively - certainly not in the final sprints of RST and SIT sessions - this type of HIIT is expected to utilize and trigger the anaerobic energy pathway for the production of adenosine triphosphate (ATP; (53)). Adaptations after RST and SIT are mostly attributed to improvements in neuromuscular signalling and peripheral O_2 utilization capacity (such as an increased skeletal muscle mitochondrial content and capillary density). Weston et al. (29) showed that a low-volume protocol of cycling SIT produced a moderate increase in $\dot{V}O_2$max of active non-athletic males (6.2% ± 3.1%), and active non-athletic females (3.6%; ± 4.3%). However, the effect of SIT on the $\dot{V}O_2$max of athletic males (baseline $\dot{V}O_2\text{max} \geq 60$ mL·kg·min^{-1}) was unclear (2.7 % ± 4.6 %), and low-volume SIT had an unclear effect on peak and mean sprint power in both males and females.

2.2.2 Aerobic interval training

HIIT incorporating long work intervals (up to 16 min) can be described as ‘aerobic interval training’ (AIT), as work intensities are undeniably high - but ultimately submaximal (54). In contrast to the anaerobic energy pathway utilized in RST and SIT, the ATP production in AIT sessions is dependent on a mix of energy from (primarily) the aerobic and (secondary) anaerobic energy systems (13). The longer work interval protocols elicit maximal oxygen uptake, or at least a very high percentage of $\dot{V}O_2$max, and may therefore provide a more effective stimulus for enhancing the $\dot{V}O_2$max compared to SIT (5). It was suggested by Thevenet et al. (55) that the time athletes spent in their ‘red zone’ per AIT could serve as a good criterion to judge the effectiveness of a protocol. The ‘red zone’ refers to the intensity domain close to $\dot{V}O_2$max (≥ 90% $\dot{V}O_2$max) in which the oxygen delivery and utilization systems are maximally stressed, a near to maximal cardiac output is attained, and it is thought that more (type II muscle fibres) motor units are recruited (14).

2.3 Optimizing HIIT protocols – Considerations for HIIT prescription

Whilst the dose response relationship between the time spent at or near VO_2max (*t*90$\dot{V}O_2$max, (28)) per HIIT sessions and subsequent improvements in physical capacity and performance is unclear, sport scientist have strived to optimize HIIT protocols in general, and AIT specifically in a way that athletes maximize *t*90$\dot{V}O_2$max per session. In the next section, we review how manipulations in the different key components of AIT are previously studied in attempts to construct an optimal AIT session. When it comes to the manipulations of the recovery duration, next to its importance in AIT sessions, we further review the moderating role of this key component in RST and SIT.

2.3.1 Prescription of the exercise intensity in work intervals

In an attempt to individualize HIIT programmes, the speed or power output associated with $\dot{V}O_2$max (*v*$\dot{V}O_2$max and *p*$\dot{V}O_2$max respectively) are shown to be useful reference intensities (56,57). In theory, *v*$\dot{V}O_2$max and *p*$\dot{V}O_2$max are the lowest exercise intensities that elicit $\dot{V}O_2$max, and therewith integrate a measure of both $\dot{V}O_2$max and the energetic cost of running / cycling into a single factor (14). It was suggested by Åstrand et al. (16) that the exercise intensity of work intervals in AIT sessions does not need to be maximal to elicit $\dot{V}O_2$max, because $\dot{V}O_2$ is likely to increase after repeated exercise bouts with the development of a $\dot{V}O_2$ slow component. Research suggests that for longer duration intervals, an exercise intensity that corresponds to approximately 80 - 90% of an individuals' maximal workload can elicit physiological responses ≥ 90% $\dot{V}O_2$max (21,58,59).

Multiple training studies examined the effectiveness of individualized protocols in both running and cycling. In only one study (35), improvements were shown in $\dot{V}O_2$max in already highly trained runners, after 8 – 12 training sessions, using 50 – 70 % *t*Lim as interval duration (*t*Lim is the time to exhaustion when athletes ran on *v*$\dot{V}O_2$max). Other studies in incorporating individualized protocols failed to influence $\dot{V}O_2$max (60–63). However, despite no improvements in $\dot{V}O_2$max, runners improved 1500 m (62), 3000 m (35,60), or their *v*VO_2max (61,63), which all highlight improvements in endurance performance. In less trained runners, $\dot{V}O_2$max increased using similar protocols (64–67). This improvement was often accompanied by improvements in *v*VO_2max and / or timed running performance (66,67). Although the use of individualized interval intensities and interval durations proved to be successful in lab settings, it has to be acknowledged that (especially in running research) *v*VO_2max appears to be inversely related to the terrain or treadmill slope (68) and therefore has a limited ecological validity.

A more generic training protocol that has been adopted in running research is the so called '*Helgerud protocol*' (69,70). In this protocol, the exercise intensity in work intervals is based on an athletes' individual maximal heart rate (HRmax). In short, the interval training session consists of four 4 min running intervals at an exercise intensity of 90 – 95% HRmax, separated by periods of 3 min jogging at 50 – 70% HRmax (69). As little as five training sessions resulted in substantial improvements in 3000 m running performance (pre intervention time: 815 ± 123 s, post intervention time: 766 ± 93 s) in military recruits from Norway (71). The same protocol was shown to be effective at improving $\dot{V}O_2$max in junior elite football players (69,72) and in trained student populations (70,73,74). Although these studies were effective in improving performance and / or physiological capacity, the protocol has not been tested in highly trained participants. Furthermore, the use of heart rate (HR) to control or adjust exercise intensity in AIT may be limited. HR cannot inform the intensity of physical work performed above the speed / power output associated with $\dot{V}O_2$max. In an attempt to evaluate the physiological responses to a cycling based '*Helgerud protocol'*, Tucker et al. (75) showed that average power output was reduced by 20% from the first (226 ± 51 W) to the fourth work interval (179 ± 37 W). Despite this reduction in power output, HR still reached ~98% HRmax during the last three work intervals. The dissociation between HR, $\dot{V}O_2$, blood lactate concentration ([BLa]) and exercise intensities limits the ability to accurately estimate intensities during AIT sessions using HR alone. This is mostly due to the HR lag at exercise onset, which is much slower compared than the $\dot{V}O_2$ response (76). With this considered, the average HR over a work interval would underestimate the actual effort. Further, the HR inertia at exercise cessation (i.e. HR recovery) can also be problematic in this context, and this can create an overestimation of the actual work / physiological load that occurs during recovery periods (77,78).

A third commonly used method to prescribe the exercise intensity in interval training sessions, is using the ratings of perceived exertion (RPE, (79,80)). In this approach, coaches or scientists generally prescribe independent variables such as the duration of work and rest intervals (22), in which the athletes then can self-regulate their exercise intensity based on their perceived effort. In a recent study by Seiler et al. (42), participants were instructed to complete their AIT sessions at ’the maximal tolerable cycling intensity’ for respectively four 16 min, four 8 min or four 4 min intervals. Post intervention analysis showed that training sessions were performed at 88 ± 2, 90 ± 2, and 94 ± 2% of HRmax, in the 16 min, 8 min, and 4 min groups respectively. Both the ’16 min’ and ‘8 min’ groups improved $\dot{V}O_2$max, whilst all groups increased their peak power output (PPO). In another study (81), there was no improvement in the $\dot{V}O_2$max or PPO of trained cyclists after six training sessions incorporating three 4 min work intervals, also based on the maximal sustainable effort. However, a 2.3 ± 4.2% improvement in 16.1 km time trial performance showed the usefulness of this RPE based short training intervention. Although more research is needed comparing RPE training to HR based and / or individualized training protocols, RPE appears be a good ‘exercise regulator’, which controls for day-to-day variations in fitness levels and environmental conditions (14). The RPE method does have some limitations, since it is does not allow the precise manipulation of the physiological response to a given AIT session. Exemplary for this delicate relationship, Tucker et al. (75) evidenced that RPE increased from ~5 – 6 during the first minute to ~7 – 8 during the fourth minute (in a 4 min work interval), despite the aforementioned 20% reduction in exercise intensity from the first to the last minute. There is also evidence to suggest that the ability to adjust exercise intensities based on RPE may be fitness (82) and / or exercise intensity dependent (83). This in fact could limit the ability to target a specific adaptation, and might constitute to a suboptimal pacing in AIT sessions. It is widely recognized that an athlete's 'pacing strategy', or how an athlete distributes work and energy throughout an exercise task, can have a significant impact on performance (84). Earlier research highlighted the negative effects on work intensities later on in AIT sessions, when the initial work intervals in simulated AIT sessions were performed on (retrospectively) too high work rates (39,85). It can be assumed that experienced / trained athletes are likely more attuned to internal pacing cues, and are able to maintain high and stable work intensities throughout AIT sessions. To successfully implement *isoeffort* AIT training (and mainly avoid poor pacing in the initial work intervals of AIT sessions), preventive instructions on ‘attainable’ target intensities can help athletes to perform better in these sessions.

2.3.2 Prescription of the duration of work intervals

If $\dot{V}O_2$max is to be reached during the first interval of a sequence, logically, the duration of work intervals must at least be equal to the time needed to reach $\dot{V}O_2$max. Although trained subjects are unlikely to reach $\dot{V}O_2$max in their first interval bout (86), an adequate warm up may accelerate $\dot{V}O_2$ kinetics, and so, decrease the time needed to reach $\dot{V}O_2$max (87). The time needed to reach $\dot{V}O_2$max is affected by exercise intensity (88), training status (89,90), and is accelerated during running compared to cycling exercise (90,91). Even with these possible confounders considered, the time needed to reach $\dot{V}O_2$max remains highly variable and has a high inter-subject variability. For instance, Hill & Rowell (58) reported that in single isolated runs, $\dot{V}O_2$max was achieved after 234 ± 49 s (range 157 – 301 s, coefficient of variation (CV) = 21%) and maintained for 56 ± 48 s (range 10 – 155 s, CV = 86%) in 12 of 13 trained females, running at their individual $v\dot{V}O_2$max. In contrast, $\dot{V}O_2$max was attained by only 6 of 11 recreationally active runners after 155 ± 48 s (range 113 – 233 s, CV = 31%) and then maintained for 82 ± 28 s. (range 20-93 s, CV = 34%) (92). These results (58,92) not only highlight the variation in the time needed to reach $\dot{V}O_2$max, but also show a large variation in the time to exhaustion (TTE) when $\dot{V}O_2$max is attained.

Fixed work durations are most commonly prescribed by sport scientists or coaches. Depending on the intensity of the work interval and training status, athletes are able to perform exercise around their $\dot{V}O_2$max for ~10-min (18,56), when adequate recovery intervals are present. In an attempt to identify the optimal duration of work intervals, Stepto et al. (23) modelled the duration of work intervals as a polynomial function, after analysing the effects of five different training interventions on 40 km time trial performance. The polynomial function predicted a maximum enhancement in performance after work bouts of 3 - 6 min and an intensity of ~85% PPO. These findings were supported by Seiler & Sjursen (22), who reported that a work duration of 4 min approximated an optimal duration for achieving peak cardiovascular responses under self-paced conditions in male runners. These findings were later evidenced by Laurent et al. (2014) assessing female runners. However, another study by Seiler et al. (42) showed a greater increase in physiological capacity when AIT sessions consisted of four 8 min intervals compared to four 4 min intervals. Although the total training time between these two training groups differed, which might have influenced the magnitude of adaptations, an interval duration of 8 min (performed on 90 + 2

% HRmax) showed an appropriate stimulus and in fact strengthens the descriptive findings of Billat & Koralsztein (56) and Billat et al. (94).

As an alternative to using fixed work durations, using 50 - 70 % of *t*Lim at $v\dot{V}O_2max$ / $p\dot{V}O_2max$ has been suggested as an alternative to individualize AIT (21,35). While the rationale of this approach is sound, *t*Lim is only a moderately reliable measure (95), and there in not a strong link between *t*Lim and the actual time to reach $\dot{V}O_2max$ (96). Finally, intervals lasting over 70% *t*Lim are extremely hard to execute (14). In the prescription of work duration, it appears more logical to use the time needed to reach $\dot{V}O_2max$ to individualize interval length instead of fixed percentage of *t*Lim (e.g. time needed to reach $\dot{V}O_2max$ + 1 to 5 min). If no data on *t*Lim are available, it has been suggested to use intervals of between 4 – 6-min to maximize cardiovascular responses (22,23,93).

2.3.4 Prescription of the intensity of recovery intervals

There is a general belief that active recovery leads to better performance during subsequent periods of high-intensity exercise compared to passive recovery (14). Performing active recovery between interval bouts is appealing to reduce the time needed to reach $\dot{V}O_2max$ and in turn, induce a higher fractional contribution of aerobic metabolism to the total energy turnover in the next work interval (28,97).

In attempts to determine the optimal recovery intensity, multiple studies investigated the acute responses to manipulations in recovery intensity in isolated training sessions, but results are equivocal. Dorado et al. (97) showed that the sum of work performed in maximal sustainable cycling intervals was respectively 13% and 9% greater after active recovery (20% $\dot{V}O_2max$) between work interval bouts, compared to passive recovery or stretching. In a later study, Menzies et al. (25) showed a decrease in accumulated [BLa] when treadmill running at 90% $v\dot{V}O_2max$ was followed by active rather than passive recovery. However, they reported that active recovery at 80 – 100% of the individual lactate threshold (LT, i.e. at or just below LT) was more effective than active recovery at lower exercise intensities (25). Although [BLa] does not have a direct relationship with performance capacity (98), the proposed recovery intensity of Menzies et al. (25) around LT (~75% $\dot{V}O_2max$), is considerably higher than suggested by Dorado et al. (97). Independent of the prescribed recovery intensity, the current understanding is that an active recovery can lower muscle oxygenation (99), impair the re-synthesis of phosphocreatine (PCr) and trigger an increased anaerobic engagement during the following work intervals (100). All these processes exacerbate metabolic and acid–base disturbances, and can hypothetically augment subsequent training adaptations (46). However, although active recovery at relatively high intensities is shown to be theoretically favourable, in practice, it is physically and psychologically difficult to apply for the majority of athletes (14). When moderately trained runners were asked to self-select the intensity and duration of their rest interval during a six 4 min sequence (running intensity 85% HRmax), they choose to walk for about 2 minutes (77). The results of studies that adopted self-paced training sessions, incorporating a teleoanticipatory approach (101), highlight the discrepancy between scientific optimal results and the practical usefulness and feasibility of these results in a ‘real world’ training session. Active recovery might have physiological benefits, but as claimed by Buchheit & Laursen (14), passive recovery might be more realistic in recovery intervals.

2.3.4 Prescription of the duration of recovery intervals

A multitude of approaches are available for the prescription of recovery intervals in AIT sessions. The most common approach is the use of a fixed work:recovery ratio (i.e., W:R ratio = 2:1, 1:1, 1:8). A fixed W:R ratio separates work intervals by an *a priori* set recovery duration, for instance, when W:R ratio = 1:2, the recovery duration is twice the duration of the work interval.

In an attempt to individualize recovery intervals, the return of HR to a set threshold value or to a percentage of HRmax is used (10,21). However, the present understandings of the determinants of HR recovery suggest that this practice is not appropriate in the prescription of recovery durations (78), as HR is neither related to systemic O_2 demand nor muscular energy turnover, but rather influenced to the magnitude of the central command and metaboreflex stimulations (14,78). This was for instance evidenced by Edwards et al. (101), who reported decreases up to ~10 - 15 s for each 1000 m running effort in five·1000 m repeats when recovery intervals where based on HR return, compared to a W:R ratio = 1:1 protocol, of which the latter resulted in ~80 s extra recovery time between repetitions.

Lastly, a number of studies have used self-selected (SS) recovery durations in HIIT protocols, in which athletes started subsequent work intervals when they felt ‘adequately recovered to exercise at the required intensity’ (77,101–105). While a considerable amount of variation was evident in SS recovery durations across different HIIT protocols, and SS recovery time selection is potentially dependent on maturation status (102,105), the current understanding is that athletes can adequately select recovery durations to achieve the required exercise intensities in subsequent work intervals in both RST and SIT (see **Figure 2.1**) and AIT protocols (see **Figure 2.2**). Athletes new to the use of SS recovery intervals will likely choose a ‘shorter than optimal’ recovery time, as common HIIT protocols typically incorporate ‘short’ recovery durations (e.g. a 1000 m work : 200 m recovery sequences equates to 3 - 4 min work intervals, separated by 1 - 2 min recovery intervals), which potentially compromises training effects.

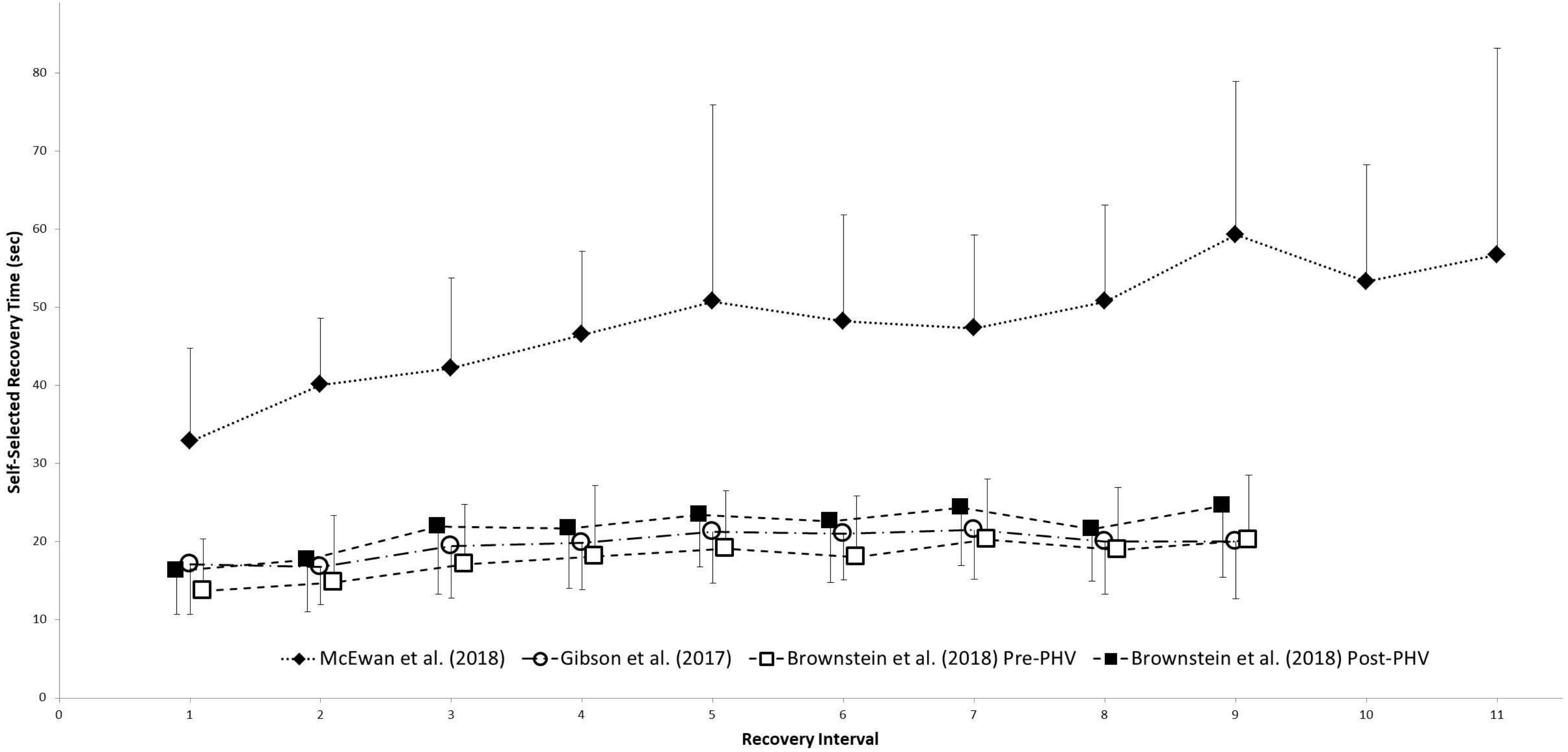


Figure 2.1: Self-selected recovery duration between 12 x 30 sec (103) , or 12 x 30m (102,105) intervals (mean ± standard deviation)

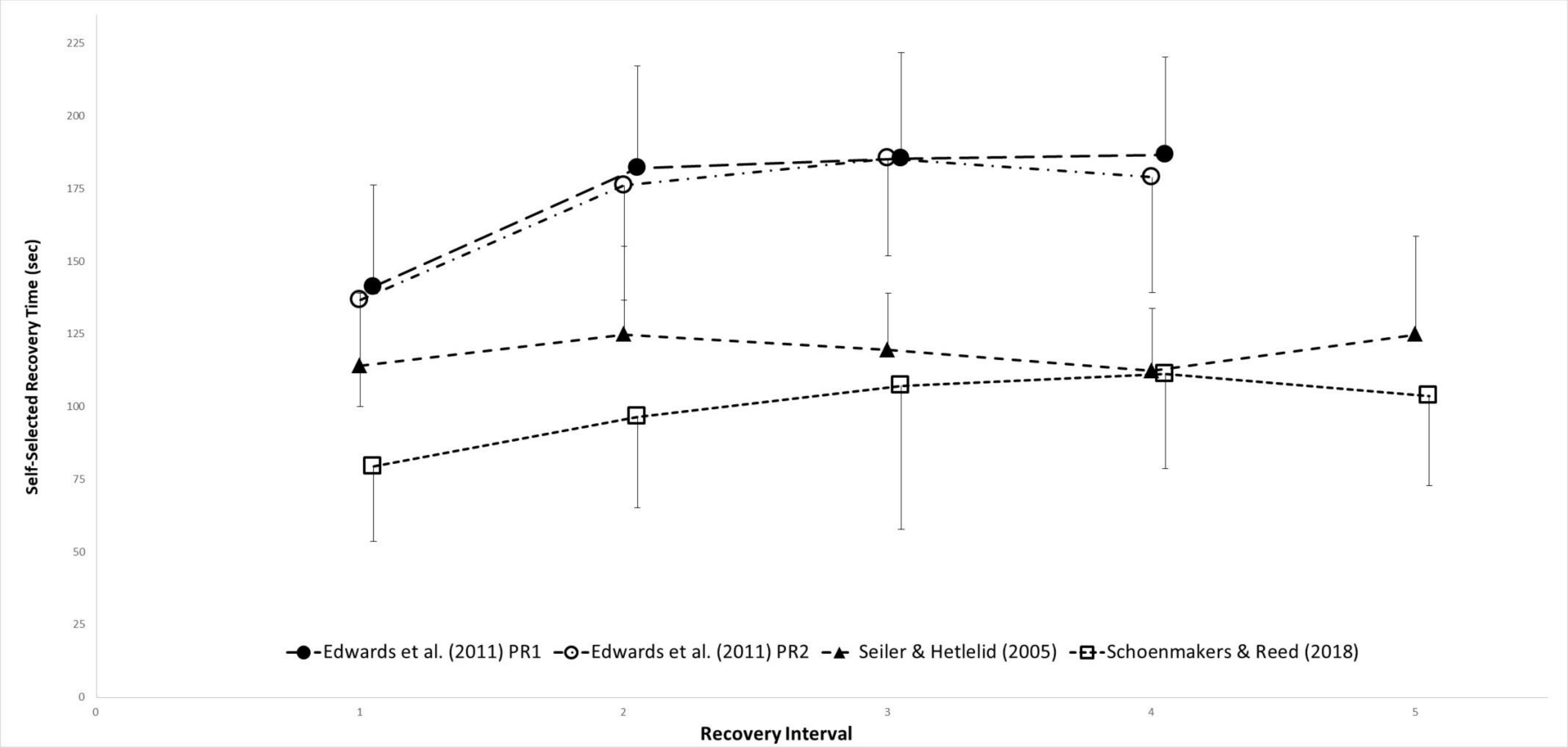


Figure 2.2: Self-selected recovery duration between 6 x 4 min (77,104) , or 5 x 1000m (101) intervals (mean ± standard deviation)

2.4 The moderating role of recovery intervals in HIIT sessions

The acute responses to manipulations in recovery durations in RST, SIT and AIT protocols have recently begun to receive scientific interest however, limited studies have manipulated only the recovery duration in RST, SIT or AIT protocols to analyze the role of recovery durations on long term training adaptations (see **Table 2.1**).

In RST, a positive effect on performance in subsequent 4 – 8 s supramaximal sprints in cycling power (106–109) and running speed (110,111) has been reported when longer recovery durations were employed. Longer recovery intervals resulted in a lower average HR and $\dot{V}O_2$ over the training session (106,107,109,112). Further, the fatigue index (percentage decline between PPO first and last sprint), [BLa] and RPE were lower when sprints were interspersed with longer recovery intervals (107,111), which was accompanied by a greater muscular re-oxygenation (112).

In SIT protocols, similar beneficial performance outcomes were reported across a multitude of exercise modalities when recovery duration was increased between work intervals (103,113–115). McEwan et al. (103) compared the acute physiological responses and running performance in 12 × 30 s sprints, wherein the recovery duration was either fixed (30 s) or SS. SS recovery time increased over the protocol (see **Figure 2.1**) and averaged 51 ± 15 s. The longer recovery intervals in SS resulted in a reduced time ≥ 90% HRmax, but facilitated the attainment of significantly higher running speeds. In agreement with these findings, Gosselin et al. (116) reported a decrease in mean and peak $\dot{V}O_2$ and mean HR in a SIT protocol alternating 60 s work intervals with 60 s recovery, compared with 30 s recovery intervals. Less than 30 s recovery between ‘all out’ sprints seems to have a detrimental effect on power production in subsequent cycling sprints, whereas the aerobic demand in sprints separated by 120 s recovery are too low to induce endurance adaptations (114–116). Kavaliauskas et al. (115) therefore suggested 80 s recovery intervals between sprints are optimal when targeting both power and endurance adaptations.

When it comes to the moderating role of recovery durations in AIT sessions, previous research showed that trained runners reach a steady state of around 90 - 95% $\dot{V}O_2$max / HRmax across repeated 4 min work intervals, independent of an increased recovery duration between bouts. (41,77,93,104) Both Smilios et al. (41) and Schoenmakers & Reed (104) reported changes in the O_2 and HR kinetics when recovery durations increased (more so, mean response time was faster when intervals started from a lower metabolic rate), resulting in similar time spent ≥ 90% and 95% $\dot{V}O_2$max and HRmax between the different recovery durations, suggesting a comparable physiological load of the AIT protocols (41,104). Increasing the recovery duration from 1 to 4 min did not significantly affect [BLa] responses following each 4 min work intervals in runners, suggesting a balance between lactate production and lactate buffering capacity (77,93). In a study where participants were working at a greater intensity, a greater [Bla] was evident when six 2 min cycling intervals were separated by either 1 min or 3 min passive recovery intervals. (46) The shorter recovery intervals induced a lower post exercise PCr content, however, these larger perturbations in muscle metabolites did not result in greater training adaptations in $\dot{V}O_2$max or PPO between the training groups (46).

Using self-paced AIT protocols, in which work intensities were not predefined but rather determined by the integrative outcome of feedback from external and internal receptors, multiple research groups (77,93,101,104,117) have evaluated running performance across work intervals. In highly trained runners, increasing the recovery duration between repetitions in a ten 400 m sequence (60 vs. 120 vs. 180 s) resulted in a lower RPE (117). Trained male (77), and recreational active male and female runners (93) were able to increase their mean running speed in six 4 min intervals when the recovery duration was increased from 1 min to 2 min. A further increase in recovery duration (4 min) did not provide extra performance benefits for trained runners (77), however, Laurent et al. (93) reported an additional increase in running speed when extra recovery time was available in lesser trained participants. Schoenmakers & Reed (104) reported the highest mean running speed when six 4 min intervals (ran on a curved non-motorized treadmill) were separated by 3 min, compared to 1 min, 2 min or a SS recovery interval. These results overall indicate that adequate recovery will result in the attainment of the desired work intensity within the limits and requirements of a specific protocol, however, the ‘optimum’ recovery duration, most likely is highly individual and depending on training status.

2.5 Conclusion and future research directions

In RST and SIT protocols, longer recovery intervals ($\geq$ 80 s) facilitate higher work intensities in subsequent sprints and lower the fatigue index, whereas a shorter recovery duration in these protocols increases the overall physiological demands of a training session (114,115). The current understanding is that training at higher workloads in RST and SIT protocols elicit greater adaptations in PPO and $\dot{V}O_2$max, however, this has only been evidenced in cycling protocols. Long recovery intervals in AIT protocols allow athletes to attain higher workloads (speed or power) in successive work bouts when exercise intensities are not fixed, without compromising the overall physiological stimulus of a training session (77,93,104). Training at higher workloads may allow for greater training adaptations, however, this is to be determined in future research. When work intensities are fixed in AIT protocols, the same training sessions is typically completed with a lower RPE when longer recovery intervals are available, again, without compromising in the physiological stimulus (41,46,117). Ultimately, depending on the exercise intensities of work intervals, a recovery interval of 3 min is expected to be sufficient to avoid premature fatigue in AIT protocols. Further empirical evidence on a variety of RST, SIT and AIT protocols in exercise modalities other than cycling are needed to fully determine the moderating effects of recovery duration in HIIT sessions.

Table 2.1: Summary of participant and training characteristics of studies evaluating the moderating role of recovery durations in RST, SIT or AIT protocols

Study	Sample Size, Age	Exercise Modality	High Intensity Interval Training Protocol	Recovery Duration	Key Findings
Repeated Sprint Training					
Baker et al. (107)	n = 8 26.6 ± 7.8	Cycling	Participants performed 8 × 6 sec sprint on a cycling ergometer against 0.75 $g.kg^{-1}$ FFM or TBM	30 s 1MIN	AR: Peak power output was higher in both the FFM and TBM conditions in 1MIN vs 30 sec, accompanied by a significantly lower fatigue index. HR was higher in both 30 sec protocols, with no differences in RPE and end [Bla] measures evident.
Brownstein et al. (105)	pre-PHV: n = 14 12 ± 0.4	Running	Participants performed a repeated sprint sequence twice, comprising 10 × 30 m efforts (~5 sec)	30 s SS	AR: Recovery duration in SS significantly shorter (~12 sec). Mean sprint time faster in 30 sec, accompanied by smaller performance decrement. Mean and peakHR higher in SS.
	Post-PHV: n = 14 14 ± 0.5				AR: Recovery duration in SS significantly shorter (~8 sec). Mean sprint time faster in 30 sec, accompanied by smaller performance decrement. Mean and peakHR higher in SS.
Gibson et al. (102)	n = 11 14 ± 1	Running	Participants performed two repeated sprint assessment of 10 × 30 m sprint efforts (~5 sec)	30 s SS	AR: Training sequence shorter in SS, as SS recovery duration is significantly shorter (~10 sec). Mean sprint time significantly faster in 30 sec. No differences in peakHR, [Bla] and RPE.
Glaister et al. (106)	n = 25 20.6 ± 1.5	Cycling	Participants completed 20 × 5 sec maximal sprints on a friction-braked cycle ergometer	10 s 30 s	AR: Peak (~4%) and mean (~26%) power output higher in 30 sec, with lower measures of fatigue, RPE and end [Bla]. Contrary, VO_2, RER and HR measures were higher in 10 sec in both the work and recovery intervals.
Lee et al. (108)	n = 14 18.7 ± 0.8	Cycling	Participants completed two intermittent sprint cycling tests (ISCTs), which were composed of 12 × 4 sec sprints. Tests were separated by 4 min active recovery	20 s 90 s	AR: Peak and mean sprint power in both ISCTs higher in 90 sec vs 20 sec, with a lower fatigue index and RPE score. End [Bla] higher in 20 sec.
Ohya et al. (112)	n = 8 25.5 ± 2.6	Cycling	Participants performed 10 maximal 5 sec sprints interspersed with either active recovery (ACT, cycling at 40% VO_2max) or passive recovery (PAS, sitting)	25 s 50 s 100 s	AR: Mean and peak power decrement over sprints was lowest in 100 sec and, independent of ACT/PAS, inversely related to recovery time. Mean VO_2 and [Bla] were higher in 25 sec > 50 sec > 100 sec, whilst muscular reoxygenation was lower in 25 sec.
Padulo et al. (111)	n =17 16 ± 0	Running	Participants completed three testing sessions, in which they performed six maximal 40 m shuttle sprints (20+20 m with a 180º change of direction, ~6 sec)	15 s 20 s 25 s	AR: Total sprint time was ~3% faster in 25 sec compared to 15 sec, and ~1.3% compared to 20 sec. [Bla] and fatigue index were highest in 15 sec, followed by 20 sec, and lowest in 25 sec.
Shi et al. (109)	n = 13 26.2 ± 6.2	Cycling	Participants finished three RST protocols, consisting of 40 x 6 sec all-out sprints on a cycling ergometer (with resistance equating 7.5% body mass)	15 s 30 s 1MIN	AR: Peak and mean power output was higher in 1MIN compared to 15 sec and 30 sec, with a notable lower RPE. Accumulated time ≥ 80% and 90% $\dot{V}O_2$max increased as recovery time decreased, however, for HR this was only evident in time ≥ 95% HRmax.
Sprint Interval Training					
Gosselin et al. (116)	n = 8 23.1 ± 2.1	Running	Participants performed 2 different training protocols , in which they exercised at a workload corresponding to 90% $\dot{V}O_2$max for 60 sec	30 s 1MIN	AR: Mean and peak VO_2 and HR significantly higher in 30 sec compared to 1MIN, with no differences in RPE. Both protocols failed to achieve 90% $\dot{V}O_2$max.
Hazell et al. (114)	n = 48 24 ± 3.2	Cycling	Participants completed 2 weeks of SIT (3 sessions a week), in which they performed 4-6 'all out' sprint of either 30 sec (G1) or 10 sec (G2 & G3), against 100 $g.kg^{-1}$. CON did not receive SIT	G1: 4MIN G2: 4MIN G3: 2MIN	AR: Peak and mean power output in sprints higher in G2 & G3, whilst G1 performed more total work. TA: Improvements in 5 km TT were similar between groups, whereas the increase in VO2max and mean and peak Wingate power output were higher in G1 & G2 compared to G3 and CON.
Iaia et al. (110)	n = 13 18.5 ± 1	Running	Participants completed nine SIT sessions, which focussed on speed endurance production (SEP; n = 6) or speed endurance maintenance	SEP: 2MIN SEM: 40 s	AR: Mean running speed were higher in SEP sprints compared to SEM, with a lower decrement in speed across subsequent sprints. TA: SEM improved their 200-m sprint time, distance covered in Yo-Yo test increased 10.1% after SEP and 3.8% after SEM.

(SEM; n = 7). Both SEP and SEM consisted of 6–8 reps of 20 sec all-out sprints

Table 2.1: Continued

Study	Sample Size, Age	Exercise Modality	High Intensity Interval Training Protocol	Recovery Duration	Key Findings
Kavaliauskas et al. (115)	G1: n = 8, 41 ± 12 G2: n = 8, 38 ± 7 G3: n = 8, 42 ± 6	Cycling	Participants completed a total of six SIT sessions over a two week period. The SIT protocol consisted of six 10-second "all-out" cycling efforts against a resistance equalling 7.5% of body weight. CON received no SIT	G1: 30 s G2: 80 s G3: 2MIN	AR: Average HR was greater in G1 compared with G3 for all training sessions, and was greater in G2 compared with G3 for training sessions 1 and 2. TA: All three training groups increased 3km TT to a similar extent. $\dot{V}O_2$max increased in G1 & G2, but not in G3. Mean and peak Wingate power output increased after G2, whereas G3 only increased their mean power output.
McEwan et al. (103)	n = 14 30 ± 7	Running	Participants performed 12 × 30 sec running intervals at a target intensity of 105% MAS.	30 s SS	AR: Mean recovery duration longer in SS (~21 sec). Relative time ≥ 105% MAS and mean running speed greater in SS, whereas time ≥ 90% HRmax was higher in 30 sec compared to SS . No differences in end [Bla] or RPE.
Toubekis et al. (113)	n = 16 21.2 ± 0.6	Swimming	Participants completed eight repetitions of 25-m sprints (~15 sec), followed by a 50-m sprint test 6 min later. Recovery was either ACT or PAS.	45 s 2MIN	AR: Mean swimming velocity faster in PAS for both recovery durations, and faster in 2MIN compared to 45 sec with no differences in end [Bla]. 50-m sprint times were 2.4% faster in both ACT and PAS 2MIN conditions vs 45 sec.
Aerobic Interval Training					
Edge et al. (46)	n = 5 21 ± 2	Cycling	Participants completed 6 × 120 sec intervals, on a power output corresponding to 92% $\dot{V}O_2$max	1MIN 3MIN	AR: Average HR in intervals higher in 1MIN vs 3MIN. 1MIN induced a greater end [Bla], H^+ and MLa content than 3MIN, while muscle PCr content was less after 1MIN.
Edge et al. (46)	G1: n = 6, 19 ± 1 G2: n = 6	Cycling	Participants performed a total 15 HIIT sessions over a 5 week period, consisting of 6 – 10 × 120 sec intervals at a workload of 92%-111% power output at $\dot{V}O_2$max	G1: 1MIN G2: 3MIN	TA: Significant increase in $\dot{V}O_2$max, PPO and power output at lactate threshold, to a similar extent in both G1 and G2. Improvements in repeated sprint performance were similar.
Edwards et al. (118)	n = 11 26 ± 7	Running	Participants completed a series of four (5 × 1000 m) track running sessions, each at the standardized perceived exertion of RPE 17.	SS_PR1 SS_PR2 HR130 W:R = 1	AR: Recovery significantly shorter in HR130, accompanied by a significant lower mean running velocity and greater fatigue index. Similar HR and end [Bla] between all experimental conditions.
Laurent et al. (93)	G1: n = 8, 20.8 ± 2.1 G2: n = 8, 21.9 ± 3.6	Running	Trained male (G1) and female (G2) runners completed three isoeffort (maximum sustainable intensity) training sessions, each comprising six 4 min interval	1MIN 2MIN 4MIN	AR: SS running velocity increased in both groups when longer recovery was available. Independent of recovery duration, mean VO_2, HR, [Bla] and RPE were similar across conditions in both G1 & G2. Relative exercise HR and VO_2 was higher in G2.
Laursen et al. (21)	G1: n = 8, 26 ± 6 G2: n = 9, 24 ± 7	Cycling	Participants performed eight AIT sessions over a 4 week period, comprising 8 intervals at Pmax for the duration of 60% Tlim	G1: W:R = 0.5 G2: 65HRmax	AR: G1 had a significantly greater total mean recovery time (~110 sec) between bouts compared with G2. Both groups completed ~64% of prescribed interval bouts. TA: Improvements in $\dot{V}O_2$max, PPO, and 40 km TT were similar between groups.

Table 2.1: Continued

Study	Sample Size, Age	Exercise Modality	High Intensity Interval Training Protocol	Recovery Duration	Key Findings
Seiler et al. (77)	n = 9 30 ± 4	Running	Participants performed three isoeffort (maximum sustainable intensity) training sessions, each comprising six 4 min intervals at a constant 5% treadmill incline.	1MIN 2MIN 4MIN SS	AR: Higher running velocity in 2MIN (85% $v\dot{V}O_2max$) and 4MIN (84% $v\dot{V}O_2max$) vs 1MIN (83% $v\dot{V}O_2max$). Higher mean VO_2 in 2MIN and 4MIN vs 1MIN. No differences in end [Bla], HR, or RPE.
Schoenmakers et al. (104)	n =12 34 ± 11	Running	Participants performed four isoeffort (maximum sustainable intensity) training sessions, each comprising six 4 min interval on a non-motorized treadmill	1MIN 2MIN 3MIN SS_PR1	AR: Running velocity significantly higher in 3MIN compared to all other protocols, and higher in SS_PR1 vs 2MIN. No significant differences in RPE responses, time ≥ 90% and 95% $\dot{V}O_2max$, or ≥ 90% and 95% HRmax.
Smilioset al. (41)	n = 11 22.1±1	Running	Participants executed, on three separate sessions, 4×4 min runs at 90% of MAS	2MIN 3MIN 4MIN	AR: Time ≥ 80 and 90% HRmax was higher in 2MIN and 3MIN compared to 4MIN, but did not differ for VO_2 measures. Peak HR and VO_2 were similar between conditions. RPE were higher in 2MIN and 3MIN vs 4MIN, as was 2MIN end [Bla].
Zavorsky et al. (117)	n = 12 24.8 ± 5.1	Running	Participants performed three interval running workouts of 10 x 400 m on a predefined running speed	1MIN 2MIN 3MIN	AR: Mean HR significantly higher in 1MIN, but no differences in peakHR between conditions. RPE increased with decrease in recovery time.

Age is presented mean ± standard deviation

Note: 1MIN; 1 min recovery; 2MIN; 2 min recovery; 3MIN; 3 min recovery; 4MIN: 4 min recovery; ACT: active recovery; AIT: aerobic interval training; AR: Acute responses; [Bla]: blood lactate concentration; CON: control group; FFM: fat-free body mass; H^+: Hydrogen; HR: heart rate; HR130: recovery duration based on HR return to 130 bpm; HRmax: maximum heart rate; ISCTs: intermittent sprint cycling tests; MAS: maximal aerobic speed; MLa: muscle lactate; PAS: passive recovery; PCr: phosphocreatine; peakHR: peak heart rate; Pmax: minimal power output to elicit $\dot{V}O_2max$; post-PHV: post peak height velocity; PPO: peak power output; pre-PHV: pre peak height velocity; RER: respiratory exchange ratio; RPE: ratings of perceived exertion; RST: repeated sprint training SIT: sprint interval training; SS: self-selected recovery duration; SS_PR1 & SS_PR2: self-selected recovery duration based on perceived readiness scale; SEM: speed endurance maintenance; SEP: speed endurance production; TA: Adaptations to a period of training; TBM: total body mass; Tlim: time to exhaustion at Pmax; TT: time trial; VO_2: oxygen consumption; $\dot{V}O_2max$: maximum oxygen consumption $v\dot{V}O_2max$: minimum running velocity to elicit $\dot{V}O_2max$; W:R = 1: recovery duration equal to work interval duration

Chapter 3:

The effects of aerobic interval training on $\dot{V}O_2$max and performance in runners and cyclists: A systematic review and meta-analysis

Summary

Based on the duration and exercise intensities of work intervals in high intensity interval training (HIIT), HIIT can be divided into repeated sprint training (RST), sprint interval training (SIT) and aerobic interval training (AIT). Previously, studies meta-analysed the effects of HIIT, RST and SIT on changes in $\dot{V}O_2$max, however, this far failed to isolate and evaluate the effectiveness of solely AIT. This study was carried out to provide a systematic review of running and cycling based AIT interventions, and meta-analyse their effects on changes in $\dot{V}O_2$max and / or performance outcomes. After an extensive review of the literature (PubMed and Web of Science databases), pooled estimates of effect sizes (ES, Hedges' *g*) across studies for change in $\dot{V}O_2$max (n = 57) and performance (n = 20) were calculated using an inverse-variance random effects model for meta-analyses. Standardised mean differences, showed a significant increase of small to moderate magnitude in $\dot{V}O_2$max (7.6%, ES = 0.54, CI: 0.38 to 0.69), which corresponds to an increase in relative $\dot{V}O_2$max of 3.07 $mL\cdot kg\cdot min^{-1}$. Improvements in $\dot{V}O_2$max were similar between cycling and running interventions, and were not moderated by baseline fitness. Performance improved by 4.0% after AIT, which was of a small to moderate magnitude (ES = -0.49, CI:-0.75 to -0.23). The results suggest that AIT improved $\dot{V}O_2$max and performance significantly more than moderate intensity continuous training, and whilst the underlying mechanisms of adaptations may differ, improved $\dot{V}O_2$max to a similar extent as SIT.

3.1 Introduction

High intensity interval training (HIIT) is by no means a new phenomenon, but instead a training concept long appreciated by athletes and coaches to improve cardiorespiratory and metabolic functioning, and, in turn the performance of endurance athletes (9,14,47). For instance, it was reported that Hannes Kolehmainen, a 1912 Olympic gold medal winner, used HIIT in his training program: he would run five to ten 1000 m intervals in just over 3 min at a velocity close to his specific competition velocity (9,47). In the 1950s, HIIT was further popularized by Emil Zatopek, who allegedly repeated up to 100 × 400 m repetitions per day at a pace close to that of his 5000 m running velocity (9,47), interspersed by 200 m of recovery. In HIIT, repeated periods of vigorous exercise are interspersed with recovery periods, which allows for a greater accumulated time at these vigorous exercise intensities than can be achieved during a single bout of continuous exercise at this intensity (15,17,18). The workload of a HIIT session is determined by a complex interplay between the number of intervals, the exercise intensities and the duration of both the work and recovery intervals (16,17), and with the manipulation both within and between these variables, HIIT protocols are infinitely variable.

Based on the duration and exercise intensities of work intervals, HIIT is typically differentiated in two categories to which we will refer in this study as sprint interval training (SIT) and aerobic interval training (AIT). SIT is characterized by short repeated ‘all-out’ or ‘supramaximal’ 8 - 30 sec sprints efforts, performed at exercise intensities equal to or greater than those that would elicit an athlete’s maximum oxygen uptake ($\dot{V}O_2$max). Contrary to SIT, AIT incorporates long intervals (1 - 16 min), in which exercise intensities are undeniably high - but ultimately submaximal. In this study, the term moderate intensity continuous training (MICT) is used for comparative purposes to describe exercise that is performed in a continuous manner and at lower intensities than both HIIT types (see **Figure 3.1 A-C**).

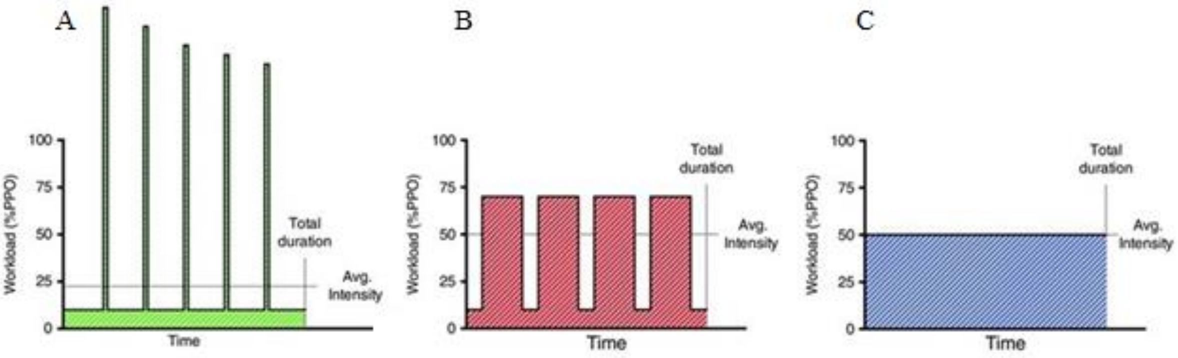


Figure 3.1: A graphical depiction of the main types of aerobic exercise, in which A–C are examples of A) sprint interval training (SIT), B) aerobic interval training (AIT) and C) moderate intensity continuous training (MICT). Workloads are depicted as a percentage of the peak power output (PPO) obtained during incremental cycling test. Figure adapted from MacInnis and Gibala (119)

Numerous retrospective studies evaluating athletes' training distributions, highlight that both HIIT and MICT are indispensable constitutes of successful endurance training programmes (for an extensive review see e.g. (7,11)), and both training modalities are important in the underlying physiological processes taking place that allow for increased physiological capacity (120,121). However, in trained athletes, an additional increase in the volume of MICT does not appear to further enhance $\dot{V}O_2$max, or other determinants of endurance performance (10,122,123), making HIIT a vital component of successful training programs. In patient populations, numerous meta-analytical reviews with a focus on HIIT have demonstrated superior outcomes compared to MICT for body composition (124,125), cardio-metabolic disease risk (126) and cardiorespiratory fitness (127,128). Additionally, HIIT was found similarly or more enjoyable than MICT (129,130), and given the shorter exercise time, HIIT is typically described a more time efficient training modality than MICT.

Whilst both aerobic and anaerobic energy systems are important for the provision of 'energy' (stored in the molecule adenosine triphosphate (ATP)) during any type of exercise (i.e., ATP consumption / ATP re-synthesis), SIT is typically considered to trigger and utilize the anaerobic energy system. Commonly, SIT protocols incorporate repeated 30 s Wingate sprints, of which it is estimated that 70 - 80% of the energy turnover is derived from anaerobic metabolism (131,132), and the oxygen uptake ($\dot{V}O_2$) only exceeds 90% $\dot{V}O_2$max during the last 5 - 10 s of each sprint (131). Recently, both Tucker et al. (75) and Follador et al. (133) showed that participants attained higher mean and peak $\dot{V}O_2$ and heart rate (HR) in

AIT sessions compared to time matched SIT protocols. AIT intervals are performed on exercise intensities close to $\dot{V}O_2$max, and in doing so contrary to SIT protocols, maximally stress the oxygen transport and utilization systems (14). Further data on the respiratory exchange ratio (RER; $\dot{V}CO_2$ / $\dot{V}O_2$) during repeated AIT work intervals, highlights the dependency on the aerobic metabolism for ATP re-synthesis in AIT, with RER values typically found to be under the unit value across intervals, indicating at least a partial reliance on fat oxidation for energy turnover (104,134,135). While the picture is far from complete, different mechanisms are ascribed to the improvements in aerobic capacity after AIT and SIT. It is now thought that AIT foremost improves skeletal muscle buffering capacity and the ability to sustain high-intensity exercise for prolonged periods (26,70,135), whereas improvements after SIT are attributed to an improved muscle oxidative potential (136,137). Given the higher endured physiological strain per HIIT sessions (75,133), AIT potentially provides a more effective stimulus to enhance $\dot{V}O_2$max than MICT and / or SIT (5,14).

Previously, multiple meta-analyses evaluated AIT in patient populations (138,139), however, limited knowledge on the effects of AIT in healthy, or trained subject is available. This gap in the literature was to some extent addressed by Bacon et al. (140) and Milanovic et al. (30), who both reported a moderate beneficial effect for longer HIIT intervals in the increase in $\dot{V}O_2$max. As a result of HIIT training programs, Bacon et al. (140) reported an average increase in $\dot{V}O_2$max of 0.51 $L \cdot min^{-1}$ (95% confidence intervals (CI): [0.43 to 0.60 $L \cdot min^{-1}$]). In a supplementary analysis, the protocols of nine studies that reported the largest mean increase in $\dot{V}O_2$max (0.87 ± 0.15 $L \cdot min^{-1}$) were compared to the nine studies that reported the smallest mean increase in $\dot{V}O_2$max (0.27 ± 0.05 $L \cdot min^{-1}$). Many of the nine studies reporting larger improvements, incorporated long work intervals (3 – 5 min), however, it was also evident that the total training interventions of these nine was longer (total training time 479 ± 246 vs 696 ± 264 min) and that exercise intensities of the work intervals were higher than in the nine studies showing the smaller increase (140). Whether the larger changes in $\dot{V}O_2$max therefore solely can be attributed to differences in interval duration is questionable, and may be further attenuated by potential differences in pre-intervention $\dot{V}O_2$max between the subgroups. This was recently evidenced by Milanovic et al. (30), who, compared with non-exercising control groups (CON), reported a large beneficial effect of HIIT on

$\dot{V}O_2$max (5.5 mL·kg·min^{-1} ± 1.2 mL·kg·min^{-1}), with a likely moderate greater increase for subjects with lower baseline fitness (3.2 mL·kg·min^{-1} ± 1.9 mL·kg·min^{-1}). Additionally, small additional improvements for typically longer HIT repetitions (2.2 mL·kg·min^{-1}; ± 2.1 mL·kg·min^{-1}) were evident. Where both meta-analysis of Bacon et al. (140) and Milanovic et al. (30) provide valuable information on the effectiveness of HIIT as a whole, they both fail to isolate and evaluate the effectiveness of AIT interventions separately. For instance, interventions alike the traditional Tabata protocol (141) and concurrent training program of Hickson et al. (142) were included in these studies (30,140). A meta-analysis on changes in $\dot{V}O_2$max after solely AIT interventions is therefore timely, and a further comparison between AIT vs MICT, and AIT vs SIT can provide valuable new insights in potential differences between these training modalities.

The primary aim of the current study was to provide a systematic review of AIT interventions and meta-analyse their effects on changes in $\dot{V}O_2$max. Next to this, we aimed to analyse the effects of AIT on changes in performance outcomes. $\dot{V}O_2$max is one, if not the main physiological factor determining endurance performance (143), however, improvements in performance can be achieved without an increase in $\dot{V}O_2$max. Improvements in $\dot{V}O_2$max are unlikely when highly trained athletes are subjected to AIT interventions, as it can be expected that they are already exercising close to their upper physiological limits, and the training times in AIT interventions are typically too short to improve the capacity of the cardiorespiratory system to deliver oxygen to the exercising muscles. Lastly, physiological responses are dependent on the exercise modality, and the amount of muscle mass involved (144). Therefore, similar AIT protocols using different exercise modes (e.g. running vs cycling) might result in different physiological responses, and therefore, divergent outcomes across studies. To avoid this possible confounding factor, the present study will evaluate changes in both running and cycling based AIT interventions together, but will also provide seperate analysis per exercise modality.

3.2 Methods

3.2.1 Experimental approach to the problem

This review was carried out in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines (145), and aimed to identify studies that examined changes in $\dot{V}O_2max$ and / or timed performance after a minimum of 4 running or cycling based AIT sessions. Ethical approval in eligible studies was verified before inclusion.

3.2.2 Literature search

With no date restrictions, an extensive search of the PubMed and Web of Science databases was conducted, along with the reference lists of peer-reviewed original research and review articles published in English. Search terms, individually or in conjunction with each other, included MeSH terms provided for ‘running’, ‘cycling, ‘high intensity interval training’, ‘HIIT’, ‘AIT’, ‘aerobic interval training’, ‘$\dot{V}O_2max$’, ‘oxygen uptake’, ‘aerobic capacity’, ‘endurance adaptations’ and ‘performance’. The initial search for this study was conducted in January 2017, and was updated monthly hereafter.

3.2.3 Study selection

Specific criteria determined the eligibility of studies for inclusion in this meta-analytical review. We focused on lab or field-based AIT interventions, with work interval lasting between 1 – 16 min. Studies in which AIT was combined with other interventions, other than low intensity endurance training, were excluded from analysis. No inclusion criteria were set for baseline fitness, but studies must include healthy, non-obese adult participants (BMI $\leq$ 30.0 kg/m^2). Baseline $\dot{V}O_2max$ was used to assign participants into four performance levels (PL1 – PL4), in which PL1 included studies with a mean reported $\dot{V}O_2max \leq 40.0$ mL·kg·min^{-1}, PL2 40.0 $\leq$ 50.0 mL·kg·min^{-1}, PL3 50.0 $\leq$ 60.0 mL·kg·min^{-1}, and PL4 $\geq$ 60.0 mL·kg·min^{-1}. PL allocation for studies only assessing performance outcomes (71,146–148), was based on indirect estimations of $\dot{V}O_2max$ from running velocities (149), or based on peak power output classification norms in cyclists (150).

After removal of duplicate records, study selection involved a review of all seemingly relevant article titles and was followed by an evaluation of article abstracts and, then, full published articles. After this, reference lists were searched (see **Figure 3.2**). Following the initial selection process, there were 349 potentially eligible studies. The final dataset combined 57 studies that comprised 69 individual AIT interventions evaluating changes in $\dot{V}O_2$max, and 20 studies providing 27 estimates for changes in performance after AIT. Descriptive statistics for studies included in the meta-analysis are presented in T**able 3.1** and **Table 3.2**.

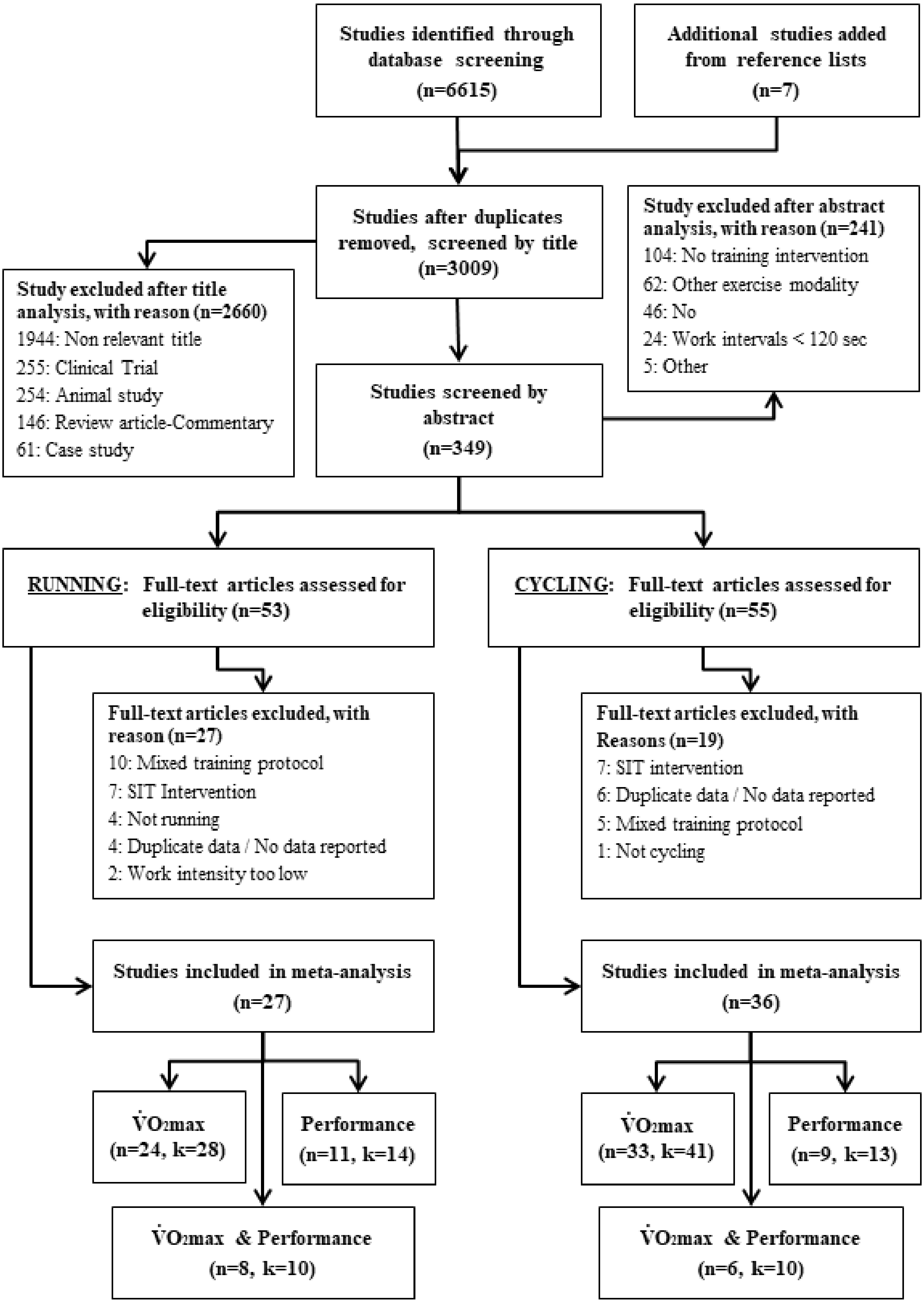


Figure 3.2: Flow diagram of study selection and screening process (n = number of studies, k = number of unique AIT interventions in the included studies)

3.2.4 Data extraction

Data extraction was undertaken by two reviewers (PS and KR). All data was collected by PS in a standardized spreadsheet, before KR verified its accuracy and the eligibility of studies for inclusion. Full text articles were assessed for mean pre and post AIT intervention $\dot{V}O_2max$ values (in $L \cdot min^{-1}$ or $mL \cdot kg \cdot min^{-1}$) and / or measures of performance time along with the associated standard deviations (SD) or standard errors of the mean (SEM). When performance on more than one distance was reported, the longest distance was included for comparison. Corresponding authors were contacted by email when insufficient data was reported, however, this yielded no responses. For several studies mean and SD were re-calculated from individual data, or calculated by converting SEM or interquartile range values to SD. Graph digitizer software (DigitizeIt, Braunschweig, Germany) was used to obtain data when only available in figures.

Besides $\dot{V}O_2max$ and / or performance values, data of the following potential moderators were extracted for each study: participant characteristics (sex, age, body mass), training parameters (work interval duration and intensity, recovery interval duration and intensity, the total number of work intervals per training sessions, number of training sessions).

3.2.5 Analysis and interpretation of results

The meta-analysis was carried out in RevMan version 5.3 (Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2014), using an inverse–variance random-effects model, with the level of statistical significance set at $p < 0.05$. This model allocates a proportionate weight to trials based on the size of their individual standard errors and facilitates analysis whilst controlling for heterogeneity across studies. A random effect model was chosen over a fixed model because of the wide variation in AIT protocols in the included studies. The main meta-analytical comparisons included a within group analysis of all estimates for $\dot{V}O_2max$ and performance outcomes (see **Figure 3.3** and **Figure 3.4**). Similar within group analyses were performed for MICT and SIT interventions. Percentage change between the pre and post intervention measures were calculated to estimate the impact of AIT, MICT or SIT interventions on both outcome measures. As a further measure to estimate the impact of AIT on $\dot{V}O_2max$, $\dot{V}O_2max$ data reported in $L \cdot min^{-1}$ were converted to $mL \cdot kg \cdot min^{-1}$, and weighted mean differences (WMD) were calculated and are presented next to the standardized mean differences (SMD). Notably, a negative percentage change in performance indicates an improvement in performance time.

Separate analysis were performed to determine the pooled effect of change in $\dot{V}O_2$max for studies comparing AIT vs MICT, AIT vs SIT or AIT vs CON. Mean and SD for post-intervention $\dot{V}O_2$max in experimental and control groups were used to calculate an effect size. Studies that did not incorporate a control group were excluded from this analysis in order to allow for differentiation of the effects. In case there was more than one AIT intervention group in a given study, the control group (either MICT, SIT or CON) was proportionately divided to facilitate comparison across all participants.

Effect sizes (ES) in all analyses are calculated and represented by Hedges' *g*, to account for small sample sizes, and are presented alongside [95% confidence intervals (CI)]. The calculated effect sizes were interpreted using conventions outlined by Hopkins et al. (151) i.e., < 0.2 = trivial; 0.2 – 0.59 = small, 0.6 – 1.19 = moderate, and 1.2 – 1.99 = large.

To identify potential sources of heterogeneity, moderator variables were determined and assessed. A summary of these can be seen in **Table 3.5**. Analysed with a random-effects model, moderator variables were selected based on differences in participant characteristics (gender) or training programme configurations that could influence outcome measures (duration work interval, duration AIT session, duration total AIT intervention, duration recovery interval, calculated work:recovery ratio (W:R ratio)). The duration of the work intervals, AIT sessions, and total AIT intervention were selected because longer training programmes could lead to sustained performance improvements (30,140,152), and the W:R ratio was evaluated because previously unclear effect were reported (30,152).

Study heterogeneity was confirmed via I^2 statistics. Higgins & Thompson (153) stated that low, moderate and high heterogeneity corresponds to I^2 values of 25%, 50% and 75%, respectively. In this study, no risk of bias quality scale was used to assess 'quality' of included studies. Studies of physical training have methodological constraints (e.g. blinding of participants, trainers and assessors), which can lead to lower scores relating to biases and study quality scores, making bias quality scales potentially inaccurate.

Table 3.1: Participant and training protocol characteristics of included studies evaluating changes in $\dot{V}O_2$max in cycling (C) or running (R) after AIT interventions

						Training Protocol									
Study	**[group identifier]**	**Group**	**n (female)**	**Age**	**Baseline $\dot{V}O_2$max**	**Reps**	**Work Intensity**	**Work Duration**	**Recovery Intensity**	**Recovery Duration**	**Work Duration (hr:min:sec)**	**Sessions**	**Total Training (hr:min:sec)**	**Δ $\dot{V}O_2$max**	**% Change**
Performance Level 1															
C - Dudley et al. (154)*		AIT	10 (?)	19.8 ± 1.0	38.8 ± 7.6	5	PPO	F, 300 s		F, 300 s	00:25:00	21	08:45:00	6.3	16.2%
C - Duffield et al. (155)		AIT	10 (10)	20 ± 4	2.30 ± 0.37	4 - 12	130 - 180% POlt	F, 120 s		F, 60 s	00:16:00	24	06:28:00	0.48	20.9%
C - Keramidas et al. (156)		AIT	10 (7)	22.7 ± 4.7	38.0 ± 5.5	7 - 9	90% PPO	F, 120 s	50% PPO	F, 120 s	00:33:00	18	09:54:00	-1.6	-4.2%
C - Naves et al. (157)		AIT	25 (25)	31.0 ± 6.0	37.7 ± 7.2	4	90 - 95% HRmax	F, 240 s	50 - 60% HRmax	F, 180 s	00:16:00	24	06:28:00	4.4	11.7%
		SIT	24 (24)	29.8 ± 6.4	32.0 ± 7.2	4	All Out sprint	F, 30 s	No load	F, 240 s	00:02:00	24	00:48:00	4.5	14.1%
C - Robinson et al. (158)		AIT	13 (?)	23.6 ± 3.7	38.9 ± 3.4	5	85 - 120% PPO	F, 120 s	Complete rest	F, 60 s	00:10:00	12	02:00:00	1.4	3.6%
		CON	8 (?)	21.0 ± 2.4	39.1 ± 4.5	CON continued their normal activity pattern								-0.2	-0.5%
C - Talanian et al. (159)*		AIT	7 (7)	22.1 ± 0.6	36.3 ± 10.5	10	90% $\dot{V}O_2$peak	F, 240 s		F, 120 s	00:40:00	7	04:40:00	4.6	12.7%
C - Tsai et al. (160)*		AIT	20	23.0 ± 7.6	34.0 ± 6.3	5	80% $\dot{V}O_2$max	F, 180 s	40% $\dot{V}O_2$max	F, 180 s	00:15:00	30	07:30:00	6.9	20.3%
		MICT	20	22.1 ± 4	33.1 ± 5.4	1	60% $\dot{V}O_2$max	F, 30 min			00:30:00	30	15:00:00	4.6	13.9%
		CON	20	22.5 ± 5.8	32.2 ± 4.5	CON did not undergo any extra exercise but were carefully monitored								2.9	9.0%
C - Walter et al. (161)*		AIT	19 (19)	21.7 ± 4.4	30.5 ± 5.1	5	90 - 115% PPO	F, 120 s		F, 60 s	00:10:00	18	03:00:00	4.9	16.1%
		CON	11 (11)	22.2 ± 4.1	32.3 ± 8.0	CON did not engage in exercise training or ingested any supplements								1.6	5.0%
C - Warburton et al. (162)		AIT	6	30 ± 5	38.7 ± 7.9	8 - 12	90% $\dot{V}O_2$max	F, 120 s	40% $\dot{V}O_2$max	F, 120 s	00:20:40	36	12:48:00	8.6	22.2%
		MICT	6	30 ± 4	40.4 ± 6.3	1	1% < POlt	F, 30 – 48 min			00:42:00	36	25:12:00	9.2	22.8%
		CON	8	29 ± 3	39.0 ± 7.8	CON maintained their normal physical activity habits								-0.2	-0.5%
C - Weber et al. (163)*	**[female]**	AIT	7 (7)	22.7 ± 6.9	2.55 ± 0.29	3	82.5 - 100% MAOD	F, 120 s		F, 360 s	00:06:00	24	02:24:00	0.07	2.7%
R - Sijie et al. (164)		AIT	17 (17)	19.8 ± 1.0	33.3 ± 3.9	5	85% $\dot{V}O_2$max	F, 180 s	50% $\dot{V}O_2$max	F, 180 s	00:15:00	60	15:00:00	2.8	8.4%
		MICT	16 (16)	19.3 ± 0.7	32.9 ± 4.7	1	50% $\dot{V}O_2$max	F, 40 min	-	-	00:40:00	60	40:00:00	1.6	4.9%
		CON	19 (19)	19.5 ± 0.8	32.8 ± 4.1	CON maintained their individual habits of physical activity and refrained from any other forms of prescribed exercise training								0.8	2.4%
R - Tsekouras et al. (165)*		AIT	7	[20 - 40]	36.7 ± 7.1	4	90% $\dot{V}O_2$max	F, 240 s	60% $\dot{V}O_2$max	F, 240 s	00:16:00	24	06:24:00	7.2	19.6%
		CON	8		39.8 ± 5.6	CON maintained their normal physical activity habits, and completely refrained from exercise during the last week								-1.4	-3.5%
Performance Level 2															
C - Edge et al. (166)*		AIT	10 (10)	19 ± 1	42.8 ± 6.3	4 - 10	120 - 140% POlt	F, 120 s		F, 60 s	00:14:00	15	03:34:00	5.3	12.4%
		MICT	10 (10)		41.5 ± 6.3	1	85 - 95% POlt	F, 12 – 30 min			00:22:24	15	05:36:00	4.2	10.1%
C - Edge et al. (167)*		AIT	8 (8)	20 ± 1	42.7 ± 8	2 - 10	120 - 140% POlt	F, 120 s	‘complete rest’	F, 60 s	00:12:40	15	03:20:00	6.0	14.0%
		MICT	8 (8)	19 ± 1	40.5 ± 5.4	1	85 - 95% POlt	F, 12 – 30 min			00:22:24	15	05:36:00	5.2	12.8%
C - Edge et al. (46)	**[1min]**	AIT	6 (6)	19 ± 1	45.6 ± 6.8	6 - 10	140 - 170% LTdmax	F, 120 s	‘passive’	F, 60 s	00:16:00	15	04:02:00	4.4	9.6%
	[3min]	AIT	6 (6)	19 ± 1	45.6 ± 4.4	6 - 10	140 - 170% LTdmax	F, 120 s	‘passive’	F, 180 s	00:16:00	15	04:02:00	4.0	8.8%

Table 3.1: Continued

						Training Protocol									
Study	**[group identifier]**	**Group**	**n (female)**	**Age**	**Baseline $\dot{V}O_2$max**	**Reps**	**Work Intensity**	**Work Duration**	**Recovery Intensity**	**Recovery Duration**	**Work Duration (hr:min:sec)**	**Sessions**	**Total Training (hr:min:sec)**	**Δ $\dot{V}O_2$max**	**% Change**
C - Graef et al. (168)		AIT	17	22.6 ± 4.9	3.65 ± 0.59	5	90 - 120% PPO	F, 120 s	'passive'	F, 60 s	00:10:00	12	02:00:00	0.35	9.6%
		CON	10		3.67 ± 0.71	CON neither supplemented nor completed HIIT								-0.13	-3.5%
C - O'Leary et al. (169)		AIT	10 (2)	27 ± 6	3.52 ± 0.71	6 - 8	POΔ50	F, 300 s		F, 60 s	00:35:00	18	10:30:00	0.28	8.0%
		MICT	10 (2)	27 ± 4	3.33 ± 0.92	1	90% POlt	F, 70 min			01:10:00	18	21:00:00	0.29	8.7%
C - Perry et al. (170)*		AIT	8 (3)	24 ± 3	3.29 ± 0.7	10	90% PPO	F, 240 s		F, 120 s	00:40:00	18	12:00:00	0.29	8.8%
C - Robinson et al. (171)	[HR]	AIT	10	36.9 ± 16	48.5 ± 9.2	11	HR POlt	F, 300 s	65% HRmax	F, 240 s	00:55:00	8	07:20:00	-0.1	-0.2%
	[PO]	AIT	10	30.9 ± 9.5	50.3 ± 9.7	11	POlt	F, 300 s	65% HRmax	F, 240 s	00:55:00	8	07:20:00	0.4	0.8%
C - Smith et al. (172)		AIT	18	22.2 ± 2.7	3.25 ± 0.63	5 - 6	90 - 115% PPO	F, 120 s		F, 60 s	00:10:30	18	03:04:00	0.41	12.6%
C - Weber et al. (163)*	[male]	AIT	7	23.7 ± 4.2	3.58 ± 0.50	3	82.5 - 100% MAOD	F, 120 s		F, 360 s	00:06:00	24	02:24:00	0.27	7.5%
C - Weng et al. (173)*		AIT	10	22.3 ± 0.6	46.5 ± 5.4	5	80% PPO	F, 180 s	40% PPO	F, 180 s	00:15:00	25	06:15:00	11.4	24.5%
		MICT	10	22.5 ± 3.2	46.3 ± 4.7	1	60% PPO	F, 30 min			00:30:00	25	12:30:00	5.6	12.1%
		CON	10	22.4 ± 2.8	45.9 ± 5.4	CON did not receive any exercise but were carefully monitored								-1.5	-3.3%
R - Born et al. (174)		AIT	16	25 ± 4	49.0 ± 4.5	4	90 - 95% HRmax	F, 240 s	70 - 75% HRmax	F, 180 s	00:16:00	9	02:24:00	2.5	5.1%
		MICT	12	25 ± 3	52.4 ± 4.8	1	70 - 75% HRmax	F, 60 - 80 min			01:10:00	9	10:30:00	-0.6	-1.2%
R - Chtara et al. (64)		AIT	10	21.4 ± 1.3	49.8 ± 3.1	5	Vmax	I, Tlim, 156 s	50% Vmax	F, 156 s	00:13:00	24	05:12:00	4.9	9.8%
		CON	9	21.4 ± 1.3	50.7 ± 6.3	CON maintained their normal physical activity habits								-0.1	-0.3%
R - Estes et al. (175)		AIT	12 (10)	19.9 ± 0.5	42.1 ± 1.6	4	90 - 95% HRmax	F, 240 s	70% HRmax	F, 180 s	00:16:00	25	06:40:00	2.4	5.7%
Performance Level 3															
C - Etxebarria et al. (176)		AIT	7	33 ± 8	4.47 ± 0.36	6 - 8	80% PPO	F, 300 s	'active'	F, 60 s	00:35:00	6	03:30:00	0.31	6.9%
		SIT	7		4.53 ± 0.41	9 - 11	All Out sprint	F, 10 - 40 s	'active'	F, variable	00:11:40	6	01:10:00	0.32	7.0%
C - Gaesser et al. (177)*		AIT	6	22.3 ± 1.5	55.0 ± 11.1	10	PPO	F, 120 s		F, 120 s	00:20:00	18	06:00:00	4.1	7.4%
		MICT	5	21.4 ± 0.9	54.9 ± 4.6	1	50% PPO	F, 40 min			00:40:00	18	12:00:00	1.5	2.7%
C - Miyachi et al. (178)*		AIT	6	23 ± 4	50.9 ± 5.6	5	PPO	F, 180 s	50% PPO	F, 120 s	00:15:00	48	12:00:00	10.7	21.0%
		CON	5		49.9 ± 5.2	CON maintained their normal physical activity habits								1.9	3.8%
C - Poole et al. (179)*		AIT	8	22 ± 1.9	3.81 ± 0.59	10	105% PPO	F, 120 s		F, 120 s	00:20:00	21	07:00:00	0.58	15.2%
C - Seiler et al. (42)	[4*4]	AIT	9 (2)	43 ± 7	50.4 ± 5.8	4	Max session effort	F, 240 s		F, 120 s	00:16:00	14	03:44:00	2.8	5.6%
	[4*8]	AIT	9	43 ± 7	52.8 ± 4.8	4	Max session effort	F, 480 s		F, 120 s	00:32:00	14	07:28:00	5.5	10.4%
	[4*16]	AIT	9 (2)	43 ± 4	51.1 ± 5.8	4	Max session effort	F, 960 s		F, 180 s	01:04:00	14	14:56:00	3.3	6.5%
		CON	8 (2)	40 ± 6	52.7 ± 8.0	CON maintained their normal physical activity with a 20-30% increased volume							59:30:00	1.8	3.4%
C - Zieman et al. (180)		AIT	10	21.6 ± 1.1	50.1 ± 3.1	6	80% PPO	F, 90 s	'passive'	F, 180 s	00:09:00	18	02:42:00	5.5	11.0%

Table 3.1: Continued

Study	[group identifier]	Group	n (female)	Age	Baseline $\dot{V}O_2$max	Training Protocol						Sessions	Total Training (hr:min:sec)	Δ $\dot{V}O_2$max	% Change
						Reps	Work Intensity	Work Duration	Recovery Intensity	Recovery Duration	Work Duration (hr:min:sec)				
		CON	11	21.0 ± 0.9	48.2 ± 4.7	CON maintained their normal routine								0.3	0.6%
R - Croft et al. (181)		AIT	5	20 ± 1	55.9 ± 6.8	5	90% $\dot{V}O_2$max	F, 180 s	25-50% $\dot{V}O_2$max	F, 180 s	00:15:00	24	06:00:00	4.9	8.8%
R - Czuba et al. (182)		AIT	6	22 ± 2.4	53.0 ± 5.2	4 - 5	90% $\dot{V}O_2$max	F, 240 s	60% $\dot{V}O_2$max	F, 240 s	00:16:00	9	02:36:00	1.1	2.1%
R - Denadai et al. (62)	**[G95%]**	AIT	9	27.4 ± 4.4	59.1 ± 6.0	4	95% v$\dot{V}O_2$max	I, Tlim, 332 s	50% v$\dot{V}O_2$max	F, 166 s	00:22:10	8	02:56:49	-1.6	-0.1%
	[G100%]	AIT	8	27.4 ± 4.4	59.9 ± 6.0	5	v$\dot{V}O_2$max	I, Tlim, 285 se	50% v$\dot{V}O_2$max	F, 285 s	00:23:47	8	03:10:12	-0.1	-2.7%
R - Esfarjani et al. (66)		AIT	6	19 ± 2	51.3 ± 2.4	5 - 8	v$\dot{V}O_2$max	I, Tlim, 210 s	50% v$\dot{V}O_2$max	F, 210 s	00:21:00	20	07:00:00	4.7	9.2%
		MICT	5		51.8 ± 2.8	1	75% v$\dot{V}O_2$max	F, 60 min			01:00:00	20	20:00:00	1.1	2.1%
		SIT	6		51.7 ± 3.4	12	130% v$\dot{V}O_2$max	F, 30 s		F, 270 s	00:06:00	20	02:00:00	3.2	6.2%
R - Ferley et al. (63)		AIT	12 (6)	27.4 ± 3.8	59.4 ± 8.9	4 - 6	v$\dot{V}O_2$max	I, Tlim, 136 s		I, 65HR, 142 s	00:11:20	12	02:16:00	0.2	0.3%
		SIT	12		63.3 ± 8.0	10 - 14	Vmax	F, 30 s		I, 65HR, 135 s	00:06:00	12	01:12:00	-0.6	-0.9%
		CON	8		59.9 ± 8.6	CON continued their normal weekly training programs away from the training facility								-1.6	-2.7%
R - Ferrari Bravo et al. (183)		AIT	13	21.1 ± 5.1	52.8 ± 3.2	4	90 - 95% HRmax	F, 240 s	60 - 70% HRmax	F, 180 s	00:16:00	14	03:44:00	3.5	6.6%
		SIT	13		55.7 ± 2.3	3*6	40m Sprint	I, ~6 s		F, 20 s	00:01:48	14	00:25:12	2.8	5.0%
R - Gojanovic et al. (67)		AIT	5	38.4 ± 9.7	57.6 ± 2.5	4 - 5	v$\dot{V}O_2$max	I, Tlim, 184 s	50% v$\dot{V}O_2$max	F, 184 s	00:13:49	8	01:50:24	2.0	3.5%
R - Hatle et al. (73)	**[high freq]**	AIT	9 (3/4)	23.1 ± 2.3	51.5 ± 5.5	3 - 4	90 - 95% HRmax	F, 240 s	70% HRmax	F, 180 s	00:16:00	24	06:16:00	5.4	10.5%
	[moderate freq]	AIT	10 (5/6)	23.7 ± 2.7	52.2 ± 7.0	3 - 4	90 - 95% HRmax	F, 240 s	70% HRmax	F, 180 s	00:16:00	24	06:16:00	1.5	2.9%
R - Helgerud et al. (69)		AIT	9	18.1 ± 0.8	58.1 ± 4.5	4	90 - 95% HRmax	F, 240 s	50 - 60% HRmax	F, 180 s	00:16:00	16	04:16:00	6.2	10.7%
		CON	10		58.4 ± 4.3	CON performed extra technical training such as heading, practice free kicks, and exercises related to receiving the ball and changing direction								1.1	1.9%
R - Helgerud et al. (70)		AIT	10	24.6 ± 3.8	55.5 ± 7.4	4	90 - 95% HRmax	F, 240 s	70% HRmax	F, 180 s	00:16:00	24	06:24:00	4.9	8.8%
		MICT	10		55.8 ± 6.6	1	70% HRmax	F, 45 min	-	-	00:45:00	24	18:00:00	1.0	1.8%
		SIT	10		60.5 ± 6.4	47	90 - 95% HRmax	F, 15 s	70% HRmax	F, 15 s	00:11:45	24	04:42:00	3.9	6.4%
		LT	10		59.6 ± 7.6	1	85% HRmax	F, 24:25 min	-	-	00:24:15	24	09:42:00	1.2	2.0%
R - Lamboley et al. (65)		AIT	8 (4)	23.4 ± 0.8	51.7 ± 2.7	5	v$\dot{V}O_2$max	I, Tlim, 125 s	60% v$\dot{V}O_2$max	F, 125 s	00:10:25	15	02:36:15	4.4	8.4%
R - Silva et al. (184)		AIT	8	35 ± 6	54.5 ± 8.1	5	v$\dot{V}O_2$max	I, Tlim, 133 s	60% v$\dot{V}O_2$max	F, 133 s	00:11:03	8	01:28:25	2.6	4.8%
		CON	8	32 ± 9	56.6 ± 7.3	CON maintained their previous endurance training routine								0.3	0.5%
R - Wiewelhove et al. (185)	**[act R]**	AIT	13	24.0 ± 2.7	55.2 ± 3.5	4 - 9	90-100 % v$\dot{V}O_2$max	F, 120 - 240 s	‘passive'	F, 120 - 180 s	00:17:30	12	03:30:00	0.4	0.7%
	[pas R]	AIT	13	23.0 ± 2.2	55.5 ± 4.2	4 - 9	90-100 % v$\dot{V}O_2$max	F, 120 - 240 s	‘passive'	F, 120 - 180 s	00:17:30	12	03:30:00	-0.5	-0.9%
Performance Level 4															
C - Aughey et al. (186)		AIT	12	31 ± 3	4.96 ± 0.56	8	80% PPO	F, 300 s	~.1.3 W/kg	F, 60 s	00:40:00	7	04:40:00	0.12	2.4%
		CON	12		4.98 ± 0.63	CON maintained their normal physical activity of > 350 km cycling per week at a low to moderate intensity								-0.02	-0.4%

Table 3.1: Continued

Study	[group identifier]	Group	n (female)	Age	Baseline $\dot{V}O_2$max	Training Protocol						Sessions	Total Training (hr:min:sec)	Δ $\dot{V}O_2$max	% Change
						Reps	Work Intensity	Work Duration	Recovery Intensity	Recovery Duration	Work Duration (hr:min:sec)				
C - Gross et al. (187)	**[consecutive]**	AIT	9 (2)	21.9 ± 3.4	4.25 ± 1.15	8	PPO	F, 150 s	25% PPO	F, 240 s	00:20:00	9	03:00:00	0.23	5.4%
	[non-consecutive]	AIT	6 (2)	20.5 ± 1.9	4.34 ± 1.34	8	PPO	F, 150 s	25% PPO	F, 240 s	00:20:00	9	03:00:00	0.20	4.6%
C - Inoue et al. (188)		AIT	7	34.0 ± 6.7	63.1 ± 4.2	2 - 10	Max session effort	F, 240 - 360 s	RPE 10 - 15	F, 240 - 360 s	00:26:00	17	07:22:00	2.5	4.0%
		SIT	9	30.6 ± 6.3	60.6 ± 4.3	2 - 12	All Out sprint	F, 30 s	RPE 10 - 15	240 s	00:03:55	17	01:06:30	3.4	5.6%
C - Lamberts et al. (189)		AIT	14	30 ± 6	60.3 ± 7.2	8	80% PPO	F, 240 s	‘self-paced’	F, 90 s	00:32:00	8	04:16:00	1.4	2.3%
C - Laursen et al. (21)	**[G1]**	AIT	8	26 ± 6	5.00 ± 0.52	8	Pmax	I, Tlim, 145 s		F, 290 s	00:19:20	8	02:34:40	0.26	5.2%
	[G2]	AIT	9	24 ± 7	4.89 ± 0.38	8	Pmax	I, Tlim, 149 s		I, 65HR, 178 s	00:19:52	8	02:38:54	0.39	8.0%
		SIT	10	25 ± 6	4.91 ± 0.37	12	175% PPO	F, 30 s		F, 270 s	00:06:00	8	00:48:00	0.15	3.1%
		CON	11	25 ± 5	4.92 ± 0.45	CON maintained their regular low to moderate intensity based training program								0.04	0.8%
C - Roels et al. (190)		AIT	8	33 ± 2.8	4.47 ± 0.36	4 - 8	90 - 100% PPO	F, 120 - 480 s		F, 120 – 240 s	00:19:05	13	04:28:00	0.22	4.9%
C - Rønnestad et al. (191) *		AIT	7	33 ± 10	4.99 ± 0.58	4	Max session effort	F, 300 s	50% PO Work	F, 150 s	00:20:00	20	03:40:00	0.12	2.6%
		SIT	9		4.98 ± 0.44	3*13	Max session effort	F, 30 s	50% PO Work	F, 15 s	00:19:20	20	03:30:00	0.44	8.8%
C - Swart et al. (192)	**[HR]**	AIT	6	30 ± 5	60.3 ± 4	8	HR 80% PPO	F, 240 s	‘self-paced’	F, 90 s	00:32:00	8	04:16:00	2.2	3.6%
	[PO]	AIT	6	30 ± 8	60.0 ± 7	8	80% PPO	F, 240 s	‘self-paced’	F, 90 s	00:32:00	8	04:16:00	0.2	0.3%
		CON	5	34 ± 4	54.4 ± 7	CON performed a 40 km self-paced training ride twice a week at an intensity below 70% PPO								0.1	0.1%
R - Kohn et al. (193)		AIT	18		67 ± 5.0	6	94% Vmax	I, Tlim, 162 s		F, 81 s	00:16:12	12	03:14:24	1.0	1.5%
		CON	10		67 ± 4.0	CON continued their regular endurance training with a mean volume of 54±18 km per week								0	0.0%
R - Laffite et al. (61)		AIT	7	25.3 ± 4.5	60.6 ± 4.4	? (5)	vΔ50	I, Tlim, 255 s	50% v$\dot{V}O_2$max	F, 127.5 s	(00:21:15)	16	(05:40:00)	2.4	4.0%
R - Menz et al. (74)		AIT	19 (5)	27 ± 3	63.6 ± 7.5	4	90 - 95% HRmax	F, 240 s	‘active'	F, 240 s	00:16:00	11	02:56:00	2.2	3.5%
		CON	16 (3)	24 ± 2	63.7 ± 8.2	CON maintained their usual training								1.0	1.6%
R - Salazar-Martinez et al. (194)		AIT	8	25.6 ± 3.2	68.4 ± 2.7	4	90 - 95% HRmax	F, 240 s	‘active'	F, 240 s	00:16:00	11	02:56:00	1.4	2.0%
		CON	8	25 ± 3.4	67.1 ± 6.5	CON maintained their usual endurance training							16:35:00	-0.3	-0.4%
R - Smith et al. (35)*		AIT	5	22.8 ± 4.5	61.5 ± 6.6	5 - 6	v$\dot{V}O_2$max	I, Tlim, 150 s		F, 75 s	00:13:26	8	01:47:30	3.0	4.9%
R - Smith et al. (60)*	**[G60%]**	AIT	9	25.2 ± 6.8	60.5 ± 5.7	6	v$\dot{V}O_2$max	I, Tlim, 133 s		F, 266 s	00:13:20	8	01:46:43	3.6	6.0%
	[G70%]	AIT	9	25.2 ± 6.8	60.1 ± 1.8	5	v$\dot{V}O_2$max	I, Tlim, 154 s		F, 308 s	00:12:50	8	01:42:40	2.5	4.2%
		CON	9		63.6 ± 6.0	CON continued their normal training that comprised low-intensity/long duration maintenance training								0.4	0.6%

Values are displayed as mean ± SD, * indicates SD are calculated from individual data or SEM, or are obtained from figures. Baseline $\dot{V}O_2$max is displayed in $L{\cdot}min^{-1}$ or $mL{\cdot}kg{\cdot}min^{-1}$

Abbreviations; 65HR: heart rate recovery to 65% HRmax, AIT: aerobic interval training, CON: control, F: fixed recovery duration, HIIT: high intensity interval training, HR: heart rate, %HRmax: intensity corresponding to percentage of maximal heart rate determined in pre-intervention incremental test, I: individualised recovery duration, LT, lactate threshold, %LTdmax: intensity corresponding to percentage of lactate threshold determined using d-max method, %MAOD: intensity corresponding to percentage of power output determined in maximal anaerobic oxygen deficit test, MICT: moderate intensity continuous training, Pmax: minimal power output that elicited $\dot{V}O_2$peak, PO: power output, POΔ50:

power output corresponding to the halfway point between POlt and PPO, %POlt: intensity corresponding to percentage of lactate threshold determined in pre-intervention incremental test, %PPO: intensity corresponding to percentage of peak power output determined in pre-intervention incremental test, RPE: ratings of perceived exertion, SIT: sprint interval training, Tlim: time to exhaustion on Pmax, Vmax or v$\dot{V}O_2$max, vΔ50: velocity corresponding to the halfway point between running velocity on LT and Vmax, %Vmax: intensity corresponding to percentage of maximal running velocity determined in pre-intervention incremental test, %$\dot{V}O_2$peak / $\dot{V}O_2$max: intensity corresponding to percentage of maximal oxygen uptake intensity determined in pre-intervention incremental exercise test, %v$\dot{V}O_2$max: intensity corresponding to the minimum running velocity that elicits $\dot{V}O_2$max determined in pre-intervention incremental test

Table 3.2: Participant and training protocol characteristics of included studies evaluating changes in cycling (C) or running (R) performance after AIT interventions

						Training Protocol									
Study	**[group identifier]**	**Group**	**n (female)**	**Age**	**Distance**	**Reps**	**Work Intensity**	**Work Duration**	**Recovery Intensity**	**Recovery Duration**	**Work Duration (hr:min:sec)**	**Sessions**	**Total Training (hr:min:sec)**	**Δ Time (sec)**	**% Change**
Performance Level 1															
R - Cicioni-Kolsky et al.(148)	**[female]**	AIT	9 (9)	18.4 ± 1.3	3000 m	4 - 6	100% AV3000	F, 240 s	‘passive’	F, 240 s	00:20:00	12	04:00:00	-86.0	7.7%
		MICT	9 (9)	18.6 ± 1		1	75% AV3000					12	?	-91.0	-7.9%
		SIT	14 (14)	18.6 ± 1		7 - 12	130% AV3000	F, 30 s		F, 270 s	00:04:30	12	00:54:00	0.8	2.4%
Performance Level 2															
C - Robinson et al. (171)	**[HR]**	AIT	10	36.9 ± 16	20 km	11	HR POlt	F, 300 s	65% HRmax	F, 240 s	00:55:00	8	07:20:00	- 115	4.9%
	[PO]	AIT	10	50.3 ± 9.7		11	POlt	F, 300 s	65% HRmax	F, 240 s	00:55:00	8	07:20:00	- 119	4.8%
R - Chtara et al. (64)		AIT	10	21.4 ± 1.3	4000 m	5	Vmax	I, Tlim, 156 s	50% Vmax	F, 156 s	00:13:00	24	05:12:00	-53.2	-5.7%
		CON	9			CON maintained their normal physical activity habits								3.0	0.3%
R - Cicioni-Kolsky et al. (148)	**[male]**	AIT	10	20.8 ± 3.8	3000 m	4 - 6	100% AV3000	F, 240 s	‘passive’	F, 240 s	00:20:00	12	04:00:00	-59.0	-7.3%
		MICT	7	19.7 ± 1.4		1	75% AV3000					12	?	-2.0	-0.3%
		SIT	6	20.2 ± 3.1		7 - 12	130% AV300	F, 30 s		F, 270 s	00:04:30	12	00:54:00	-47.0	-5.9%
R - Musa et al. (147)		AIT	20	29.8 ± 4.5	2400 m	4	90% HRmax	F, 288 s	‘passive’	F, 288 s	00:19:12	24	07:40:48	-66.0	-9.2%
		CON	16	29.4 ± 4.9		CON was instructed not to undertake any vigorous exercise during the training period								18.0	2.4%
Performance Level 3															
R - Denadai et al. (62)	**[G95%]**	AIT	9	27.4 ± 4.4	5000 m	4	95% v$\dot{V}O_2$max	I, Tlim, 333 s	50% v$\dot{V}O_2$max	F, 166 s	00:22:10	8	02:56:49	-15.0	-1.5%
	[G100%]	AIT	8			5	v$\dot{V}O_2$max	I, Tlim, 285 s	50% v$\dot{V}O_2$max	F, 285 s	00:23:47	8	03:10:12	-13.7	-1.4%
R - Esfarjani & Laursen (66)*		AIT	6	19 ± 2	3000 m	5 - 8	v$\dot{V}O_2$max	I, Tlim, 210 s	50% v$\dot{V}O_2$max	F, 210 s	00:21:00	20	07:00:00	-50.5	-7.4%
		MICT	5			1	75% v$\dot{V}O_2$max	F, 60 min			01:00:00	20	20:00:00	-0.7	-0.1%
		SIT	6			12	130% v$\dot{V}O_2$max	F, 30 s		F, 270 s	00:06:00	20	02:00:00	-22.3	-3.3%
R - Gojanovic et al. (67)		AIT	5	38.4 ± 9.7	3200 m	4 - 5	v$\dot{V}O_2$max	I, Tlim, 184 s	50% v$\dot{V}O_2$max	F, 184 s	00:13:49	8	01:50:24	18.0	2.4%
R - Riiser et al. (71)*		AIT	8 (1)	19 ± 0.4	3000 m	4	85-95% HRmax	F, 240 s	70-75% HRmax	F, 120 s	00:16:00	5	01:20:00	-82	-10.1%
		MICT	11			1	70-75% HRmax	F, 45 min			00:45:00	5	03:45:00	-56	-6.5%
		RACE	6			1	3000m 'race'	I, RACE			00:14:00	5	01:10:00	-44	-5.0%
		CON	8			CON performed no cardiorespiratory training beside daily basic (military) training								6	0.8%
R - Silva et al. (184)		AIT	8	35 ± 6	5000 m	5	v$\dot{V}O_2$max	I, Tlim, 133 s	60% v$\dot{V}O_2$max	F, 133 s	00:11:03	8	01:28:25	-28.0	-2.3%
		CON	8	32 ± 9		CON maintained their previous endurance training routine								16.0	1.4%
Performance Level 4															
C - Gross et al. (187)	**[consecutive]**	AIT	9 (2)	21.9 ± 3.4	5 km	8	PPO	F, 150 s	25% PPO	F, 240 s	00:20:00	9	03:00:00	- 10	-2.1%

Table 3.2: continued

						Training Protocol									
Study	**[group identifier]**	**Group**	**n (female)**	**Age**	**Distance**	**Reps**	**Work Intensity**	**Work Duration**	**Recovery Intensity**	**Recovery Duration**	**Work Duration (hr:min:sec)**	**Sessions**	**Total Training (hr:min:sec)**	**Δ Time (sec)**	**% Change**
	[non-consecutive]	AIT	6 (2)	20.5 ± 1.9		8	PPO	F, 150 s	25% PPO	F, 240 s	00:20:00	9	03:00:00	- 14	-2.9%
C - Inoue et al. (188)		AIT	7	34.0 ± 6.7	40 km	2 - 10	Max session effort	F, 240 - 360 s	RPE 10 - 15	F, 240 - 360 s	00:26:00	17	07:22:00	- 306	-5.0%
		SIT	9	30.6 ± 6.3		2 - 12	All Out sprint	F, 30 s	RPE 10 - 15	240 s	00:03:55	17	01:06:30	- 182	-2.9%
C - Lamberts et al. (189)		AIT	14	30 ± 6	40 km	8	80% PPO	F, 240 s	‘self-paced’	F, 90 s	00:32:00	8	04:16:00	- 90	-2.3%
C - Laursen et al. (21)	**[G1]**	AIT	8	26 ± 6	40 km	8	Pmax	I, Tlim, 145 s		F, 290 s	00:19:20	8	02:34:40	- 169	-4.9%
	[G2]	AIT	9	24 ± 7		8	Pmax	I, Tlim, 149 s		I, 65HR, 178 s	00:19:52	8	02:38:54	- 183	-5.3%
		SIT	10	25 ± 6		12	175% PPO	F, 30 s		F, 270 s	00:06:00	8	00:48:00	- 142	-4.1%
		CON	11	25 ± 5		CON maintained their regular low to moderate intensity based training program								33	0.9%
C - Lindsay et al. (195)*		AIT	8	25.5 ± 3.4	40 km	6 - 8	80% PPO	F, 300 s	~100 W	F, 60 s	00:35:00	6	03:30:00	- 114	-3.3%
C - Swart et al. (192)	**[HR]**	AIT	6	30 ± 5	40 km	8	HR 80% PPO	F, 240 s	‘self-paced’	F, 90 s	00:32:00	8	04:16:00	- 87	-2.2%
	[PO]	AIT	6	30 ± 8		8	80% PPO	F, 240 s	‘self-paced’	F, 90 s	00:32:00	8	04:16:00	- 74	-1.9%
		CON	5	34 ± 4		CON performed a 40 km self-paced training ride twice a week at an intensity below 70% PPO								- 4	-0.1%
C - Westgarth-Taylor et al. (146)*		AIT	12	25 ± 4	40 km	6 - 9	80% PPO	F, 300 s	≤ 100 W	F, 60 s	00:37:20	12	07:30:00	- 80	-2.3%
C - Weston et al. (26)*		AIT	6	22.5 ± 3	40 km	6 - 8	80% PPO	F, 300 s	100 W	F, 60 s	00:35:00	6	03:30:00	- 72	-2.1%
R - Salazar-Martinez et al. (194)		AIT	8	25.6 ± 3.2	400 m	4	90 - 95% HRmax	F, 240 s	‘active’	F, 240 s	00:16:00	11	02:56:00	-1.3	-2.2%
		CON	8	25 ± 3.4		CON maintained their usual endurance training								-0.6	-1.0%
R - Smith et al. (35)*		AIT	5	22.8 ± 4.5	3000 m	5 - 6	v$\dot{V}O_2$max	I, Tlim, 150 s		F, 75 s	00:13:26	8	01:47:30	-17.0	-2.8%
R - Smith et al. (60)*	**[G60%]**	AIT	9	25.2 ± 6.8	5000 m	6	v$\dot{V}O_2$max	I, Tlim, 133 s		F, 266 s	00:13:20	8	01:46:43	-25.7	-2.3%
	[G70%]	AIT	9			5	v$\dot{V}O_2$max	I, Tlim, 154 s		F, 308 se	00:12:50	8	01:42:40	-3.6	-0.3%
		CON	9			CON continued their normal training that comprised low-intensity/long duration maintenance training								-9.3	-0.9%

Values are displayed as mean ± SD, * indicates data are calculated from individual data, SEM, interquartile range, or are obtained from figures

Abbreviations: 65HR: heart rate recovery to 65% HRmax, AIT: aerobic interval training, %AV3000: intensity corresponding to percentage of 3000m average running velocity, CON: control, F: fixed recovery duration, HR: heart rate, %HRmax: intensity corresponding to percentage of maximal heart rate determined in pre-intervention incremental test, I: individualised recovery duration, MICT: moderate intensity continuous training, PO: power output, %POlt: intensity corresponding to percentage of lactate threshold determined in pre-intervention incremental test, %PPO: intensity corresponding to percentage of peak power output determined in pre-intervention incremental test, Pmax: minimal power output that elicited $\dot{V}O_2$peak, RACE: intensity corresponding to fastest possible 3000m, RPE: ratings of perceived exertion, SIT: sprint interval training, Tlim: time to exhaustion on Pmax,Vmax or v$\dot{V}O_2$max, %Vmax: intensity corresponding to percentage of maximal running velocity determined in pre-intervention incremental test, %v$\dot{V}O_2$max: intensity corresponding to the minimum running velocity that elicits $\dot{V}O_2$max determined in pre-intervention incremental test

3.3 Results

3.3.1 Main effects of AIT interventions

3.3.1.1 Improvements in $\dot{V}O_2$max

The pooled mean estimate across all studies showed a significant increase of a small to moderate magnitude in $\dot{V}O_2$max (see **Figure 3.3**; $p < 0.01$, ES = 0.54 [0.38, 0.69]). The absolute and relative improvements in $\dot{V}O_2$max ($\Delta\dot{V}O_2$max and % Change) differed considerably across the included studies (see **Table 3.1**), however, the reported overall improvement in $\dot{V}O_2$max was highly homogenous across all studies ($I^2 = 0\%$, $p = 1.00$) and averaged 7.6% (see **Table 3.3**). In line with the variation between the included studies in the magnitude of improvements in $\dot{V}O_2$max shown in **Table 3.1**, Hedges' *g* estimates and weighing factors of the individual AIT interventions were variable (see **Figure 3.3**).

The standardized mean difference (Hedges' *g*) of 0.54 [0.38, 0.69] corresponds to a WMD of 3.07 [2.39, 3.75] $mL\cdot kg\cdot min^{-1}$. No significant differences were evident between performance levels in the compete sample ($\chi^2 = 1.63$, $p = 0.65$), however, mean improvements in PL1 and PL2 were of moderate magnitude whereas improvements in PL3 and PL4 were small. The improvements in $\dot{V}O_2$max were similar between cycling and running interventions (see **Table 3.3**). Neither in the included cycling or running studies, improvements significantly differed between performance levels ($\chi^2 = 1.50$, $p = 0.68$, $\chi^2 = 2.47$, $p = 0.48$ for AIT in cycling and running respectively). The increase in $\dot{V}O_2$max in PL2 and PL3 are notably larger after cycling AIT compared to running AIT interventions.

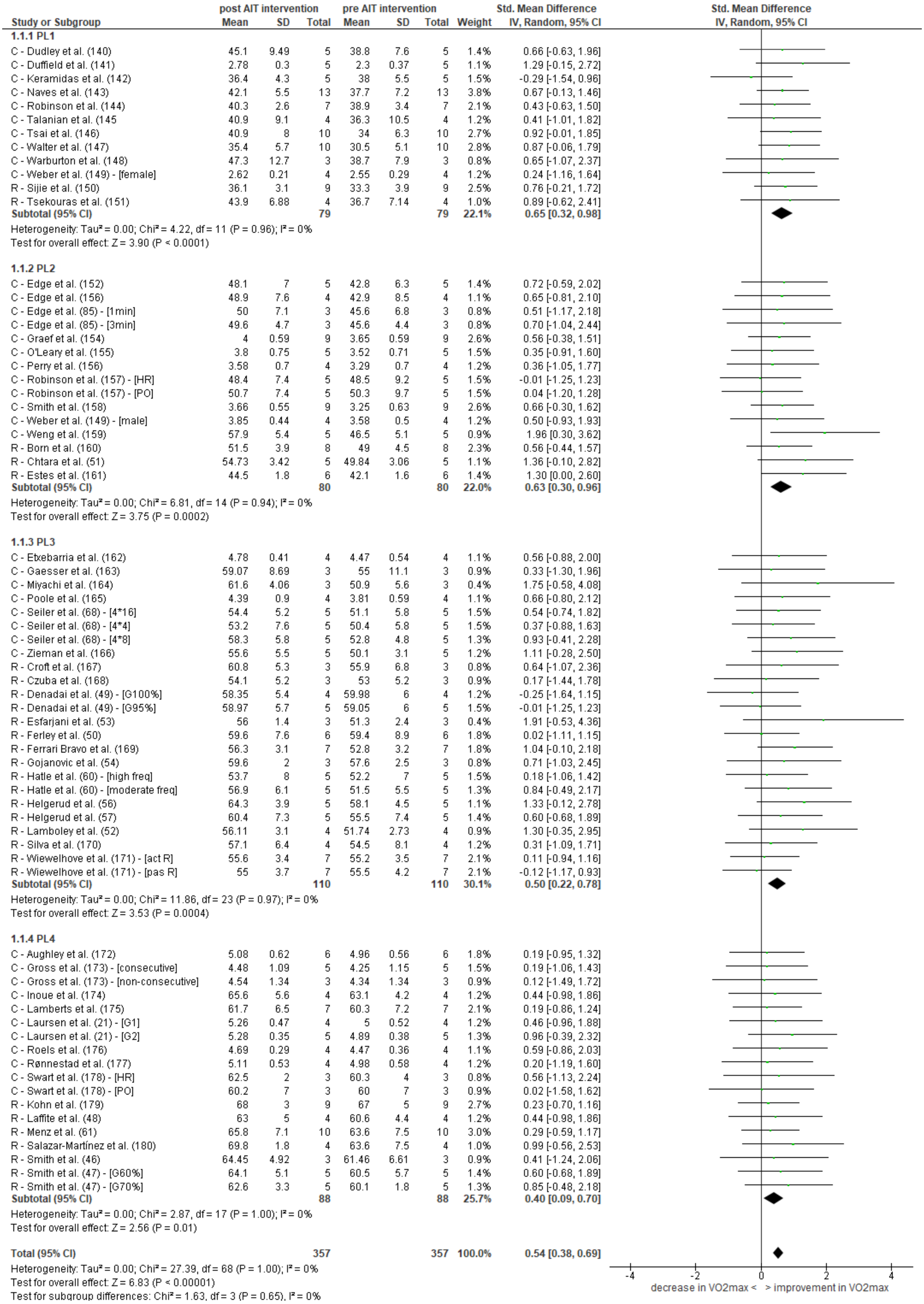
Table 3.3: Percentage change in $\dot{V}O_2$max of the included studies, organised by performance level

PL	All AIT Interventions	Cycling AIT Interventions	Running AIT Interventions
1	12.5%, ES = 0.65 [0.32, 0.98] ^{a}	12.2%, ES = 0.62 [0.26, 0.98] ^{a}	14.0%, ES = 0.80 [-0.02, 1.61]
2	9.1%, ES = 0.63 [0.30, 0.96] ^{a}	9.7%, ES = 0.53 [0.16, 0.91] ^{a}	6.9%, ES = 0.96 [0.26, 1.66] ^{a}
3	6.6%, ES = 0.50 [0.22, 0.78] ^{a}	10.5%, ES = 0.70 [0.19, 1.21] ^{a}	4.6%, ES = 0.42 [0.09, 0.76] ^{b}
4	4.3%, ES = 0.40 [0.09, 0.70]	4.0%, ES = 0.34 [-0.07, 0.75]	3.7%, ES = 0.43 [-0.02, 0.87]
All	7.6%, ES = 0.54 [0.38, 0.69] ^{a}	8.9%, ES = 0.54 [0.34, 0.74] ^{a}	5.3%, ES = 0.52 [0.28, 0.76] ^{a}

Values are presented as percentage improvement, ES [95% Confidence Intervals]

^{a} $p < 0.01$, ^{b} $p < 0.05$

Note; ES = Effect Size



	post AIT intervention			pre AIT intervention				Std. Mean Difference
Study or Subgroup	**Mean**	**SD**	**Total**	**Mean**	**SD**	**Total**	**Weight**	**IV, Random, 95% CI**
1.1.1 PL1								
C - Dudley et al. (140)	45.1	9.49	5	38.8	7.6	5	1.4%	0.66 [-0.63, 1.96]
C - Duffield et al. (141)	2.78	0.3	5	2.3	0.37	5	1.1%	1.29 [-0.15, 2.72]
C - Keramidas et al. (142)	36.4	4.3	5	38	5.5	5	1.5%	-0.29 [-1.54, 0.96]
C - Naves et al. (143)	42.1	5.5	13	37.7	7.2	13	3.8%	0.67 [-0.13, 1.46]
C - Robinson et al. (144)	40.3	2.6	7	38.9	3.4	7	2.1%	0.43 [-0.63, 1.50]
C - Talanian et al. (145	40.9	9.1	4	36.3	10.5	4	1.2%	0.41 [-1.01, 1.82]
C - Tsai et al. (146)	40.9	8	10	34	6.3	10	2.7%	0.92 [-0.01, 1.85]
C - Walter et al. (147)	35.4	5.7	10	30.5	5.1	10	2.8%	0.87 [-0.06, 1.79]
C - Warburton et al. (148)	47.3	12.7	3	38.7	7.9	3	0.8%	0.65 [-1.07, 2.37]
C - Weber et al. (149) - [female]	2.62	0.21	4	2.55	0.29	4	1.2%	0.24 [-1.16, 1.64]
R - Sijie et al. (150)	36.1	3.1	9	33.3	3.9	9	2.5%	0.76 [-0.21, 1.72]
R - Tsekouras et al. (151)	43.9	6.88	4	36.7	7.14	4	1.0%	0.89 [-0.62, 2.41]
Subtotal (95% CI)			**79**			**79**	**22.1%**	**0.65 [0.32, 0.98]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 4.22$, df = 11 (P = 0.96); $I^2 = 0\%$								
Test for overall effect: Z = 3.90 (P < 0.0001)								
1.1.2 PL2								
C - Edge et al. (152)	48.1	7	5	42.8	6.3	5	1.4%	0.72 [-0.59, 2.02]
C - Edge et al. (156)	48.9	7.6	4	42.9	8.5	4	1.1%	0.65 [-0.81, 2.10]
C - Edge et al. (85) - [1min]	50	7.1	3	45.6	6.8	3	0.8%	0.51 [-1.17, 2.18]
C - Edge et al. (85) - [3min]	49.6	4.7	3	45.6	4.4	3	0.8%	0.70 [-1.04, 2.44]
C - Graef et al. (154)	4	0.59	9	3.65	0.59	9	2.6%	0.56 [-0.38, 1.51]
C - O'Leary et al. (155)	3.8	0.75	5	3.52	0.71	5	1.5%	0.35 [-0.91, 1.60]
C - Perry et al. (156)	3.58	0.7	4	3.29	0.7	4	1.2%	0.36 [-1.05, 1.77]
C - Robinson et al. (157) - [HR]	48.4	7.4	5	48.5	9.2	5	1.5%	-0.01 [-1.25, 1.23]
C - Robinson et al. (157) - [PO]	50.7	7.4	5	50.3	9.7	5	1.5%	0.04 [-1.20, 1.28]
C - Smith et al. (158)	3.66	0.55	9	3.25	0.63	9	2.6%	0.66 [-0.30, 1.62]
C - Weber et al. (149) - [male]	3.85	0.44	4	3.58	0.5	4	1.2%	0.50 [-0.93, 1.93]
C - Weng et al. (159)	57.9	5.4	5	46.5	5.1	5	0.9%	1.96 [0.30, 3.62]
R - Born et al. (160)	51.5	3.9	8	49	4.5	8	2.3%	0.56 [-0.44, 1.57]
R - Chtara et al. (51)	54.73	3.42	5	49.84	3.06	5	1.1%	1.36 [-0.10, 2.82]
R - Estes et al. (161)	44.5	1.8	6	42.1	1.6	6	1.4%	1.30 [0.00, 2.60]
Subtotal (95% CI)			**80**			**80**	**22.0%**	**0.63 [0.30, 0.96]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 6.81$, df = 14 (P = 0.94); $I^2 = 0\%$								
Test for overall effect: Z = 3.75 (P = 0.0002)								
1.1.3 PL3								
C - Etxebarria et al. (162)	4.78	0.41	4	4.47	0.54	4	1.1%	0.56 [-0.88, 2.00]
C - Gaesser et al. (163)	59.07	8.69	3	55	11.1	3	0.9%	0.33 [-1.30, 1.96]
C - Miyachi et al. (164)	61.6	4.06	3	50.9	5.6	3	0.4%	1.75 [-0.58, 4.08]
C - Poole et al. (165)	4.39	0.9	4	3.81	0.59	4	1.1%	0.66 [-0.80, 2.12]
C - Seiler et al. (68) - [4*16]	54.4	5.2	5	51.1	5.8	5	1.5%	0.54 [-0.74, 1.82]
C - Seiler et al. (68) - [4*4]	53.2	7.6	5	50.4	5.8	5	1.5%	0.37 [-0.88, 1.63]
C - Seiler et al. (68) - [4*8]	58.3	5.8	5	52.8	4.8	5	1.3%	0.93 [-0.41, 2.28]
C - Zieman et al. (166)	55.6	5.5	5	50.1	3.1	5	1.2%	1.11 [-0.28, 2.50]
R - Croft et al. (167)	60.8	5.3	3	55.9	6.8	3	0.8%	0.64 [-1.07, 2.36]
R - Czuba et al. (168)	54.1	5.2	3	53	5.2	3	0.9%	0.17 [-1.44, 1.78]
R - Denadai et al. (49) - [G100%]	58.35	5.4	4	59.98	6	4	1.2%	-0.25 [-1.64, 1.15]
R - Denadai et al. (49) - [G95%]	58.97	5.7	5	59.05	6	5	1.5%	-0.01 [-1.25, 1.23]
R - Esfarjani et al. (53)	56	1.4	3	51.3	2.4	3	0.4%	1.91 [-0.53, 4.36]
R - Ferley et al. (50)	59.6	7.6	6	59.4	8.9	6	1.8%	0.02 [-1.11, 1.15]
R - Ferrari Bravo et al. (169)	56.3	3.1	7	52.8	3.2	7	1.8%	1.04 [-0.10, 2.18]
R - Gojanovic et al. (54)	59.6	2	3	57.6	2.5	3	0.8%	0.71 [-1.03, 2.45]
R - Hatle et al. (60) - [high freq]	53.7	8	5	52.2	7	5	1.5%	0.18 [-1.06, 1.42]
R - Hatle et al. (60) - [moderate freq]	56.9	6.1	5	51.5	5.5	5	1.3%	0.84 [-0.49, 2.17]
R - Helgerud et al. (56)	64.3	3.9	5	58.1	4.5	5	1.1%	1.33 [-0.12, 2.78]
R - Helgerud et al. (57)	60.4	7.3	5	55.5	7.4	5	1.4%	0.60 [-0.68, 1.89]
R - Lamboley et al. (52)	56.11	3.1	4	51.74	2.73	4	0.9%	1.30 [-0.35, 2.95]
R - Silva et al. (170)	57.1	6.4	4	54.5	8.1	4	1.2%	0.31 [-1.09, 1.71]
R - Wiewelhove et al. (171) - [act R]	55.6	3.4	7	55.2	3.5	7	2.1%	0.11 [-0.94, 1.16]
R - Wiewelhove et al. (171) - [pas R]	55	3.7	7	55.5	4.2	7	2.1%	-0.12 [-1.17, 0.93]
Subtotal (95% CI)			**110**			**110**	**30.1%**	**0.50 [0.22, 0.78]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 11.86$, df = 23 (P = 0.97); $I^2 = 0\%$								
Test for overall effect: Z = 3.53 (P = 0.0004)								
1.1.4 PL4								
C - Aughley et al. (172)	5.08	0.62	6	4.96	0.56	6	1.8%	0.19 [-0.95, 1.32]
C - Gross et al. (173) - [consecutive]	4.48	1.09	5	4.25	1.15	5	1.5%	0.19 [-1.06, 1.43]
C - Gross et al. (173) - [non-consecutive]	4.54	1.34	3	4.34	1.34	3	0.9%	0.12 [-1.49, 1.72]
C - Inoue et al. (174)	65.6	5.6	4	63.1	4.2	4	1.2%	0.44 [-0.98, 1.86]
C - Lamberts et al. (175)	61.7	6.5	7	60.3	7.2	7	2.1%	0.19 [-0.86, 1.24]
C - Laursen et al. (21) - [G1]	5.26	0.47	4	5	0.52	4	1.2%	0.46 [-0.96, 1.88]
C - Laursen et al. (21) - [G2]	5.28	0.35	5	4.89	0.38	5	1.3%	0.96 [-0.39, 2.32]
C - Roels et al. (176)	4.69	0.29	4	4.47	0.36	4	1.1%	0.59 [-0.86, 2.03]
C - Rønnestad et al. (177)	5.11	0.53	4	4.98	0.58	4	1.2%	0.20 [-1.19, 1.60]
C - Swart et al. (178) - [HR]	62.5	2	3	60.3	4	3	0.8%	0.56 [-1.13, 2.24]
C - Swart et al. (178) - [PO]	60.2	7	3	60	7	3	0.9%	0.02 [-1.58, 1.62]
R - Kohn et al. (179)	68	3	9	67	5	9	2.7%	0.23 [-0.70, 1.16]
R - Laffite et al. (48)	63	5	4	60.6	4.4	4	1.2%	0.44 [-0.98, 1.86]
R - Menz et al. (61)	65.8	7.1	10	63.6	7.5	10	3.0%	0.29 [-0.59, 1.17]
R - Salazar-Martínez et al. (180)	69.8	1.8	4	63.6	7.5	4	1.0%	0.99 [-0.56, 2.53]
R - Smith et al. (46)	64.45	4.92	3	61.46	6.61	3	0.9%	0.41 [-1.24, 2.06]
R - Smith et al. (47) - [G60%]	64.1	5.1	5	60.5	5.7	5	1.4%	0.60 [-0.68, 1.89]
R - Smith et al. (47) - [G70%]	62.6	3.3	5	60.1	1.8	5	1.3%	0.85 [-0.48, 2.18]
Subtotal (95% CI)			**88**			**88**	**25.7%**	**0.40 [0.09, 0.70]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 2.87$, df = 17 (P = 1.00); $I^2 = 0\%$								
Test for overall effect: Z = 2.56 (P = 0.01)								
Total (95% CI)			**357**			**357**	**100.0%**	**0.54 [0.38, 0.69]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 27.39$, df = 68 (P = 1.00); $I^2 = 0\%$								
Test for overall effect: Z = 6.83 (P < 0.00001)								
Test for subgroup differences: $Chi^2 = 1.63$, df = 3 (P = 0.65), $I^2 = 0\%$								

Figure 3.3: Forest plot of pre – post AIT intervention comparison for change in $\dot{V}O_2$max (C: cycling, R: running)

3.3.1.2 Improvements in performance

Small to moderate improvements in performance were found across the included studies (see **Figure 3.4**; $p < 0.01$, ES = -0.52 [-0.78 to -0.26]), with an average decrease in performance time of -4.0% (see **Table 3.4**). This improvement was highly homogenous ($I^2 = 0\%$, p = 1.00), and similar between performance levels ($\chi^2 = 1.61$, p = 0.66). The magnitude of performance improvements varied across the included studies (see ΔTime and % Change in **Table 3.2**), which was further reflected in the different weighing factors and effect size estimates (Hedges' *g*) for the individual studies reported in **Figure 3.4**.

Limited or no studies were performed in PL1 and PL3, especially in cycling, which did not allow for statistical analysis of these groups. Between exercise modalities, improvements in PL2 were larger in running performance assessments compared to cycling.

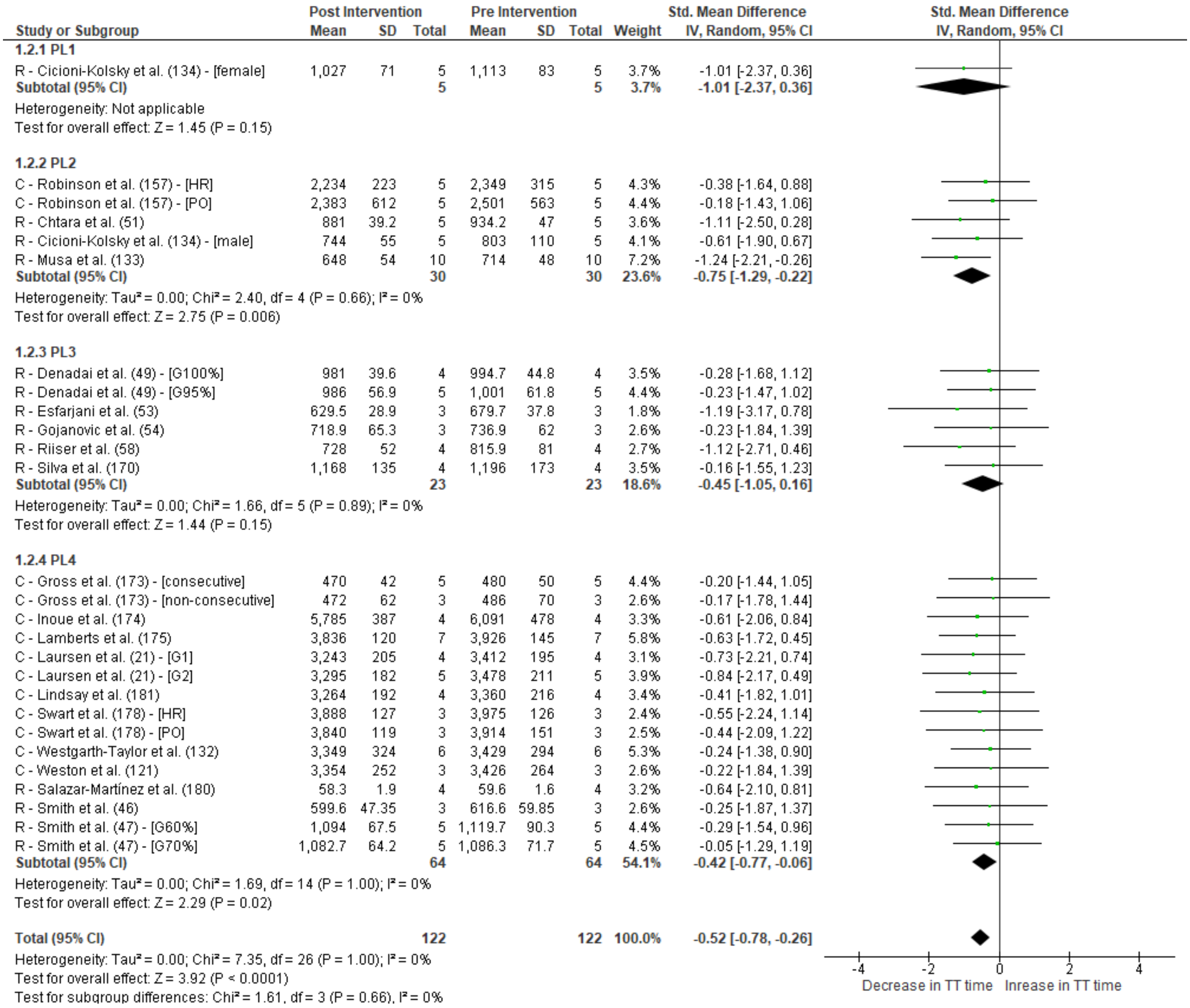
Table 3.4: Percentage change in performance of the included studies, organised by performance level

PL	All AIT Interventions	Cycling AIT Interventions	Running AIT Interventions
1	-7.7%, ES = -1.01 [-2.37 to 0.36]	na	-7.7%, ES = -1.01 [-2.37 to 0.36]
2	-6.4%, ES = -0.75 [-1.29 to -0.22] [a]	-4.8%, ES = -0.28 [-1.16 to 0.60]	-7.4%, ES = -1.03 [-1.71 to -0.36] [a]
3	-4.3%, ES = -0.45 [-1.05 to 0.16]	Na	-3.5%, ES = -0.45 [-1.05 to 0.16]
4	-2.8%, ES = -0.42 [-0.77 to -0.06] [b]	-3.1%, ES = -0.46 [-0.88 to -0.05] [b]	-1.9%, ES = -0.29 [-0.97 to 0.39]
All	-4.0%, ES = -0.52[-0.78 to -0.26] [a]	-3.3%, ES = -0.43 [-0.81 to -0.05] [b]	-4.2%, ES = -0.61 [-0.97 to -0.25] [a]

Values are presented as percentage improvement, ES [95% Confidence Intervals]

[a] $p < 0.01$, [b] $p < 0.05$

Note; AIT: aerobic interval training, ES: effect size



Study or Subgroup	Post Intervention Mean	Post Intervention SD	Post Intervention Total	Pre Intervention Mean	Pre Intervention SD	Pre Intervention Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.2.1 PL1								
R - Cicioni-Kolsky et al. (134) - [female]	1,027	71	5	1,113	83	5	3.7%	-1.01 [-2.37, 0.36]
Subtotal (95% CI)			**5**			**5**	**3.7%**	**-1.01 [-2.37, 0.36]**
Heterogeneity: Not applicable								
Test for overall effect: Z = 1.45 (P = 0.15)								
1.2.2 PL2								
C - Robinson et al. (157) - [HR]	2,234	223	5	2,349	315	5	4.3%	-0.38 [-1.64, 0.88]
C - Robinson et al. (157) - [PO]	2,383	612	5	2,501	563	5	4.4%	-0.18 [-1.43, 1.06]
R - Chtara et al. (51)	881	39.2	5	934.2	47	5	3.6%	-1.11 [-2.50, 0.28]
R - Cicioni-Kolsky et al. (134) - [male]	744	55	5	803	110	5	4.1%	-0.61 [-1.90, 0.67]
R - Musa et al. (133)	648	54	10	714	48	10	7.2%	-1.24 [-2.21, -0.26]
Subtotal (95% CI)			**30**			**30**	**23.6%**	**-0.75 [-1.29, -0.22]**
Heterogeneity: Tau² = 0.00; Chi² = 2.40, df = 4 (P = 0.66); I² = 0%								
Test for overall effect: Z = 2.75 (P = 0.006)								
1.2.3 PL3								
R - Denadai et al. (49) - [G100%]	981	39.6	4	994.7	44.8	4	3.5%	-0.28 [-1.68, 1.12]
R - Denadai et al. (49) - [G95%]	986	56.9	5	1,001	61.8	5	4.4%	-0.23 [-1.47, 1.02]
R - Esfarjani et al. (53)	629.5	28.9	3	679.7	37.8	3	1.8%	-1.19 [-3.17, 0.78]
R - Gojanovic et al. (54)	718.9	65.3	3	736.9	62	3	2.6%	-0.23 [-1.84, 1.39]
R - Riiser et al. (58)	728	52	4	815.9	81	4	2.7%	-1.12 [-2.71, 0.46]
R - Silva et al. (170)	1,168	135	4	1,196	173	4	3.5%	-0.16 [-1.55, 1.23]
Subtotal (95% CI)			**23**			**23**	**18.6%**	**-0.45 [-1.05, 0.16]**
Heterogeneity: Tau² = 0.00; Chi² = 1.66, df = 5 (P = 0.89); I² = 0%								
Test for overall effect: Z = 1.44 (P = 0.15)								
1.2.4 PL4								
C - Gross et al. (173) - [consecutive]	470	42	5	480	50	5	4.4%	-0.20 [-1.44, 1.05]
C - Gross et al. (173) - [non-consecutive]	472	62	3	486	70	3	2.6%	-0.17 [-1.78, 1.44]
C - Inoue et al. (174)	5,785	387	4	6,091	478	4	3.3%	-0.61 [-2.06, 0.84]
C - Lamberts et al. (175)	3,836	120	7	3,926	145	7	5.8%	-0.63 [-1.72, 0.45]
C - Laursen et al. (21) - [G1]	3,243	205	4	3,412	195	4	3.1%	-0.73 [-2.21, 0.74]
C - Laursen et al. (21) - [G2]	3,295	182	5	3,478	211	5	3.9%	-0.84 [-2.17, 0.49]
C - Lindsay et al. (181)	3,264	192	4	3,360	216	4	3.4%	-0.41 [-1.82, 1.01]
C - Swart et al. (178) - [HR]	3,888	127	3	3,975	126	3	2.4%	-0.55 [-2.24, 1.14]
C - Swart et al. (178) - [PO]	3,840	119	3	3,914	151	3	2.5%	-0.44 [-2.09, 1.22]
C - Westgarth-Taylor et al. (132)	3,349	324	6	3,429	294	6	5.3%	-0.24 [-1.38, 0.90]
C - Weston et al. (121)	3,354	252	3	3,426	264	3	2.6%	-0.22 [-1.84, 1.39]
R - Salazar-Martínez et al. (180)	58.3	1.9	4	59.6	1.6	4	3.2%	-0.64 [-2.10, 0.81]
R - Smith et al. (46)	599.6	47.35	3	616.6	59.85	3	2.6%	-0.25 [-1.87, 1.37]
R - Smith et al. (47) - [G60%]	1,094	67.5	5	1,119.7	90.3	5	4.4%	-0.29 [-1.54, 0.96]
R - Smith et al. (47) - [G70%]	1,082.7	64.2	5	1,086.3	71.7	5	4.5%	-0.05 [-1.29, 1.19]
Subtotal (95% CI)			**64**			**64**	**54.1%**	**-0.42 [-0.77, -0.06]**
Heterogeneity: Tau² = 0.00; Chi² = 1.69, df = 14 (P = 1.00); I² = 0%								
Test for overall effect: Z = 2.29 (P = 0.02)								
Total (95% CI)			**122**			**122**	**100.0%**	**-0.52 [-0.78, -0.26]**
Heterogeneity: Tau² = 0.00; Chi² = 7.35, df = 26 (P = 1.00); I² = 0%								
Test for overall effect: Z = 3.92 (P < 0.0001)								
Test for subgroup differences: Chi² = 1.61, df = 3 (P = 0.66), I² = 0%								

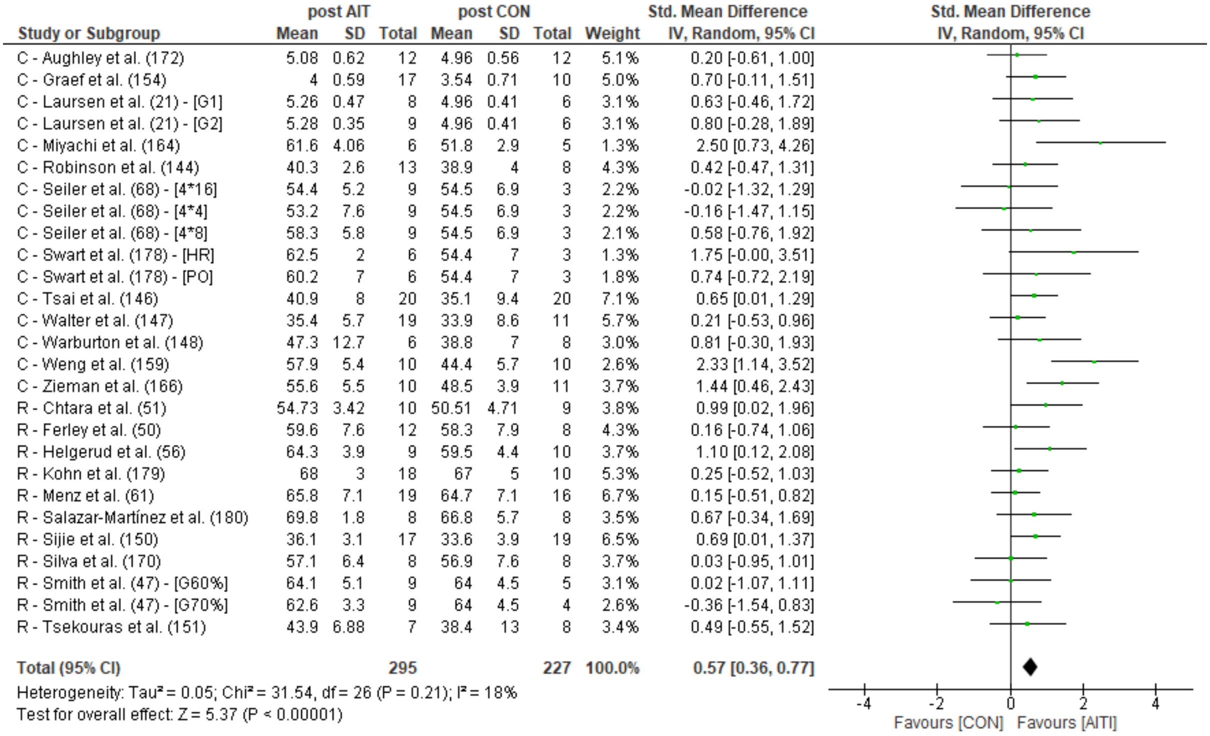
Figure 3.4: Forest plot of pre – post AIT intervention comparison for change in performance (C: cycling, R: running)

3.3.2 AIT vs MICT, SIT and CON interventions

Next to the AIT interventions, numerous studies included training (MICT and / or SIT) or non-training (CON) control groups (see **Table 3.1** and **Table 3.2**). Within group analysis of these groups revealed trivial improvements in $\dot{V}O_2$max ($p = 0.36$, ES: 0.12 [-0.14 to 0.39]) and performance ($p = 0.74$, ES: 0.08 [-0.38 to 0.53]) after CON. MICT yielded a small significant improvement in $\dot{V}O_2$max ($p = 0.02$, ES: 0.47 [0.09 to 0.85]) and moderate improvements in performance ($p = 0.03$, ES: -0.79 [-1.50 to -0.07]. Comparative SIT groups showed to significantly improve $\dot{V}O_2$max ($p < 0.01$, ES: 0.60 [0.20 to 1.00]) and performance ($p = 0.04$, ES: -0.64 [1.24 to -0.03]), with both these improvements of moderate magnitude.

3.3.2.1 Improvements in $\dot{V}O_2$max

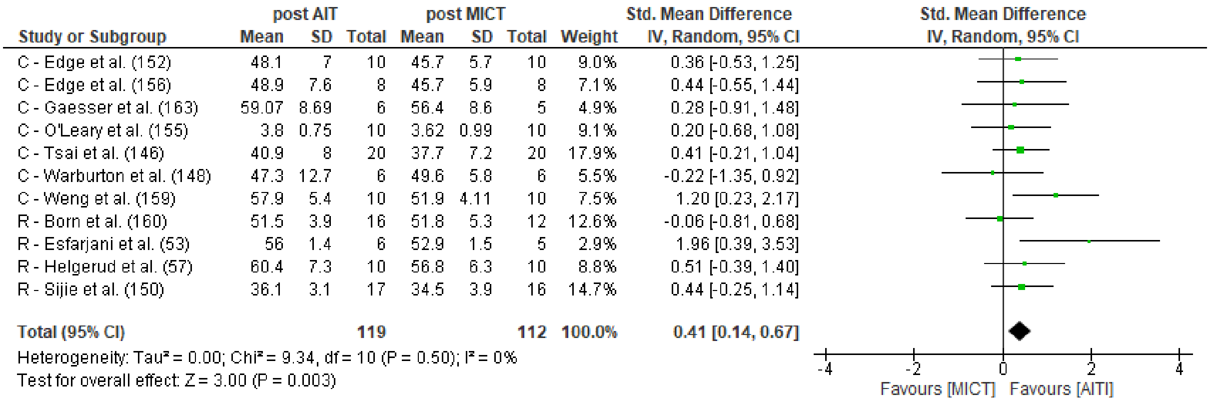
AIT improved $\dot{V}O_2$max significantly more than MICT and CON, and to a similar extent compared to SIT. Compared to CON (see **Figure 3.5**), a significant small to moderate additional increase in $\dot{V}O_2$max was found after AIT (8.9% vs 0.7%, $p < 0.01$, ES = 0.57 [0.36, 0.77]), equalling an additional improvement of 3.58 [2.22, 4.93] mL·kg·min^{-1}. A mean improvement in $\dot{V}O_2$max of 8.3% was evident after MICT (see **Figure 3.6**), which was significantly lower than after AIT in the included studies (12.8%, $p < 0.01$, ES = 0.41 [0.14, 0.67]), which corresponds to an additional improvement of 2.55 [1.43, 3.67] mL·kg·min^{-1}. No differences in improvements of $\dot{V}O_2$max were found between AIT and SIT interventions (see **Figure 3.7**; 6.3% vs 6.1%, $p = 0.91$, ES = 0.03 [-0.39, 0.44]).



	post AIT			post CON				Std. Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
C - Aughley et al. (172)	5.08	0.62	12	4.96	0.56	12	5.1%	0.20 [-0.61, 1.00]
C - Graef et al. (154)	4	0.59	17	3.54	0.71	10	5.0%	0.70 [-0.11, 1.51]
C - Laursen et al. (21) - [G1]	5.26	0.47	8	4.96	0.41	6	3.1%	0.63 [-0.46, 1.72]
C - Laursen et al. (21) - [G2]	5.28	0.35	9	4.96	0.41	6	3.1%	0.80 [-0.28, 1.89]
C - Miyachi et al. (164)	61.6	4.06	6	51.8	2.9	5	1.3%	2.50 [0.73, 4.26]
C - Robinson et al. (144)	40.3	2.6	13	38.9	4	8	4.3%	0.42 [-0.47, 1.31]
C - Seiler et al. (68) - [4*16]	54.4	5.2	9	54.5	6.9	3	2.2%	-0.02 [-1.32, 1.29]
C - Seiler et al. (68) - [4*4]	53.2	7.6	9	54.5	6.9	3	2.2%	-0.16 [-1.47, 1.15]
C - Seiler et al. (68) - [4*8]	58.3	5.8	9	54.5	6.9	3	2.1%	0.58 [-0.76, 1.92]
C - Swart et al. (178) - [HR]	62.5	2	6	54.4	7	3	1.3%	1.75 [-0.00, 3.51]
C - Swart et al. (178) - [PO]	60.2	7	6	54.4	7	3	1.8%	0.74 [-0.72, 2.19]
C - Tsai et al. (146)	40.9	8	20	35.1	9.4	20	7.1%	0.65 [0.01, 1.29]
C - Walter et al. (147)	35.4	5.7	19	33.9	8.6	11	5.7%	0.21 [-0.53, 0.96]
C - Warburton et al. (148)	47.3	12.7	6	38.8	7	8	3.0%	0.81 [-0.30, 1.93]
C - Weng et al. (159)	57.9	5.4	10	44.4	5.7	10	2.6%	2.33 [1.14, 3.52]
C - Zieman et al. (166)	55.6	5.5	10	48.5	3.9	11	3.7%	1.44 [0.46, 2.43]
R - Chtara et al. (51)	54.73	3.42	10	50.51	4.71	9	3.8%	0.99 [0.02, 1.96]
R - Ferley et al. (50)	59.6	7.6	12	58.3	7.9	8	4.3%	0.16 [-0.74, 1.06]
R - Helgerud et al. (56)	64.3	3.9	9	59.5	4.4	10	3.7%	1.10 [0.12, 2.08]
R - Kohn et al. (179)	68	3	18	67	5	10	5.3%	0.25 [-0.52, 1.03]
R - Menz et al. (61)	65.8	7.1	19	64.7	7.1	16	6.7%	0.15 [-0.51, 0.82]
R - Salazar-Martínez et al. (180)	69.8	1.8	8	66.8	5.7	8	3.5%	0.67 [-0.34, 1.69]
R - Sijie et al. (150)	36.1	3.1	17	33.6	3.9	19	6.5%	0.69 [0.01, 1.37]
R - Silva et al. (170)	57.1	6.4	8	56.9	7.6	8	3.7%	0.03 [-0.95, 1.01]
R - Smith et al. (47) - [G60%]	64.1	5.1	9	64	4.5	5	3.1%	0.02 [-1.07, 1.11]
R - Smith et al. (47) - [G70%]	62.6	3.3	9	64	4.5	4	2.6%	-0.36 [-1.54, 0.83]
R - Tsekouras et al. (151)	43.9	6.88	7	38.4	13	8	3.4%	0.49 [-0.55, 1.52]
Total (95% CI)			**295**			**227**	**100.0%**	**0.57 [0.36, 0.77]**

Heterogeneity: Tau² = 0.05; Chi² = 31.54, df = 26 (P = 0.21); I² = 18%
Test for overall effect: Z = 5.37 (P < 0.00001)

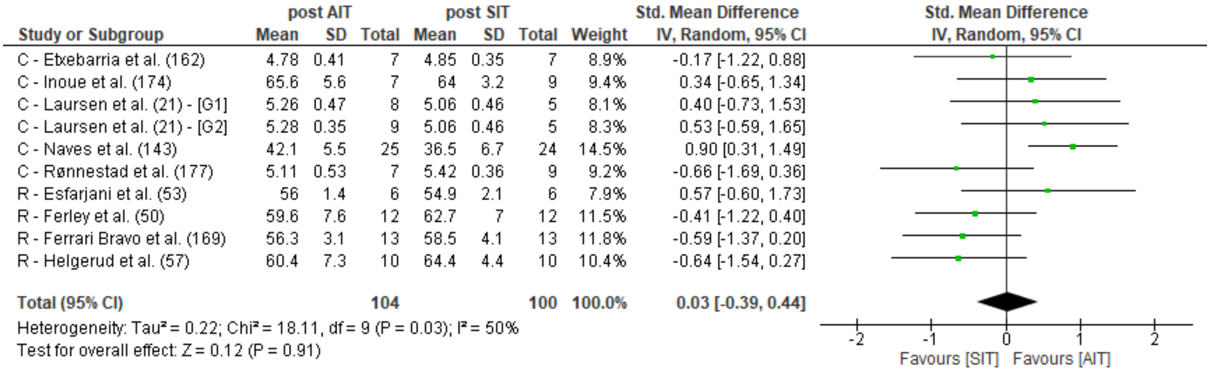
Figure 3.5: Effects of AIT vs CON interventions on post intervention $\dot{V}O_2$max (C: cycling, R: running)



Study or Subgroup	post AIT Mean	post AIT SD	post AIT Total	post MICT Mean	post MICT SD	post MICT Total	Weight	Std. Mean Difference IV, Random, 95% CI
C - Edge et al. (152)	48.1	7	10	45.7	5.7	10	9.0%	0.36 [-0.53, 1.25]
C - Edge et al. (156)	48.9	7.6	8	45.7	5.9	8	7.1%	0.44 [-0.55, 1.44]
C - Gaesser et al. (163)	59.07	8.69	6	56.4	8.6	5	4.9%	0.28 [-0.91, 1.48]
C - O'Leary et al. (155)	3.8	0.75	10	3.62	0.99	10	9.1%	0.20 [-0.68, 1.08]
C - Tsai et al. (146)	40.9	8	20	37.7	7.2	20	17.9%	0.41 [-0.21, 1.04]
C - Warburton et al. (148)	47.3	12.7	6	49.6	5.8	6	5.5%	-0.22 [-1.35, 0.92]
C - Weng et al. (159)	57.9	5.4	10	51.9	4.11	10	7.5%	1.20 [0.23, 2.17]
R - Born et al. (160)	51.5	3.9	16	51.8	5.3	12	12.6%	-0.06 [-0.81, 0.68]
R - Esfarjani et al. (53)	56	1.4	6	52.9	1.5	5	2.9%	1.96 [0.39, 3.53]
R - Helgerud et al. (57)	60.4	7.3	10	56.8	6.3	10	8.8%	0.51 [-0.39, 1.40]
R - Sijie et al. (150)	36.1	3.1	17	34.5	3.9	16	14.7%	0.44 [-0.25, 1.14]
Total (95% CI)			**119**			**112**	**100.0%**	**0.41 [0.14, 0.67]**

Heterogeneity: Tau² = 0.00; Chi² = 9.34, df = 10 (P = 0.50); I² = 0%
Test for overall effect: Z = 3.00 (P = 0.003)

Figure 3.6: Effects of AIT vs MICT interventions on post intervention $\dot{V}O_2$max (C: cycling, R: running)



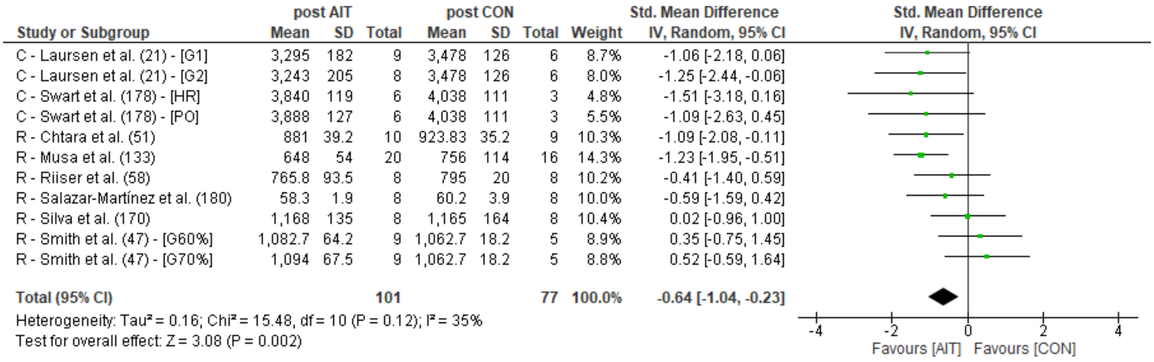
Study or Subgroup	post AIT Mean	post AIT SD	post AIT Total	post SIT Mean	post SIT SD	post SIT Total	Weight	Std. Mean Difference IV, Random, 95% CI
C - Etxebarria et al. (162)	4.78	0.41	7	4.85	0.35	7	8.9%	-0.17 [-1.22, 0.88]
C - Inoue et al. (174)	65.6	5.6	7	64	3.2	9	9.4%	0.34 [-0.65, 1.34]
C - Laursen et al. (21) - [G1]	5.26	0.47	8	5.06	0.46	5	8.1%	0.40 [-0.73, 1.53]
C - Laursen et al. (21) - [G2]	5.28	0.35	9	5.06	0.46	5	8.3%	0.53 [-0.59, 1.65]
C - Naves et al. (143)	42.1	5.5	25	36.5	6.7	24	14.5%	0.90 [0.31, 1.49]
C - Rønnestad et al. (177)	5.11	0.53	7	5.42	0.36	9	9.2%	-0.66 [-1.69, 0.36]
R - Esfarjani et al. (53)	56	1.4	6	54.9	2.1	6	7.9%	0.57 [-0.60, 1.73]
R - Ferley et al. (50)	59.6	7.6	12	62.7	7	12	11.5%	-0.41 [-1.22, 0.40]
R - Ferrari Bravo et al. (169)	56.3	3.1	13	58.5	4.1	13	11.8%	-0.59 [-1.37, 0.20]
R - Helgerud et al. (57)	60.4	7.3	10	64.4	4.4	10	10.4%	-0.64 [-1.54, 0.27]
Total (95% CI)			**104**			**100**	**100.0%**	**0.03 [-0.39, 0.44]**

Heterogeneity: Tau² = 0.22; Chi² = 18.11, df = 9 (P = 0.03); I² = 50%
Test for overall effect: Z = 0.12 (P = 0.91)

Figure 3.7: Effects of AIT vs SIT interventions on post intervention $\dot{V}O_2$max (C: cycling, R: running)

3.3.2.2 Improvements in Performance

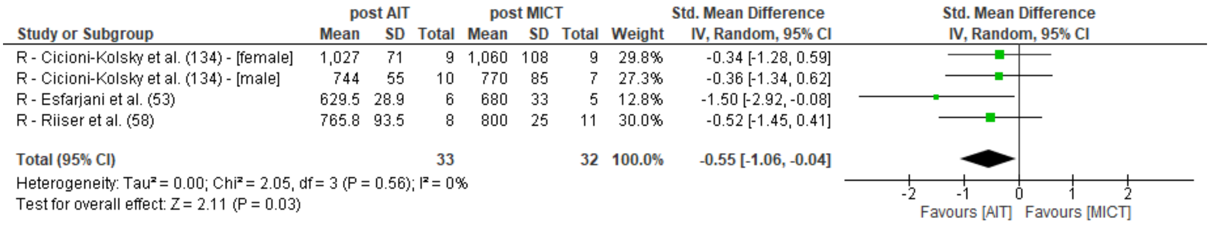
Improvements in performance were significantly greater after AIT compared to CON (see **Figure 3.8**;-4.2% vs +0.5%, p < 0.01, ES = -0.64 [-1.04 to -0.23]) and MICT (see **Figure 3.9**;-8.2% vs -3.7%, p = 0.03, ES = -0.55 [-1.06 to -0.04], however, of a similar magnitude after AIT and SIT interventions (see **Figure 3.10**;-6.3% vs -6.1%, p = 0.50, ES = -0.14 [-0.56 to 0.27]).



Study or Subgroup	post AIT Mean	post AIT SD	post AIT Total	post CON Mean	post CON SD	post CON Total	Weight	Std. Mean Difference IV, Random, 95% CI
C - Laursen et al. (21) - [G1]	3,295	182	9	3,478	126	6	8.7%	-1.06 [-2.18, 0.06]
C - Laursen et al. (21) - [G2]	3,243	205	8	3,478	126	6	8.0%	-1.25 [-2.44, -0.06]
C - Swart et al. (178) - [HR]	3,840	119	6	4,038	111	3	4.8%	-1.51 [-3.18, 0.16]
C - Swart et al. (178) - [PO]	3,888	127	6	4,038	111	3	5.5%	-1.09 [-2.63, 0.45]
R - Chtara et al. (51)	881	39.2	10	923.83	35.2	9	10.3%	-1.09 [-2.08, -0.11]
R - Musa et al. (133)	648	54	20	756	114	16	14.3%	-1.23 [-1.95, -0.51]
R - Riiser et al. (58)	765.8	93.5	8	795	20	8	10.2%	-0.41 [-1.40, 0.59]
R - Salazar-Martínez et al. (180)	58.3	1.9	8	60.2	3.9	8	10.0%	-0.59 [-1.59, 0.42]
R - Silva et al. (170)	1,168	135	8	1,165	164	8	10.4%	0.02 [-0.96, 1.00]
R - Smith et al. (47) - [G60%]	1,082.7	64.2	9	1,062.7	18.2	5	8.9%	0.35 [-0.75, 1.45]
R - Smith et al. (47) - [G70%]	1,094	67.5	9	1,062.7	18.2	5	8.8%	0.52 [-0.59, 1.64]
Total (95% CI)			**101**			**77**	**100.0%**	**-0.64 [-1.04, -0.23]**

Heterogeneity: Tau² = 0.16; Chi² = 15.48, df = 10 (P = 0.12); I² = 35%
Test for overall effect: Z = 3.08 (P = 0.002)

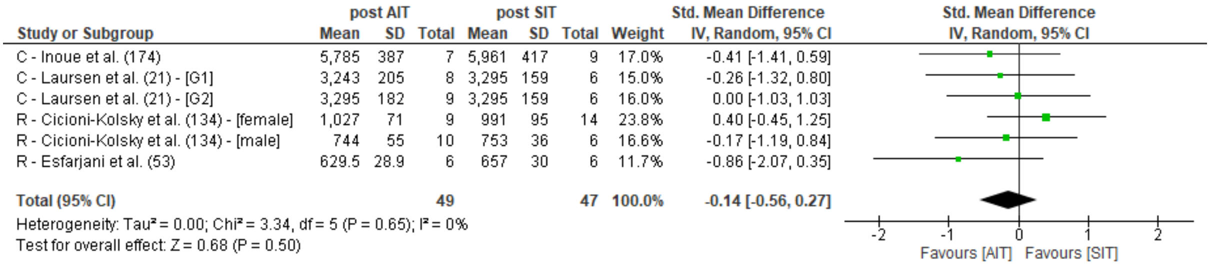
Figure 3.8: Effects of AIT vs CON interventions on post intervention performance measures (C: cycling, R: running)



	post AIT			post MICT				Std. Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
R - Cicioni-Kolsky et al. (134) - [female]	1,027	71	9	1,060	108	9	29.8%	-0.34 [-1.28, 0.59]
R - Cicioni-Kolsky et al. (134) - [male]	744	55	10	770	85	7	27.3%	-0.36 [-1.34, 0.62]
R - Esfarjani et al. (53)	629.5	28.9	6	680	33	5	12.8%	-1.50 [-2.92, -0.08]
R - Riiser et al. (58)	765.8	93.5	8	800	25	11	30.0%	-0.52 [-1.45, 0.41]
Total (95% CI)			**33**			**32**	**100.0%**	**-0.55 [-1.06, -0.04]**

Heterogeneity: Tau² = 0.00; Chi² = 2.05, df = 3 (P = 0.56); I² = 0%
Test for overall effect: Z = 2.11 (P = 0.03)

Figure 3.9: Effects of AIT vs MICT interventions on post intervention performance measures (C: cycling, R: running)



	post AIT			post SIT				Std. Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
C - Inoue et al. (174)	5,785	387	7	5,961	417	9	17.0%	-0.41 [-1.41, 0.59]
C - Laursen et al. (21) - [G1]	3,243	205	8	3,295	159	6	15.0%	-0.26 [-1.32, 0.80]
C - Laursen et al. (21) - [G2]	3,295	182	9	3,295	159	6	16.0%	0.00 [-1.03, 1.03]
R - Cicioni-Kolsky et al. (134) - [female]	1,027	71	9	991	95	14	23.8%	0.40 [-0.45, 1.25]
R - Cicioni-Kolsky et al. (134) - [male]	744	55	10	753	36	6	16.6%	-0.17 [-1.19, 0.84]
R - Esfarjani et al. (53)	629.5	28.9	6	657	30	6	11.7%	-0.86 [-2.07, 0.35]
Total (95% CI)			**49**			**47**	**100.0%**	**-0.14 [-0.56, 0.27]**

Heterogeneity: Tau² = 0.00; Chi² = 3.34, df = 5 (P = 0.65); I² = 0%
Test for overall effect: Z = 0.68 (P = 0.50)

Figure 3.10: Effects of AIT vs SIT interventions on post intervention performance measures (C: cycling, R: running)

3.3.3 Effect of moderator variables on changes in $\dot{V}O_2$max

Improvements in $\dot{V}O_2$max were highly homogenous across included studies (I^2 = 0%, see **Figure 3.11**), which is likely explained by the high number of included studies and the large range in exercise time per single AIT session 21 min 58 s ± 14 min 31 s (see **Table 3.**1) and the variety in the total duration of the AIT interventions included (6 hrs 55 min 56 s ± 8 hrs 10 min 24 s, see **Table 3.**1). This widespread variation in AIT protocols across the different performance levels, seemingly resulted in a blended, homogenous improvement in $\dot{V}O_2$max. High levels of homogeneity do not warrant further analyses of moderating variables, however, in an attempt to better understand potential moderating factors of AIT protocols, separate analyses were performed and are presented in **Table 3.5**. In the initial meta-analytical model, baseline PL did not show to significant moderate improvements in $\dot{V}O_2$max, however, changes were progressively smaller with an increase in PL. Improvements were larger in female participants, however, this may be caused by lower baseline $\dot{V}O_2$max. The results indicate no further moderating effects of the duration of a single work interval, the duration of a single AIT session, the duration of the total AIT intervention, or the recovery interval duration and calculated work:rest ratio.

Table 3.5: Effects of moderator variables on effect size for change in $\dot{V}O_2$max

	Moderator	n studies; participants	baseline $\dot{V}O_2$max	ES [95% CI]	Subgroup differences
Gender	Male	44; 434	54.8 ± 8.1	0.53 [0.34 to 0.73]	M vs F: $\chi^2 = 0.38$, $p = 0.54$
	Female	10; 120	39.3 ± 5.1 [a]	0.67 [0.29 to 1.04]	M vs F vs Mixed: $\chi^2 = 1.09$, $p = 0.58$
	(Mixed)	15; 160	50.2 ± 8.9	0.41 [0.09 to 0.73]	
Duration single AIT interval [x]	≤ 3 min	35; 356	49.2 ± 10.4	0.61 [0.39 to 0.83]	$\chi^2 = 0.61$, $p = 0.43$
	> 3 min	30; 314	53.2 ± 8.1	0.49 [0.26 to 0.72]	
Duration single AIT session [x]	< 16 min	22; 244	47.8 ± 9.3	0.69 [0.42 to 0.96]	$\chi^2 = 4.44$, $p = 0.11$
	16 – 20 min	19; 218	52.3 ± 9.9	0.65 [0.37 to 0.93]	
	≥ 20 min	24; 208	53.1 ± 9.1	0.31 [0.03 to 0.59]	
Duration total AIT intervention	≤ 3 hrs	22; 232	54.5 ± 9.8	0.51 [0.24 to 0.78]	$\chi^2 = 1.40$, $p = 0.50$
	3 - 6 hrs	24; 236	54.4 ± 8.4	0.44 [0.17 to 0.70]	
	≥ 6 hrs	23; 246	45.7 ± 7.8 [a]	0.66 [0.39 to 0.93]	
Duration single recovery interval [x]	≤ 2 min	26; 266	48.8 ± 9.9	0.48 [0.23, 0.73]	$\chi^2 = 0.23$, $p = 0.23$
	2 – 3 min	23; 262	51.3 ± 8.6	0.73 [0.47, 0.98]	
	> 3 min	16; 142	54.4 ± 9.8	0.39 [0.04, 0.73]	
Work : rest ratio	≤ 1	4; 36	54.1 ± 5.9	0.82 [0.12 to 1.52]	$\chi^2 = 0.77$, $p = 0.68$
	1	20; 190	52.1 ± 9.4	0.57 [0.26 to 0.87]	
	≥ 1	45; 488	49.7 ± 10.3	0.50 [0.32, 0.69]	

[a] baseline $\dot{V}O_2$max significantly lower than other subgroups, $p < 0.05$

[x] data excluded from (185,188,196) for analysis due changing work interval durations

3.4 Discussion

This study presents a quantitative evaluation of running and cycling based AIT for $\dot{V}O_2$max and performance improvements in healthy adults. Our results show that AIT is an effective training modality, evidenced by the significant improvements in $\dot{V}O_2$max and performance across the included studies. In studies where AIT and MICT interventions were directly compared, there was a small to moderate beneficial effect for AIT in the improvements of both $\dot{V}O_2$max and performance. When compared to SIT interventions, the current results show trivial differences in improvements of both these parameters.

The results of our systematic review and meta-analysis are in line with the conclusions of previous studies, conforming that AIT, SIT and also MICT are effective methods to improve $\dot{V}O_2$max (30,152,197). We are the first to evaluate the effectiveness of solely AIT interventions, and irrespective of AIT protocol, we found small to moderate improvements in $\dot{V}O_2$max (ES = 0.54 [0.38 to 0.69]). This SMD corresponds to a mean increase of 3.07 mL·kg·min^{-1}, in line with previous meta-analysis evaluating HIIT (30,140,197) and SIT (152,198–200) interventions. Previously, Bacon et al. (140) reported larger improvements in $\dot{V}O_2$max after HIIT (SMD = 0.86 [0.72 to 0.99]) than the current findings. This difference is likely explained by the exclusion of trained participants (defined as baseline $\dot{V}O_2$max ≥ 55.0 mL·kg·min^{-1} for men and ≥ 49.5 mL·kg·min^{-1} for women) by Bacon et al. (140), while no exclusion criteria were set for baseline fitness in the current study. We grouped participants into four performance levels, and while across all studies the change in $\dot{V}O_2$max was not significantly different between PLs, lesser trained participants (PL1 and PL2) benefited more from AIT than athletic populations (PL3 and PL4), especially in running based AIT interventions (see **Table 3.3**). Already in 1976 Henriksson & Reitman (201) showed that the increase of $\dot{V}O_2$max is inversely related to baseline $\dot{V}O_2$max, a finding that is consistent with previous meta-analysis stating that aerobic training in general has an apparent adaptive effect on $\dot{V}O_2$max favouring the subjects with a lower baseline $\dot{V}O_2$max (30,140,152,197). Significant small to moderate improvements in $\dot{V}O_2$max were evident in all PLs (see **Figure 3.3** and **Table 3.3**), and contrary to our hypothesis, AIT did elicit further improvements in PL4 (including participants with a baseline $\dot{V}O_2$max ≥ 60.0 mL·kg·min^{-1}). This highlights that, while lesser-trained participants may benefit more from AIT, the inclusion of AIT in the training programs of highly trained runners (e.g. (193,194)) and cyclists (e.g. (188,202) is highly relevant.

Compared with MICT, AIT had a small beneficial effect on $\dot{V}O_2$max (WMD = 2.55 $mL \cdot kg \cdot min^{-1}$). This improvement was similar to previous estimates, comparing HIIT vs MICT (30,197). Our results further indicate that AIT improved $\dot{V}O_2$max to a similar extent as SIT, in line with the findings of Wen et al. (197). Helgerud et al. (70) concluded that increases in $\dot{V}O_2$max in short training interventions (2 – 6 weeks) seem to be a function of an increased cardiac output, driven by an increase in stroke volume. In their study, both SIT and AIT protocols elicit improvements in $\dot{V}O_2$max, but despite a greater training volume, no improvements in $\dot{V}O_2$max were evident after MICT (70). The underlying physiological mechanisms and cell signalling pathways subtending the improvements in $\dot{V}O_2$max following either HIIT or MICT are thought to differ (120,121,136), and while beyond the scope of this study and this thesis, our results highlight that both SIT and AIT are more time efficient training modalities to improve $\dot{V}O_2$max than MICT. The results further go to show, that in the light of improvements in $\dot{V}O_2$max, the intensity of training cannot be compensated for by longer duration (70,203).

The acute physiological responses to AIT are greater than commonly reported for SIT (75,133), and we expected that the greater exercise time close to $\dot{V}O_2$max. / HRmax in AIT sessions would allow for greater improvements in $\dot{V}O_2$max. In line with the SMD of the current study, previous meta-analyses demonstrated beneficial effects of SIT (SMD = 0.63 – 0.69) on $\dot{V}O_2$max compared to CON (198,200). Therefore maybe unsurprisingly, we found no differences in improvements across the included studies that compared AIT and SIT interventions (see **Figure 3.12**). AIT protocols typically involve less, but longer work intervals compared to the training configuration of SIT (see **Table 3.1**), however, the longer recovery intervals separating repeated all-out (or ‘supramaximal’(50)) sprint intervals result in a similar overall training time of SIT sessions. The improvements in $\dot{V}O_2$max *per minute of exercise* seemingly are greater in SIT than AIT, however, in contrast to the additional beneficial improvements after AIT compared to MICT, only a trivial effect (SMD = 0.04 – 0.08) was observed when SIT was compared to MICT (29,197,198). Traditional AIT is therefore recommended to ensure or enhance training effects, and was shown a safe and feasible training modality for the general and patient populations (126,127).

The change in $\dot{V}O_2$max was highly homogenous, in contrast to previous meta-analytical comparisons (140,197). The homogenous improvement is surprising, given the diversity of AIT protocols in the included studies, and traditionally would not warrant further analysis of moderating variables. The results however speculatively indicate that long AIT interventions, incorporating a total AIT exercise time per session of ≤ 20 min with work intervals of ≤ 3 min separated by recovery intervals of not more than 3 min may yield larger improvements in $\dot{V}O_2$max. Further, female participants improved $\dot{V}O_2$max more than male participants, however, this finding may be confounded by their lower initial $\dot{V}O_2$max (see **Table 3.5**). Only ten studies examined AIT in a group of solely female participants, and all these studies were situated in PL1 and PL2. Apart from grouped data in PL3 ((42,63,65,73) and PL4 (74,187), data on the effects of AIT in trained females is scarce. Previously, women demonstrated a greater cardiovascular strain in AIT sessions than men (93), and future studies are needed to determine if changes in $\dot{V}O_2$max and / or performance are of similar magnitude as male participants.

We are the first to compare changes in performance after AIT, next to the classical evaluation of changes in $\dot{V}O_2$max after training interventions. Running performance was evaluated over a range of distances, varying from 400 – 5000 m, and cycling based AIT interventions assessed performance in lab based time trials, or in a simulated race setting. Performance improved significant in all PLs (ES = -0.52 [-0.78 to -0.26]), with (non-significant) larger improvements for the lower PLs (see **Table 3.4**). The addition of strength training to the training programs of runners and cyclists (204,205), previously proved to improve performance to similar extent (SMD = - 0.50 - 0.52), whereas the effect of carbohydrate mouth rinsing on cycling performance was of a smaller magnitude (SMD = - 0.12, (206)). Although the number of comparative studies was small (see **Figure 3.8** – **Figure 3.10**), the results indicate that AIT allows for greater improvements than CON and MICT. Alike the changes in $\dot{V}O_2$max after AIT and SIT, the improvements in performance were of similar magnitude for these training modalities (6.3% vs -6.1%). A total of fourteen studies evaluated both changes in $\dot{V}O_2$max and performance (21,35,60,62,64,66,67,171,184,187–189,192,194). PL of the participants in these studies varied between PL2 to PL4, and surprisingly, both the improvements in $\dot{V}O_2$max (ES = 0.41 [0.10 to 0.73]) and performance (ES: -0.44 [-0.75 to -0.12]) were of a small to moderate magnitude (see **Table 3.1** and **Table 3.2**) with no differences between PL (forest plot not shown).

In this study, we provide a comprehensive review of more than 80 unique AIT protocols. The programming puzzle to the optimal AIT protocol is complex and far from complete, but next to the manipulation in the key components of AIT sessions (14,16,17), secondary programming considerations have started to gain scientific interest. In most of the included studies, participants performed two AIT sessions per week, with sessions separated by at least 48 hr to allow for adequate recovery (207). Whether 48 hr recovery between AIT sessions is needed, or yields greater improvements than less recovery days was recently questioned (73,187), and while the adaptations following a high frequency AIT programme (24 sessions in three weeks) were delayed compared to a moderate frequency (24 sessions in eight weeks), no differences in changes in $\dot{V}O_2max$ were found (73,187). Another new line of research focussed on how dietary intake might moderate the acute physiological responses to AIT sessions (208,209). No studies in the included analysis of the current study reported dietary habits of participants, were new findings suggest that changes in substrate utilization are likely in high intensity exercise when participants adhere to a low carb high fat diet (208). In future studies, it is advised to track habitual food intake during AIT interventions.

In addition to the well-known limitations associated with retrospective analysis of data reported previously, there are specific limitations to our analysis. We extracted absolute or relative $\dot{V}O_2max$ values from the included studies, however, studies reporting relative values often failed to report measures of both pre and post intervention body weight, of which changes may in turn magnify the training effect on $\dot{V}O_2max$. Second, based on the institutional affiliation of first authors, it is expected that 80% of the included participant were (likely Caucasian) young men and this could explain at least some of the increased responsiveness that we saw. Lastly, the majority of the included studies use the term '$\dot{V}O_2max$' to describe the maximum rate of oxygen uptake of participants obtained in incremental exercise tests. Data averaging methods in the assessment $\dot{V}O_2max$ widely differed between studies, impacting the value of $\dot{V}O_2max$ (210,211). Only few studies incorporated verification test protocols of the attainment of a $\dot{V}O_2$ plateau during these incremental exercise tests, which is the unambiguous validation of $\dot{V}O_2max$ (212).

$\dot{V}O_2$max values of exercise test naïve or less motivated participants who may stop exercising before their $\dot{V}O_2$max is reached might therefore more likely represent a measure of $\dot{V}O_2$peak (simply the highest $\dot{V}O_2$ reached on a given test). This methodological concern might underestimate the true '$\dot{V}O_2$max' of participants in some of the included studies, especially for participants in PL1 and PL2.

3.5 Practical applications

Aerobic interval training is an effective training modality to improve both $\dot{V}O_2$max and performance in healthy adult participants. Improvements in these variables were evident independent of baseline fitness, highlighting the wide applicability of AIT across a range of fitness levels. AIT is not only a time-efficient alternative of MICT, it further yields small beneficial additional improvements in both $\dot{V}O_2$max and performance compared to MICT. The improvements are greater in individuals with lower pre-training fitness. Based on the results, individual athletes and coaches are advised to incorporate AIT in their training programs if the goal is to maximize the training effects on $\dot{V}O_2$max or surpass the MICT.

Chapter 4:

The physiological and perceptual demands of running on a curved non-motorised treadmill: Implications for self-paced training

Citation:

Schoenmakers, P. & Reed, K. (2018). The physiological and perceptual demands of running on a curved non-motorised treadmill: Implications for self-paced training. *Journal of science and medicine in sport*, *21*(12), 1293-1297, DOI: 10.1016/j.jsams.2018.05.011

Summary

The aim of this study was to compare the physiological and perceptual response of running on a curved non-motorized treadmill (cNMT) with running on a motorized treadmill (MT). A secondary aim was to determine the running velocity at which a physiological response ≥ 90% $\dot{V}O_2max$ was elicited on both treadmills. Thirteen trained male runners (mean ± SD; 36 ± 11 years, 1.80 ± 0.06 m, 70 ± 4 kg, $\dot{V}O_2max$: 57.3 ± 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$) performed an incremental running test on a MT to determine $\dot{V}O_2max$ and the accompanying maximum aerobic velocity (MAV). In their second visit, participants completed a familiarization session on the cNMT. Next, participants ran for 4 min at five / six progressively higher velocities (40 - 90% MAV) on the cNMT and MT in two separate visits in a randomized and counterbalanced order. No participant was able to complete the 4 min run at 80% MAV on the cNMT. Running on the cNMT elicit a higher $\dot{V}O_2$ across all velocities compared to the MT (32.5 ± 5%, $p < 0.01$, ES: 3.3 ± 0.9). This higher $\dot{V}O_2$ was accompanied by significantly higher heart rates (16.8 ± 3%, $p < 0.01$, ES: 3.4 ± 1.5), an altered cadence (2.6 ± 0.7%, $p < 0.01$, ES: 0.8 ± 0.3) and higher ratings of perceived exertion (27.2 ± 5%, $p < 0.01$, ES: 2.3 ± 0.6). A less efficient running economy was evident when running on the cNMT (+38.4 ± 16%, $p < 0.01$, ES: 2.73). Individual (n=9) linear interpolation predicted an exercise intensity of 90% $\dot{V}O_2max$ was achieved in the non-motorized condition when running at 62.1 ± 3.5% MAV ($R^2 = 0.986 \pm 0.01$), which was notably slower than the predicted running velocity of the MT run (MAV: 81.4 ± 5.6%, $R^2 = 0.985 \pm 0.02$; $p < 0.01$, ES: 3.87). Our results show that running on the cNMT has higher physiological and perceptual demands than running on a MT, and running cadence is influenced. When using the cNMT, it is advised to lower the running velocity by 20% compared to MT runs, to generate a comparable physiological stimulus.

4.1 Introduction

Treadmills are an indispensable piece of laboratory equipment, and have become a key piece of exercise testing and training equipment. They are considered a valid measure of outdoor running performance, as evidenced by Jones & Doust (213), who showed that the oxygen uptake ($\dot{V}O_2$) during overground running and running on a motorized treadmill (MT) was strongly correlated with the use of a 1% treadmill grade. However, when performing a running task on a MT, moment-to-moment changes in velocity are not possible due to the fixed belt speed, and changes in velocity are controlled by an external motor which further requires a manual action to be changed (214,215). With the change of velocity controlled 'externally of the runner', deciding to change the running velocity requires a conscious decision by the runner. It is however suggested that the regulation of intensity during endurance exercise occurs unconsciously, based on live interactions with the environment and by both central and peripheral control mechanisms (44,216), and therefore the ecological validity of MT running may be questionable.

Recently, it has been argued that athletes measure and pace their work in training sessions in general, and in high intensity interval training (HIIT) specifically, on ratings of perceived exertion (RPE) and accumulated fatigue (42). This '*isoeffort*' approach is in sharp contrast with protocols often used in lab based experiments, in which responses to predefined exercise intensities are studied. In self-paced HIIT, the maximum sustainable intensity is employed for a set number of work intervals of fixed durations. Athletes can then self-regulate their exercise intensity, based on their knowledge of the total volume of the session, the memory of similar events, as well as feedback from external and internal receptors (42,44). It is suggested that athletes should spend at least several minutes per HIIT in their 'red zone', which refers to the intensity domain close to their maximal oxygen uptake and heart rate (≥ 90% $\dot{V}O_2$max and HRmax respectively) (14,217). While self-paced HIIT has been addressed recently in cycling (42,218), there is a paucity of research exploring the use of self-paced HIIT in running exercise.

Previously, the acute physiological responses to self-paced running HIIT protocols of varying work durations and / or recovery durations have been studied (22,77,93). However, in these studies participants ran on a MT and the velocity could only be increased or decreased via a hand signal to the test administrator controlling the treadmill, highlighting the conscious external decision making process required (22,77,93). Standard MTs do not allow to study the quick and frequent adjustments in running velocities that occur during self-paced exercise (45). Non-motorized treadmills (NMT) on the other hand, are participant driven and allow runners to self-select their pace and dictate the speed of the treadmill belt with every step, which makes the overall locomotion more consistent with outdoor running (214,215). Previously, a commercially available curved non-motorized treadmill (cNMT, see **Figure 4.1**) demonstrated good reliability and validity for the assessment of $\dot{V}O_2$max (219), endurance performance (215,220), sprint (221) and repeated sprint intervals (222). To evaluate the potential use of the cNMT for self-paced HIIT sessions, it is important to understand the physiological responses associated with running on the cNMT. The aim of this study therefore was to determine the physiological and perceptual demands of running on a cNMT over a range of velocities commonly used in training and races of trained runners, and compare these to the demands of running on a MT set to a 1% gradient. The second aim was to determine at which running velocity a physiological response ≥ 90% $\dot{V}O_2$max was elicited on both the cNMT and MT. Trained club level runners were used in this study as they would likely be more attuned to internal pacing cues, and be able to maintain high workloads for sufficient time for reliable measures to be taken. It was hypothesized that the physiological demands when running on the cNMT would be higher than on a MT at any given velocity, since the curved design introduces a slight incline to the front aspect of the treadmill, which in theory demands higher energy expenditure.

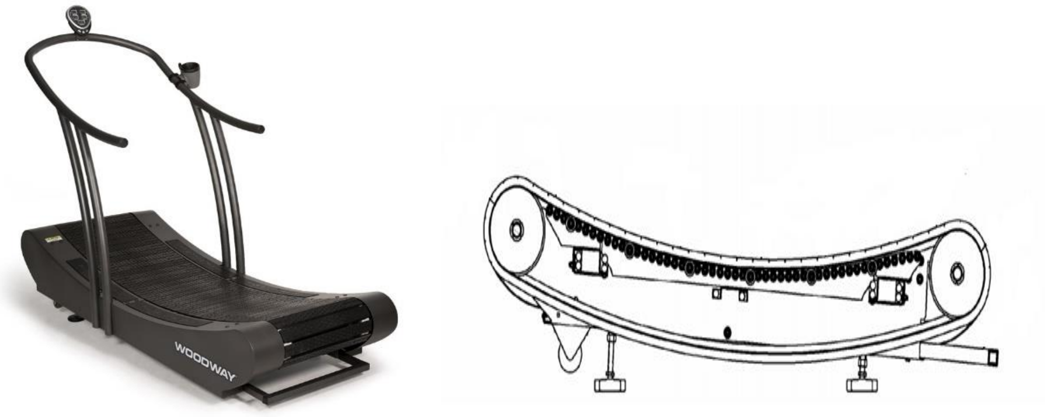


Figure 4.1: Woodway Curve XL, and close-up of the concave treadmill belt

4.2 Methods

4.2.1 Experimental approach to the problem

Participants visited the laboratory on four different occasions over a two-week period, with visits separated by at least 48 hours. On their first visit, participants performed an incremental running test on a MT (Pulsar 3p, H/P Cosmos, Nussdorf-Traunstein, Germany) to determine $\dot{V}O_2max$, HRmax and the associated running intensity (maximum aerobic velocity (MAV)). During the second visit, participants performed the experimental running protocol (detailed below in **Section 4.2.4**) on the cNMT (Woodway Curve XL, Woodway Inc, Waukesha, USA) as a familiarisation session (cNMTfam). Two comparative experimental runs on the cNMT (cNMTrun) and MT (MTrun) in the third and fourth visit were performed in a counterbalanced randomised order. All visits were completed on the same time of the day (± 1 h). The accuracy of both the MT and cNMT velocity measures was verified prior to the study, using a video camera and found to be within < 1.1 %.

4.2.2 Considerations and implications of sample size selection in sports science studies

Selecting an appropriate sample size is a crucial step in designing a successful study (223,224). A study with an insufficient sample may not have sufficient statistical power to detect meaningful differences and may produce unreliable answers to research questions and hypotheses (Type II error, or false negative). On the other hand, a study with an excessive sample size wastes resources and may unnecessarily expose study participants to potential harm. A large sample size further increases the chance to conclude there is a significant difference when in fact there is not (Type I error, or false positive), as calculated p-values depend on the size of the sample, but the alpha level of significance is fixed *a priori*. Generally the larger the sample size, the more likely a study will find a significant relationship between variables if one exists. As the sample size increases the impact of random error is reduced. Additionally, the overall variability is decreased, and measures become more precise for a population as a whole. This increased precision allows for detection of smaller differences between groups (225,226), however, these might be of limited practical relevance (151).

4.2.3 Participants

Thirteen recreationally trained male runners (mean ± standard deviations (SD), age: 36 ± 11 years; stature: 1.80 ± 0.06 m; body mass: 70 ± 4 kg; $\dot{V}O_2max$: 57.3 ± 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$; MAV: 5.0 ± 0.2 $m \cdot s^{-1}$) participated in this study. *A priori* power analysis (G*Power 3.1) indicated a minimum sample size of 12 participants was required to detect small differences (Cohen's d = 0.2) in the physiological and perceptual responses between cNMT and MT running at the various experimental velocities. None of the participants had prior experience with (curved) NMT running. Prior to their active participation, all subjects provided voluntary written informed consent. The study received approval from the local ethics committee (University of Essex, Colchester, UK) and was conducted in accordance with the Declaration of Helsinki. Participants were asked to report for testing well-rested and well-hydrated, wearing the same footwear on each visit. Participants were further asked to refrain from any strenuous exercise or alcohol consumption in the preceding 24 h, and refrain from caffeine and food consumption, 4 and 2 h before the start of the test, respectively.

4.2.4 Incremental running test protocol

During their first visit, participants performed an incremental running test on the MT, with the gradient set at 1% (213). This test started at 2.22 $m \cdot s^{-1}$, which was increased by 0.28 $m \cdot s^{-1}$ each minute until participants reached volitional exhaustion or when one of the following criteria was met: 1) HRmax at least equal to 90% of the age-predicted maximum; 2) respiratory exchange ratio (RER) $\geq$ 1.1; 3) stable oxygen consumption ($\dot{V}O_2$) despite increased intensity (212). $\dot{V}O_2max$ was defined as the highest 30 s averaged $\dot{V}O_2$ collected during the incremental test. HRmax was defined as the highest value obtained at the end of the test. MAV was defined as the highest velocity that could be maintained for a complete minute, or as the velocity of the last complete stage added to the completed fraction of an incomplete stage. MAV was calculated according to the equation $MAV = Vcomp + (0.28\ m \cdot s^{-1} \times t/60)$, in which Vcomp is the velocity of the last completed stage and t the time in seconds sustained during the final incomplete stage.

4.2.5 Experimental running protocol

In the familiarisation and comparative experimental runs, participants were required to run for 4 min at five different individualized velocities (40%, 50%, 60%, 70%, 80% MAV; velocity range [2.0 ± 0.1 – 4.0 ± 0.2 $m\cdot s^{-1}$]), with 3 min passive recovery between the 4 min runs. A subset of eight participants volunteered to complete a further (6th) running bout at 90% MAV on the MT (velocity: 4.5 ± 0.2 $m\cdot s^{-1}$). In cNMTfam and cNMTrun, participants were instructed to monitor their speed on the treadmill's LCD screen and maintain it as close to the prescribed speed as possible (215). Verbal cues to do so were provided if necessary. Average $\dot{V}O_2$, heart rate (HR), RER and running cadence were determined during the last minute of each stage, together with overall RPE on the standard Borg scale (80).

4.2.6 Data collection and analysis

Running economy was calculated using the averaged $\dot{V}O_2$ and RER from the final min of the runs conducted at 50% MAV (2.5 ± 0.09 $m\cdot s^{-1}$). This velocity was selected as 11 subjects completed cNMTrun and MTrun at this run with an RER < 1.0. Running economy was expressed as gross oxygen unit cost ($mL\cdot kg^{-1}\cdot km^{-1}$), as well as a gross caloric unit cost (the energy required to cover a given distance; $kcal\cdot kg^{-1}\cdot km^{-1}$). The gross caloric unit cost was calculated as described by Fletcher et al. (227) in which the averaged RER was used to determine the caloric equivalent of $\dot{V}O_2$.

During the incremental running test, cNMTfam, and the two comparative experimental runs, HR and running cadence were measured continuously at 1 Hz using a Garmin heart rate monitor and a telemetric foot pod (910XT, Garmin Ltd., Schaffhausen, Switzerland). Respiratory parameters were measured breath by breath, using open circuit spirometry (Oxycon Pro, Jaeger, Höchberg, Germany). The gas analyser was calibrated prior to each test using room air and a calibration gas of known concentration (16.0% O_2, 5.0% CO_2). The physiological measures of both $\dot{V}O_2$ and HR were indexed for individual $\dot{V}O_2$max and HRmax (%$\dot{V}O_2$max and %HRmax respectively), to use these relative values as an insightful indicator of the relative exercise intensity, especially in the intense exercise domain in which $\dot{V}O_2$ is not expected to reach steady state. Running velocity in the cNMT trials was sampled at 4 Hz, and was assessed in the accompanying product software.

4.2.7 Statistical analysis

Data were analysed using SPSS 23.0 (SPSS Inc., Chicago, USA) and are presented as mean ± SD Differences in running velocities were compared between cNMTfam, cNMTrun and MTrun using repeated measures analysis of variances (ANOVA). A comparison between cNMTfam and cNMTrun was carried out to evaluate any learning effects due to the novelty of running on this piece of equipment. The test-retest reliability of the main outcome variables (%$\dot{V}O_2$max, %HRmax, cadence and RPE) was determined as the coefficient of variation (CV) between cNMTfam and cNMTrun. The CV methodology was considered the most suitable description of test-retest reliability in this study as it enables both valid and practical comparisons between test parameters from a single variable (223). The CV is expressed as a percentage and calculated as: $CV = 100 \cdot SD_{\text{diff}} / X$. The SD_{diff} indicated the SD of the difference between the duplicate measurements, and X the mean of these measurements (223).

Repeated measures ANOVAs were carried out to compare differences between the experimental conditions (cNMTrun vs MTrun) for each velocity (40 - 80% MAV) in %$\dot{V}O_2$, %HR, RER, measures of running economy, running cadence and RPE. In the event of significant main or interaction effects, Tukey’s post hoc tests were used to determine differences between the two treadmills and / or across the different running velocities.

In an attempt to determine the running velocity which elicited comparable exercise intensities between the cNMT and MT, data collected during 90% MAV on the MT were compared with data collected during the 70% MAV cNMT run (n = 8) using paired t-tests. The running velocity at which the physiological response corresponded to 90% $\dot{V}O_2$max was determined individually, through linear interpolation for both treadmills. The significance level of all tests was set at < 0.05. Standardized effect sizes (ES) are reported as Cohen’s d. Qualitative interpretation of d was based on the guidelines provided by Hopkins et al. (151): < 0.2 trivial; 0.20 - 0.59 small; 0.6 - 1.19 moderate; 1.20 - 1.99 large; ≥ 2.00 very large.

4.3 Results

No participant was able to complete the 4 min running bout at 80% MAV in cNMTfam or cNMTrun. No differences in running velocities were found between cNMTfam and cNMTrun (40.2 ± 0.8 vs 40.3 ± 0.8; 50.2 ± 0.6 vs 50.1 ± 0.6; 60.2 ± 0.7 vs 60.2 ± 0.7; 70.0 ± 0.6 vs 70.2 ± 0.7 for 40, 50, 60, 70% MAV respectively, $p > 0.05$ for all conditions), or between cNMTrun and cMTrun ($p > 0.05$ for all conditions). Participants monitored their speed on the treadmill's LCD screen and maintained it as close to the prescribed speed as possible. **Figure 4.2** shows the typical variation in running velocity around the target velocities of 40 – 70% MAV. Across the participants, variation was highest in 40% MAV (5.6%), which decreased with an increase in running velocity (50% MAV: 4.8%, 60% MAV: 3.4%, 70% MAV: 3.4%).

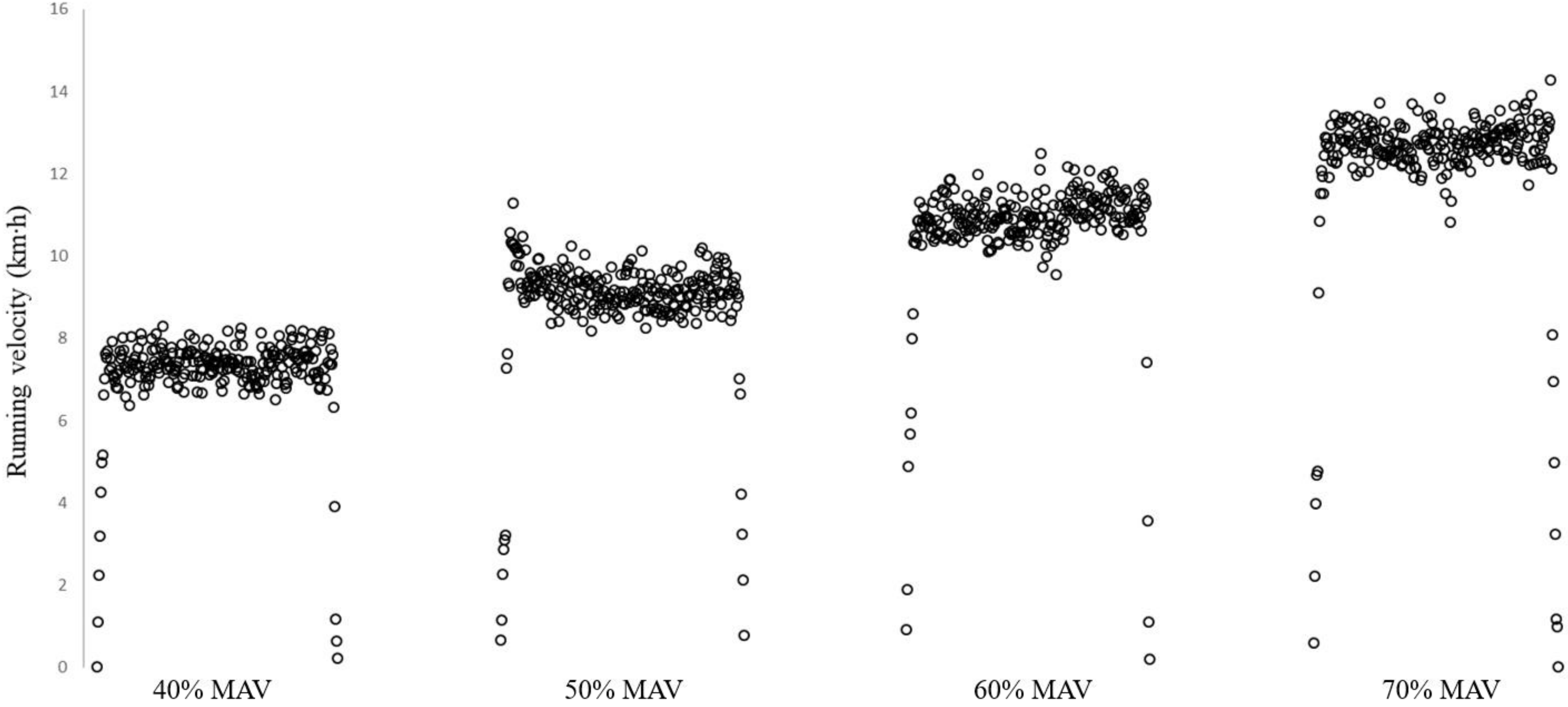


Figure 4.2: Mean running velocity (1-s sample) of a representative participant. Target velocities were 7.4 km·h, 9.2 km·h, 11.0 km·h and 12.8 km·h respectively

Participants rated their perceived exertion in 40% MAV cNMTrun significantly lower after the familiarisation sessions, which was accompanied by a reduced oxygen consumption (see **Table 4.1).** No further learning effects were evident after the familiarisation session, as only trivial or small differences were apparent between cNMTfam and cNMTrun in all experimental variables ($p > 0.05$ for all conditions, see **Table 4.1**). The mean oxygen consumption (CV ≈ 3%), mean exercise heart rate (CV ≈ 1%) and running cadence (CV ≈ 1.5%) were highly similar between cNMTfam and cNMTrun. Despite the similarity in mean RPE between cNMTfam and cNMTrun across the different velocities, this measure was more prone to variation and was found less reliable, especially in the lower running velocities (see **Table 4.1**).

A summary of the main experimental variables is presented in **Table 4.2**. The average oxygen uptake in cNMTrun was significantly higher at all velocities compared to MTrun ($p < 0.01$). On average, across the four different velocities, the oxygen consumption was 32.3 ± 4% higher in cNMTrun (see **Table 4.2**). The higher oxygen uptake was accompanied by significantly higher exercise heart rates (+16.8 ± 3%, $p < 0.01$) and ratings of perceived exertion (+27 ± 5%, $p < 0.01$). Running cadence was higher at all velocities in cNMTrun (+2.4 ± 0.8%), which reached statistical significance at 60% and 70% MAV ($p < 0.05$).

Table 4.1: Test-retest reliability measurements for relative oxygen uptake (%$\dot{V}O_2$max), heart rate (%HRmax), ratings of perceived exertion (RPE) and running cadence (steps per min) between cNMTfam and cNMTrun according to mean differences (MD), effect sizes (ES) and coefficients of variation (CV)

Running Velocity	% $\dot{V}O_2$max			%HRmax			RPE			Running Cadence		
(%MAV)	MD	ES	CV	MD	ES	CV	MD	ES	CV	MD	ES	CV
40	-2.1 ± 3.2[a]	0.38	3.4%	-0.9 ± 3.4	0.22	1.9%	-1.0 ± 1.6[a]	0.57	11.7%	-2.7 ± 5.9	0.22	1.8%
50	-0.1 ± 4.0	0.02	3.1%	-0.8 ± 1.4	0.23	1.0%	-0.1 ± 1.7	0.05	8.1%	-1.2 ± 4.7	0.09	1.4%
60	0.6 ± 4.0	0.10	2.9%	-0.6 ± 1.6	0.21	0.8%	0.2 ± 1.5	0.10	5.4%	-0.8 ± 4.4	0.06	1.4%
70	-1.3 ± 6.2	0.21	3.1%	-0.2 ± 1.2	0.15	0.6%	-0.3 ± 0.9	0.19	2.6%	-1.5 ± 4.8	0.13	1.5%

[a] $p < 0.05$ between cNMTfam and cNMTrun

Note; CV: coefficient of variation, ES: effect size, HRmax: maximum heart rate, MAV: maximum aerobic velocity, MD: mean difference cNMTfam – cNMTrun (nb: negative MD indicates lower mean cNMTrun), RPE: ratings of perceived exertion, $\dot{V}O_2$max: maximum oxygen uptake

Table 4.2: Relative oxygen uptake (%$\dot{V}O_2$max), heart rate (%HRmax), respiratory exchange ratio (RER), ratings of perceived exertion (RPE) and running cadence (steps per min) in each experimental condition (n = 13 for 40 - 80% MAV, n = 8 for 90% MAV)

Running Velocity	%$\dot{V}O_2$max			%HRmax			RER			RPE			Running Cadence		
(%MAV)	cNMTrun	MTrun	ES	cNMTrun	MTrun	ES	cNMTrun	MTrun	ES	cNMTrun	MTrun	ES	cNMTrun	MTrun	ES
40	64.7 ± 5.6	49.1 ± 6.6 ^{a}	2.37	74.7 ± 3.6	63.8 ± 5.2 ^{a}	1.84	0.93 ± 0.04	0.87 ± 0.05 ^{a}	1.32	9.3 ± 1.7	7.5 ± 1.1 ^{a}	1.52	162 ± 13	159 ± 8	0.43
50	76.5 ± 6.5	56.5 ± 5.5 ^{a}	3.26	84.3 ± 3.3	70.9 ± 3.4 ^{a}	2.78	0.97 ± 0.04	0.89 ± 0.05 ^{a}	1.77	11.6 ± 1.9	9.4 ± 1.4 ^{a}	2.04	167 ± 11	164 ± 9	0.47
60	88.5 ± 5.0	66.8 ± 6.1 ^{a}	4.55	91.5 ± 2.7	78.0 ± 2.9 ^{a}	3.74	1.02 ± 0.04	0.93 ± 0.04 ^{a}	2.25	14.2 ± 1.4	11.2 ± 0.8 ^{a}	2.45	172 ± 12	168 ± 9 ^{b}	1.02
70	96.9 ± 4.1	77.2 ± 6.0 ^{a}	2.89	96.9 ± 1.6	85.2 ± 2.4 ^{a}	5.36	1.10 ± 0.04	0.97 ± 0.06 ^{a}	2.55	17.3 ± 1.8	12.9 ± 0.9 ^{a}	3.03	178 ± 11	172 ± 11 ^{b}	1.06
80		87.7 ± 6.5		-	92.2 ± 2.3			1.02 ± 0.03		-	15.0 ± 1.2		-	178 ± 12	
90		97.1 ± 3.1			98.4 ± 1.3			1.09 ± 0.05			17.8 ± 1.1			190 ± 7	

^{a} $p < 0.01$, ^{b} $p < 0.05$ between cNMTrun and MTrun

Note; cNMTrun: curved non-motorized treadmill run, ES: effect size, HRmax: maximum heart rate, MAV: maximum aerobic velocity, MTrun: motorized treadmill run, RER: respiratory exchange ratio, RPE: ratings of perceived exertion $\dot{V}O_2$max: maximum oxygen uptake

Differences in running economy were evident between both treadmills (see **Table 4.3**), with the economy in gross oxygen cost and in caloric cost being significantly lower in MTrun compared to cNMTrun (-38.4 ± 16%, $p < 0.01$, ES 2.73), indicating more economical running in MTrun.

Table 4.3: Running economy for each experimental treadmill, running on 50% MAV (n = 11)

Running Economy:	cNMTrun	MTrun	ES
Oxygen unit cost (ml $O^2 \cdot kg^{-1} \cdot km^{-1}$)	279 ± 37	206 ± 29 [a]	2.73
Caloric Unit Cost ($kcal \cdot kg^{-1} \cdot km^{-1}$)	1.39 ± 0.19	1.01 ± 0.14 [a]	

[a] $p < 0.01$ between cNMTrun and MTrun

Note; cNMTrun: curved non-motorized treadmill run, ES: effect size, MTrun: motorized treadmill run

Table 4.4 shows data comparing 70% MAV cNMT and 90% MAV MT (n = 8). Apart from a significantly higher cadence in MTrun ($p = 0.001$), there were no differences in physiological or psychological responses. All thirteen participants reached an exercise intensity of ≥ 90% $\dot{V}O_2$max in cNMTrun. Linear interpolation of the available data in cNMTrun predicted an exercise intensity of 90% $\dot{V}O_2$max was achieved when running above 62.7 ± 3.3% MAV ($R^2 = 0.986 \pm 0.01$). Nine out of the thirteen participants reached 90% $\dot{V}O_2$max in MTrun, at a running velocity of 81.4 ± 5.6% MAV ($R^2 = 0.985 \pm 0.02$), which was significantly higher ($p < 0.01$, ES: 3.87). This approximate 20% difference was dispersed in a linear fashion across the work rates of the experimental runs **(**see **Figure 4.3).**

Table 4.4: Comparison of relative oxygen uptake (%$\dot{V}O_2$ max), heart rate (%HRmax), respiratory exchange ratio (RER), ratings of perceived exertion (RPE) and running cadence (steps per min) between 70% MAV cNMTrun and 90% MAV MTrun (n = 8)

	Running Velocity		
	70% MAV cNMTrun	90% MAV MTrun	ES
% $\dot{V}O_2$max	97.9 ± 3.8	97.1 ± 3.1	0.18
%HRmax	97.0 ± 1.5	98.2 ± 1.5	0.35
RER	1.10 ± 0.04	1.09 ± 0.05	0.45
RPE (au)	17.5 ± 1.7	17.8 ± 1.2	0.95
Cadence	182 ± 6	190 ± 8 [a]	1.82

[a] $p < 0.01$ between cNMTrun and MTrun

Note; au: arbitrary unit, cNMTrun: curved non-motorized treadmill run, ES: effect size, HRmax: maximum heart rate, MAV: maximum aerobic velocity, MTrun: motorized treadmill run, RER: respiratory exchange ratio, RPE: ratings of perceived exertion $\dot{V}O_2$max: maximum oxygen uptake

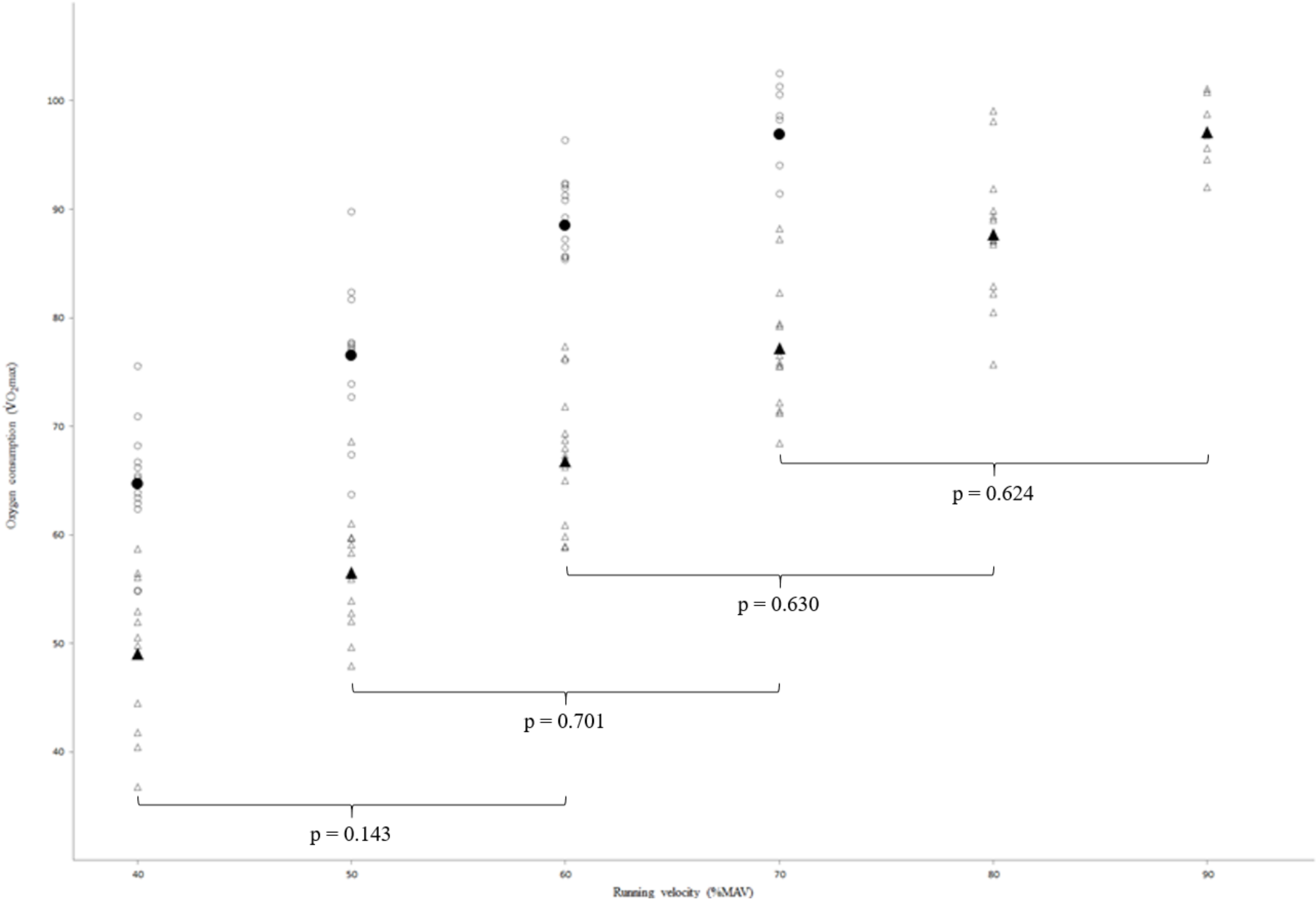


Figure 4.3: Individual (△ and ○) and mean (▲ and ●) relative oxygen uptake (%$\dot{V}O_2$max) for each experimental condition (△'s = MTrun, ○'s = cNMTrun). P values represent the difference between the respective ▲ and ●, in which ▲ is compared with 20% MAV lower ● trials (60% MTrun vs 40% cNMTrun etc.)

4.4 Discussion

Non-motorized treadmills allow runners to adjust their running velocity subconsciously, consistent with outdoor running, and thus may be more appropriate apparatus to study self-paced training in standardized laboratory conditions. This study aimed to 1) determine the physiological and perceptual demands of running on a curved NMT over a range of velocities, and 2) verify at which running velocity a physiological response $\geq$ 90% $\dot{V}O_2$max was elicited.

When running on a NMT, participants must generate power to move themselves vertically of the treadmill's surface and to propel the treadmill belt (228), which, together with the curved design of the cNMT, results in a 30% higher caloric expenditure compared to running on a standard MT according to the manufacturer. Part of this higher energy expenditure may be due to a range of cNMT characteristics (e.g. a high mechanical resistance and rubber material of the treadmill belt (229)), and may be inherent to the treadmill design. Findings of the current study support the manufacturers claim, as $\dot{V}O_2$ was, on average 32.2 ± 4% higher in NMTrun across the different velocities. Furthermore, an increase in caloric cost of 38.4 ± 16% was evident when participants ran at 50% MAV (1.39 ± 0.19 vs 1.01 ± 0.14 $kcal \cdot kg^{-1} \cdot km^{-1}$ for cNMT and MTrun respectively). These results are in line with Smoliga et al. (230), who showed that walking (1.34 $m \cdot s^{-1}$) and running (2.24 $m \cdot s^{-1}$) on the cNMT elicits a greater physiological stimulus than that on MT. The running velocity of 2.24 $m \cdot s^{-1}$ used by Smoliga et al.(230) corresponds to 45% MAV of the participants in the current study. This study aimed to evaluate the physiological responses to a broader range of (higher) running velocities, and, additionally, attempted to identify the running velocity that elicits an exercise intensity $\geq$ 90% $\dot{V}O_2$max on both treadmills. Linear interpolation showed this intensity was achieved when running at 62.7 ± 3.3% MAV on the cNMT. Similar exercise intensity was reached in nine out of thirteen participants on the MT at 81.4 ± 5.6% MAV. The difference in running velocity for the nine participants that reached $\geq$ 90% $\dot{V}O_2$max in both NMTrun and MTrun was 19.1 ± 5.1%. This is similar to the findings of Stevens et al. (215) and Waldman et al. (220) who both reported that 5 km running performance on the curved NMT was significantly slower compared to overground running (22%) and MT running (24%), even though no differences in $\dot{V}O_2$ and HR were found. In another recent study, Morgan et al. (219) observed that participants achieved a 15% lower MAV when they performed an incremental running test on the cNMT, compared to the same test protocol on a MT, where again, the participants were exerting the same exercise intensity in both tests. The large differences in running velocities while exercising at comparable exercise intensities highlights the disparity between the two treadmills.

The nature of the cNMT is such that users are required to run on an uphill gradient. To increase running velocity, participants position their feet closer to the front of the curved belt, which allows a greater contribution of vertical force to treadmill belt propulsion. Curved treadmill belts may facilitate a more natural gait pattern, allowing increased stride length and longer swing phase, which is observed with over-ground locomotion. Indeed, the results of the current study show a similar increase in cadence between cNMTrun and MTrun when running velocities were increased across the experimental trials. Derived from the running velocity and cadence (see **Table 4.2**), on the cNMT, average step length increased from 0.74 m/step in 40% MAV to 1.35 m/step in 70% MAV, whereas this increase in MT was 0.76 m/step to 1.39 m/step. We are the first to show the cNMT does allow for an increased step length when runners want to accelerate, and this increase is comparable to the increase profound whilst running on a MT.

Observational analysis by Smoliga et al. (230) revealed that subjects contact the curved treadmill belt approximately at a five to ten degree incline above the horizontal and this angle decreases throughout the stance phase of the stride cycle. It has been suggested that runners always optimise their technique to minimise metabolic costs, and when an inclination is present, runners will modify mechanical variables to achieve optimal metabolic efficiency (231). Stevens et al. (215) reported a change in running technique between overground and cNMT running. In overground running their subjects (n = 10) were classified as predominantly rearfoot strikers (n = 9, and 1 midfoot striker), which in cNMT running changed to midfoot strikers (n = 8, and 2 rearfoot strikers). The change in running technique was further evident in changes in muscle recruitment patterns between cNMT and overground running, as they showed a decline in iEMG activity for *tibialis anterior*, *vastus lateralis* and *rectus femoris* in the former (215). The decrease in iEMG is most likely compensated with an increased iEMG activity of the *gluteus maximus* and *bicep femoris* while running uphill (232).

Whilst no kinetic measures were taken during the current study, the change in foot strike pattern reported by Stevens et al. (215) is an adaptation in running technique that from a biomechanical perspective is sound as it promotes more economical running. There are 3 types of foot strike patterns: 1) rearfoot, 2) midfoot, and 3) forefoot strikes (233). These foot strike patterns are categorised depending on the portion of the foot that initially contacts the running surface (233,234). The landing pattern of rearfoot strike runners is for instance characterised by the centre of pressure of the ground reaction force (GRF) being located in the posterior third of the foot at initial contact and a dorsiflexed ankle. During initial contact in midfoot strike runners, the GRF centre of pressure is located in the middle third of the foot, and is characterised by a neutral ankle angle. Lastly, the forefoot strike landing has its GRF centre of pressure located in the anterior third of the foot at initial contact, and is characterised by a plantarflexed ankle (233,234). The position of the foot at initial impact relative to the centre of mass of the runner widely differs between the strike patterns (see **Figure 4.4**), which has implication on the magnitude of braking force experienced by the runner (233,235).

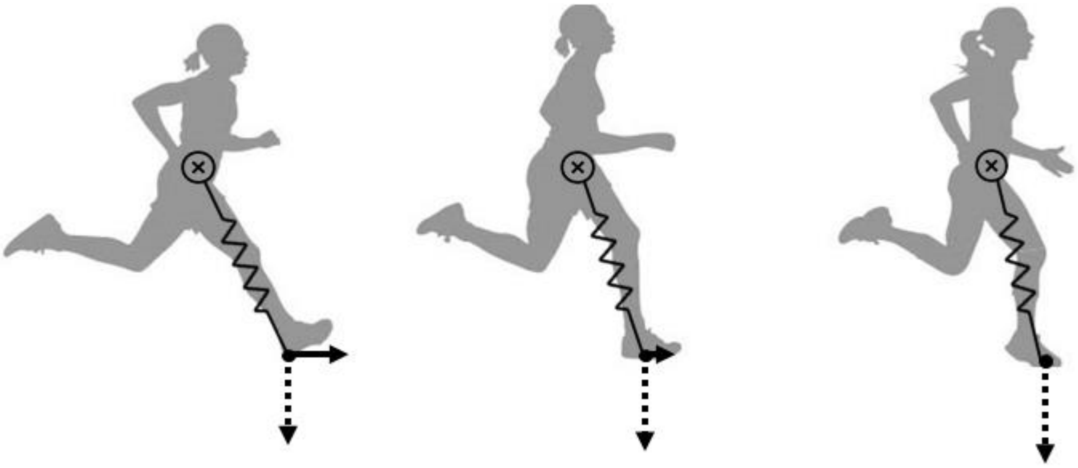


Figure 4.4: Approximate position of centre of mass (Θ) in rearfoot, midfoot and forefoot strike runners upon initial contact relative to the foot position ●, presented alongside the estimated vertical (dashed arrow) and horizontal components (solid arrow) of ground reaction force

When rearfoot strike runners run at a pace of 3 m/s, previous studies indicated the vertical component of the GRF quickly forms an impact peak of ~1.6 body weight (BW), which continues to slowly rise to ~2.5 BW at mid stance (233,235). As the centre of mass of the runner is positioned behind the point of impact, the horizontal component of the GRF in rearfoot strike runners is initially negative and acts as a braking force of ~0.3 BW (see **Figure 4.4**). Contrary to these findings, forefoot strike runners were shown to not have a visible (vertical) impact peak in the first 10% of stance phase but have a larger active peak at mid stance than rearfoot strikers (236,237). The centre of mass in forefoot strikers is positioned closely above the centre of pressure on initial contact, which results in a trivial parallel (horizontal) braking force (see **Figure 4.4**). Parallel braking forces correspond to aspects of the metabolic cost for running, where braking forces represent eccentric muscles contractions and propulsive forces represent concentric muscle contractions (238,239). In line with previous research, an increase in energy expenditure, and running cadence was found in cNMTrun compared to MTrun during all experimental velocities (231,240), highlighting the uphill running character of the cNMT. Uphill running has a large metabolic cost since concentric muscle contractions are more metabolically taxing than eccentric muscle contractions (238,239). Previous research further evidenced significantly higher propulsive forces during uphill treadmill or ramp running at an incline of 9° compared to level ground running (235,241), increasing the demands on concentric posterior chain muscle groups. The concave treadmill belt design (see **Figure 4.1**), and the necessity for force production per foot strike to maintain the treadmill velocity might even exacerbate the energy demands of running on the cNMT compared to uphill treadmill or ramp running (235,241), however, this is to be established in future studies.

Recently, several studies have examined the effects of a variety of uphill HIIT protocols, using repeated short (6 – 30 s) and / or long (3 – 5-min) work intervals on a variety of treadmill gradients (242,243). These studies showed improvements in various physiological, biomechanical, and neuromuscular parameters relevant to running performance, and provide support to incorporate uphill HIIT in the training programs of distance runners. Further research to determine which MT gradient is most comparable to the curved design of the NMT is presented in **Chapter 5**, in an attempt to provide athletes and coaches information on the most appropriate training protocols when using the cNMT. The cNMT might be a valuable asset when uphill training is geographically challenging, or sub-optimal weather conditions discourage outdoor training, and from a scientific perspective, the cNMT allows evaluation of physiological responses in a well-controlled lab setting.

In the current study $\dot{V}O_2max$ and MAV were determined using a traditional incremental running test, performed on a MT. The obtained $\dot{V}O_2max$ was then used to compute and compare the relative oxygen uptake between cNMTrun and MTrun on different individualized running velocities. It is well known that $\dot{V}O_2max$ is dependent on the physiological conditions present during an exercise protocol (212), and it has been shown that a self-paced $\dot{V}O_2max$ test performed on a NMT could possibly result in an elevated $\dot{V}O_2max$ (244). In fact, $\dot{V}O_2$ in three of the thirteen participants was higher in cNMTrun while running at 70% MAV than reached during their incremental running test. Conversely, no differences in $\dot{V}O_2max$ or HRmax attained in an incremental running test were found between MT and the cNMT (219). Thus, the increased $\dot{V}O_2$ in those few individuals in the current study may be attributed to the difference in bout duration between the experimental runs (4 min) and stage length in the incremental exercise test (1 min), rather than the different treadmills. $\dot{V}O_2$ continued to increase at 70% MAV in cNMTrun, showing ‘oxygen drift’. Oxygen drift is potentially caused by increased muscle fibre recruitment, changes in efficiency, body temperature and the increase of muscle fatigue over time, which all contribute to a larger amplitude in the slow component of $\dot{V}O_2$ (245). The increased contribution of this slow component of $\dot{V}O_2$ likely elevated the oxygen uptake in the 4 min run.

A limitation of this study is the inability to state the anaerobic contrition to metabolic work during the higher intensity intervals. When RER exceeds 1.0 the energetic cost of the exercise is more difficult to estimate, and it is not possible to compare energetic cost across individuals or across trials.

The results of the present study further information in the field of NMT running, by providing comparison velocities at which physiological work rate is matched. Participants in the current study ran on higher and individualized velocities compared to previous studies, which yield new insights in the physiological and perceptual response in the intense exercise domain. Only a subgroup (n = 8) opted to complete the 90% MAV MTrun, and this would have had implications related to statistical power.

4.5 Practical Applications

The cNMT can be a useful tool to study self-paced high intensity interval training. When prescribing exercise intensities, specialists often assign a specific (treadmill) velocity and duration as the primary training variables. Our data show that exercise prescriptions that are appropriate for overground or MT running may not be achievable on the cNMT because of the differences in energetic requirements. Based on our results, it is therefore advised to lower the running velocity by 20% when running on the cNMT, to generate the comparable physiological stimulus. Running on the cNMT mimics uphill running, and therefore training adaptations may differ compared to overground or regular treadmill training.

Chapter 5:

The physiological and perceptual responses while running on a curved non-motorized treadmill compare to a 6 - 8% motorized treadmill grade

Summary

The current study compared the physiological and perceptual demands of running on a commercially available curved non-motorized treadmill (cNMT) to different incline grades on a motorized treadmill (MT). Ten male team-sport athletes completed, after a familiarization session, a 6 min run at a target velocity of 2.78 $m \cdot s^{-1}$ (10 $km \cdot h^{-1}$) on the cNMT (cNMTrun). Mean individual running velocity of cNMTrun was then used as warm-up and experimental running velocity in three subsequent visits, in which participants ran for 6 min on the MT set at different grades (4%, 6% or 8%). In all experimental trials (cNMTrun, 4MTrun, 6MTrun and 8MTrun) and in the warm-up of the participants' third visit (1MTrun), oxygen consumption ($\dot{V}O_2$) and heart rate (HR) were monitored, and ratings of perceived exertion (RPE) were obtained. HR in cNMTrun was significantly higher compared to all MT trials. $\dot{V}O_2$ and RPE were significantly higher in cNMTrun compared to 1MTrun and 4MTrun, but not different to 6MTrun and 8MTrun. The relationship between $\dot{V}O_2$ and MT grade was highly linear, and using linear interpolation, the concave curved design of the cNMT was estimated to mimic a 6.8 ± 2.6% MT grade. These results show, that on matched running velocities, $\dot{V}O_2$ and RPE responses while running on the cNMT are similar to a 6 - 8% MT grade. These findings can be used as reference value by athletes and coaches in the planning of cNMT training sessions, and amend running velocities accordingly. Future studies are needed to determine whether this estimate is similar for lighter and / or female runners.

5.1 Introduction

A variety of non-motorized treadmill (NMT) designs have become widely available to sports scientists and the general public. NMTs are participant driven and allow runners to self-select and change their pace in a subconscious fashion with every treadmill contact (246). This makes the overall locomotion more consistent with outdoor running, and allows for a more ecologically valid lab assessment of running performance. A recently developed NMT with a concave curved surface (cNMT) has received considerable scientific interest. When compared to running on matched submaximal velocities on a motorized treadmill (MT; MT grade 1%), the physiological responses and ratings of perceived exertion (RPE) were considerably greater on the cNMT (229,230,246,247). This was accompanied by a less efficient running economy and a larger caloric cost of movement. (229,246,247) When matched for exercise intensities, it was established that on the cNMT a comparable oxygen consumption ($\dot{V}O_2$) and heart rate (HR) are achieved on running velocities up to 25% lower than on a MT (215,219,220,246). Despite these differences, the cNMT is thought to be a reliable and valid piece of lab equipment to evaluate self-paced high intensity interval training (HIIT) sessions, endurance and (repeated) sprint performance (215,220,221,246,248).

The altered energy demands of the cNMT are likely closely linked to its mechanical characteristics and design (belt friction and curvature). Recently, Bruseghini et al. (229) determined the friction of the 29kg heavy treadmill belt, which was found to equal 8.81 N. In an attempt to determine the curvature of the cNMT, previous observational analysis revealed that participants contact the cNMT belt at an approximated five to ten degree incline above the horizontal, which then decreased throughout the stance phase. (230) Running on the cNMT may therefore better mimic uphill running, and training adaptations potentially differ from overground or MT training. Uphill running represents a frequently prescribed form of HIIT in training regimes of distance runners (63,231,243) , and the cNMT might be a valuable asset when uphill training is geographically challenging, or sub-optimal weather conditions discourage outdoor training. In aid to design appropriate exercise protocols for the cNMT, the current study compared the physiological and perceptual demands of running on the cMNT with running on different incline grades on a MT.

5.2 Methods

5.2.1 Experimental approach to the problem

Participants were required to visit the sports and exercise science lab on five occasions over a three-week period. Based on similar comparative studies and the previously reported high correlation between $\dot{V}O_2$ and MT grades (213,246,247), an *a priori* power analysis indicated a minimum sample size of 8 participants (G*Power 3.1). After an initial familiarization session, participants performed the comparative 6 min run on the cNMT in their second visit (detailed below in **Section 5.2.3**). In three subsequent visits, participants ran for 6 min on the MT set at different grades (4%, 6% or 8%, 4MTrun, 6MTrun and 8MTrun respectively), with experimental conditions distributed in a randomized and counterbalanced order. Accuracy of velocity measures of both treadmills used in this study (cNMT: Woodway Curve XL, Woodway Inc, USA and MT: Pulsar 3p, H/P Cosmos, Nussdorf-Traunstein, Germany), were verified previously in our lab, and found to be within 1.1% of the described velocity (246).

5.2.2 Participants

Ten physically active male team-sport players (mean ± standard deviations (SD), age 22 ± 2, stature 180 ± 6 cm, mass 77 ± 11 kg) volunteered to take part in this study. By study design, this study did not incorporate an incremental running test. All participants provided voluntary written informed consent. The study received approval from the local ethics committee and was conducted in accordance with the Declaration of Helsinki. Participants were asked to report for testing well-rested and well-hydrated, wearing the same footwear on each visit. Participants were further asked to refrain from any strenuous exercise or alcohol consumption in the preceding 24 h, and refrain from caffeine and food consumption, 4 and 2 h before the start of the test, respectively.

5.2.3 Experimental running protocol

In their initial visit, participants familiarized with running on the cNMT and were instructed to run as close as possible to a target velocity of 2.78 $m\cdot s^{-1}$ (10 $km\cdot h^{-1}$). This velocity was selected in line with previous studies (246,247). During the second visit, participants repeated this exercise, and performed a 6 min run on the cNMT (cNMTrun). Individual running velocities of cNMTrun were sampled at 4 Hz and assessed in the accompanying product software. The calculated mean running velocity of cNMTrun was then used in three subsequent visits as warm-up and experimental running velocity. Participants performed the same warm-up routine prior to all MT trials, which involved a 6 min run on the MT with the grade set at 1%. The warm-up was followed by the experimental trial, in which the participants ran for 6 min on the MT, with the treadmill gradient set at 4%, 6% or 8%.

5.2.4 Data collection and analysis

In all experimental runs (cNMTrun, 4MTrun, 6MTrun and 8MTrun) and in the warm-up of the participants' third visit (1MTrun), $\dot{V}O_2$ and HR were monitored continuously, and RPE on the traditional Borg 6 - 20 scale were obtained upon completion of the trial (80). Comparative mean $\dot{V}O_2$ and HR were determined during the last minute of each condition. During the experimental runs, HR was measured using a Garmin HR monitor (910XT, Garmin Ltd., Schaffhausen, Switzerland), and respiratory parameters were sampled breath-by-breath, using open circuit spirometry (Oxycon Pro, Jaeger, Höchberg, Germany). Before each experimental trial, the gas analyser and turbine flow meter were calibrated according to the manufacturer's instructions.

5.2.5 Statistical analysis

Data were analysed using SPSS 25.0 (SPSS Inc., Chicago, USA) and are presented as mean ± SD. Attainment of steady state in the last minute of each experimental condition was verified using Pearson correlation comparisons of $\dot{V}O_2$ and HR obtained in the 5th and 6th min, and paired t-tests. Differences in $\dot{V}O_2$, HR and RPE between cNMTrun and the experimental MT runs were compared using one-way repeated measures analysis of variances (ANOVA), followed by Tukey post hoc tests. The MT grade that best replicates the curvature of the cNMT was estimated through linear interpolation of individual mean $\dot{V}O_2$ of the four MT grades and cNMTrun. The significance level of all tests was set at $p < 0.05$. Effect sizes (ES) are presented for interpretation as Cohen's d along 95% confidence intervals in **Table 5.1** and **Table 5.3**.

5.3 Results

Steady state in $\dot{V}O_2$ was confirmed, as no differences were found between the 5th and 6th min in any of the experimental trials (see **Table 5.1**), however, HR was significantly higher in the 6th min in cNMTrun, 4MTrun, 6MTrun and 8MTrun compared to the 5th min ($p < 0.01$ for all conditions). $\dot{V}O_2$, HR and RPE increased in a linear fashion with the increased MT grade (see **Table 5.2**). $\dot{V}O_2$ and RPE were significantly higher in cNMTrun compared to 1MTrun and 4MTrun ($p < 0.01$), but not different to 6MTrun and 8MTrun. HR in cNMTrun was significantly higher compared to all MT trials ($p < 0.01$ for all conditions).

The relationship between $\dot{V}O_2$ and MT grade was highly linear ($R^2 = 0.99$, see **Figure 5.1**), and $\dot{V}O_2$ was calculated using the following formula: $\dot{V}O_2 = 1.7 * \text{MT grade} + 34.4$. Individual linear interpolation estimated that the concave curvature of the cNMT was best replicated by a 6.8 ± 2.6 % MT grade.

Table 5.1: Difference (Δ) in mean $\dot{V}O2$ and HR between 5th and 6th min in all experimental runs

	cNMTrun	ES [95% CI]	1MTrun	ES [95% CI]	4MTrun	ES [95% CI]	6MTrun	ES [95% CI]	8MTrun	ES [95% CI]
$\Delta \dot{V}O_2$ (L·min^{-1})	0.1 ± 0.2	0.36 [-0.54 to 1.23]	0.1 ± 0.1	0.28 [-0.62 to 1.14]	0.04 ± 0.3	0.08 [-0.80 to 0.96]	-0.1 ± 0.3	0.12 [-0.76 to 0.99]	-0.1 ± 0.2	0.17 [-0.71 to 1.04]
$\Delta \dot{V}O_2$ (mL·kg^{-1}·min^{-1})	1.9 ± 3.4	0.53 [-0.38 to 1.40]	1.2 ± 3.0	0.68 [-0.25 to 1.55]	0.5 ± 3.6	0.19 [-0.70 to 1.06]	-0.8 ± 4.2	0.18 [-0.71 to 1.05]	-0.8 ± 3.1	0.15 [-0.73 to 1.03]
Δ HR (beats/min)	2.3 ± 1.4*	0.23 [-0.66 to 1.10]	0.8 ± 1.7	0.23 [-0.66 to 1.10]	1.4 ± 1.0*	0.12 [-0.76 to 0.99]	2.5 ± 1.3*	0.21 [-0.68 to 1.08]	1.6 ± 1.1*	0.20 [-0.69 to 1.07]

* Significantly higher than 5th min ($p < 0.01$)

Note; cNMTrun: curved non-motorized treadmill run, ES: effect size, HR: heart rate, MTrun: motorized treadmill run, $\dot{V}O_2$: oxygen uptake

Table 5.2: Physiological and Perceptual responses for all experimental runs

	cNMTrun	1MTrun	4MTrun	6MTrun	8MTrun
$\dot{V}O_2$ ($L\cdot min^{-1}$)	3.57 ± 0.4 [a,b]	2.53 ± 0.3 [*]	3.19 ± 0.5 [*]	3.42 ± 0.5 [a,b,d]	3.73 ± 0.4 [a-c]
$\dot{V}O_2$ ($mL\cdot kg^{-1}\cdot min^{-1}$)	46.4 ± 3.7 [a,b]	36.2 ± 3.9 [*]	41.3 ± 2.8 [*]	44.2 ± 2.8 [a,b,d]	48.6 ± 4.2 [a-c]
HR (beats$\cdot min^{-1}$)	185 ± 10 [*]	139 ± 10 [*]	167 ± 12 [*]	176 ± 12 [*]	181 ± 9 [*]
RPE (au)	14.7 ± 3.1 [a,b]	9.5 ± 1.4 [*]	12.7 ± 2.5 [*]	14.0 ± 2.9 [a,b,d]	15.4 ± 2.1 [a-c]

[*] Significantly different from ($p < 0.05$) all other experimental runs, [a] 1% grade, [b] 4% grade, [c] 6% grade, [d] 8% grade

Note; au: arbitrary unit, cNMTrun: curved non-motorized treadmill run, HR: heart rate, MTrun: motorized treadmill run, RPE: ratings of perceived exertion, $\dot{V}O_2$, oxygen consumption

Table 5.3: Effect Size [95% Confidence intervals] comparison between all experimental runs

		cNMTrun	1MTrun	4MTrun	6MTrun
$\dot{V}O_2$	1MTrun	2.65 [1.36 to 3.72]			
	4MTrun	1.56 [0.50 to 2.48]	1.49 [0.44 to 2.41]		
	6MTrun	0.65 [-0.27 to 1.53]	2.37 [1.14 to 3.39]	1.08 [0.10 to 1.97]	
	8MTrun	0.55 [-0.37 to 1.41]	3.04 [1.65 to 4.16]	2.05 [0.90 to 3.03]	1.22 [0.22 to 2.11]
HR	1MTrun	4.56 [2.75 to 5.98]			
	4MTrun	1.59 [0.53 to 2.52]	2.44 [1.20 to 3.48]		
	6MTrun	0.81 [-0.14 to 1.68]	3.31 [1.85 to 4.48]	0.74 [-0.20 to 1.61]	
	8MTrun	0.38 [-0.52 to 1.25]	4.44 [2.67 to 5.84]	1.33 [0.31 to 2.23]	0.50 [-0.41 to 1.37]
RPE	1MTrun	2.20 [1.01 to 3.20]			
	4MTrun	0.72 [0.21 to 1.59]	1.62 [0.55 to 2.55]		
	6MTrun	0.23 [-0.66 to 1.10]	1.95 [0.82 to 2.91]	0.48 [-0.43 to 1.34]	
	8MTrun	0.29 [-0.48 to 1.04]	3.38 [1.90 to 4.56]	1.19 [0.20 to 2.09]	0.55 [-0.37 to 1.41]

Note: cNMTrun: curved non-motorized treadmill run, HR: heart rate; MTrun: motorized treadmill run, RPE: ratings of perceived exertion, $\dot{V}O_2$: oxygen consumption;

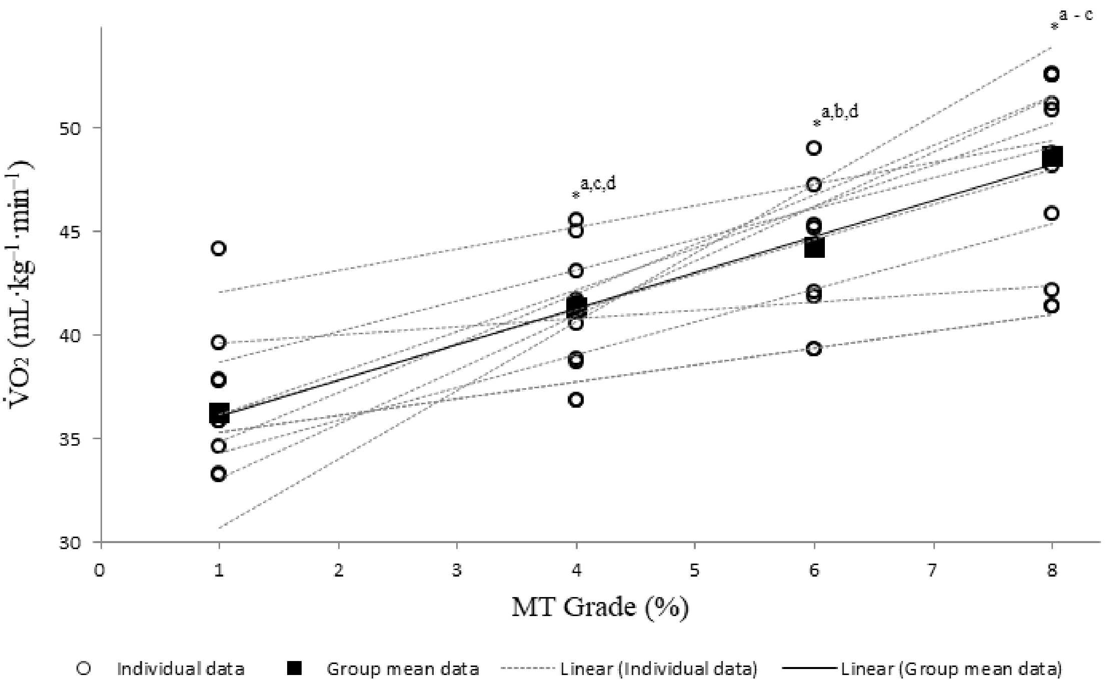


Figure 5.1: Individual and grouped mean $\dot{V}O_2$ when running on different MT grades at 2.78 $m \cdot s^{-1}$
* Significantly different from ($p < 0.05$) all other experimental runs, ^{a} 1% grade, ^{b} 4% grade, ^{c} 6% grade, ^{d} 8% grade

5.4 Discussion

The current study compared the physiological and perceptual demands of running on a curved non-motorized treadmill to different incline grades on a motorized treadmill. The main finding was that $\dot{V}O_2$ and RPE (but not HR) were similar in cNMTrun, 6MTrun and 8MTrun. The relationship between $\dot{V}O_2$ and MT grade was highly linear, and using linear interpolation of the individual data of cNMTrun, the incline of the cNMT was estimated to mimic a 6.8% MT grade.

For an accurate evaluation of the energy demands of the experimental trials, attainment of a steady state in every condition was required (213). Running on the cNMT by design is unsteady, as the velocity fluctuates with every treadmill contact. Running velocity of cNMTrun averaged 2.78 ± 0.11$m \cdot s^{-1}$. The participants' individual mean running velocity in cNMTrun was used in subsequent MT trials, however, without any random fluctuations in pace. Steady state $\dot{V}O_2$ was confirmed, as no differences were evident between the 5th and 6th min in any of the experimental trials. In contrast to $\dot{V}O_2$, HR only reached steady state in1MTrun. HR has long been considered an important means to monitor exercise intensities, however, our results indicate that HR cannot adequately inform coaches and athletes on the aerobic demands of the 6 min uphill MT runs and cNMTrun.

No differences were found in $\dot{V}O_2$ and RPE between cNMTrun, 6MTrun and 8MTrun, confirming the observational analysis of Smoliga et al. (230), who revealed that subjects contact the curved treadmill belt approximately at a five to ten degree incline above the horizontal and this angle decreases throughout the stance phase of the stride cycle.

The correlation between $\dot{V}O_2$ and MT grades in the current study was highly linear, and both the slope and intercept of the proposed linear fit trendline, is in line with previously reported data of trained runners as can be seen in **Figure 5.2** (213,231).

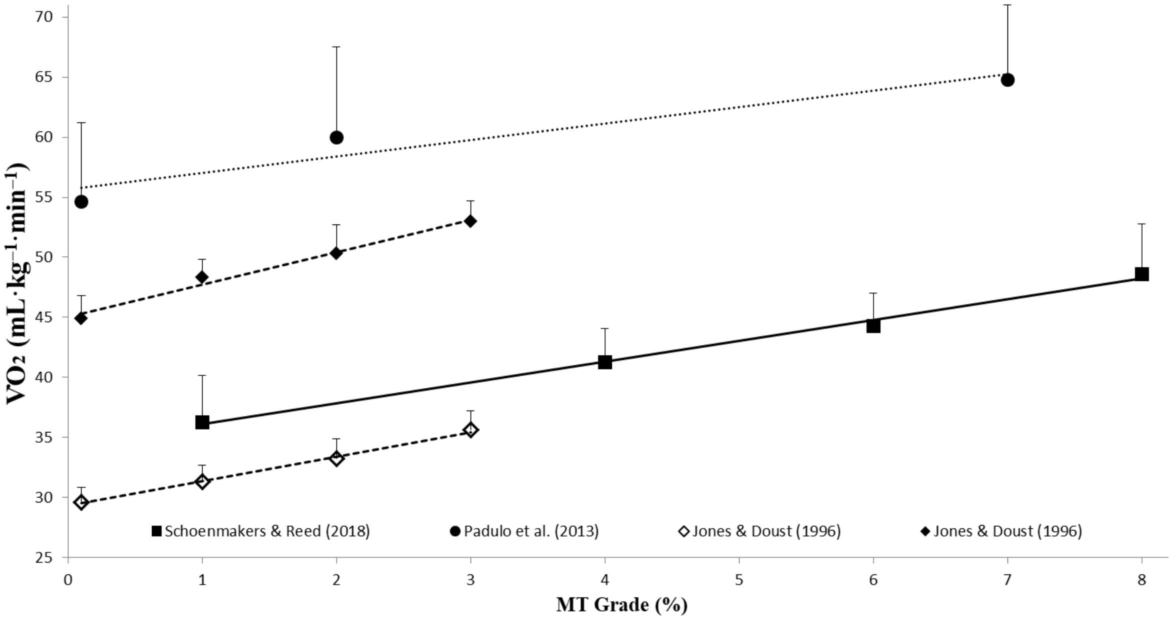


Figure 5.2: Comparison between studies of $\dot{V}O_2$ response when running on different MT grades. Running velocity in ■ Schoenmakers & Reed: 2.78 m·s^{-1}, ● Padulo et al. (231): 4.17 m·s^{-1}, ◇ Jones & Doust (213): 2.92 m·s^{-1}, ◆ Jones & Doust (213): 4.17 m·s^{-1}

$\dot{V}O_2$ at 1MTrun in the current study was considerably higher compared to the findings of Jones & Doust (213), despite that participants in the current study ran at a lower velocity. These differences can be attributed to the training status of the participants, whereas trained runners can be expected to have a greater running economy than the current participants. The physiological responses in the participants of the current study already showed a considerable amount of variability (see **Figure 5.1**). The mean $\dot{V}O_2$

response indicated a 6.8% MT grade would replicate the incline of the cNMT, however, individual estimates showed a ranges of inclines between 2.0% to 11.3% MT grade was needed to replicate the demands of the cNMT. Non-reported statistical analysis showed that the exclusion of both these outliers would result in a more stable estimate of MT grade, i.e. 6.9 ± 1.6 %, ranging between an estimated MT grade of 4.2% to 9.5%. Excluding the participants did not alter the goodness of fit of the linear regression ($R^2 = 0.99$), but amended the regression equation: $\dot{V}O_2 = 2.0 * \text{MT grade} + 33.7$. Additionally, Edwards et al. (247) reported that females perceived running on the cNMT harder than males over a range of velocities (indicated by higher RPE scores), which was further accompanied by a higher relative $\dot{V}O_2$ for female runners. These differences are most likely a reflection of the lighter body mass of female runners, which may put them at a disadvantage in overcoming the treadmill belt resistance (229,247). Unfortunately, the individual variability present in the current study cannot be interpreted on the basis of training status, or running economy of the participants since no incremental exercise test was included in the study design. In line with the previous study of Edwards et al. (247), the lowest estimated MT grade was calculated for the heaviest participant and the highest MT grade for the lightest participant. How the result of the current study transfer to a homogenous group of lighter and / or female runners is questionable, and future research is needed to establish the regression equation for these populations. Previously, Edwards et al. (247) reported a very strong negative relationship between participant body mass and the decrease in running economy when running on the cNMT trial. This indicates that the absolute oxygen cost is higher when participants are lighter. In contrast to the findings of the current study, both the physiological and perceptual responses for lighter or female runners may be better represented by a larger (= steeper) MT grade.

5.5 Practical Applications

The results of this and previous studies (215,246–248) indicate, that the cNMT can be used to assess running performance in the lab and to perform ‘uphill’ HIIT sessions, when uphill training is geographically challenging or sub-optimal weather conditions discourage outdoor training. The findings of the current study can be used as reference value by athletes and coaches in the planning of cNMT training sessions, and amend running velocities accordingly. On matched running velocities, $\dot{V}O_2$ and

RPE responses while running on the cNMT are similar to a 6 - 8% MT grade. Using the highly linear relation between $\dot{V}O_2$ and MT grades, the incline of the cNMT was estimated to mimic a 6.8 ± 2.6% MT grade.

Chapter 6:

The effects of recovery duration on physiological and perceptual responses of trained runners during four self-paced HIIT sessions

Citation:

Schoenmakers, P. & Reed, K. (2019). The effects of recovery duration on physiological and perceptual responses of trained runners during four self-paced HIIT sessions. *Journal of science and medicine in sport*, *22*(4), 462-466. DOI: 10.1016/j.jsams.2018.09.230

Summary

This study aimed to examine the effects of different recovery durations on self-selected running velocities, physiological responses, and ratings of perceived exertion (RPE) in a commonly used high intensity interval training (HIIT) protocol. Twelve trained runners performed an incremental treadmill exercise test to determine maximal oxygen uptake ($\dot{V}O_2$max) and heart rate (HRmax). In four subsequent visits, participants performed a HIIT session comprising six 4 min work intervals, in which the recovery duration between work intervals equalled either a fixed (1MIN, 2MIN, 3MIN) or a self-selected duration (ssMIN). HIIT sessions were run on a curved non-motorized treadmill, and were performed under *'isoeffort'* conditions. Mean running velocity was significantly higher in 3MIN compared with all other protocols, and higher in ssMIN compared with 2MIN. No significant differences in time spent ≥ 90% and 95% $\dot{V}O_2$max, or ≥ 90% and 95% HRmax were evident between the four protocols. RPE responses were similar across and within the protocols showing a gradual increase with each progressive interval. These results indicate that in a self-paced HIIT session, the length of recovery durations had a limited effect on the total physiological strain endured in the training. However, running velocities were higher when participants received the longest recovery period (3MIN). Longer recovery durations may facilitate a higher external training load (faster running), whilst maintaining a similar internal training load (physiological stimulus), and may therefore allow for greater training adaptations.

6.1 Introduction

High intensity interval training (HIIT) is often regarded as the most effective training modality to improve cardiorespiratory and metabolic functioning, and, in turn endurance performance (14). Previously, Demarie et al. (18) showed that athletes can spend up to 10 minutes per HIIT session in their ‘red zone’; the intensity domain close to the maximal oxygen uptake and heart rate (≥ 90% $\dot{V}O_2$max and HRmax respectively). At these exercise intensities the oxygen delivery and utilization systems are maximally stressed, which may provide the most effective stimulus to enhance $\dot{V}O_2$max. (3,9,14) Even though HIIT is common practice in training regimes of endurance athletes, little is known how manipulating HIIT protocols may maximize time spent around $\dot{V}O_2$max per training session.

The workload of a HIIT session is determined by the exercise intensities and durations of both the work and recovery intervals, and the total of intervals performed (16,17). Of these, a potent, but frequently disregarded variable is the manipulation of recovery durations between subsequent work intervals (54). Recovery durations within HIIT running protocols are traditionally based on fixed work:recovery ratios or on the return of heart rate to a fixed percentage of HRmax (e.g. (66,70)). Theoretically, work intervals interspersed with short recovery intervals maximize the physiological stimulus of a HIIT session, as subsequent work intervals will start from an elevated oxygen uptake ($\dot{V}O_2$) and heart rate (HR). However, insufficient recovery can lead to premature fatigue, resulting in a reduced number of completed intervals and / or a reduction in exercise intensity in work intervals. Longer recovery between work intervals conversely, will lead to a lower $\dot{V}O_2$ and HR at the start of subsequent intervals which may attenuate the peak values achieved during the work intervals, and potentially decreasing the total exercise time performed in the ‘red zone’. While longer recovery may lower the physiological strain, a delayed fatigue may allow athletes to achieve higher external work intensities (i.e. running velocity) in work intervals. It is commonly accepted that the internal training load, that is the disturbance in homeostasis of the physiological (e.g. cardiovascular, respiratory and metabolic) provoked by a training session, is the most important feature of a training session and the primary stimulus to adaptations in endurance performance (282). Whilst every configuration of HIIT protocol can lead to a significant disturbance of homeostasis, causing improvements in $\dot{V}O_2$max (see **Chapter 3**), combining a high internal load with altered exercise intensities during HIIT sessions might be beneficial to athletes.

Understanding the acute response to manipulating recovery durations is important when designing HIIT sessions. Smilios et al. (41) noted that an increased recovery duration (2, 3 or 4 min) did not affect the percentage of $\dot{V}O_2$max attained and the total time spend ≥ 80%, 90% and 95% of $\dot{V}O_2$max or HRmax during four 4 min intervals, ran at 90% maximal aerobic velocity (MAV). Although the data from the above study is informative (41), it also is a prime example of most published data, as acute physiological responses are evaluated to a HIIT protocol that incorporates predefined fixed work intensities. In contrast to standardized exercise protocols, it was recently proposed that athletes measure and pace their work in training sessions on ratings of perceived exertion (RPE) and accumulated fatigue (42). In this so called *'isoeffort'* or self-paced HIIT, the actual work intensity per interval therewith is not a stable function of power or velocity over time, but rather the integrative outcome of feedback from external and internal receptors, and knowledge of the session demands (43,44).

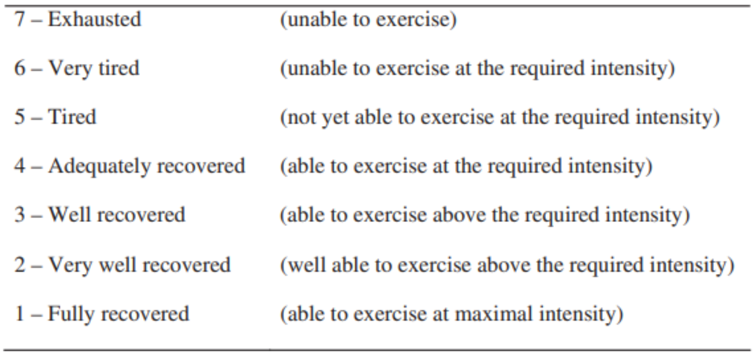
While self-paced HIIT has been addressed in cycling recently (42,218), there is a paucity of research exploring its use in running. Recently, we and others showed that a newly designed curved non-motorized treadmill (cNMT) can be a useful tool to study self-paced running in a lab setting (246,247). Running on the cNMT is participant driven and provides a closer experience to overground locomotion by allowing for rapid changes of velocity, step-to-step gait variability and, most importantly, an unconsciousness decision making process to change pace (249).

The aim of this study was to compare the effect of different recovery durations on the acute physiological and perceptual responses, and the accompanying running velocities in a HIIT session performed under *'isoeffort'* conditions. A theoretical trade-off was expected between the physiological stimulus (time spent ≥ 90% and 95% $\dot{V}O_2$max and HRmax) and the external stimulus (running velocity). In this, it was hypothesised that a short recovery between work intervals would lead to an increased physiological stimulus at the cost of a decreased running velocity. Conversely, it was expected that longer recovery intervals would lower the physiological strain of the HIIT protocol, whilst maintaining a higher running velocity throughout the HIIT session.

6.2 Methods

6.2.1 Experimental approach to the problem

Participants visited the laboratory on five different occasions over a four-week period, with visits separated by a minimum of two days. In the first visit, participants performed an incremental running test on a motorized treadmill (Pulsar 3p, H/P Cosmos, Nussdorf-Traunstein, Germany), and one 4 min effort on the cNMT (Woodway Curve XL, Woodway Inc, Waukesha, USA) to familiarize with this piece of equipment. In the four following visits, participants performed a HIIT session on the cNMT. Participants were familiarized with the concept of using the 15-point Borg scale (80) and a perceived readiness scale (PR, (101)) as a means of self-determining readiness to recommence exercise between work intervals (see **Figure 6.1**).



7 – Exhausted	(unable to exercise)
6 – Very tired	(unable to exercise at the required intensity)
5 – Tired	(not yet able to exercise at the required intensity)
4 – Adequately recovered	(able to exercise at the required intensity)
3 – Well recovered	(able to exercise above the required intensity)
2 – Very well recovered	(well able to exercise above the required intensity)
1 – Fully recovered	(able to exercise at maximal intensity)

Figure 6.1: Perceived readiness scale. Figure adapted from Edwards et al. (101)

6.2.2 Participants

Twelve recreationally trained male runners (mean ± standard deviations (SD); 34 ± 11 years; stature: 1.80 ± 0.06 m; mass: 74 ± 6 kg; $\dot{V}O_2max$: 53 ± 7 $mL \cdot kg^{-1} \cdot min^{-1}$) participated, providing voluntary written informed consent. *A priori* power analysis (G*Power 3.1) indicated a minimum sample size of 10 participants was required to detect small differences (Cohen's d = 0.2) in the physiological and perceptual responses between the different simulated HIIT sessions. It was decided to recruit twelve participants to complete three full rounds of counterbalanced randomization of the experimental visits. The study received approval from the local ethics committee (University of Essex, UK) and was conducted in accordance with the Declaration of Helsinki. Participants were asked to report for testing well-rested and well-hydrated, wearing the same footwear on each visit and were instructed to avoid any form of strenuous exercise 48 h before each visit.

6.2.3 Incremental running test protocol

The incremental running was performed on a motorised treadmill, with the gradient set at 1% (213). The test started at 8 kmh^{-1}, increasing 1 kmh^{-1} every minute until volitional exhaustion or when at least two of the following criteria were met: 1) HR $\geq$ 90% of the age-predicted maximum; 2) respiratory exchange ratio (RER) $\geq$ 1.10; 3) stable $\dot{V}O_2$ despite increased intensity (212). $\dot{V}O_2$max was defined as the highest average $\dot{V}O_2$ over a 30 s period. HRmax was defined as the highest value obtained at the end of the test. MAV was defined as the highest velocity (kmh^{-1}) that could be maintained for a complete minute, or, as the velocity of the last complete stage added to the completed fraction of an incomplete stage. Gas exchange threshold (GET) was determined from a cluster of measures, previously outlined by Bailey et al. (250): 1) the first disproportionate increase in CO_2 ventilation ($\dot{V}CO_2$) from visual inspection of individual plots of $\dot{V}CO_2$ versus $\dot{V}O_2$, 2) an increase in expired ventilation VE/$\dot{V}O_2$ with no increase in VE/$\dot{V}CO_2$.

The running velocity corresponding to 70% of the difference (Δ) between the velocity at GET and MAV was then calculated, and converted to the corresponding running velocity on the cNMT (246). Participants were then instructed to run one 4 min effort on 65% MAV on the cNMT, which would result in a (calculated) exercise intensity of 92.5% $\dot{V}O_2$max (246).

6.2.4 Experimental simulated HIIT sessions

Over the next four visits, participants performed a simulated HIIT session comprising six 4 min work intervals, separated by either 1, 2, 3-min or a self-selected recovery duration (1MIN, 2MIN, 3MIN, ssMIN respectively), which were distributed in a randomized and counterbalanced order. Prior to each HIIT session participants performed a 6 min priming warm-up at 70% ΔGET on the cNMT, followed by a 9 min break (250). Exercise intensity of the warm-up was verified in the first experimental visit.

Participants were instructed to maintain the highest average running velocity across the work intervals of each session, and to finish the HIIT session on a RPE $\geq$ 17. As previously discussed by Mattern et al. (85), athletes may fail to select an adequate start strategy in self-paced efforts and often start too fast, which hampers optimal performance. To avoid poor pacing, participants were instructed (but not restricted) to target a velocity of 65% MAV in the first interval. Continuous feedback was available on elapsed time and running velocity during the work intervals. In the recovery intervals, participants were free to select either walking or standing. RPE were obtained immediately after every work interval, and PR was scored every 45 s during recovery in 1MIN, 2MIN and 3MIN, but only in ssMIN did this indicate the start of a work interval (when participants scored '4' on the PR scale, indicating 'adequate recovery' (101)). In ssMIN, participants were blinded to elapsed recovery time. Participants were blinded to the experimental condition (that is, the duration of the recovery intervals) until after the completion of the first work interval.

6.2.5 Data collection and analysis

During the incremental running test and the four HIIT sessions, HR and running cadence were measured continuously at 1 Hz using a Garmin HR monitor and a telemetric foot pod (Garmin 910XT, Garmin Ltd., Schaffhausen, Switzerland). Respiratory parameters were obtained breath by breath, using open circuit spirometry (Oxycon Pro, Jaeger, Höchberg, Germany), and indexed. Before each experimental trial, the gas analyser and turbine flow meter were calibrated according to the manufacturer's for $\dot{V}O_2$max and HRmax instructions. Self-selected running velocity was sampled at 4 Hz in the accompanying cNMT product software (Woodway Curve 1.5 Software v2.1).

6.2.6 $\dot{V}O_2$ and HR kinetic modelling

Breath-by-breath $\dot{V}O_2$ data were linearly interpolated to one second values, and were then fitted from the onset to the end of each work interval using a mono-exponential growth curve. The mean response time (MRT) was calculated using the formula below.

$\dot{V}O_2(t) = \dot{V}O_2\text{baseline} + A\dot{V}O_2 \cdot (1 – e\text{-}t/\tau)$

In this, $\dot{V}O_2(t)$ represents the $\dot{V}O_2$ at a given time (t); $\dot{V}O_2$baseline the mean $\dot{V}O_2$ of the last 30 s before the start of each repetition; $A\dot{V}O_2$ the amplitude of the $\dot{V}O_2$ response ($\dot{V}O_2$ plateau – $\dot{V}O_2$baseline); and τ the time constant for the model. Similar calculations were performed for the analyses of HR kinetics

6.2.7 Statistical analysis

All data in text, tables, and figures are presented as mean ± SD, and were analysed using SPSS software (Version 25.0, SPSS Inc., Chicago, USA). Only the physiological measurements obtained *during* the work intervals were analysed. Differences between protocols in physiological responses (exercise time ≥ 90% and 95% $\dot{V}O_2$max and HRmax, average $\dot{V}O_2$ and HR in work intervals, during the last minute of the work intervals, and 30 s before the start of work intervals) were assessed using one-way repeated measures analysis of variance (ANOVA). A two-way repeated measures (protocol × interval) ANOVA was conducted to examine differences in RER, running velocity and RPE across intervals between and within protocols. In the event of a significant main or interaction effects, Tukey's post hoc tests were used to determine differences between protocols and/or across intervals within each protocol. Pearson correlations were used to establish the relationship between exercise time ≥ 90% and 95% $\dot{V}O_2$max and HRmax for all protocols. Additionally standardized effect sizes (ES) are reported as Cohen's d. Qualitative interpretation of d was based on the guidelines provided by Hopkins et al. (151): < 0.2 trivial; 0.20 - 0.59 small; 0.6 - 1.19 moderate; 1.20 - 1.99 large; ≥ 2.00 very large. The level of significance for all statistical analysis was set at $p < 0.05$.

6.3 Results

A difference in mean running velocity was found between HIIT protocols. Post-hoc analysis showed that participants ran faster in 3MIN compared to 1MIN, 2MIN and ssMIN ($p < 0.01$). Further, the mean running velocity in ssMIN was higher compared to 2MIN ($p = 0.001$). Subtle fluctuations in running velocities were apparent in all protocols across work intervals (see **Table 6.1**). RPE responses were similar across and within the protocols (see **Table 6.1**), and independent of recovery duration, participants rated the last interval an average RPE score of ≥ 19, verifying isoeffort conditions. **Table 6.1** further depicts the mean RER per interval for each experimental protocol. A significant interaction effect was evident ($p = 0.004$), with a higher RER in intervals 4 - 6 in 1MIN compared with 2MIN and 3MIN.

Table 6.1: Mean ± SD of RER, RPE and running velocity measured during work intervals 1 through 6 in the 1MIN, 2MIN, 3MIN and ssMIN protocol (n = 12)

		HIIT Protocol			
	Work Interval	1MIN	2MIN	3MIN	ssMIN
RER	1	0.95 ± 0.05	0.97 ± 0.08	0.96 ± 0.03	0.96 ± 0.07
	2	0.99 ± 0.05 [a]	0.98 ± 0.08	0.96 ± 0.02	0.99 ± 0.07 [a]
	3	0.96 ± 0.05 [a]	0.94 ± 0.07 [a]	0.93 ± 0.02 [a]	0.96 ± 0.07 [a]
	4	0.96 ± 0.05 [*]	0.93 ± 0.07 [a]	0.93 ± 0.02	0.94 ± 0.07 [a]
	5	0.95 ± 0.05 [*]	0.92 ± 0.06	0.92 ± 0.02	0.93 ± 0.06 [a]
	6	0.95 ± 0.05 [*]	0.92 ± 0.04	0.92 ± 0.02	0.93 ± 0.06
RPE (au)	1	14.6 ± 1.9	15.0 ± 1.7	14.1 ± 2.0	15.1 ± 1.4
	2	16.3 ± 1.5 [a]	16.7 ± 1.6 [a]	16.6 ± 1.6 [a]	16.4 ± 1.4 [a]
	3	17.2 ± 1.3 [a]	17.3 ± 1.1 [a]	17.3 ± 1.4 [a]	17.3 ± 1.2 [a]
	4	18.6 ± 0.8 [a]	17.8 ± 1.0	18.2 ± 1.0 [a]	18.0 ± 1.2 [a]
	5	18.8 ± 0.7	18.3 ± 0.9 [a]	18.4 ± 0.8	18.5 ± 1.0 [a]
	6	19.3 ± 0.5	19.2 ± 0.6 [a]	19.0 ± 0.7 [a]	19.2 ± 0.8 [a]
Velocity ($km \cdot h^{-1}$)	1	11.7 ± 0.9	12.0 ± 1.1	11.9 ± 1.1	11.8 ± 0.9
	2	11.8 ± 1.1	11.9 ± 1.0	12.2 ± 1.1	12.0 ± 1.0
	3	11.6 ± 1.2	11.5 ± 1.0 [a]	12.1 ± 1.1	11.8 ± 1.1 [a]
	4	11.5 ± 1.2	11.2 ± 1.1 [a]	12.0 ± 1.1	11.7 ± 1.1
	5	11.4 ± 1.3	11.1 ± 1.1	11.8 ± 1.0	11.6 ± 1.1
	6	11.5 ± 1.3	11.3 ± 0.9 [a]	12.0 ± 1.0 [a]	11.7 ± 1.0

[*] $p < 0.05$ compared to 2MIN and 3MIN, [a] $p < 0.05$ compared to previous work interval

Note; au: arbitrary unit, HIIT: high intensity interval training, RER: respiratory exchange ratio ($\dot{V}CO_2$/ $\dot{V}O_2$); RPE: ratings of perceived exertion

During the recovery intervals 6 participants walked on all occasions, and 6 participants decided to stand still each time. There was no difference in the $\dot{V}O_2$ / HR kinetics according to activity in the recovery period (data not shown).

Experimental outcomes for $\dot{V}O_2$ measures are shown in **Table 6.2**. Repeated measure ANOVA showed no differences in the total exercise time ≥ 90% (p = 0.24) or ≥ 95% (p = 0.12) $\dot{V}O_2$max between protocols. The most notable difference in these variables was the moderately larger exercise time ≥ 90% and ≥ 95% $\dot{V}O_2$max in 3MIN compared with 2MIN (see **Table 6.4**). Considerate variability between participants was evident in exercise time ≥ 90% $\dot{V}O_2$max across the simulated HIIT sessions (see **Figure 6.3**). Mean $\dot{V}O_2$ before subsequent work intervals was higher in 1MIN compared to all other protocols (p < 0.01), and moderately higher in ssMIN compared to 3MIN (p = 0.014). Mono-exponential modelling provided an adequate fit for the $\dot{V}O_2$ data (R^2 range 0.73 ± 0.15 – 0.79 ± 0.10). The mean response time (MRT) was significantly slower in 1MIN compared to all other protocols, which was accompanied by a lower $\dot{V}O_2$ amplitude. No differences were found between protocols in $\dot{V}O_2$ plateau ($p = 0.22$), average $\dot{V}O_2$ during ($p = 0.36$), or $\dot{V}O_2$ in the final minute of the work intervals ($p = 0.21$).

No significant differences were evident between protocols for time spent ≥ 90% ($p = 0.24$) and ≥ 95% HRmax ($p = 0.12$; see **Table 6.3**), supported by trivial or small differences between protocols (see **Table 6.5**). Baseline HR was significantly higher in 1MIN compared to all other protocols, and lower in 3MIN compared to 2MIN and ssMIN. Mono-exponential modelling showed a very good fit for the data (R^2 range 0.96 ± 0.06 – 0.99 ± 0.01). MRT was significant slower in 1MIN than all other recovery durations and slower in 2MIN and ssMIN than in 3MIN (see **Table 6.3**). Average HR in the work intervals was higher in 1MIN compared to 3MIN and ssMIN (small effect), but not different in the last 60 s between protocols.

Across the recovery intervals in ssMIN, self-selected recovery duration averaged 100 ± 34 seconds (see **Figure 6.2**). Recovery time was significant shorter between the first and second work interval (80 ± 25 s) compared to the subsequent recovery phases, in which the duration remained constant (ranging between 97 ± 31 – 111 ± 33 s).

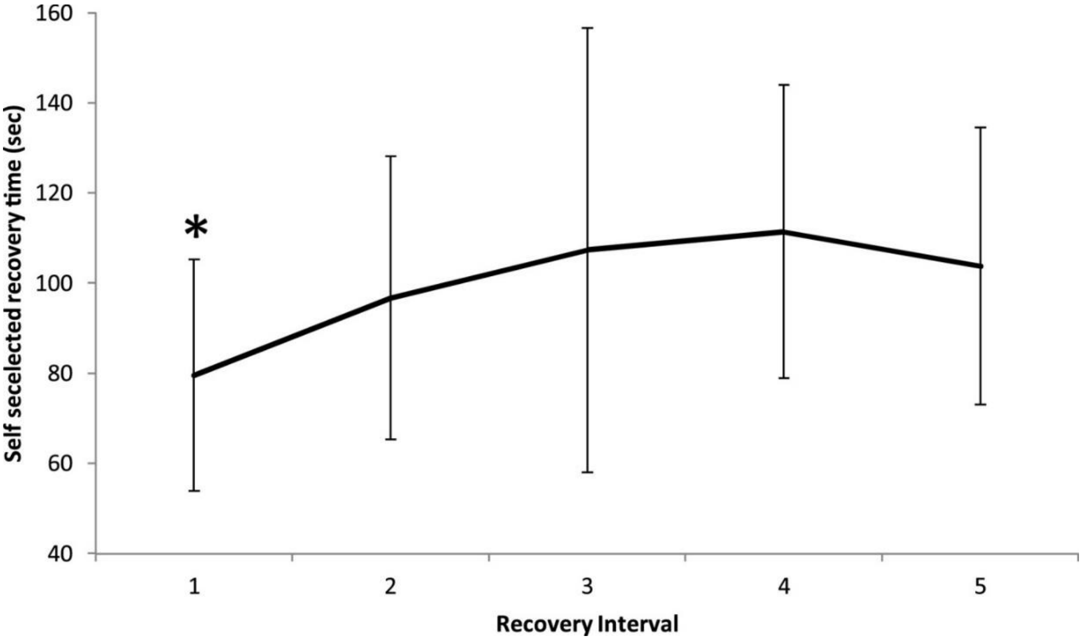


Figure 6.2: Mean ± SD self-selected recovery duration in subsequent recovery intervals (n = 12)
* Significantly different from ($p < 0.05$) all other recovery durations

Table 6.2: Oxygen uptake measures during simulated HIIT sessions, with 1MIN, 2MIN, 3MIN or ssMIN recovery between subsequent work intervals

	HIIT Protocol			
	1MIN	2MIN	3MIN	ssMIN
exercise time ≥ 90% $\dot{V}O_2$max (s)	849 ± 341	727 ± 388	918 ± 232	776 ± 335
exercise time ≥ 95% $\dot{V}O_2$max (s)	574 ± 373	422 ± 347	629 ± 330	476 ± 408
$\dot{V}O_2$ last 30sec of recovery ($mL\cdot kg^{-1}\cdot min^{-1}$)	26.6 ± 4.1[*]	18.6 ± 4.0	17.8 ± 5.7	20.3 ± 5.6 [a]
$\dot{V}O_2$ Plateau ($mL\cdot kg^{-1}\cdot min^{-1}$)	50.3 ± 6.8	49.0 ± 6.3	51.6 ± 7.8	50.1 ± 6.6
Mean response time (s)	33.1 ± 2.6[*]	30.2 ± 4.2	28.8 ± 3.0	29.2 ± 5.4
average $\dot{V}O_2$ interval (%$\dot{V}O_2$max)	90.1 ± 8.5	87.1 ± 5.2	91.0 ± 6.2	89.4 ± 7.5
average $\dot{V}O_2$ last 60sec of interval (%$\dot{V}O_2$max)	96.1 ± 8.7	92.9 ± 6.4	98.0 ± 6.5	95.8 ± 8.2

[*] $p < 0.01$ vs 2MIN, 3MIN and ssMIN, [a] $p < 0.05$ vs 3MIN

Note; HIIT: high intensity interval training, $\dot{V}O_2$ oxygen uptake, $\dot{V}O_2$max: maximum oxygen uptake

Table 6.3: Heart rate measures during simulated HIIT sessions, with 1MIN, 2MIN, 3MIN or ssMIN recovery between subsequent work intervals

	HIIT Protocol			
	1MIN	2MIN	3MIN	ssMIN
exercise time ≥ 90% HRmax (s)	979 ± 257	1017 ± 231	989 ± 149	953 ± 198
exercise time ≥ 95% HRmax (s)	468 ± 317	493 ± 347	441 ± 296	372 ± 287
HR last 30sec of recovery (bpm)	140 ± 14 [*]	126 ± 15	115 ± 14 [a]	126 ± 16
HR Plateau (bpm)	177 ± 12	177 ± 10	176 ± 11	175 ± 11
Mean response time (s)	45.2 ± 7.5 [b]	40.7 ± 4.5 [c]	37.3 ± 4.2	40.3 ± 7.0
average HR interval (%HRmax)	90.2 ± 3.2 [b]	89.2 ± 4.6	88.6 ± 3.1	88.4 ± 3.1
average HR last 60sec of interval (%HRmax)	94.9 ± 2.2	95.3 ± 3.1	95.4 ± 1.6	94.5 ± 1.8

[*] $p < 0.01$ vs 2MIN, 3MIN and ssMIN, [a] $p < 0.05$ vs 2MIN and ssMIN, [b] $p < 0.05$ vs 3MIN and ssMIN, [c] $p < 0.05$

Note; bpm: beats per minute, HIIT: high intensity interval training, HR: heart rate, HRmax: maximum heart rate

Table 6.4: Effect size (Cohen’s d) comparison between oxygen uptake measures during the simulated HIIT sessions, with 1MIN, 2MIN, 3MIN or ssMIN recovery between subsequent work intervals

		HIIT Protocol		
		1MIN	2MIN	3MIN
exercise time ≥ 90% $\dot{V}O_2$max	2MIN	0.33		
	3MIN	0.24	0.60	
	ssMIN	0.22	0.14	0.49
exercise time ≥ 95% $\dot{V}O_2$max	2MIN	0.42		
	3MIN	0.16	0.61	
	ssMIN	0.25	0.14	0.41
$\dot{V}O_2$ last 30sec of recovery	2MIN	1.98		
	3MIN	1.77	0.16	
	ssMIN	1.28	0.44	0.55
$\dot{V}O_2$ Plateau	2MIN	0.20		
	3MIN	0.18	0.37	
	ssMIN	0.03	0.21	0.21
Mean response time	2MIN	0.83		
	3MIN	1.53	0.38	
	ssMIN	0.92	0.21	0.09
average $\dot{V}O_2$ interval	2MIN	0.43		
	3MIN	0.12	0.68	
	ssMIN	0.09	0.36	0.23
average $\dot{V}O_2$ last 60sec of interval	2MIN	0.42		
	3MIN	0.25	0.79	
	ssMIN	0.04	0.39	0.30

Note; HIIT: high intensity interval training, $\dot{V}O_2$ oxygen uptake, $\dot{V}O_2$max: maximum oxygen uptake

Table 6.5: Effect size (Cohen's d) comparison between heart rate measures during the simulated HIIT sessions, with 1MIN, 2MIN, 3MIN or ssMIN recovery between subsequent work intervals

		HIIT Protocol		
		1MIN	2MIN	3MIN
exercise time ≥ 90% HRmax	2MIN	0.16		
	3MIN	0.05	0.14	
	ssMIN	0.11	0.29	0.21
exercise time ≥ 95% HRmax	2MIN	0.08		
	3MIN	0.09	0.16	
	ssMIN	0.32	0.38	0.24
HR last 30sec of recovery	2MIN	0.96		
	3MIN	1.79	0.76	
	ssMIN	0.93	< 0.01	0.73
HR Plateau	2MIN	< 0.01		
	3MIN	0.09	0.10	
	ssMIN	0.17	0.19	0.09
Mean response time	2MIN	0.73		
	3MIN	1.30	0.78	
	ssMIN	0.68	0.07	0.52
average HR interval	2MIN	0.25		
	3MIN	0.51	0.15	
	ssMIN	0.57	0.20	0.06
average HR last 60sec of interval	2MIN	0.15		
	3MIN	0.26	0.04	
	ssMIN	0.19	0.32	0.53

Note; HIIT: high intensity interval training, HR: heart rate, HRmax: maximum heart rate

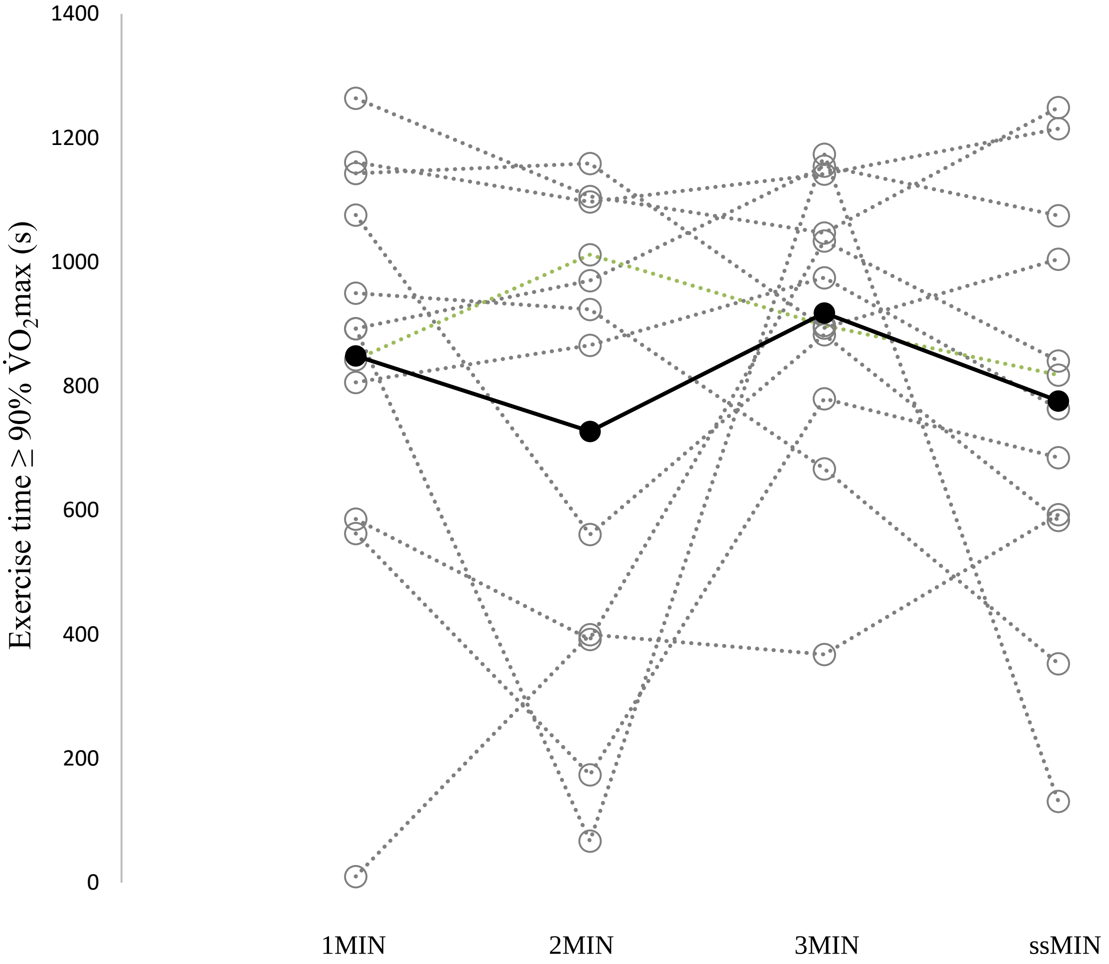


Figure 6.3: Individual (○) and grouped (●) exercise time ≥ 90% $\dot{V}O_2$max (s) in the simulated HIIT sessions

In dept analysis of exercise time ≥ 90% $\dot{V}O_2$max showed three participants accumulated most time ≥ 90% $\dot{V}O_2$max in 1MIN, two participants in 2MIN, five participants in 3MIN, and two participants in ssMIN (see **Figure 6.3**). ssMIN recovery times of these two participants were 99.8 ± 19 s and 67.6 ± 5 s respectively, and time ≥ 90% $\dot{V}O_2$max of the nearest fixed recovery duration (2MIN and 1MIN respectively) was their second highest obtained time ≥ 90% $\dot{V}O_2$max.

6.4 Discussion

This study aimed to examine the effects of different recovery durations on self-selected running velocities and the accompanying physiological and perceptual responses. Mean running velocity was highest when participants received a longer recovery period (3MIN) between intervals, however, total time spent at or above 90% and 95 %$\dot{V}O_2$max did not differ between protocols. Similarly, time spent ≥ 90% and 95% HRmax did not differ between protocols.

HIIT aims to enhance the metabolic overload of a training session by maximizing the total accumulated time spent at high exercise intensities (≥ 90% $\dot{V}O_2$max and HRmax). In line with previous studies, the current data showed that repeated high intensity work intervals of 4 min are performed around 95% $\dot{V}O_2$max by recreationally trained runners, and that $\dot{V}O_2$ in the last minute reaches values close to $\dot{V}O_2$max (41,93,135). Repeated 4 min work intervals are often described as 'long aerobic intervals', and in line with this description, the RER values in the current study were under the unit value across all intervals (see **Table 6.1**), highlighting the dependency on the aerobic metabolism for ATP re-synthesis. Hetlelid et al. (135) found training status of participants likely plays an important role in the ability to achieve a steady state even in high-intensity interval exercise. The results of the present study add to those findings, showing a decline in RER with successive high intensity work intervals, despite a *maintained* **-** or elevated oxygen consumption and running velocity. These results confirm the strong aerobic training stimulus of long work intervals in HIIT.

Total time spent at or above 90% and 95 %$\dot{V}O_2$max, the average $\dot{V}O_2$ in the work intervals and the average $\dot{V}O_2$ in the last minute of the work intervals did not differ between protocols. Participants spend around 57% of the exercise time ≥ 90%, and 37% of time ≥ 95% $\dot{V}O_2$max (see **Table 6.2**). These findings are in agreement those of Smilios et al. (41), though subtle differences are noticeable between study outcomes. Smilios et al. (41) found a (non-significant) linear decrease in time ≥ 80%, 90% and 95% $\dot{V}O_2$max with the increase of recovery duration. In contrast, a more U-shaped response was prevalent in the current study (see **Table 6.2**). Despite not reaching statistical significance, time ≥ 90% $\dot{V}O_2$max was considerably higher when participants received 3 min recovery compared with other recovery periods, and for 1MIN compared with 2MIN and ssMIN. A similar trend was found for time ≥ 95% $\dot{V}O_2$max. Basic oxygen kinetic analysis revealed no differences in $\dot{V}O_2$ plateau between protocols, despite subsequent work intervals starting from a lower metabolic rate in 3MIN and 2MIN compared with 1MIN and ssMIN. Starting intervals from an increased metabolic rate lengthened time needed to reach $\dot{V}O_2$ plateau in 1MIN, which was accompanied by the lowest $\dot{V}O_2$ amplitude. In line with the findings of Smilios et al. (41), our results show a decrease in MRT with the longer recovery duration, with the amplitude following a contrariwise response. This relationship suggests that $\dot{V}O_2$ kinetics adjust to regulate the oxygen supply that corresponds to the metabolic requirements of the exercise stimulus, and differences in $\dot{V}O_2$ kinetics therewith reflect changes in oxidative metabolism within the muscle (245,251). Wilson (252) evidenced that the magnitude of this response is dependent on the energy state of the cells, in particular to the concentration of adenosine diphosphate (ADP). Higher work rates in the preceding work intervals in 3MIN potentially elevated ADP concentrations and activated the oxidative phosphorylation to a greater extent compared to 1MIN, 2MIN and ssMIN (252,253), ultimately producing faster $\dot{V}O_2$ kinetics (245,251). This mechanism leads to the possibility to commence subsequent work intervals at a higher work rate, which would maximize time ≥ 90% $\dot{V}O_2$max.

Previously, an increased work rate in the initial 30 s of respectively 3- or 5 min work intervals failed to increase time ≥ 90% $\dot{V}O_2$max in trained cyclists (39,254). It is therefore unlikely that the absolute time ≥ 90% $\dot{V}O_2$max per AIT session is the only training variable accountable for improvements in $\dot{V}O_2$max. The relatively poor reliability of the measure of time ≥ 90% $\dot{V}O_2$max must also be taken into account (95, see **Figure 6.3** and **Figure 7.1** for additionally emperical data). These results are in line with our assumption prompted in **Chapter** (**Section 2.4**), in which we stated that the 'optimum' recovery duration, is most likely highly individual and depending on training status. The individual response presented in **Figure 6.3** are of interest to athletes, as it can help them verifying their 'optimum' recovery duration between subsequent 4 min work intervals to maximize time ≥ 90% $\dot{V}O_2$max. Whether the physiological responses to a single simulated HIIT session are reliably enough is to define this recovery duration is to be evaluated in future studies, as again, the day-to-day measure of time ≥ 90% $\dot{V}O_2$max showed to be of low reliability (95).

Heart rate monitoring has long been considered an important means to monitor exercise intensities, yet much research shows that it is neither related to systemic O_2 demand nor muscular energy turnover (14). We found only weak correlations between the measures of the times spent 90% and 95 %$\dot{V}O_2$max and HRmax across the different protocols (data not shown). The most notable differences in the time spent ≥ 90% and 95% HRmax were found between 2MIN and ssMIN (64 and 121 s, respectively), though the magnitude of these differences was considerably lower than the $\dot{V}O_2$ measures. A heart rate plateau was found around 95% HRmax independently of recovery duration, and MRT was, as in the $\dot{V}O_2$ measures, moderated by the elevation of baseline levels in 1MIN, 2MIN and ssMIN. Overall, subsequent work intervals in 3MIN started from the lowest metabolic rate, but similar times in the exercise zones were achieved because a faster MRT and higher HR amplitude (see **Table 6.3**). The low correlations between the measures of $\dot{V}O_2$ and HR indicate that heart rate may not accurately represent the aerobic metabolic requirements of an interval session. The results suggest that HR cannot inform coaches and athletes on the intensity of physical work performed, as we showed similarities in HR plateau and average interval HR across intervals, while differences in running velocities were present between and within protocols (see **Table 6.1**).

In contrast to motorized treadmills, the cNMT used in the current study required the participants to actively pull their legs through for propulsion at the beginning of every work interval for the treadmill belt speed to increase before reaching a steady running velocity for the remaining of the work interval. The concave curved design of the cNMT would allow the treadmill belt to accelerate if participants would mount onto the treadmill at the highest point of its curve (see **Figure 4.1**), however, without any further movement participants would come to a standstill at the bottom of the curve (see **Figure 4.1**). As previously explained in **Chapter 4** (**Section 4.4**), step by step muscle force production therefor is instrumental whilst running on the cNMT. Other studies that examined the physiological responses during interval running relied on researchers adjusting treadmill velocities between work and recovery intervals (e.g. (41,77)), or required participants to straddle on a spinning treadmill during recovery intervals and then re-join at the start of the next work interval (255). Both these approaches undermine the physiological strain imposed on a runner at the start of work intervals as that would be evident in ‘real life conditions’, as a time-delayed acceleration (41,77) or a no acceleration (255) phase will obviate the high metabolic cost of overcoming inertia (256). As shown in **Table 6.2** and **Table 6.3**, results of the current study show a notable faster MRT in both the heart rate and oxygen uptake kinetics compared to Smilios et al. (41). As Billat et al. (257) previously did not find differences in the oxygen kinetics in free vs constant pace runs, the faster MRT in the current study is most likely explained by the increased metabolic cost of overcoming inertia (256), and may further be attenuated by the 'uphill' characteristic of the cNMT (202, and see **Chapter 5)**, and the effective use of a priming warm up (250).

In the present study, participants were instructed to run at their highest sustainable running velocity throughout the work intervals, and to finish the sessions on a RPE $\geq$ 17. Previously, Seiler & Hetlelid (77) reported that well-trained male runners ran faster when the recovery duration increased from 1 to 2 min, but a further increase to 4 min had no additional effect on self-selected running velocities. Laurent et al. (93) reported an increase in running velocity when the recovery duration was increased from 1 to 2 min *and* from 2 to 4 min. In line with these findings, our results show participants ran faster in 3MIN compared to all other conditions and the running velocity was higher in ssMIN compared to 2MIN. However, in contrast to the earlier findings of both Seiler & Hetlelid (77) and Laurent (93), we did not find an increase in running velocity when recovery time was increased from 1 to 2 min.

In ssMIN, participants were instructed to start subsequent work intervals when they felt 'adequately recovered'. Self-selected recovery averaged 100 ± 34 seconds, similar to earlier findings of Seiler & Hetlelid (77), but almost a minute shorter than was reported by Edwards et al. (101) in a comparable interval session. The ssMIN protocol produced the most stable pacing profile, with the difference between the fastest and slowest work interval being only 0.53 ± 0.3 $\text{km}\cdot\text{h}^{-1}$, however, average running velocities were slower compared to 3MIN. With this in mind, athletes in the present study may have been more accustomed to a 'short' recovery between work intervals, and therefore may not have fully utilized the opportunity to increase their recovery duration.

Independent of the recovery duration, an increase in running velocity was evident in the final work interval in all simulated HIIT sessions, which reached statistical significance in 2MIN and 3MIN. While a faster finish is counterintuitive with the increase of fatigue over time, an end spurt is a common phenomenon in competitive races (84) and also in experimental settings (e.g. Edwards et al (101)). The end spurt across all protocols highlights that pacing is an important feature in interval training sessions (39), and it further shows that in each interval a decision on the 'maximum sustainable exercise intensity' is made within the context of available recovery time so as to avoid catastrophic fatigue and premature cessation of exercise (44,258). The end spurt further suggest the existence of a physiological reserve which is only utilized when the endpoint of, in this case, the end of a training sessions is within the limits of the available metabolic reserve (259).

The use of the *'isoeffort'* approach in a scientific setting shifts the decision making on interval exercise intensities towards the participant, thus increasing the external validity of the protocol. Participants in the current study rated their final intervals ~19.0, which indicates 'extremely hard' exercise. In previous studies, exercise intensities have been both over- and / or underestimated leading to a reduced number of completed intervals (21) or a 'too easy' HIIT session (indicated by a final RPE of 15, (41)). While the results of the current study suggest that recovery duration has a limited effect on the total physiological strain of the training, running velocities were fastest when participants received the longest recovery period. Longer recovery durations may facilitate a higher external training load (running speed) whilst maintaining a similar internal load (physiological stimulus) in HIIT sessions, and therefore, may allow for greater training adaptations.

6.5 Practical applications

Coaches should take into account that a longer recovery interval (3 min) between repeated 4 min efforts facilitates a faster running velocity, which is particularly important when the focus of the session is speed work. The results of this study further show that the recovery duration did not influence total metabolic load of a single training session, thus athletes can recovery for a greater period than may be traditionally thought. A self-selected recovery period results in the most consistent running velocity, which may be of importance when athletes are working on pacing.

Chapter 7:

The moderating role of recovery interval duration in simulated high intensity interval training sessions of trained cyclists

Summary

The total time spent at high percentages of $\dot{V}O_2$max ($\geq$ 90% (t90$\dot{V}O_2$max), or $\geq$ 95% $\dot{V}O_2$max (t95$\dot{V}O_2$max)) per high intensity interval training (HIIT) could serve as a good criterion to judge the effectiveness of HIIT protocols. This study compared the acute physiological and perceptual responses and accompanying exercise intensities to changes in the recovery interval duration in four simulated HIIT sessions. After completing an incremental cycling test to determine $\dot{V}O_2$max, HRmax and peak power output in an initial visit, 11 recreationally trained male cyclists performed four HIIT session comprising six 4 min work intervals. Work intervals were separated by either 1, 2, 3 min or a self-selected recovery duration (1MIN, 2MIN, 3MIN, ssMIN respectively), and participants were instructed to perform every session on their maximal sustainable exercise intensity. The results showed similar perceptual responses within and across the different protocols. No statistical differences were found in t90$\dot{V}O_2$max and t95$\dot{V}O_2$max between protocols, however, participants spend a notable ~200 s extra time in t90$\dot{V}O_2$max, and ~170 s in t95$\dot{V}O_2$max in 1MIN compared to 2MIN, 3MIN and ssMIN. Power output across work intervals was higher in 3MIN and ssMIN than in 1MIN, and the decrease in power output between the initial and final interval in 1MIN was greater compared to all other protocols. This study demonstrates a trade-off between the physiological stimulus and the external workload of a simulated HIIT session. The results can help coaches and athletes to select adequate lengths of recovery intervals according to their training goals.

7.1 Introduction

High intensity interval training (HIIT) is by no means a new phenomenon, but instead a training concept long appreciated by endurance athletes to improve cardiorespiratory and metabolic functioning, and, in turn endurance performance (13,14). HIIT aims to enhance the metabolic overload of a training session to a greater extent than is possible with traditional continuous training, by maximizing the total accumulated time at exercise intensities at or near the maximum oxygen uptake ($\dot{V}O_2$max) and heart rate (HRmax). At these intensities the oxygen delivery and utilization systems are maximally stressed, and it is assumed that the percentage of $\dot{V}O_2$max attained and the time for which it is sustained per HIIT session can serve as a relevant criterion to characterise and analyse the effectiveness of a HIIT protocol (5,14,55).

The total workload of HIIT sessions is determined by a complex interplay between the exercise intensities and the duration of both the work and recovery intervals, and the total number of intervals performed (16,17). Over recent years, multiple studies have manipulated work intensities (260), work durations (23,59,75), pacing strategies (39), and / or additional aids like muscle vibration (40) to increase the time spent at high percentages of $\dot{V}O_2$max (typically ≥ 90% ($t90\dot{V}O_2$max), or ≥ 95% $\dot{V}O_2$max ($t95\dot{V}O_2$max)). In contrast to these manipulations in work intervals, surprisingly little research has explored the overall impact of recovery intervals on the overall effectiveness of HIIT protocols, however, the duration of recovery intervals may be an important moderator to increase $t90\dot{V}O_2$max and / or $t95\dot{V}O_2$max (54). As hypothesised by Schoenmakers & Reed (104), short recovery intervals may maximize the physiological stimulus of a HIIT session, by starting subsequent work intervals from an elevated oxygen uptake ($\dot{V}O_2$) and heart rate (HR). Insufficiently short recovery intervals however can lead to premature fatigue, which may reduce the number of completed intervals or lower the work intensities in subsequent intervals as was evident in previous research (21,187). Conversely, work intervals interspersed with long recovery intervals will start from a lower metabolic rate, which may attenuate peak values achieved during work intervals, and potentially decreases the $t90\dot{V}O_2$max and / or $t95\dot{V}O_2$max. While longer recovery intervals may lower the physiological strain, delayed fatigue can allow athletes to achieve higher exercise intensities in work intervals which may allow for greater training adaptations.

Previously, research on trained runners showed that intervals indeed started from a lower metabolic rate when long recovery intervals were available across repeated 4 min work intervals compared to shorter recovery intervals (41,104). In line with findings from single bout transitions in cycling (261), it was evident that $\dot{V}O_2$ and HR kinetics were faster when work intervals started from this lower metabolic rate, and consequently, $t90\dot{V}O_2max$ and $t95\dot{V}O_2max$ were similar between different recovery durations (41,104). In contrast to the standardized protocol used by Smilios et al. (41), Schoenmakers & Reed (104) reported a significant higher running velocity was achieved by the participants, when longer recovery intervals were available in self-paced HIIT sessions. Self-paced HIIT interventions have recently been addressed in cycling (42,218), however the potential moderating role of recovery durations in HIIT protocol remains unclear. Whilst the findings on the acute effects of manipulations in recovery durations in runners are insightful, different exercise modalities (e.g. running vs cycling) might result in different physiological responses and, therefore, may divergent outcomes (144). The aim of this study therefore was to compare the physiological and perceptual responses and accompanying work intensities in self-paced HIIT sessions in recreationally trained cyclists. As a secondary aim, we examined the moderating role of the recovery interval duration on the potential trade-off between the physiological stimulus and the external workload. In line with the previous findings of Schoenmakers & Reed (104) in trained runners, no differences in the physiological or perceptual responses were expected between HIIT protocols which only differed in the recovery duration between subsequent work intervals. It was however expected that longer recovery intervals would maximize the exercise intensities attained in the work intervals.

7.2 Methods

7.2.1 Experimental approach to the problem

Participants visited the laboratory on five different occasions over a four-week period, with visits separated by a minimum of two days. During their initial visit, participants completed an incremental cycling test to determine $\dot{V}O_2max$, HRmax, gas exchange threshold (GET) and peak power output (PPO), and one self-paced 4 min ‘work interval’ effort as familiarisation. In the remaining four visits, participants performed a simulated HIIT session comprising six 4 min work intervals. Between visits, recovery duration between work intervals was manipulated.

7.2.2 Participants

Eleven male cyclists (mean ± standard deviation (SD); age: 35 ± 10 years; height 1.77 ± 0.1 m; weight 76 ± 10 kg; $\dot{V}O_2max$: 51 ± 7; HRmax: 180 ± 13 bpm; PPO: 370 ± 53 W) with previous HIIT experience volunteered to participated. According to $\dot{V}O_2max$ based classification norms (150), participants were categorized in performance levels 1 (n = 2), 2 (n = 4), 3 (n = 4), and 4 (n = 1). In line with our study presented in **Chapter 6** (104), *a priori* power analysis (G*Power 3.1) indicated a minimum sample size of 10 participants was required to detect small differences (Cohen's d = 0.2) in the physiological and perceptual responses between the different simulated HIIT sessions. We strived to recruit twelve participants to complete three full rounds of counterbalanced randomization of the experimental visits. The study received approval from the local ethics and was conducted in accordance with the Declaration of Helsinki and the ethical standards of the International Journal of Sports Medicine (262).

7.2.3 Incremental cycling test protocol

After a 5 min warm-up, performed at an intensity of 1.5 $W \cdot kg^{-1}$, participants completed an incremental cycling test on an electronically-braked cycle ergometer (Velotron Dynafit Pro, Racermate Inc., Seattle, USA). This cycle ergometer has been shown a reliable and valid tool to assess cycling performance (263,264). The test started at 100 W and power output (PO) increased by 25 $W \cdot min^{-1}$ until volitional exhaustion (defined as drop in > 10 revolutions per minute of self-selected cadence), or when at least two of the following criteria were met: 1) HR ≥ 90% of age-predicted maximum; 2) respiratory exchange ratio ≥ 1.10; 3) stable $\dot{V}O_2$ despite increased intensity (212).

On completion of the test, $\dot{V}O_2max$ was defined as the highest average $\dot{V}O_2$ over a 30 s period, and HRmax as the highest obtained value in the test. PPO was calculated as the PO that was maintained for the final completed stage, or, as the completed fraction of an incomplete final stage added to the PO of the last completed stage (265). GET was determined from a cluster of measures, previously outlined by Bailey et al.(250) and detailed in **Chapter 6** (**Section 6.2.3**). The PO corresponding to 70% of the difference (Δ) between the PO at GET and PPO was calculated, and used as warm-up intensity in the remaining visits.

After completion of the incremental cycling test, and a brief recovery period (~10 min), participants performed one self-paced 4 min effort in the training set-up of the ergometer (Velotron Coaching Software) to familiarize with this set-up and the simulated gear shifting available on the ergometer. Participants were further familiarized with the concept of using the ratings of perceived exertion (RPE, (80)) and perceived readiness scale (PR, (101)) to monitor their efforts in HIIT sessions. Individual bike set-up (saddle height, saddle set back and reach to bars) were reported after completion of the first visit, and copied in all further visits.

7.2.4 Experimental simulated HIIT session

In the four remaining visits, participants performed a HIIT session comprising six 4 min work intervals, separated by either 1, 2, 3-min or a self-selected recovery duration (1MIN, 2MIN, 3MIN and ssMIN respectively). Prior to each HIIT session participants performed a 6 min warm-up at 70% Δ GET, followed by a 9 min break (250). Participants were instructed to perform every HIIT session on their maximal sustainable intensity across the work intervals (‘*isoeffort*’), and to finish the HIIT session on a RPE ≥ 17. To avoid poor pacing participants were instructed (but not restricted) to target a work intensity of 75% PPO in the first interval, based on previous research (40,42,266). Continuous feedback was available on elapsed time and PO during the work intervals.

In the recovery intervals, participants were instructed to cycle at 1 $W \cdot kg^{-1}$. RPE were obtained immediately after every work interval. PR was scored every 45 sec during the recovery interval, but only in ssMIN, with participants blinded for elapsed time, PR indicated the start of subsequent work intervals when participants indicated to feel ‘adequate recovered to exercise at the required intensity’ (101). In all trials, participants were blinded to the experimental condition until the completion of the first work interval. Session RPE (sRPE, (267)) was obtained 30 min after completion of the training session based on the question ‘How hard was your workout?’.

7.2.5 Data collection and analysis

During the incremental cycling test and the four HIIT sessions, HR was recorded at 1 Hz using a Garmin HR monitor (910XT, Garmin Ltd., Schaffhausen, Switzerland), and respiratory parameters were sampled breath-by-breath using open circuit spirometry (Oxycon Pro, Jaeger, Höchberg, Germany). As per manufacturer's recommendations, the O_2 and CO_2 analysers were calibrated using ambient air and calibration gases of known concentrations before every experimental trial. PO in the simulated HIIT sessions was sampled at 4 Hz in the accompanying product software. Prior to every experimental trial, the cycling ergometer was calibrated.

7.2.6 Statistical analysis

Data were analysed using SPSS 25.0 (SPSS Inc., Chicago, USA), and are presented as mean ± SD. Mean differences in $t90\dot{V}O_2\mathrm{max}$ and $t95\dot{V}O_2\mathrm{max}$, time ≥ 90% and 95% HRmax (*t*90HRmax and *t*95HRmax respectively), PO, as well as the perceptual responses were analysed using one-way repeated measures analysis of variance (ANOVA). Only data obtained *during* work intervals were analysed. A two-way repeated measure ANOVA (protocol×interval) was used to analyse differences in the 30 sec baseline, mean, and final min $\dot{V}O_2$ and HR across the different protocols, followed by Turkey's post hoc tests were appropriate. Additionally standardized effect sizes (ES) are reported as Cohen's d. Qualitative interpretation of d was based on the guidelines provided by Hopkins et al. (151): < 0.2 trivial; 0.20 - 0.59 small; 0.6 - 1.19 moderate; 1.20 - 1.99 large; ≥ 2.00 very large. Significance for all tests was set at $p < 0.05$.

7.3 Results

The physiological and perceptual responses to the four HIIT protocols, and the accompanying exercise intensities are shown in **Table 7.2**. *t*90HRmax was higher in 1MIN, 2MIN and ssMIN compared to 3MIN, but not significantly different between protocols for *t*95HRmax, $t90\dot{V}O_2\mathrm{max}$ and $t95\dot{V}O_2\mathrm{max}$. All physiological measures evaluated in the current study showed large amounts of individual variability, highlighted in **Figure 7.1,** which depicts the individual and grouped responses of $t90\dot{V}O_2\mathrm{max}$ across the simulated HIIT sessions. The difference in t90HRmax between 3MIN and the other experimental conditions was of a small magnitude (see **Table 7.2**). Mean power output across the work intervals was higher in 3MIN and ssMIN than in 1MIN, whilst this difference was only of small (vs 3MIN) or trivial (vs ssMIN) magnitude. Fluctuations in power output were evident in all protocols, and averaged 74.4 ±

2.2, 75.5 ± 2.4, 77.2 ± 1.6 and 76.6 ± 1.8 %PPO across the work intervals in 1MIN, 2MIN, 3MIN and ssMIN respectively. Both meanRPE and peakRPE were similar between the HIIT protocols, as well as sRPE.

Baseline, mean, and last min $\dot{V}O_2$ and HR for all work interval are shown in **Table 7.4**. Significant main effects for protocol and interval and a significant interaction effect (interval*protocol) were found for both $\dot{V}O_2$ and HR baseline measures. Post hoc analysis revealed that intervals started from an elevated $\dot{V}O_2$ and HR after the 1st interval in all protocols. The elevated baseline $\dot{V}O_2$ in 1MIN was higher from the 2nd to 5th work interval compared to 2MIN, 3MIN and ssMIN, and also higher in the 6th interval compared to ssMIN. Similarly, baseline HR was higher in 1MIN compared to all other protocols for the remaining intervals. No differences in mean $\dot{V}O_2$ and HR, and $\dot{V}O_2$ and HR of the final min were evident between any of the intervals.

Participants rated their final work interval in all protocols an RPE score of ≥ 17, verifying '*isoeffort'* conditions. In ssMIN, self-selected recovery time steadily increased throughout the recovery intervals, and averaged 118 ± 17 s (see **Table 7.1**). None of the self-selected recovery durations was significantly longer than the preceding recovery duration ($p > 0.05$ for all).

Table 7.1: Mean ± SD Self-selected recovery duration between subsequent work intervals

	Recovery interval				
	1	2	3	4	5
Time (sec)	97 ± 24	112 ± 26	127 ± 24	138 ± 32	139 ± 32
range	55 - 130	68 - 141	67 - 165	80 - 160	90 – 207

Table 7.2: Mean ± SD physiological, performance and perceptual responses to the four simulated HIIT sessions (n = 11)

	HIIT Protocol								
	1MIN	Range	2MIN	range	3MIN	Range	ssMIN	range	p value interaction effect
*t*90$\dot{V}O_2$max (s)	717 ± 403	(97 - 1294)	532 ± 320	(74 - 1041)	527 ± 372	(110 - 1300)	501 ± 408	(0 - 1185)	0.217
*t*95$\dot{V}O_2$max (s)	468 ± 420	(22 - 1189)	282 ± 271	(20 - 792)	310 ± 391	(20 - 1245)	296 ± 389	(0 - 1085)	0.239
*t*90HRmax (s)	828 ± 408 [a]	(191 - 1269)	885 ± 381 [a]	(287 - 1315)	649 ± 415	(10 - 1252)	838 ± 393 [a]	(110 - 1255)	0.030
*t*95HRmax (s)	323 ± 371	(0 - 968)	368 ± 351	(0 - 1019)	248 ± 332	(0 - 941)	317 ± 394	(0 - 975)	0.234
mean Power Output (W)	275 ± 47	(196 - 365)	280 ± 46	(203 - 376)	286 ± 45 [b]	(215 - 369)	283 ± 46 [b]	(210 - 370)	0.025
meanRPE (au)	16.9 ± 1.2	(14.3 - 19.0)	16.6 ± 0.8	(15.5 - 18.3)	16.9 ± 1.1	(15.8 - 17.8)	16.9 ± 1.1	(14.5 - 18.5)	0.280
peakRPE (au)	18.8 ± 0.9	(17 - 20)	18.4 ± 0.8	(17 - 19)	18.7 ± 0.8	(17 - 20)	18.7 ± 0.9	(17 - 20)	0.372
sRPE (au)	8.0 ± 1.1	(6 - 10)	7.3 ± 1.0	(6 - 9)	8.1 ± 0.7	(7 - 9)	7.6 ± 1.2	(5 - 9)	0.086

[a] greater than 3MIN; $p < 0.05$, [b] greater than 1MIN; $p < 0.05$

Note; au: arbitrary unit, HIIT: high intensity interval training, HRmax: maximal heart rate; RPE, ratings of perceived exertion; sRPE, session rating of perceived exertion. *t*90: time ≥ 90% $\dot{V}O_2$max / HRmax, *t*95: time ≥ 95% $\dot{V}O_2$max / HRmax, $\dot{V}O_2$max: maximum oxygen uptake

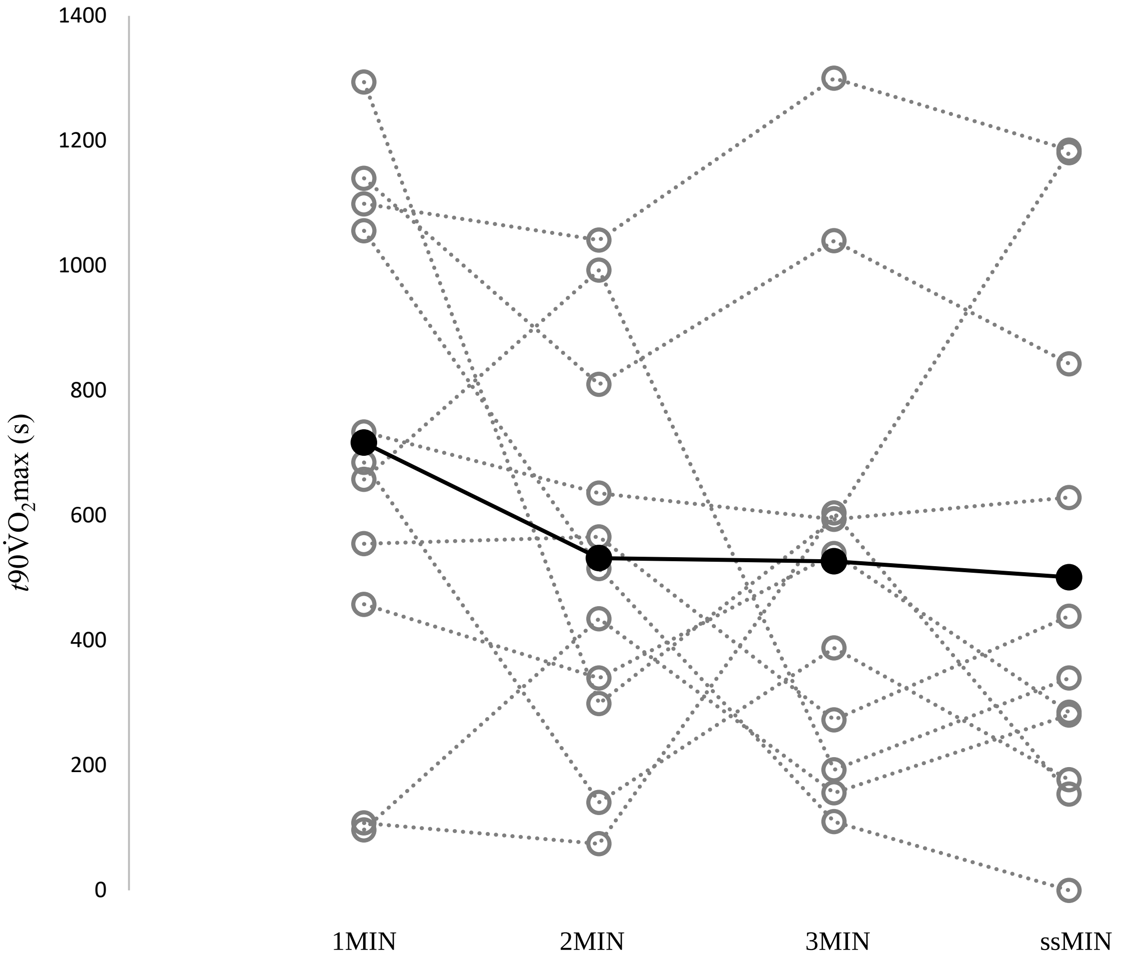


Figure 7.1: Individual (○) and grouped (●) $t90\dot{V}O_2max$ (s) in the simulated HIIT sessions

In dept analysis of the data presented in **Figure 7.1** revealed five participants accumulated most time ≥ 90% $\dot{V}O_2max$ in 1MIN, three participants in 2MIN and three participants in 3MIN. For no participants the ssMIN resulted in the highest $t90\dot{V}O_2max$.

Table 7.3: Effect size (Cohen's d) comparison between all experimental protocols

		HIIT Protocol		
		1MIN	2MIN	3MIN
*t*90$\dot{V}O_2$max	2MIN	0.51		
	3MIN	0.49	0.01	
	ssMIN	0.53	0.08	0.07
*t*95$\dot{V}O_2$max	2MIN	0.53		
	3MIN	0.39	0.08	
	ssMIN	0.42	0.04	0.04
*t*90HRmax	2MIN	0.14		
	3MIN	0.43	0.59	
	ssMIN	0.02	0.12	0.47
*t*95HRmax	2MIN	0.12		
	3MIN	0.21	0.35	
	ssMIN	0.02	0.14	0.19
mean Power Output	2MIN	0.11		
	3MIN	0.24	0.13	
	ssMIN	0.17	0.07	0.07
meanRPE	2MIN	0.29		
	3MIN	< 0.01	0.31	
	ssMIN	< 0.01	0.31	< 0.01
peakRPE	2MIN	0.47		
	3MIN	0.12	0.38	
	ssMIN	0.11	0.35	< 0.01
sRPE	2MIN	0.67		
	3MIN	0.11	0.93	
	ssMIN	0.35	0.27	0.51

Note; HIIT: high intensity interval training, HRmax: maximal heart rate; RPE, ratings of perceived exertion; sRPE, session rating of perceived exertion. *t*90: time ≥ 90% $\dot{V}O_2$max / HRmax, *t*95: time ≥ 95% $\dot{V}O_2$max / HRmax, $\dot{V}O_2$max: maximum oxygen uptake

Table 7.4: Baseline, mean and last minute $\dot{V}O_2$ (in $mL \cdot kg^{-1} \cdot min^{-1}$) and HR (in beats per minute) per work interval for the simulated HIIT sessions

	Work Interval						
	1	2	3	4	5	6	p value interaction effect
Baseline $\dot{V}O_2$							
1Min	24.8 ± 6.8	32.4 ± 6.4 [a,c]	32.5 ± 5.9 [a]	31.8 ± 5.6 [a]	30.3 ± 6.7 [a]	28.9 ± 7.2 [b]	$p < 0.01$
2Min	21.7 ± 5.8	25.0 ± 4.4 [c]	25.1 ± 4.4	25.9 ± 4.3	26.3 ± 4.5	26.7 ± 4.3	
3Min	23.4 ± 5.3	26.9 ± 5.1 [c]	25.6 ± 6.7	25.1 ± 6.4	25.0 ± 6.7	24.6 ± 6.3	
ssMin	23.2 ± 6.6	26.7 ± 6.2 [c]	27.2 ± 4.9	25.2 ± 6.0.	24.1 ± 3.9	24.0 ± 4.1	
Mean $\dot{V}O_2$							
1Min	44.6 ± 7.7	46.6 ± 8.2	46.3 ± 8.6	45.8 ± 8.6	44.7 ± 8.7	44.3 ± 9.5	$p = 0.74$
2Min	42.9 ± 9.4	44.7 ± 8.3	44.0 ± 8.4	44.1 ± 8.8	44.0 ± 8.4	44.4 ± 8.7	
3Min	43.1 ± 7.3	44.9 ± 7.4	44.8 ± 7.8	44.4 ± 7.9	44.1 ± 7.5	44.5 ± 7.6	
ssMin	42.8 ± 8.3	45.1 ± 8.3	44.0 ± 8.5	43.5 ± 9.9	42.7 ± 8.6	43.5 ± 8.1	
Last min $\dot{V}O_2$							
1Min	47.4 ± 8.0	48.2 ± 8.9	48.4 ± 9.6	47.0 ± 8.9	46.0 ± 9.5	46.0 ± 9.7	$p = 0.65$
2Min	45.8 ± 9.7	47.1 ± 9.2	46.8 ± 9.1	46.6 ± 9.1	46.5 ± 8.8	46.7 ± 9.1	
3Min	47.2 ± 8.4	47.5 ± 8.4	47.5 ± 8.8	46.6 ± 9.2	46.4 ± 8.4	46.5 ± 8.4	
ssMin	46.5 ± 8.6	47.6 ± 8.8	46.5 ± 9.2	46.9 ± 9.7	45.4 ± 9.4	46.1 ± 8.6	
Baseline HR							
1Min	117 ± 11	140 ± 13 [a,c]	142 ± 13 [a]	147 ± 15 [a,c]	149 ± 15 [a,c]	150 ± 15 [a]	$p < 0.01$
2Min	115 ± 17	124 ± 13 [c]	127 ± 15 [c]	129 ± 16	131 ± 15	132 ± 16	
3Min	115 ± 10	120 ± 11 [c]	120 ± 15	122 ± 15	123 ± 15	125 ± 15	
ssMin	118 ± 14	127 ± 13 [c]	129 ± 13	129 ± 14	127 ± 15 [c]	130 ± 13 [c]	
Mean HR							
1Min	155 ± 13	160 ± 12	162 ± 12	163 ± 13	164 ± 13	166 ± 13	$p = 0.72$
2Min	155 ± 16	160 ± 14	161 ± 14	163 ± 14	163 ± 13	165 ± 15	
3Min	154 ± 13	158 ± 12	159 ± 13	159 ± 12	160 ± 12	161 ± 12	
ssMin	155 ± 14	160 ± 13	162 ± 14	162 ± 14	162 ± 13	163 ± 13	
Last min HR							
1Min	164 ± 12	167 ± 12	169 ± 12	169 ± 12	170 ± 12	171 ± 13	$p = 0.95$
2Min	165 ± 14	169 ± 13	170 ± 13	171 ± 13	171 ± 12	173 ± 13	
3Min	163 ± 12	166 ± 11	167 ± 12	168 ± 11	168 ± 11	170 ± 11	
ssMin	164 ± 14	169 ± 13	170 ± 13	170 ± 12	170 ± 13	172 ± 12	

Data are presented as mean ± SD

[a] sign. higher than comparable work interval in 2MIN, 3MIN and ssMIN; [b] sign. higher than comparable work interval in ssMIN; [c] sign. different from previous work interval

Note; $\dot{V}O_2$: oxygen consumption; HR: heart rate

7.4 Discussion

This study examined the moderating role of the recovery interval duration on the physiological and perceptual responses and accompanying exercise intensities in four simulated HIIT sessions, all performed under '*isoeffor't* conditions. Furthermore, the trade-off between the physiological stimulus and external workload of these sessions were examined. The perceptual responses were similar across (sRPE) and within (RPE) the HIIT protocols. The length of recovery intervals had a limited effect on the total physiological load of the training session, with a similar *t*90$\dot{V}O_2$max, *t*95$\dot{V}O_2$max and *t*95HRmax between protocols. While the perceptual and physiological responses were similar, results show that the mean PO was higher when work intervals were separated by 3 min or a self-selected recovery duration compared to 1 min recovery intervals.

It has been suggested that the time athletes spend in their 'red zone' per HIIT session could serve as a good criterion to judge the effectiveness of HIIT protocols (14,55). Previously, the addition of muscle vibrations (40) and an all-out pacing strategy (39) to work intervals increased *t*90$\dot{V}O_2$max in trained cyclists. To the best of our knowledge, this is the first study in cyclists to evaluate the acute physiological responses to changes in the duration of recovery intervals in four simulated HIIT sessions. In line with findings in trained runners (41,104), no differences were found in *t*90$\dot{V}O_2$max and *t*95$\dot{V}O_2$max between the protocols. While no statistical differences were evident, participants spent a notable ~200 s extra in *t*90$\dot{V}O_2$max, and ~170 sin *t*95$\dot{V}O_2$max in 1MIN compared to 2MIN, 3MIN and ssMIN (see **Table 7.1**). *t*90HRmax was significantly lower in 3MIN compared to the shorter recovery intervals (~200 s, see **Table 7.1**), but not different in *t*95HRmax. Work intervals in 1MIN started from an elevated $\dot{V}O_2$ and HR compared to all other protocols (see **Table 7.4**), however, this different metabolic rate did not attenuate the mean $\dot{V}O_2$ or HR attained during the complete, or final minute of the work intervals across the different protocols. In line with previous studies in cyclists of different performance levels (e.g. (42,75,266)), $\dot{V}O_2$ and HR in the 4 min intervals averaged 85 - 90% $\dot{V}O_2$max and HRmax, which increased to 90 - 95% $\dot{V}O_2$max and HRmax in the final minute. Both mean and last minute $\dot{V}O_2$ and HR in the current study are ~5% lower than typically reported in similar HIIT sessions of runners (77,104), highlighting the discrepancy between the physiological responses to cycling and running. These results are in line with the findings previously summarized by Millet (144), which suggests that physiological responses are dependent on the exercise modality, and the amount of muscle mass involved. Since more muscle mass is involved whilst running than whilst cycling, the 'red zone' in runners coincides with a higher fractional utilization of $\dot{V}O_2$max than in cyclist (144). New data from our lab, collected in trained triathletes, showed that also the relative exercise intensity that marked the lower limit of Zone 3 (see **Figure 1.1)** was significantly higher whilst running compared to cycling (84.5 ± 4.3% vs 76.6 ± 4.9% of respective maximum work intensity, $p < 0.01$ (data collection not part of doctoral work and hence not shown)). Both the higher fractional utilization of $\dot{V}O_2$max and the higher relative exercise on the lower limit of Zone 3, allow runners to exercise at higher work rates compared to cyclists, as we evidence in **Chapter 6** and **Chapter 7**.

Recently, it was proposed that *peak* HR at the end of an interval can serve as a sensitive intensity indicator, however, it was also stated that care should be taken when using HR to guide exercise intensities (268). Exemplary, Tucker et al. (75) indeed used HR to guide the exercise intensity in four 4 min intervals, which led to a significant 20% reduction of PO from the first to last interval to maintain HR within the desired 90 - 95% HRmax range. In the current study, participants performed every work interval on their maximal sustainable intensity across the HIIT sessions. PO in the first interval was not different between protocols, and decreased throughout all protocols after the initial interval, however, to a far lesser extent than the reduction reported by Tucker et al. (75). The decrease in PO between the initial and final interval was greater in 1MIN (7%) compared to all other protocols (4%, 4%, and 5% for 2MIN, 3MIN and ssMIN, respectively), while HR was similar within and between these protocols (see **Table 7.4**). In line with previous research (104,268), our results confirm that HR cannot inform coaches and athletes on the aerobic demands and physical work performed in a HIIT session, and caution should be taken when HR intensities are used to determine workloads.

The use of '*isoeffort*' intervals in a scientific setting shifts the decision making on work intensities per HIIT to the participant, as it rests on the notion that athletes know how to train hard when they are required to train hard (42). This approach further allows scientists to study the potential trade-off between the physiological stimulus and the external workload of a HIIT session, which is impossible when work intensities are predefined. Participants achieved similar relative workloads as previously reported in studies that examined '*isoeffort'* intervals of a similar duration (39,40,42,266). Power output across the work intervals was higher in 3MIN and ssMIN than in 1MIN, which is indicative for a higher accumulation of fatigue in 1MIN.

Large variability in the performance levels of the included participants was evident, based on absolute values for $\dot{V}O_2$max, HRmax and PPO, or according to the proposed guidelines of De Pauw (150). To account for this, all physiological measures ($\dot{V}O_2$ and HR) were indexed to their respective individual maximum, and the variability later found in the results was not dissimilar to the variation present in $\dot{V}O_2$max and HRmax (see **Table 7.4**). The same was true for the metric of power output across the experimental visits, in which the variation in work rates during the simulated HIIT sessions was similar to the variability present in the participants' PPO (see **Table 7.2**). Participants in this study were included on the basis of prior experience with HIIT, rather than the recruitment of a highly homogenous group of cyclists. A more homogenous participant pool potentially would have resulted in more homogenous work rates across participants, however, large variability in the measure of $t90\dot{V}O_2$max have been reported previously in highly homogenous groups of runners (28) and cyclists (40,254). Training status or performance level however may effect the response in $\dot{V}O_2$ and HR kinetics (90,245), and future studies are therefore advised to include participants nested within the same performance level (150).

In conclusion, this study compared the acute responses to a simple manipulation in the design of a HIIT session, by manipulating the recovery duration between work intervals. The results demonstrated, in contrast to earlier findings in runners (104), a trade-off between the physiological stimulus and the external workload of the simulated self-paced HIIT session. The short recovery interval in 1MIN provided the largest $t90\dot{V}O_2$max and $t95\dot{V}O_2$max, at the cost of a decreased PO. Conversely, longer recovery intervals resulted in a decreased physiological load, but participants performed the HIIT session on a higher external workload.

7.5 Practical applications

We believe these results have general relevance to other HIIT protocols incorporating intervals of a similar duration (1 – 8 min), in which exercise intensities are high, but ultimately submaximal. Future studies incorporating self-paced '*isoeffort*' HIIT sessions, using trained triathletes who are accustomed to both running and cycling, are welcomed to evaluate if these differences are exercise or participant dependent. The results of this study can be used by coaches and athletes in the design of HIIT sessions, and adequate recovery intervals can be selected according to their training goals.

Chapter 8:

The moderating role of the recovery interval duration in predefined HIIT protocols is limited in team sport athletes – an intervention study

Summary

High intensity interval training (HIIT) is an indispensable constitute of successful training programs of many athletes, historically, particularly for those involved in endurance sports. In team sports, HIIT is typically administered as small sided games. In the pre-season conditioning of contact team sports like rugby, a further increase in game-based conditioning might be undesirable considering potential injuries, and generic running HIIT interventions might be beneficial to improve aerobic fitness. Prior to and immediately after a three week pre-season conditioning period, 25 collegiate rugby players performed 1) an incremental run test to determine $\dot{V}O_2$max, HRmax and maximal aerobic velocity (MAV), and 2) a time to exhaustion test. Participants were matched on absolute $\dot{V}O_2$max and then randomly assigned to one of three training groups: 1MIN (n = 9), 3MIN (n = 9) or CON (n = 7). All participants completed a training program prescribed by the club, with no additional HIIT (CON), or an extra five HIIT sessions. These sessions comprised six 4 min work intervals ran at 90% MAV, separated by either 1 min (1MIN) or 3 min (3MIN) passive recovery to evaluate the moderating role of recovery interval durations. The physiological load in the HIIT sessions of 1MIN and 3MIN was similar when expressed as time ≥ 90% HRmax ($p > 0.05$, ES = 0.08). Repeated measures analysis of variance indicated that the addition of 2-hr generic HIIT resulted in improvements in $\dot{V}O_2$max in 1MIN (3.72%, ES = 1.54) and 3MIN (2.98%, ES = 0.52), and increased time to exhaustion in these groups to a moderate extent, but improvements were not significantly different between the training groups ($p = 0.254$ for $\dot{V}O_2$max and $p = 0.442$ for TTE respectively). These results indicate that the duration of the recovery intervals in HIIT sessions, run on predefined exercise intensities, did not attenuate the magnitude of changes in these outcome variables.

8.1 Introduction

In endurance sports, a high maximum oxygen uptake ($\dot{V}O_2max$) is one of the most important determinants and predictors of performance (217,269). In contrast to endurance sports, performance in team sports not solely relies on the physiological capacity of players but also on their technical and tactical proficiencies which are often made the core of team sports training programs (69,270). Games in team sports like field hockey, soccer and rugby are predominantly aerobic in nature as players interchange high-intensity movements of relatively short durations with rest periods throughout the game (271–273). In soccer players, it was estimated that aerobic energy contributes approximately 90% of the total energy cost during competitive play (52), and the relevance of aerobic fitness was further confirmed by studies showing a relationship between $\dot{V}O_2max$, distance covered and running velocities during a match (69,72,274). This suggests that a well-developed aerobic energy system is an important physiological determinant of team sport performance too, and training to improve the players' aerobic capacity is highly relevant.

As outlined in **Chapter 3** and further evidenced by Bacon et al. (140) and Milanovic et al. (30), high intensity interval training (HIIT) is regarded a time efficient and highly effective training modality to improve cardiorespiratory and metabolic functioning (14). Historically, HIIT has formed an indispensable constitute in training regimes of many athletes, particularly those involved in endurance sports (14,47). In team sports, small-sided games (SSGs) are typically used to target endurance adaptations and simultaneously develop technical and tactical skills, as SSGs mimic the conditions of actual match-play where athletes must perform under pressure and fatigue (275,276). It is worthy to note that SSGs seem to have numerous advantages over generic running or cycling HIIT for team sport players (275,277); nevertheless, unlike generic HIIT, in sports like rugby, SSGs do subject players to scenarios that have an increased injury risk (i.e. increased chance of heavy contact collisions). Injury rates for runners reported in the literature vary from 2.5 to 12.1 injuries per 1000 hours of running (278), which is at most, less than half the injury rate reported in rugby players while participating in SSGs (26.0 per 1000 training hours, (279)). In the aerobic conditioning of rugby players, a further increase in the amount of SSGs might therefore be undesirable, especially in pre-season conditioning periods, in which the training volume and workload are already high and players are most prone for injuries (280). In young and adolescent soccer players, it was previously demonstrated that generic HIIT improved $\dot{V}O_2$max to a similar extent as SSGs (276) and repeated sprint training (15), and significantly more than after extra technique training (69) with no negative effect on strength, power or sprint performance (69,72,276). In the pre-season of rugby players, additional HIIT therefore potentially is a safer and more suitable training modality than SSGs to improve aerobic fitness.

In HIIT, repeated periods of vigorous exercise are interspersed with recovery periods (14,15), and a complex interplay between the number of intervals, the exercise intensities and the duration of both the work and recovery intervals determine the workload of a HIIT session (16,17). Based on the configuration of predominantly the work intervals (54), HIIT can be divided in repeated sprint training (RST), sprint interval training (SIT) and aerobic interval training (AIT). The format of HIIT allows athletes to exercise longer at vigorous exercise intensities per training, and furthermore, especially in AIT and SIT sessions, increase time spent near $\dot{V}O_2$max and maximum heart rate (HRmax) compared to continuous exercise (18,281).

In **Chapter 3** we summarized over 80 unique AIT protocols (see **Table 3.1** and **Table 3.2**), and, in line with the results of meta-analysis evaluating SIT protocols (e.g. (152,198,200)), we showed that the majority of these AIT protocols yield improvements in $\dot{V}O_2$max. This can make believe that ‘all roads lead to Rome’ when it comes to the programming of HIIT sessions, and that further optimization of HIIT protocols is needless. It was suggested by Thevenet et al. (55) that the effectiveness of specifically AIT protocols can be expressed as the time athletes spend at or close to their $\dot{V}O_2$max per session ($\geq$ 90% $\dot{V}O_2$max; $t90\dot{V}O_2$max), in the expectation that a higher $t90\dot{V}O_2$max per session will allow for greater training adaptations (55,282). In the quest to increase $t90\dot{V}O_2$max, many studies have tried to optimize the work intervals of AIT protocols by manipulating work intensities (33,34) and work durations (20,35–37), where others examined different recovery intensities (38), pacing strategies (39), and even the use of additional aids like muscle vibration in cyclists (40). A demanding work interval is needed to facilitate training adaptations, with adaptations determined at a cellular level by heat shock proteins, PCG1a and other components (50), but a successful AIT protocol can only be achieved when work bouts are separated by adequate recovery intervals (54).

Surprisingly little research has explored the overall impact of recovery intervals, and a better understanding of optimum exercise intensities and recovery durations in HIIT protocols is therefore timely. In highly trained male cyclists (21) and recreationally active female team sport players (46), previous studies demonstrated a limited effect of in the recovey duration between work intervals, when AIT protocols were matched for total training volume and work intensities. Whilst insightfull, both these studies administered a cycling intervention to their participants (21,46), and how these results generalize to running based AIT interventions is questionable, evidenced by the notable different physiological responses to HIIT sessions in runners (**Chapter 6**) and cyclists (**Chapter 7**). The aim of the current study therefore was to evaluate the moderating role of the recovery interval duration in intensity matched AIT protocols, in the context of a pre-season conditioning period of collegiate rugby players. Since work intensities were fixed in the current study, based on the results of previous studies conducted in cyclists (21,46), no differences in adaptations were expected between the employed HIIT interventions.

8.2 Methods

8.2.1 Experimental approach to the problem

Twenty-five collegiate male rugby players, accustomed to traditional on feet conditioning and resistance training but unaccustomed to generic HIIT, took part in the study (means ± standard deviation (SD): age: 21 ± 1 year; height: 1.83 ± 0.06 m; body mass: 91 ± 12 kg). During an initial team meeting, study details and participation requirements were explained, and voluntary written informed consent was obtained. The study received approval from the local ethics committee (University of Essex) and was conducted in accordance with the Declaration of Helsinki.

Players returned for training at the rugby club following a 6-week off-season. The first week back in training was in early August, in which baseline testing of all participants was performed. Baseline testing comprised of 1) an incremental running test to determine $\dot{V}O_2$max, HRmax and maximal aerobic velocity (MAV), and 2) a time to exhaustion test. Participants were matched on absolute $\dot{V}O_2$max, and then randomly assigned to one of three training groups: 1MIN (n = 9), 3MIN (n = 9) or CON (n = 7). Within 4-7 days of baseline testing, all players began a 3-week pre-season training program prescribed by the club (a summary of the pre-season training plan can be seen in **Table 8.1**). Next to this training program, 1MIN and 3MIN completed five additional HIIT sessions. The HIIT protocols of 1MIN and 3MIN only differed in the duration of the recovery intervals (1 min vs 3 min). CON received no additional HIIT and acted as control group in this study. Participants in 1MIN and 3MIN completed post intervention testing 4-7 days after their final HIIT session, and CON completed their post intervention tests 3-4 days after the regular last training session.

Table 8.1: Overview of the 3-week pre-season training program

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
AM	Lower-body gym (60 min)	Free	Upper-body gym (60min)	Free	Lower-body gym (60 min)	Free	Free
Mid-AM		HIIT	Gym circuit (30 min)	HIIT	Gym circuit (30 min)	On feet conditioning (30 min) and Rugby (60 min)	Free
PM	On feet conditioning (45 min) and Rugby (45 min)	Free	On feet conditioning (45 min) and Rugby (60 min)	Free	Free	Free	Free

Note; AM**:** ante meridiem**,** HIIT: high intensity interval training**,** PM: post meridiem

8.2.2 Incremental running test and Time to exhaustion test protocol

All participants performed the incremental running and time to exhaustion test before and after the 3-week training intervention. Both these tests took place in the sports and exercise science laboratory, and were performed on a motorised treadmill (Pulsar 3p, H/P Cosmos, Nussdorf-Traunstein, Germany), with the gradient set at 1% (213). Participants were asked to refrain from consuming alcohol and caffeine for at least 24-h prior to testing, as well as from engaging in strenuous exercise in the 48-h leading up to the tests. All lab visits were completed at the same time of the day (± 1 h).

After a 5 min warm-up at 8 kmh^{-1} and a short break, the first 2 min stage of the incremental running test started at 8 kmh^{-1}. Hereafter, the treadmill velocity was increased by 1 kmh^{-1} every 2 min until participants reached volitional exhaustion or when at least two of the following criteria were met: 1) heart rate (HR) $\geq$ 90% of the age-predicted maximum; 2) respiratory exchange ratio ≥ 1.10; 3) stable $\dot{V}O_2$ despite increased intensity (212). $\dot{V}O_2$max was defined as the highest average $\dot{V}O_2$ over a 30 s period. HRmax was defined as the highest HR value obtained by the end of the test. MAV was defined as the highest velocity that could be maintained for a complete stage, or, as the velocity of the last complete stage added to the completed fraction of an incomplete stage.

After a brief (10 min) passive recovery period, participants commenced the time to exhaustion test on the treadmill, with the treadmill velocity set equal to MAV. Participants were instructed to run as long as possible on this velocity, without any feedback on elapsed time. The test was terminated when the participants jumped on the side-border of the moving treadmill belt. MAV attained in baseline testing was also used in the post intervention time to exhaustion test.

8.2.3 High intensity interval training session of 1MIN and 3MIN

Participants in 1MIN and 3MIN performed five HIIT sessions, comprising six 4 min work intervals, separated by either 1 min or 3 min passive recovery. The exercise intensity for the work intervals was fixed at a running velocity of 90% MAV. Sessions were run on an outdoor grass pitch, on which a 4 x 50 m grid was set out with marking cones every 10 m. Weather conditions were stable during the HIIT sessions, with an average temperature of 17-19 ºC.

Prior to every HIIT, participants were instructed individually on the distance to cover per 1 min segment, and complete 4 min work interval (calculated from 90% MAV, varying between 720 m and 970 m). All participants were fitted with a HR watch, allowing for HR monitoring, providing feedback on elapsed time in work and recovery intervals and further aiding in pacing cues. Throughout the work intervals, the principal investigator and the head coach of the collegiate rugby team provided feedback to the participants every minute regarding their progress in the work intervals to further ensure exercise intensities were maintained at 90% MAV. Both the principle investigator and the head coach were situated in the middle of the 4 x 50 m grid and were both equipped with a handout, specifying the distance to cover per 1 min segment for all participants. To avoid clustering and potential benefits of drafting (283), participants started their session in 30 s staggered intervals. Further, the HIIT was performed by 9 participants at a time, made up from both 1MIN and 3MIN training groups. In the recovery intervals, participants walked / jogged back to the starting point. At the starting point, water was available *ad libitum.*

8.2.4 Data collection and analysis

During the incremental running test, HR was measured at 1 Hz using a Garmin HR monitor (910XT, Garmin Ltd., Schaffhausen, Switzerland), and expired air was analysed continuously for O_2 and CO_2 concentrations using open circuit spirometry (Oxycon Pro, Jaeger, Höchberg, Germany). Before each experimental trial, the gas analyser and turbine flow meter were calibrated following the manufacturer's instructions.

HR in the HIIT sessions was monitored continuously, using a Polar HR monitor (RCX5, Polar Electro, Kempele, Finland). The physiological responses to the HIIT sessions were indexed for HRmax, and time ≥ 90% HRmax (*t*90HRmax) during the work intervals was calculated. Ratings of perceived exertion (RPE) were obtained on the 6-20 Borg Scale (80) on completion of every work interval. Session RPE (sRPE, (267)) was obtained 30 min after completion of the training session based on the question 'How hard was your workout?'. The physiological and perceptual responses were collected in all intervals of every HIIT session.

8.2.5 Statistical analysis

All data were analysed using SPSS 25.0 (SPSS Inc., Chicago, USA), and are presented as means ± SD. Participant characteristics of the three training groups, and differences in perceptual and HR response to the HIIT sessions of 1MIN and 3MIN were compared using one way analysis of variance (ANOVA). The effect of the intervention on the physiological capacity ($\dot{V}O_2$max), and performance (MAV and time to exhaustion) were evaluated using a 3 x 2 (training group * time) repeated measures ANOVA. *Post hoc* Bonferroni pairwise comparisons were used to show differences between experimental groups where appropriate. The significance level of all tests was set at $p < 0.05$. Standardized effect sizes (ES) are reported as Cohen's d. Qualitative interpretation of d was based on the guidelines provided by Hopkins et al. (151): < 0.2 trivial; 0.20 – 0.59 small; 0.6 – 1.19 moderate; 1.20 – 1.99 large.

8.3 Results

8.3.1 Acute responses to HIIT sessions in 1MIN and 3MIN

Table 8.2 presents the psychophysiological responses to the five HIIT sessions for both 1MIN and 3MIN. Work intervals started from a significantly elevated heart rate in 1MIN (82.8 ± 1.7 %HRmax) compared with 3MIN (62.5 ± 3.5 HRmax; $p < 0.05$). The average heart rate during the work intervals was moderately higher in 1MN, however, not significantly different compared with 3MIN (1MIN: 91.5 ± 2.0 %HRmax vs 3MIN: 89.3 ± 2.7 %HRmax, $p = 0.07$). The heart rate achieved during the last min in the work intervals (1MIN: 95.3 ± 1.8 %HRmax vs 3MIN: 94.2 ± 2.0 %HRmax, $p = 0.26$) and the time ≥ 90% HRmax in the HIIT sessions was similar between 1MIN and 3MIN ($p = 0.87$).

RPE scores were significantly higher in 1MIN after completion of the sixth work interval in the HIIT sessions ($p < 0.05$), however, no differences were detected in the overall session RPE between 1MIN and 3MIN ($p = 0.26$, see **Table 8.2**).

Table 8.2: Heart rate and Perceptual Responses to HIIT protocols in 1MIN and 3MIN

	Training Group		
	1MIN	3MIN	ES
Heart rate			
30-s Baseline (%HRmax)	82.8 ± 1.7[a]	62.5 ± 3.5	7.30
4-min Interval (%HRmax)	91.5 ± 2.0	89.3 ± 2.7	0.93
Final min (%HRmax)	95.3 ± 1.8	94.2 ± 2.0	0.56
*t*90HRmax (sec)	929 ± 229	913 ± 186	0.08
Ratings of perceived exertion			
RPE at the end of protocols (au)	17.2 ± 1.5[b]	15.5 ± 1.2	1.29
session RPE (au)	7.6 ± 1.4	6.7 ± 1.4	0.55

[a] $p < 0.01$, [b] $p < 0.05$

Note; ES: effect size, HRmax: maximum heart rate, *t*90HRmax: time ≥ 90% HRmax, RPE: ratings of perceived exertion, au: arbitrary unit

8.3.2 Changes in physiological capacity and performance

Participants were matched on absolute $\dot{V}O_2$max, and accordingly did not differ on this variable. Further, no differences with regards to age, height, body mass, and performance parameters were evident between the training groups before the pre-season training period. All participants completed the training intervention, with no changes in body mass. Repeated measures ANOVA showed no significant interaction effects on $\dot{V}O_2$max, MAV and TTE (see **Table 8.3**). The improvement of $\dot{V}O_2$max was of a large magnitude in 1MIN (3.72%, ES = 1.54), in contrast to the small improvement in 3MIN (2.98%, ES = 0.52), and trivial improvement in CON (0.41%, ES = 0.14). Whilst not being statistically different, all training groups improved their performance on the TTE test, with the changes in 1MIN (24 ± 33 s) and 3MIN (29 ± 35 s) being both of a moderate magnitude – whereas the increased TTE in CON was only small (7 ± 32 s).

Table 8.3: Changes in physiological and performance parameters over the pre-season period

	1MIN		3MIN		CON		
	pre-test	post-test	pre-test	post-test	pre-test	post-test	(group*time) *P* value
$\dot{V}O_2max$ (L·min^{-1})	4.20 ± 0.32	4.35 ± 0.35	4.14 ± 0.31	4.26 ± 0.41	4.11 ± 0.29	4.13 ± 0.31	0.254
MAV (km·h^{-1})	13.9 ± 0.8	14.1 ± 1.0	13.9 ± 1.2	14.2 ± 1.2	14.0 ± 1.1	14.1 ± 0.7	0.920
TTE (s)	180 ± 31	204 ± 44	193 ± 73	222 ± 64	205 ± 68	213 ± 74	0.442

Note; $\dot{V}O_2max$: maximum oxygen uptake, MAV, maximum aerobic velocity, TTE: time to exhaustion

8.4 Discussion

In this study, we evaluated the moderating role of the recovery interval duration in HIIT protocols in the context of a pre-season conditioning period of collegiate rugby players. Participants completed a 3-week training program prescribed by the club, without HIIT (CON), or with an additional five extra HIIT sessions, that comprised six 4 min work intervals, interspersed by either 1 min (1MIN) or 3 min passive recovery (3MIN). When interspersed with only 1 min recovery, HIIT sessions were perceived more exerting, however, the physiological strain was similar in the protocols of 1MIN and 3MIN, with ~65% of the exercise time spent ≥ 90% HRmax. $\dot{V}O_2$max, MAV and time to exhaustion improved to a similar extent in both 1MIN and 3MIN, suggesting that the duration of the recovery intervals in HIIT sessions, run on fixed exercise intensities, does not affect the magnitude of changes in these variables.

Pre-season conditioning periods allow for a structured period of physiological, technical and tactical overloading, and as the planning of training sessions in this period is not interfered by competitive match-play, strong foundations are laid for the upcoming season. Classically, conditioning for rugby players only has a small to moderate emphasis on improvements in aerobic fitness, highlighted by the trivial improvements in $\dot{V}O_2$max of CON. The addition of just 2 hours of generic HIIT resulted in improvements in $\dot{V}O_2$max in 1MIN (3.72%) and 3MIN (2.98%), in line with improvements of other HIIT interventions of a similar configuration and total duration (see **Table 3.1**, (63,67,182,284)). Rugby players are a-typical participants in running based HIIT interventions, but comparable to the body composition of the participants in the current study (height and body mass), Czuba et al. (182) reported similar improvements (+0.12 $L \cdot min^{-1}$, +2.8%) in well trained male basketball players. As 1MIN and 3MIN performed their HIIT on days with no planned gym sessions, we consider this study not to perform 'concurrent training' in its traditional form (142). The improvements in aerobic capacity are of a similar magnitude to studies that did evaluate 6 - 8 weeks of concurrent resistance training and SIT or RST in rugby players (285,286). The results of the current study might indicate that separating days of aerobic conditioning and resistance training elicits faster improvements in $\dot{V}O_2$max, as concurrent training seems to blunt or postpone adaptations (285,286).

HIIT is by no means a new phenomenon, but instead a training concept long-appreciated by athletes and coaches, from as early as the 1930s (47), and previously, manipulations in the exercise intensity and / or duration of work intervals showed to significantly influence $t90\dot{V}O_2max$ (20,33,34,36). The internal training load, that is the disturbance in homeostasis of the physiological (e.g. cardiovascular, respiratory and metabolic) and psychological processes provoked by a training session, is considered the most important feature of a training session and the primary stimulus to adaptations in endurance performance (282). In an attempt to increase the internal load (expressed as *t*90HRmax), we added two 4 min work intervals to the classic *'Norwegian HIIT protocol'* introduced by Helgerud et al. (69). This protocol has been shown to effectively improve aerobic fitness in numerous studies (e.g. (69,70)), whilst analysis of the acute physiological responses to this protocol show athletes only spent 6 to 8 min per session at or above 90% HRmax and $\dot{V}O_2max$ (41,75). We now show that an extra two 4 min work intervals can be added to this protocol safely, and in doing so, firstly the high intensity exercise time is increased to 24 min, and secondly, *t*90HRmax in the current study (1MIN: 929 ± 229 s, 3MIN: 913 ± 186 s) was almost double the time that was found in the evaluation the classic *'Norwegian HIIT protocol'* (481 ± 221 s, (41)). All participants completed every planned work interval, an indicator of sufficient recovery time between subsequent bouts in both training groups. 1MIN rated their perceived exertion after the final work interval significantly higher than 3MIN, however, from a time-efficiency point of view, we further show that 1 min recovery between work intervals is sufficient in this HIIT configuration.

Smilios et al. (41) provided a first insight how perceptual and physiological responses differ in matched intensity HIIT sessions, when only recovery interval durations are manipulated. In their study, recreationally trained male runners executed, on 3 separate sessions, four 4 min runs at 90% MAV interspersed by 2, 3 or 4 min recovery intervals. In agreement with these findings, intervals in the current study started from a significantly elevated heart rate when the recovery duration was shortest, whereas the average heart rate during the complete 4 min interval, and the last min of the work intervals was not different between protocols. Smilios et al. (41) reported that participants spent ~140 s less in *t*90HRmax when recovery durations increased from 2 min to 4 min, however, the 2 min longer recovery interval of 3MIN in the current study did not result in a lower *t*90HRmax compared to 1MIN. A likely explanation for this difference is the fact that HIIT sessions in the current study were performed on an outdoor grass pitch (255,256), compared to the treadmill based HIIT sessions evaluated by Smilios et al. (41). Running on treadmills yields lower physiological responses than overground running, in both continuous (213) and interval running protocols (255,256), and to create the same physiological response during treadmill and outdoor runs, an increase in treadmill gradient or running velocity is advised (213,255).

Participants in both 1MIN and 3MIN performed ~65% of their exercise time in the 24 min HIIT protocols above 90% HRmax, and whilst heart rate measures might not be the most valid measure of the physiological load of a HIIT session (41,104), these results indicate the physiological stimuli in 1MIN and 3MIN were of similar magnitude. Our results thereby confirm the previously reported findings in cyclists (21,46), that when HIIT protocols are matched for total training volume and work intensities, no differences in improvements are to be expexted because of differences in recovery intreval durations. Metabolically, through the use of muscle biopsy sampling, Edge et al. (46) evidenced that changes in muscle metabolites (specifically phosphocreatine, lactate and hydrogen ions) were larger when recovery intervals were shorter (1 min vs 3 min) in an interval sequence of six 2 min work intervals. These larger perturbations did not yield greater improvements in $\dot{V}O_2$max, and were therefore not considered a crucial factor in regulating adaptations of the contracting muscle (46). While heart rate kinetics were not assessed in this current study *per se*, the profile of the obtained heart rate variables (30 s baseline, average heart rate final min) and the comparable *t*90HRmax in both 1MIN and 3MIN, indicate a faster mean response time and increased absolute amplitude in 3MIN (41,104,261). As these differences in the kinetical on-phase did not affect the magnitude of change in $\dot{V}O_2$max in 1MIN and 3MIN, data of the current study suggest that these variables do not act as a strong enough moderating factor to differentiate improvements in work and intensity matched HIIT protocols.

With this study, we are the first to demonstrate that physiological and performance adaptations were not altered differently in collegiate rugby players after a running based HIIT intervention, when protocols only differed in the recovery interval duration. To isolate, and solely study the potential moderating role of the recovery interval duration, it was important to further match the protocols of 1MIN and 3MIN (54). Previously, we and others argued that athletes pace their effort in HIIT sessions on RPE and feelings of accumulated fatigue (104,268), rather than adhering to predefined work intensities. Adopting this self-paced approach, as we discussed in **Chapter 6** and **Chapter 7**, longer recovery intervals in a six 4 min HIIT session facilitated higher exercise intensities in subsequent work intervals (higher running velocities in runners, higher power outputs in cyclists), whilst maintaining a similar physiological stimulus ($t90\dot{V}O_2max$ and $t90HRmax$). In **Chapter 6,** recreationally trained runners rated their final interval a RPE score of 19 ± 0.7 when they received 3 min recovery, whereas 3MIN in the current study rated their final interval with a RPE score of only 15.5 ± 1.2. This might indicate that participants in 3MIN were restricted by the fixed exercise intensities and could have run faster in their work intervals when allowed, which in turn may have generated greater training adaptations.

Self-paced SIT and AIT interventions have been shown effective to improve $\dot{V}O_2max$ and performance parameters in cyclist (42,218), and recently, a self-paced running SIT intervention (involving 10 sessions of 6 to 8 all-out 30 s sprints) significantly improved $\dot{V}O_2max$ and time to exhaustion in adolescent Taekwondo athletes (287). The improvements in $\dot{V}O_2max$ of these Taekwondo athletes were greater when sprints were separated by 120 s, compared to 60 s or 240 s recovery intervals, which for the first time does show a moderating role of the recovery duration (287). Unfortunately, the physiological strain nor the running velocities of the different training groups were reported (287), and therefore it remains unanswered if a higher external training load (higher running velocity) can trigger larger adaptations. Whether self-paced AIT interventions improve aerobic fitness and performance more than the classic fixed HIIT interventions is unknown and leaves room for exploration in future studies.

8.5 Practical applications

Classically, conditioning for rugby players only has a small to moderate emphasis on improvements in aerobic fitness. The addition of five generic HIIT sessions (comprising six 4 min intervals, run at 90% MAV per session) in pre-season conditioning periods of collegiate rugby players resulted in improvements in $\dot{V}O_2max$ and increased time to exhaustion. Using short recovery intervals (1MIN) during this HIIT protocol does not offer any advantage (and even negatively, results in higher ratings of perceived exertion) over the use of longer recovery intervals (3MIN) when training intensity and volume are matched. Generic

HIIT is not there to replace SSGs, but can offer an additional stimulus to the aerobic capacity of rugby players over a very short period.

Chapter 9:

General Discussion

9.1 General discussion

High intensity interval training (HIIT) is an indispensable constitute of successful training programs of many athletes, historically, particularly for those involved in endurance sports (13,14,47). For team sport athletes, small-sided games (SSGs) are typically used to target endurance adaptations and simultaneously develop technical and tactical skills, however, HIIT has become an increasingly popular, safe and effective alternative to SSGs (69,183,288). Based on the duration and exercise intensities of work intervals, HIIT can be divided in to three subcategories: repeated sprint training (RST), sprint interval training (SIT) and aerobic interval training (AIT), each targeting different physiological, neuromuscular and mechanical adaptations (14).

In this thesis, we evaluated the potential moderating role of the recovery duration between subsequent work intervals in AIT sessions. AIT incorporates repeated long work intervals (up to 16 min), performed at undeniably high, but ultimately submaximal work intensities (54). The intermittent format of AIT sessions allow athletes to exercise longer at these vigorous exercise intensities than can be achieved during a single bout of continuous exercise at this intensity (15,17,18). In the context of a pre-season conditioning period of collegiate rugby players, we showed in **Chapter 8** that short recovery intervals (1 min) did not offer any advantage over the use of longer recovery intervals (3 min) in volume and intensity matched AIT protocols. We are the first to evidence these findings after a running based AIT intervention, and these results are in line with previous findings after AIT interventions in cyclists, when AIT protocols only differed in the recovery interval duration (21,46).

Deviating from predefining fixed exercise intensities in work intervals, the results of this thesis further indicate that in self-paced AIT protocols (incorporating six 4 min work intervals), the duration of recovery intervals (1 min, 2 min, 3 min or a self-selected recovery duration) had a limited effect on the physiological stimulus of the training session in runners and cyclists (see **Chapter 6** and **Chapter 7**). However, in both runners and cyclists, exercise intensities (running velocity and power output, respectively) were markedly higher when participants received 3 min recovery between subsequent work intervals, and higher when participants self-selected their recovery durations compared to 1 min recovery intervals. Training on higher work intensities as a result of longer or self-selected recovery intervals may allow for greater adaptations in maximum oxygen uptake ($\dot{V}O_2$max), maximum work capacity and / or performance; potentially differentiating from improvements shown after volume and intensity matched AIT protocols.

The workload of AIT sessions is determined by a complex interplay between the number of intervals, the exercise intensities and the duration of both the work and recovery intervals (16,17). Thevenet et al. (55) suggested that the effectiveness of AIT protocols can be expressed as the time athletes spent at, or close, to their $\dot{V}O_2$max per session ($\geq$ 90% $\dot{V}O_2$max; $t90\dot{V}O_2$max), under the assumption that a higher $t90\dot{V}O_2$max per session will allow for greater training adaptations (55,282). In **Chapter 3**, we were the first to solely summarize and meta-analyse changes in $\dot{V}O_2$max and performance in over 80 unique AIT protocols, and, irrespective of the widely differing configurations of these protocols (see **Table 3.1** and **Table 3.2**), the results indicated that the majority yielded improvements in $\dot{V}O_2$max and / or performance (see **Figure 3.3** and **Figure 3.13**). Across the included studies, improvements in $\dot{V}O_2$max were of a small to moderate magnitude (Hedges' g = 0.54, 95% CI [0.38 to 0.69]), which corresponds to an average increase of 3.07 mL·kg·min^{-1}. Improvements in performance were of a similar magnitude (Hedges' g = -0.52, 95% CI [-0.78 to -0.26]), averaging a decrease in performance time of -4.0%. The average improvements in $\dot{V}O_2$max presented in **Chapter 3** are of a similar magnitude as previously reported in meta-analysis examining HIIT (30,140,197) and SIT interventions (152,198–200). Our results further suggest that AIT improved $\dot{V}O_2$max and performance significantly more than moderate intensity continuous training, and whilst the underlying mechanisms of adaptations may differ, improved $\dot{V}O_2$max to a similar extent as SIT. The highly homogenous improvements in $\dot{V}O_2$max and performance can make believe that attempts to optimize AIT protocols to further increase $t90\dot{V}O_2$max are needless, however, multiple research groups showed that manipulations in work intensities (33,34,55,289,290), work durations (20,22,35–37,291), recovery intensities (38,292), pacing strategies (39), and even the use of muscle vibration in cyclists (40) positively influenced $t90\dot{V}O_2$max per AIT sessions.

Surprisingly little research explored the overall impact of the duration of recovery intervals in HIIT in general, and in AIT sessions specifically (see **Table 2.1**). Smilios et al. (41) were the first to examine how $t90\dot{V}O_2$max was influenced by an increase in recovery duration between four 4 min intervals, ran at 90% maximal aerobic velocity (MAV). The results indicated that the recovery duration did not affect the percentage of $\dot{V}O_2$max attained in the work intervals, nor the total $t90\dot{V}O_2$max per session. While informative, these results are a prime example of most published data, as the authors evaluated the acute physiological, metabolic and perceptual responses to an AIT protocol that incorporated predefined work intensities (41). In this thesis we diverted from the use of fixed exercise intensities in the work intervals of AIT sessions, but rather examined the acute physiological and perceptual responses in self-paced AIT sessions. Performed under '*isoeffort'* conditions (participants in **Chapter 6** and **Chapter 7** were instructed to approach every experimental visit as a hard training sessions, and perform each work interval across the AIT sessions at their maximal sustainable exercise intensity), the actual exercise intensity per work interval is not a stable function of velocity or power output over time, but rather the integrative outcome of feedback from external and internal receptors, and knowledge of the session demands (43,44). The use of '*isoeffort'* intervals shifts the decision making on work intensities to the participant, as it rests upon the notion that athletes know how to train hard when they are required to 'train hard' (42).While new to this approach, participants in both **Chapter 6** and **Chapter 7** successfully paced their efforts across the six work intervals of the AIT sessions, with only subtle variations in the self-selected exercise intensities over the work intervals. After completing the final work interval, participants rated their perceived exertion (RPE) ≈ 19 on the classic Borg scale (80), fulfilling the instruction to complete the simulated AIT sessions on a RPE ≥ 17.

The *'isoeffort'* approach allowed for the evaluation of the trade-off between the internal (the physiological stimulus, i.a. $t90\dot{V}O_2$max) and external training load (i.e. running velocity / power output) of AIT sessions. We hypothesized that short recovery intervals would maximize the physiological stimulus of an AIT session, as work intervals will start from an elevated $\dot{V}O_2$, theoretically decreasing the time needed to reach high levels of $\dot{V}O_2$ in subsequent work intervals. Long recovery intervals on the other hand were expected to lower the $\dot{V}O_2$ at the start of subsequent intervals, potentially decreasing the total exercise time performed in the 'red zone'. Longer recovery intervals provide more time for the replenishment of energy substrates and the breakdown of accumulated metabolites, which may delay the onset of fatigue and we expected this would allow athletes to achieve higher work intensities throughout the work intervals. In line with our hypothesis, work intervals did start from an elevated metabolic rate in both runners and cyclists when only 1 min recovery intervals were available between six 4 min work intervals. Contrary to our expectations, long recovery intervals (3 min) in these simulated AIT sessions did not attenuate the mean $\dot{V}O_2$ attained during the complete intervals, or final minute of the work intervals across the different protocols and no significant differences were evident in $t90\dot{V}O_2max$. To the best of our knowledge, we are the first to show that in these self-paced AIT sessions, longer recovery intervals facilitated athletes to train on higher work intensities. These findings suggest that athletes can recover for a greater period in AIT sessions than may be traditionally thought, without compromising the metabolic load.

AIT sessions primarily target improvements in aerobic capacity and / or endurance performance, and we believe the results have general relevance to other AIT protocols incorporating intervals of a similar duration (1 – 8 min). We only examined the physiological responses in runners and cyclists, however, we expect that the extent of the results transfer to other endurance based sports like cross country skiing, rowing and swimming. Only one study examined the role of recovery durations in an exercise modality other than running or cycling (see **Table 2.1**), namely swimming (165). In agreement with the main findings of the current thesis, the results of Tsekouras et al. (165) revealed a compromised performance in 30 s high-intensity tethered swimming bouts when recovery durations were shortened from 2 min to 45 s. As discussed in **Chapter 2**, longer recovery intervals (≥ 80 s) in RST and SIT protocols likely facilitate higher work intensities in subsequent sprints, whereas shorter recovery durations in these protocols increase the overall physiological stimulus of RST and SIT sessions (114,115). Contrary to this trade-off found in RST and SIT, we found no (significant) differences in the physiological stimulus in self-paced AIT sessions after increasing the recovery intervals. In resistance training, Ibbott et al. (293) recently showed that longer inter-set recovery improved the power output of consecutive squats. The training objectives and adaptations of resistance training obviously differ from HIIT protocols, however, the main concept of longer recovery intervals to train on higher work intervals might be applicable for other intermittent training forms. The duration of recovery intervals is an important moderator of acute responses in intermittent exercise protocols, and coaches can manipulate its duration to target specific training goals. That is, if coaches want to focus on maximizing running speed, they can decide to incorporate longer recovery intervals between bouts.

Modern day cycling ergometers, like the Velotron Dynafit Pro (Racermate Inc., Seattle, USA) used in **Chapter 7**, reproduce the power-speed relationship (power output = constant · speed $^{2.4}$) for flat road cycling. It follows that a 1% change in speed requires a 2.4% change in power output (294). This characteristic, and the highly reliable measures of power output by the Velotron Dynafit Pro (263,264), enable a valid assessment of self-paced cycling performance in lab setting. To assess running performance, motorized treadmills are an indispensable piece of laboratory equipment, however, they do not allow to study the quick, unconscious and frequent adjustments in running velocities that occur during self-paced exercise (45).

In **Chapter 4 – Chapter 6**¸ we evaluated and then used a commercially available curved non-motorized treadmill (cNMT; Woodway Curve XL, Woodway Inc, Waukesha, USA) to study self-paced running performance. On the cNMT, contrary to other non-motorized treadmills, participants are not required to wear a harness, thus permitting unrestricted movements. The concave belt design further allows runners to accelerate or decelerate with every treadmill contact, using similar techniques to overground running. Previously, Smoliga et al. (230) compared the physiological demands of walking and running on the cNMT to those of a motorized treadmill (MT). In **Chapter 4** we extended these findings to a range of (higher) running velocities and identified the approximate running velocity that elicits an exercise intensity ≥ 90% $\dot{V}O_2max$ on both the cNMT and MT. Additionally, in **Chapter 5**, we evaluated which MT gradient best replicated the curved concave surface of the cNMT to substantiate the observational analysis of Smoliga et al. (230). Running on the cNMT resulted in higher physiological, calorific and perceptual responses compared to running on the MT at any given velocity, accompanied by a decreased running economy. In line with previous studies, a markedly lower running velocity on the cNMT generated a similar physiological stimulus as the MT (215,219,230,247), evidencing that exercise prescriptions appropriate for overground or MT running may not be achievable on the cNMT. These results are best explained by both the high mechanical resistance of the rubber treadmill belt (229), and the 6 – 8% gradient presented by the curved design of the cNMT (see **Chapter 5**). Running on the cNMT therefore better mimics uphill running, and if an individual aims to train on both the cNMT and MT or if they are prescribed speeds for a workout, it is prudent to adjust target speeds for the cNMT.

The results of **Chapter 4** indicate that the cNMT can be used to truly evaluate self-paced running performance and HIIT, in comparison to previous studies in which participants ran on a MT and the velocity could only be increased or decreased via a hand signal to the test administrator controlling the MT (22,77,93). Apart from an increased confidence in running on the cNMT (all participants were able to run without holding the barriers of the cNMT), surprisingly, no differences in any of the physiological and perceptual responses were evident after a familiarization session. Given the novelty of running on the cNMT, we do however recommend at least one familiarization session, and if participants are required to perform any form of intense exercise on the cNMT – a trial run mimicking the actual experimental protocol is advised alike the 4 min trial run we included in **Chapter 6** prior to the experimental visits. Participants in **Chapter 6** were instructed (but not restricted) to target a velocity of 65% MAV in their first interval, which based on the findings of **Chapter 4** would result in an exercise intensity of 92.5% $\dot{V}O_2$max (246). We opted for this preventive instruction to avoid poor pacing in the initial stage of the simulated AIT sessions, and to avoid premature fatigue due participants ‘chasing running speeds’ they are accustomed to from overground or MT running. Together with a familiarization session, we believe this preventive instruction is imperative for a successful completion of (interval) running protocols on the cNMT. Based on the results of **Chapter 4**, a reduction in running velocity from overground or MT speeds of 20% is advisable when athletes want to generate a comparable physiological stimulus to overground or MT running. This dissociation between running speeds achieved on the cNMT and high exercise intensities open new avenues for research, for instance in the evaluation of 1) pacing and decision making behaviour in time trial settings, and 2) deceptive feedback on performance. Deceptive feedback was found to improve cycling time trial performance previously (295,296), however, no studies have evaluated or examined this potential moderator of performance in runners.

With regard to the perceptual responses during the self-paced AIT sessions, the results of **Chapter 6** and **Chapter 7** show a relatively uniform response with the linear increase in RPE throughout the interval sessions, independent of the recovery interval duration. In line with other studies, participants were able to maintain relatively constant exercise intensities over repeated work bouts (see **Table 6.1** and **Chapter 7** (**Section 7.3**)) despite the perceived effort of achieving these work intensities increased from bout to bout (77,93). In the recovery intervals of all simulated AIT sessions in **Chapter 6** and **Chapter 7**, participants scored their perceived readiness (PR) to recommence subsequent work intervals. Participants' progressively increased their recovery duration over the work intervals, highlighting an increased demand in recovery time to compensate for the accumulated fatigue. Using the PR scale to self-select recovery durations resulted in stable pacing profiles of work intensities, with the difference between the fastest and slowest work interval being only 0.53 ± 0.3 $\text{km}\cdot\text{h}^{-1}$ in **Chapter 6**, and a decrease in power output of only 5% between the initial and final work interval in **Chapter 7**. Despite removing all possible timing clues, participants may have felt pressure to commence the next work interval prior to feeling completely recovered due to their habitual training practices, or the lack of familiarization with the actual use of the PR scale in AIT sessions. We decided against a familiarization session for the self-selected trials in **Chapter 6** and **Chapter 7**, as the initial study using the PR scale reported great variability (coefficient of variation = 28%) in the test-retest reproducibility of the self-selected recovery durations (101). The chosen recovery durations are likely influenced by the training status and day to day variations in an individual athlete's self-selected recovery durations and may reflect fluctuations in daily well-being. Future studies should explore this further.

In this thesis, only the actual self-selected recovery times are presented without any further analysis of PR in other protocols with fixed work durations, nor did we examine if the perceived 'adequate recovery' coincided with potential physiological demarcation points. Previous data from Edwards et al. (101) suggested that PR is as accurate as heart rate recovery or traditional work-to-recovery recommendations, however, Laurent et al. (93) showed a limited variation in PR scores when recovery durations increased from 1 min to 2 min to 4 min in a self-paced AIT session. These results reveal that individuals seem to adjust physiological and metabolic strain in such a manner that perceptual strain during *and* between intervals is stable. Interestingly, McEwan et al. (103) conducted a semi-structured interview to assess participants' training goals as well as the internal / external cues utilised during the decision-making process to start subsequent work intervals, after participants completed a SIT protocol in which they self-selected recovery durations between repeated 30 s sprints. Participants were found to use a range of afferent feedback cues, amongst these, the stabilisation of respiratory rate and the magnitude of the drop in heart rate occurring between intervals were commonly mentioned as being pivotal in determining the length of recovery (103). These findings strengthen the recently suggested notion that breathing frequency is a strong marker of physical effort (297). Next to a further analysis of the cardiorespiratory data collected in the current thesis that coincided with the starting point of work intervals, the inclusion of a semi-structured interview in future studies using the PR scale may provide valuable insights in the decision making processes involved.

9.2 Thesis limitations

Several limitations in this thesis relate to participant recruitment. Firstly, participants in all studies were male athletes, adding to the already gender biased results presented in **Chapter 3**, and how the main findings of this thesis translate to female athletes is therefore questionable. Only male participants were recruited to control for the possible effects of hormonal status on performance (298,299), nonetheless, the results of this thesis are highly relevant and of interest to female athletes. The possibility of sex differences in physiological and perceptual response is not well understood with studies yielding equivocal results (300,301), however, recent studies show that women may demonstrate higher resistance to fatigue and / or improved recovery during bouts of repeated exercise (302–305). Laurent et al. (93) showed that both perceived readiness and perception of effort during high-intensity bouts are stable within-sex, but may occur at different relative points between men and women. That is, women may incur greater cardiovascular and / or metabolic strain at a similar level of perceptive strain than men. To gain a better understanding of these potential differences, future research should replicate the studies of **Chapter 6** and **Chapter 7** in women.

Secondly, participants in **Chapter 4, Chapter 6** and **Chapter 7** were recruited based on their performance level and previous experience with HIIT, as it was expected that trained participants would likely be more attuned to internal pacing cues and be able to maintain high workloads throughout interval sessions. These inclusion criteria resulted in stable and valid comparative measures in **Chapter 4**, and all participants were able to complete the simulated AIT protocols in **Chapter 6** and **Chapter 7**. This recruitment strategy however also resulted in large variations in participants' age, contrary to the highly homogenous participant groups in **Chapter 5** and **Chapter 8**.

Finally, no information on participants' dietary habits was collected, and we did not control the diet of the participants in any of the studies. All participants were instructed to consume their normal diet and consume their last meal ≥ 3 h before experimental visits. While fasting status was not confirmed with blood testing, had participants consumed a high carbohydrate meal shortly before the experimental visits in **Chapter 4 - Chapter 7**, this would have had the tendency to decrease the contribution of lipid oxidation to meet the energy demands in these sessions, – potentially influencing the respiratory exchange ratio (135,306). New findings suggest that changes in substrate utilization are likely in high intensity exercise when participants alter their habitual diet to a very low-carbohydrate high-fat diet (208,306). To control for the potential moderating effect of dietary intake, in future studies, it is advised to track habitual food intake during AIT interventions.

A methodological concern in this thesis is the absence of verification test for $\dot{V}O_2$max measures. In this thesis we refer to the maximum oxygen uptake of the participants as $\dot{V}O_2$max, however, none of the conducted studies in this thesis incorporated a verification test protocol to unambiguously validate $\dot{V}O_2$max, by the assessment of a $\dot{V}O_2$ plateau (212). $\dot{V}O_2$max values of exercise test naïve or less motivated participants may more likely represent a measure of $\dot{V}O_2$peak (simply the highest $\dot{V}O_2$ reached on a given test), and verification protocols are advised (212). Given the training status and experience level of the included participants, we expect that values reported for $\dot{V}O_2$max are very similar to $\dot{V}O_2$peak. Respiratory data was analysed to assess the attainment of a $\dot{V}O_2$ plateau, and when no plateau was evident, $\dot{V}O_2$max was only confirmed when a multitude of secondary criteria for $\dot{V}O_2$max were achieved. This was the case in all incremental exercise tests conducted in this thesis. By study design, $\dot{V}O_2$ and HR measures in **Chapter 4** and **Chapter 6** were indexed for $\dot{V}O_2$max and HRmax values obtained in incremental running tests performed on a MT. When $\dot{V}O_2$max is measured, it is well accepted that the value attained varies with the type of exercise performed and can be further influenced by the selected test protocols. Running on NMTs and MT is markedly different, as running on a NMT requires participants to actively generate power to move themselves vertically and to propel the treadmill belt, which may in turn elicit a larger

$\dot{V}O_2$. Previously, a self-paced incremental running test performed on a flat NMT (Force 3.0, Woodway USA Inc., Waukesha, Wisconsin, USA), produced higher $\dot{V}O_2$max values than a standard incremental running test performed on a MT (244). Comparing self-paced test protocols between the cNMT used in this thesis and a MT, Morgan et al. (219) however found no differences in maximum $\dot{V}O_2$ and heart rate achieved in these tests, indicating that obtained measures of $\dot{V}O_2$max are seemingly similar.

9.3 Future research directions

We are the first to show that in self-paced AIT sessions, longer recovery intervals facilitate higher external workloads (faster running / higher power output), whilst the internal training load (physiological stimulus) was unchanged after manipulations in the recovery duration between subsequent work intervals. Self-paced SIT and AIT interventions have been shown effective to improve $\dot{V}O_2$max and performance parameters in cyclists (42,218), and recently, a self-paced running SIT intervention (involving 10 sessions of 6 to 8 all-out 30 s sprints) significantly improved $\dot{V}O_2$max and time to exhaustion in adolescent Taekwondo athletes (287). In this study, the authors also evaluated the role of recovery durations between the sprint intervals, and found that improvements in $\dot{V}O_2$max were greater when sprints were separated by 120 s, compared to 60 s or 240 s recovery intervals (287). Unfortunately, the physiological strain or running velocities of the different training groups were not reported, and therefore it remains unanswered if a higher external training load (higher running velocity) triggered these larger adaptations. Notably, these results are in disagreement with the suggestion of Kavaliauskas et al. (115), who hypothesized that the aerobic demand in sprints separated by 120 s recovery would be too low to induce endurance adaptations and 80 s recovery between sprints would be most beneficial to target both power and endurance adaptations (see **Chapter 2** (**Section 2.4**)). Whether running based self-paced AIT interventions improve aerobic fitness and performance, and if these improvements are larger compared to classic (fixed) AIT interventions is unknown and leaves room for exploration in future studies.

Historically, training studies have been designed around the evaluation of structured training interventions (see **Table 3.1** and **Table 3.2**). These specified training interventions have underpinned our understanding of training, and allows for the evaluation of dose-response relationships between training load and training adaptations. Most training interventions summarized in **Chapter 3** are undertaken in lab settings, and depending on the exercise modality, performed on cycling ergometers or motorized treadmills. We previously described the methodological concerns that accompany the use of MTs in self-paced AIT, and recommend any future studies exploring the potential beneficial effect of self-paced sessions to AIT be undertaken on NMTs, 'smartly used' MTs, or in field based interventions. The results presented in **Chapter 4** and **Chapter 5** confirm that the cNMT used in this thesis allows for self-paced AIT, however, the availability of this treadmill might be limited for athletes and scientists. Previously, Hogg et al. (307) introduced a 'zonal system', which required participants to move between marked zones on a MT (front / middle / back section) when they wanted to increase, maintain or decrease the running speed in a self-paced incremental exercise test. It is accepted that this approach does not constitute genuine self-pacing, however, it allows for a more natural and fluid running technique than previous studies in which changes of speed relied on participants using buttons on the treadmill (308), or when participants had to instruct external testers to change speed (77). Lastly, field based interventions provide the opportunity to run freely and truly self-paced. These three options all allow for the evaluation of the role of recovery durations in AIT sessions, without restricting the exercise intensities in work intervals.

Initially, we approached multiple running clubs and coaches to implement the study carried out in **Chapter 8** in an endurance trained population. Liaising with the coaches, it proved hard to standardize training load of individual athletes, and in the weekly club training sessions, coaches preferred not to deviate from their mix of typical interval workouts. A promising area for future research is to run quasi-experimental studies, in which participants only visit lab facilities for pre and post-intervention (incremental exercise) testing, and complete the actual training intervention (that is the prescribed AIT sessions) individually, away from the lab facilities. Most endurance athletes nowadays train with wearable activity trackers, such as heart rate monitors and power meters, that, combined with GPS data allow for the tracking of performance in AIT sessions. Data obtained by these devices can be shared with the scientist for evaluation. It is debatable whether within group or between group study designs are most appropriate to examine training interventions (309), however, quasi-experimental studies provide an unique platform to implement '*isoeffort*' training interventions. Self-paced AIT has been addressed in cycling recently (42,218), however, in these studies, training groups performed AIT protocols of varying configurations. To study the moderating role of recovery intervals in self-paced AIT sessions in runners or cyclists using a quasi-experimental design, participants can be instructed to perform a set number of work intervals of a fixed duration on their maximal sustainable exercise intensities. Based on pre-intervention incremental test results, experimenters can instruct participants with target work intensities for these intervals, alike we successfully implemented in **Chapter 6** and **Chapter 7**. The manipulation of the recovery durations can then be used to determine if longer recovery intervals (compared to short recovery intervals) indeed result in higher exercise intensities in subsequent work intervals, which in turn may generate greater training adaptations. Finally, in the reporting of self-paced AIT interventions, it is of great important to report the attained exercise intensities in the work intervals of different training groups.

Previous research showed that trained runners and cyclists reach a steady state around 90 - 95% $\dot{V}O_2$max / HRmax in repeated 4 min work intervals (42,75,77,93,266), and the studies carried out in the current thesis add to these findings (see **Chapter 6** and **Chapter 7**). Multiple studies have examined the physiological and perceptual responses to either four 4 min or six 4 min AIT sessions, however, limited scientific knowledge is available on these responses in AIT sessions of a comparable work duration, but adopting a different configuration (e.g. 6 4 min intervals equals 24 min, however, it is unknown if this configuration is superior to 8 3 min intervals, or 4 6 min intervals). Previous studies highlight that self-selected exercise intensities are altered by, and dependent on work interval durations (22,23,218,268). In the quest to find the 'optimal AIT protocol' (arguably, the AIT configuration that produces the highest t90$\dot{V}O_2$max), manipulations in both work and recovery interval durations, and the interaction between these variables is an exciting area for future research. The results of **Chapter 6 – Chapter 8** highlighted that athletes are able to exercise for 24 min on high work intervals in AIT sessions, which is markedly longer than the total exercise duration of most studies included in the meta-analysis presented in **Chapter 3**. Self-paced AIT sessions seemingly push athletes closer to exhaustion (or better; athletes push themselves closer to exhaustion) than classical AIT protocols using fixed exercise intensities. In **Chapter 6**, recreationally trained runners rated their final interval a RPE score of 19 ± 0.7 when they received 3 min recovery, whereas the collegiate rugby players in **Chapter 8** rated their final interval with a RPE score of only 15.5 ± 1.2. These findings have implications for the training prescription and training programming of self-paced AIT sessions, and potentially greater attention is needed to ensure recovery between interval bouts and subsequent training sessions (4).

9.4 Thesis summary and conclusion

Even though HIIT is common practice in the training regimes of (traditionally) endurance athletes, surprisingly little research has explored the overall impact and role of recovery interval durations on the effectiveness of AIT, RST and SIT protocols (see **Table 2.1**). Two recent meta-analysis reported equivocal effects on changes in $\dot{V}O_2max$ with an increase in work:recovery ratio in SIT (e.g. greater recovery between subsequent 30 s sprints). No clear scientific evidence is available on the optimal duration of recovery intervals in AIT sessions, and the aim of this thesis therefore was to assess the potential moderating role of the recovery interval duration in AIT.

AIT interventions produced significant small to moderate improvements in both $\dot{V}O_2max$ and / or performance (see **Chapter 3**). The results of our meta-analysis further suggest that AIT improves $\dot{V}O_2max$ and performance significantly more than MICT, and to a similar extent as SIT. The changes in $\dot{V}O_2max$ and performance were highly homogenous, which, given the wide variation in configurations of the AIT protocols in the included studies was surprising. The analysis of moderating variables (see **Table 3.5**) revealed that long AIT interventions, incorporating a total exercise time per session of ≤ 20 min, with work intervals of ≤ 3 min and recovery intervals of not more than 3 min,

may yield larger improvements in $\dot{V}O_2max$. However, these results are speculative, as the highly homogenous improvements across the included studies would traditionally not warrant further analysis.

In **Chapter 8**, we show that short recovery intervals (1 min, 1MIN) do not offer any advantage over the use of longer recovery intervals (3 min, 3MIN). The addition of 2 hr running based AIT in the pre-season conditioning period of collegiate rugby players did result in an improved $\dot{V}O_2max$ and time to exhaustion in both 1MIN and 3MIN, however, these improvements were not significantly different between training groups. These results suggest that in AIT protocols of matched training volume and exercise intensities, the duration of the recovery intervals has a limited effect on changes in $\dot{V}O_2max$ and time to exhaustion.

That is, if the duration of recovery intervals is adequately selected to prevent premature fatigue and to allow for the full completion of AIT sessions at the desired work intensities.

Deviating from predefined exercise intensities in the work intervals of AIT sessions, the results presented in **Chapter 6** and **Chapter 7** show that longer recovery intervals between subsequent work intervals facilitate higher external training loads (higher running velocities / higher power outputs), without decreasing the internal training load in these sessions ($t90\dot{V}O_2max$). These results indicate, that when athletes incorporate self-paced AIT sessions in their training programs, long recovery intervals will allow athletes to train on higher external loads, which potentially triggers greater training adaptations. Contrary to its role in intensity matched AIT protocols, these results further highlight that the duration of the recovery interval indeed is an important moderator of the acute responses in self-paced AIT sessions. Scientists, coaches and athletes are therefore advised to critically consider the recovery duration between work intervals in the planning of AIT sessions.

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