

**THE RELIABILITY OF 10 KM TREADMILL TIME TRIAL
PERFORMANCE AND THE EFFECT OF DIFFERENT HIGH
INTENSITY INTERVAL TRAINING STRATEGIES ON 10 KM
RUNNING PERFORMANCE AND ASSOCIATED
PHYSIOLOGICAL PARAMETERS**

By

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DECLARATION

PhD THESIS TITLE:

THE RELIABILITY OF 10 KM TREADMILL TIME TRIAL PERFORMANCE AND THE EFFECT OF DIFFERENT HIGH INTENSITY INTERVAL TRAINING STRATEGIES ON 10 KM RUNNING PERFORMANCE AND ASSOCIATED PHYSIOLOGICAL PARAMETERS.

I, Mark Courtney Kirkman, hereby declare that the work on which this thesis is based is my original work (except where acknowledgements indicate otherwise) and that neither the whole work nor any part of it has been, is being, or is to be submitted for another degree in this or any other university.

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Signed by candidate

Date: **25 May 2015**

Mark Kirkman

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ABBREVIATIONS

ANOVA:	Analysis of variance
ATP:	Adenosine tri-phosphate
BF:	<i>Biceps femoris</i>
CO ₂ :	Carbon dioxide
CT:	Contact time
CV:	Coefficient of variation
EMG:	Electromyography
FT:	Flight time
GM:	<i>Gastrocnemius medialis</i>
HIIT:	High intensity interval training
HR _{max} :	Maximal heart rate
HR:	Heart rate
HS:	Heel-strike
ICC:	Interclass correlation coefficient
LDH:	Lactate dehydrogenase
MHC:	Myosin heavy chain
MVC:	Maximal voluntary contraction
PFK:	Phosphofructokinase
POMS:	Profile of mood states
PPO:	Peak power output
PTRS:	Peak treadmill running speed
RE:	Running economy

RPE:	Ratings of perceived exertion
SD:	Standard deviation
sEMG:	Surface electromyography
SENIAM:	Surface EMG for Non-invasive Assessment of Muscles
SF:	Stride frequency
SL:	Stride length
T_{\max} :	Time for which V_{\max} can be sustained
T_{PPO} :	Time for which PPO can be sustained
TEM %:	Typical percent error
TEM:	Typical error of measurement
TO:	Toe-off
TRTT:	Track time trial
TTT:	Treadmill time trial
V_{\max} :	Velocity at which VO_2_{\max} is achieved
VL:	<i>Vastus lateralis</i>
vLT:	Velocity at the lactate threshold
VM:	<i>Vastus medialis</i>
VO_2_{\max} :	Maximal oxygen uptake
VO_2 :	Volume of oxygen inspired
% VO_2_{\max} :	Fractional utilisation of maximal oxygen uptake

ABSTRACT

Title

THE RELIABILITY OF 10 KM TREADMILL TIME TRIAL PERFORMANCE AND THE EFFECT OF DIFFERENT HIGH INTENSITY INTERVAL TRAINING STRATEGIES ON 10 KM RUNNING PERFORMANCE AND ASSOCIATED PHYSIOLOGICAL PARAMETERS

Introduction

The reliability and validity of a performance test is important in research to detect meaningful performance differences following an intervention. In accordance with this, the aim of the first study of this thesis was to investigate the reliability and validity of a self-paced 10 km treadmill time trial. This performance measure was then used in the main section of this thesis. This comprised a large training intervention study aimed to answer specific questions following three different high intensity interval training programmes. In particular, changes in 10 km running performance were investigated with respect to various physiological parameters, both immediately following the training intervention, as well as during a subsequent three-week taper period.

Methods

In the first study, a group of well-trained male runners ($n = 8$) completed four 10 km treadmill time trials and two 10 km track time trials. Comparisons in performance time were made between the 10 km treadmill time trials to determine the typical percent error between these trials. Additionally, comparisons were made between the track and treadmill time trials. In the second study, well-trained male runners ($n = 32$) were randomly assigned to one of four groups; a control group, a 400 m interval group, a 1600 m interval group and a mixed (400 m and 1600 m) interval group. The intensity of the intervals was based on the participants' current 10 km time trial time. The high intensity training interventions consisted of eight interval sessions (twice per week) over a four-week period followed by a three-week single-step 30% reduction in total training volume (while maintaining training frequency and some intensity) in all groups. Ten kilometre treadmill time trial performance,

associated physiological parameters (maximal oxygen uptake, running economy, running economy as a percentage of maximal oxygen uptake, peak treadmill running speed, percentage of maximal heart rate sustained during a 10 km time trial and 20 m sprint time), neuromuscular (muscle strength and surface electromyography) and stride parameters (contact time, flight time, stride frequency and stride length) and pacing strategies were examined during the nine-week study. Data following the training intervention were compared to pre-high intensity interval training values for the aforementioned parameters using one-way and repeated measures analysis of variance.

Results

In the first study, there were no differences ($p = 0.999$) between 10 km treadmill time trial performance in the three treadmill time trials where the typical percent error was 1% ($38:34 \pm 03:24$ vs $38:38 \pm 03:30$ vs $38:38 \pm 03:30$ (min:s) in treadmill time trial 1, 2, 3 and 4 respectively). Additionally, there was no difference ($p = 0.675$) in 10 km time trial performance between the treadmill time trials and the track time trials (mean treadmill time trail time $37:20 \pm 2:44$ and mean track time trial time $37:45 \pm 2:29$ (min:s)). In the second study, immediately following the training intervention, there was a significant $3.3 \pm 2.0\%$ improvement ($p = 0.001$) in 10 km running performance in only the mixed high intensity interval training group. No changes were observed in maximal oxygen uptake ($p = 0.490$), peak treadmill running speed ($p = 0.120$), running economy ($p = 0.339$), running economy as a percent of maximal oxygen uptake ($p = 0.757$), percentage of maximal heart rate sustained during a 10 km treadmill time trial ($p = 0.770$), 20 m sprint time ($p = 0.997$) as well as the neuromuscular characteristics measured in any of the three training groups immediately following the training intervention. Additionally, no change in pacing strategy was observed in both the mixed and 1600 m groups immediately following the training intervention, however the 400 m group showed a significantly faster start compared to the average pace ($p = 0.023$) in comparison to pre-training pace at this time point. Ten days following the start of the taper period, 10 km running performance was significantly improved in the mixed group by 4.5% ($p < 0.001$), whereas there was no change in performance in the 1600 m and 400 m groups in comparison to pre-high intensity interval training. During the remainder of the taper

period (after one 10 km treadmill time trial) there were no differences in the pacing strategies in any of the groups compared to their pacing strategy pre-high intensity interval training. Also there were no differences in the neuromuscular or physiological parameters.

Discussion and Conclusions

The 10 km treadmill time trial examined in the first study was highly reliable with a typical percent error of 1%, showing the test has sufficient precision to be able to detect small meaningful changes in running performance. In addition, this performance measure was valid, as there were no differences between treadmill and track time trial performance. In the second study, the mixed high intensity interval training programme was effective in improving 10 km running performance. This finding has practical application for coaches, as it guides on the types of intervals that should be incorporated into a high intensity interval training programme. Additionally, an easy to use prescription of interval intensity is provided. A single-step 30% reduction in total training volume, while maintaining training frequency and intensity, was an effective means of improving performance in the mixed interval group, as well as being effective in maintaining performance in the 1600 m and 400 m groups. A taper duration of ten days is optimal for this taper design. Potentially, the most significant finding of this thesis was that although there was a change in the pacing strategy of the 400 m group immediately following the training intervention where a significantly faster start compared to the average pace was observed in the time trial, the pacing strategy reverted to the same as pre-training (deemed as 'normal pacing') after the first 10 km treadmill time trial during the taper period. This is an important finding with practical application. If the intensity and duration of the high intensity interval sessions is too dissimilar to the intensity and duration of the target event, then the pacing strategy immediately following training is disrupted. It is possible, however, to reset the pacing strategy to 'normal' by a single exposure to an exercise bout of similar intensity and duration to the target event.

In conclusion, this thesis demonstrates the reliability and validity of a self-paced 10 km treadmill time trial testing protocol which has sufficient precision to detect small meaningful changes in performance. In addition, the following practical advice can be drawn from the results of the training study: (i) high intensity interval training

programmes aimed to improve 10 km running performance should contain intervals of mixed duration and intensity, (ii) a three-week, single-step, 30% reduction in training volume is effective in both maintenance and improvement of performance following different high intensity interval training programmes, and (iii) to ensure that the pacing strategy is not disrupted in a performance event following a high intensity interval training intervention, athletes should simulate their target event at least once before this event.

CHAPTER ONE – LITERATURE REVIEW

1.1 Introduction

The majority of this chapter reviews the literature that has contributed significantly to our knowledge of the physiological determinants of endurance performance, as well as some commonly used training methods employed to enhance these variables.

Adaptations to both short term and chronic submaximal endurance training have been extensively studied in previously untrained individuals (194, 281, 299). In these study participants, continuous low- to moderate-intensity exercise over a time period of several months has been shown to primarily improve aerobic capacity (270). This includes improvements in maximal oxygen uptake ($VO_{2\text{ max}}$) and associated changes in the cardiovascular system such as an increase in blood volume and resultant decrease in heart rate at the same absolute exercise intensities (165, 239, 270). Additionally at the same absolute exercise intensities, cardiac output (173, 409) as well as muscle and cutaneous blood flow are increased during exercise (101, 154).

Various metabolic changes have also been described and reviewed extensively in previously untrained individuals (165, 186, 198, 213, 214). These include increases in mitochondrial enzyme activities (186, 213), as well as lower plasma lactate concentrations at similar relative work levels (170, 172-174, 236, 313) and higher rates of fat oxidation during exercise (198).

Although it is known that trained individuals respond differently to submaximal training compared to untrained individuals, comparatively less is known about the mechanisms underlying training adaptations in already well-trained athletes (194). One reason for this may be the difficulty in persuading athletes who are training at a high level to change their training regiment for the purposes of scientific study (194, 281).

Before the impact of any training intervention on performance can be accurately measured, it is of utmost importance to be confident that the performance measure or test being utilised is both reliable and valid for the greater application of the test

(91, 107, 218-220). Section 1.2 therefore, introduces the concepts of reliability and validity of performance tests and the importance of these variables in investigations.

In section 1.3, the physiological adaptations to endurance training are reviewed. This section focuses on the physiological, biochemical, metabolic and neuromuscular changes that have been shown to be modified by endurance training in both untrained and endurance-trained individuals. Section 1.4 describes various training methods employed to further enhance endurance performance once the aforementioned physiological parameters are approaching their 'maximal' limit in already endurance-trained individuals. These training methods include altitude training (1.4.1), the inclusion of a taper period prior to competition (1.4.2), changes in pacing strategies (1.4.3), resistance and short-sprint training (1.4.4-5), and high intensity interval training (HIIT) (1.4.6). The latter will be the main focus of this literature review as this was the training method employed in this thesis.

1.2 Reliability and validity of performance measures in exercise testing

Performance tests are fundamental to the field of sports science and physiology as they allow for a controlled imitation of exercise performance in the field. According to Currell and Jeukendrup (107), there are three factors that underpin a good performance test, these are: validity, reliability and sensitivity. Importantly, no one factor is separate to another as they all interact with one another.

The reliability of a testing measure provides an indication of the effectiveness of the testing measure to give the same result repeatedly (25, 217, 220, 280, 347) and is often expressed as a typical percent error (TEM %) (220) or coefficient of variation (CV) (107). Reliability of a performance test is of particular importance when testing the effectiveness of a training intervention, as there needs to be certainty that any measured differences in performance are indeed due to the intervention and have not arisen merely due to inherent variance within the performance test. Furthermore, it has been reported by Hopkins and Hewson (219) that the intra-individual variation in the competitive performance of well-trained runners in endurance events less than 21 km is approximately 1.5%. Accordingly, a performance test needs a TEM % to be similar to, or preferably less than 1.5%, to be sensitive enough to be able to detect meaningful differences when testing this class of athlete (107, 219, 387).

Testing protocols in which athletes are required to cover a set distance or complete a fixed amount of work in a certain time (closed loop) have been shown to be more reliable than constant load tests to volitional exhaustion (open loop) (280, 383, 418-420). The first research to provide evidence that the reliability of time-to-exhaustion (open loop) tests was lower than time trial (closed loop) tests was completed by Jeukendrup *et al.* (244) on well-trained cyclists. Three test protocols were investigated, namely: a continuous cycling test at 75% maximal workload until exhaustion, a one hour time trial, and a preloaded time trial where a 15-minute time trial followed a 45-minute preload at 70% maximal workload. The mean CV's for the different tests were 26.6%, 3.4% and 3.5%, respectively, indicating the relatively poor reliability of the open-ended test-to-exhaustion. Similarly, Laursen *et al.* (280) directly compared the reliability of a time-to-exhaustion test to that of a time trial in well-trained distance runners and came to the same conclusion. In their study, participants completed two 5000 m and two 1500 m self-paced time trials as well as four time-to-exhaustion tests. In the latter test, study participants were instructed to run for as long as possible at their average 5000 m time trial running speed for two tests and at their average 1500 m time trial running speed for the other two tests. The CV's for the time-to-exhaustion tests were reported as 13.2 – 15.1%, whereas the CV's for the time trials were reported as 2.0 – 3.3%.

Another study to investigate the reliability of a closed loop time trial test on well-trained runners was conducted by Schabert *et al.* (420). In this investigation, study participants were instructed to run as far as possible in 60 minutes on three separate occasions and a CV of 2.7% was reported for this test (420). Although the results of the closed loop tests in the studies investigating well-trained runners indicate higher reliability compared to the open loop tests, the CV's are still above 1.5%, which, as mentioned previously is the value required to detect meaningful changes in well-trained runners at distances less than half marathon distance. One study, by Russel *et al.* (410), reports a CV of 1% for a 10 km treadmill time trial (TTT). However, the testing protocol included a 90-minute 'pre-loaded' run before the TTT which may have affected the variability of the performance times reported. In addition, both males and females were included in the study group. There therefore appears to be paucity in the literature with regards to a closed loop test with a CV of less than 1.5% involving well-trained male distance runners.

The validity of a performance test refers to how accurately the test is able to simulate the actual demands of performance in the field (107, 218). In addition to closed loop tests being shown to be more reliable than open loop tests, closed loop tests have also been suggested to be a more valid measure of cycling and running performance (107). Specifically, there seems to be an absence of a relationship between time-to-exhaustion tests and field performance (107), as observed by Laursen *et al.* (283), who found no significant correlation between cycling performance during an Ironman triathlon and a cycling-to-exhaustion test (at a power output at the ventilatory threshold). In contrast to this, various studies have found a strong relationship between laboratory-measured time trial performance and actual race performance in well-trained cyclists and runners. For example, Russell *et al.* (410) found that a 10 km TTT following a 90-minute preloaded run at 65% $VO_{2\max}$, had a high correlation ($r = 0.95$) with 10 km road race performance. Additionally, Palmer *et al.* (383) found a strong relationship ($r = 0.98$) between 40 km cycling time trial performance on an ergometer and that of two outdoor 40 km time trials. Furthermore, Foster *et al.* (148), showed no physiological differences in a 5 km cycling time trial and actual race performance when measuring $VO_{2\max}$ and heart rate in a mixed group of competitive athletes. It is the recommendation of Currell and Jeukendrup (107) that a time trial is a more appropriate measure to use than a time-to-exhaustion test when investigating an intervention affecting performance, particularly in sports such as running.

1.3 Physiological determinants of endurance running performance

Various physiological determinants of distance running performance have been identified, including $VO_{2\max}$ (93, 96, 100, 412), running economy (14, 93, 96, 100, 121, 135, 333, 392), fractional utilisation of $VO_{2\max}$ ($\% VO_{2\max}$) (113, 197) and the lactate threshold (43, 102, 135, 138, 194, 457, 496). These factors are reported to explain more than 70% of the intra-individual variance in distance running performance (120, 324). Additionally, there are various neuromuscular factors involved in the determination of endurance running performance such as increases in muscle strength and power (140, 328, 379), increased anaerobic enzyme activity (7, 263), shifts in fibre type (7, 155, 263, 411), enhanced muscle fibre recruitment

and synchronisation (7, 158, 294, 378, 411) and changes in stride parameters (140, 335, 378, 379).

1.3.1 Maximal oxygen uptake

$VO_{2\text{ max}}$ was first described by Hill and Lupton in 1923 as "the oxygen intake during an exercise intensity at which actual oxygen intake reaches a maximum beyond which no increase in effort can raise it" (210). They further suggested that this measurement defines the limits of the cardiovascular and respiratory systems' ability to transport oxygen (193). It is well known that one prerequisite for superior endurance performance is the ability to metabolise energy aerobically (96, 180, 412) and indeed $VO_{2\text{ max}}$ has been positively correlated to running performance in competitive distance running (93, 96, 100, 412). $VO_{2\text{ max}}$ is influenced by various factors including aerobic enzyme activity, muscle fibre type, muscle capillary density, haemoglobin mass and stroke volume, amongst others (101, 416). As mentioned previously, $VO_{2\text{ max}}$ has been shown to improve with submaximal endurance training in previously untrained individuals. Once an individual becomes accustomed to this type of training, however, improvements in $VO_{2\text{ max}}$, as well as performance, appear to plateau. Other training methods need to be employed at this stage to further enhance $VO_{2\text{ max}}$ and performance (324). The lack of further improvement in both these factors by increasing aerobic training volume alone was shown by Costill *et al.* (99), who demonstrated that when swim-training distance was more than doubled and average intensity maintained, no changes were observed in $VO_{2\text{ max}}$ or performance in well-trained swimmers.

1.3.2 Running economy

Running economy represents the metabolic demand of running (324) and has been described as the oxygen uptake required at a given submaximal speed (140). Running economy can be reported as an absolute measure or as a percentage of an individual's $VO_{2\text{ max}}$ at a given speed (88, 92, 252, 369).

There is a strong association between running economy and distance running performance (14, 36, 93, 96, 100, 121, 135, 333, 392) and some research even suggests that running economy may be more important to endurance running performance than $VO_{2\text{ max}}$ (56, 93, 99, 332). It is also known that running economy

can vary amongst runners with a similar $VO_{2\text{ max}}$, by as much as 30% (110). Di Prampero *et al.* (121) found that a 5% increase in running economy induced an approximately 4% improvement in distance running performance and similarly Conley and Krahenbuhl (93) found that 65% of the variation in race performance amongst well-trained runners of comparable ability was attributed to differences in running economy. Conversely, Williams and Cavanagh (486) and Weston *et al.* (482) found no significant relationship between running economy and performance. Specifically, in the Williams and Cavanagh (486) study, the aim was to identify the relationship between running economy and various biomechanical aspects of distance running, including 10 km running performance. No single variable was able to explain the inter-individual differences in running economy. In the Weston *et al.* (482) study, a homogenous group of African and Caucasian well-trained distance runners were investigated and compared for differences in their $VO_{2\text{ max}}$, running economy, % $VO_{2\text{ max}}$, heart rate and plasma lactate concentration during two separate six-minute workloads ($16.1\text{ km}\cdot\text{h}^{-1}$ and current 10 km race pace). At $16.1\text{ km}\cdot\text{h}^{-1}$, the African runners were 5% more economical than the Caucasian runners, but as no significant difference in 10 km time trial performance was found, running economy was not correlated with 10 km running performance.

1.3.2.1 Factors associated with improvements in running economy

An improvement in running economy would increase the running speed that is achieved over a given distance at the same % $VO_{2\text{ max}}$ (246, 416, 440, 471). The mechanisms by which running economy is improved are still not completely understood (124). Physiological factors such as core temperature, heart rate, ventilation threshold and the lactate threshold have all been shown to be associated with changes in running economy in well-trained athletes (9, 332, 460). Additionally, since improvements in muscle strength and power have resulted in improvements in running economy, it has been suggested that the improvements in running economy could occur through changes in muscle and tendon 'stiffness' (75, 108, 164, 268, 269, 271, 440). Certainly Dumke *et al.* (124) found that increased muscle stiffness was positively correlated to running economy at endurance running speeds. It has been suggested that as muscle stiffness is increased, less muscle activation is required, because more energy can be stored in a more compliant spring in the

translation of energy expenditure to ground force during running (56, 124).

Therefore, energy expenditure is decreased because less energy is being wasted in braking forces, and so efficiency of running is improved (416). It is interesting to note, however, that the muscle stiffness calculated in the aforementioned study was passive stiffness which is not representative of what would occur during running (124).

A study investigating muscle stiffness and performance by Jones (247) found a significant relationship between running economy at 16 km·h⁻¹ and the sit-and-reach test score, designed to assess lower body and trunk flexibility. The author suggested that the least flexible runners are also the most economical and infers that a greater elastic energy return during the shortening phase of the stretch-shortening cycle in the musculotendinous structures is possible when these structures are stiffer (247). Similarly, Craib *et al.* (105) found that inflexibility in the calf and hip regions in well-trained male distance runners was associated with improved running economy, and Kyrolainen *et al.* (271) concluded that stiffer muscles around the knee and ankle joints during the braking phase of running increased force production in the push-off phase. Conversely, Godges *et al.* (163) found significant improvements in gait economy at 40%, 60% and 80% VO_{2 max} following improved hip range of motion as a result of stretching. The latter finding agrees with the general belief amongst runners and coaches that improved flexibility is desired for improved running economy (105, 416). Indeed a certain amount of flexibility is required for optimal stride length at higher running speeds (416). However, it may be concluded that muscle stiffness is also important to maximise energy storage, thus a balance of the two appears necessary.

The composition of muscle fibre type could also be a factor influencing running economy as it has been suggested that a higher percentage of slow twitch Myosin Heavy Chain (MHC) Type 1 fibres are associated with better running economy than fast twitch MHC Type 2 fibres (61, 251, 486). Specifically, Horowitz *et al.* (221) showed that elite cyclists had different rates of oxygen uptake while exercising at the same power output and that the more efficient cyclists had a higher percentage of MHC Type I fibres in their *vastus lateralis*.

Once habituated to endurance training, there appear to be no changes in running economy following continued training of the same intensity and type despite an increase in training volume (324, 416), however, several other different training techniques have been shown to improve running economy, such as altitude training (to be discussed in section 1.4.1), strength and plyometric training (to be discussed in sections 1.4.4 – 5) and HIIT (to be discussed in section 1.4.6).

1.3.3 Fractional utilisation of maximal oxygen uptake

This parameter indicates the proportion of a runners' $VO_{2\text{ max}}$ that can be sustained during exercise and is dependent on the distance and duration of the athletic event or testing protocol (100, 197, 317), as well as the state of training of the individual (99, 100). Noakes *et al.* (364) found % $VO_{2\text{ max}}$ at $16\text{ km}\cdot\text{h}^{-1}$ was a good predictor of running performance in races between 10 to 90 km. Certainly, the higher the % $VO_{2\text{ max}}$ an athlete is able to sustain during an event is indicative of a possible superior aerobic fitness compared to their counterparts exhibiting lower % $VO_{2\text{ max}}$ values over the same duration of exercise (197). In 1971 Costill *et al.* (97) studied Derek Clayton, the marathon record holder at that time (2 h 08 min), and found that he was able to sustain 86% $VO_{2\text{ max}}$ at race pace (this record has been disallowed as the course was later found to be short). In comparison, Maughan and Leiper (317) studied the % $VO_{2\text{ max}}$ of non-elite male marathon runners (average marathon time of 3 h 34 min \pm 50 min) and found the fastest runners were able to sustain a pace requiring approximately 75% of their $VO_{2\text{ max}}$ whilst the slower runners exhibited values of approximately 60% of their $VO_{2\text{ max}}$, establishing that the % $VO_{2\text{ max}}$ sustained throughout the race was positively correlated to performance. Similarly, Davies and Thompson (113) showed that the faster male marathon runners in their study had higher $VO_{2\text{ max}}$ values and were also able to use a higher percentage of that $VO_{2\text{ max}}$ throughout the marathon distance compared to the slower runners. However, as previously stated, a longer duration of exercise itself dictates a lower % $VO_{2\text{ max}}$ that can be sustained in comparison to a shorter duration regardless of training status (100, 317).

In contrast to these studies, Scrimgeour *et al.* (422) studied the % $VO_{2\text{ max}}$ sustained during distances of 10 to 90 km of three different pre-race 'mileage' groups: Group 1, less than $60\text{ km}\cdot\text{wk}^{-1}$; Group 2, between $60 - 100\text{ km}\cdot\text{wk}^{-1}$ and Group 3, more than

100 km·wk⁻¹. The most heavily trained runners (Group 3), had significantly faster running times in all distances, however, although having hypothesised that the most heavily trained runners (Group 3) would run at a higher % VO_{2 max}, they found no difference between the % VO_{2 max} sustained during all distances in the three groups. The lack of a difference in % VO_{2 max} between the groups was ascribed to the high training volume group having a superior running economy (19.9% higher), allowing them to run at a higher speed while still utilising the same % VO_{2 max}.

1.3.4 Lactate threshold

The lactate threshold has been described as the highest exercise intensity that can be achieved with less than a 1 mM increase in blood lactate concentration above pre-exercise levels (324). Other definitions have also been used. The onset of blood lactate accumulation signifies when blood lactate reaches a concentration of 4 mM and is commonly used interchangeably with the lactate threshold, although in practise each represents a different point for exercise intensity and blood lactate concentration (318). An increase in the lactate threshold is a good predictor of endurance performance (43, 102, 135, 138, 194, 457, 496), even though the role of lactate in fatigue is still a debated issue (32, 70, 83, 275, 292). Exercise above the lactate threshold is associated with more rapid fatigue and an increase in metabolic, respiratory and perceptual stress (255, 429) and therefore according to Jones and Carter (248), an improvement in the lactate threshold is a clear indicator of an enhanced endurance capacity. Certainly, it has been suggested that superior endurance performance may be related to a slower accumulation of lactate in working muscles (100, 157, 171, 195, 270, 274, 431, 432, 483).

Prolonged-duration moderate-intensity running has been shown to be optimal for enhancing the lactate threshold in well-trained distance runners (300). When expressed as running speed, the lactate threshold is dependent on running economy, with an improvement in running economy tending to increase the velocity at lactate threshold (vLT) (62).

There are numerous studies examining the effects of different training regimes on the lactate threshold in distance runners (65, 199, 206, 296, 308). Some studies have suggested that training be prescribed based on the blood lactate response to

an incremental exercise test (90, 199, 480), however, other studies suggest that training at vLT will be ineffective for enhancing the lactate threshold in trained distance runners (296) as they are accustomed to high volumes of this type of training and therefore their rate of adaptive response has most likely reached a plateau (281, 324). Some studies therefore suggest prescription of training above the vLT, although this recommendation is largely based on the training responses of untrained individuals (40, 199, 296, 480). Londeree (296), however, conducted a meta-analysis to determine the effects of training intensity on the lactate threshold in both sedentary and conditioned participants. The results indicated that training at an intensity near to the lactate threshold was an adequate stimulus to improve the lactate threshold in sedentary individuals but that an intensity higher than the lactate threshold was needed to elicit a response in the conditioned individuals (296). Indeed, Tanaka *et al.* (458) found that lactate threshold was improved following running training at an intensity above vLT in well-trained runners, however, only one experimental group was used in this study and so a comparative efficiency of this type of training cannot be inferred (324). Similarly, Hamilton *et al.* (187) reported a 3.5% increase in the lactate threshold of the well-trained runners in their study when replacing some of their normal competitive phase training with 10 x 30-minute sessions of alternating resisted treadmill sprints and explosive leg jumps over the course of a five to seven-week training period. Conversely, Paavolainen *et al.* (377) found no change in the lactate threshold when explosive sprint and strength training was added to well-trained runners' training programmes.

1.3.5 Neuromuscular factors involved in the determination of distance running performance

The interaction between the neural and muscular systems is integral to all skeletal movement and effectively allows cardiorespiratory capacity to be translated into efficient movement and athletic performance (324). Just as the cardiorespiratory system is able to adapt to training, so does the neuromuscular system. Numerous studies have described endurance performance enhancements with no concomitant increases in the variables of $VO_{2\text{ max}}$, % $VO_{2\text{ max}}$ sustained, running economy and the lactate threshold in already well-trained athletes (117, 203, 230, 308, 319, 377, 428). As previously stated, factors other than those associated with the aerobic system

have been shown to contribute to performance enhancements in well-trained distance runners (175, 360, 376, 379). Specifically, various muscular and neurological factors have been described that are associated with endurance running performance improvements. These include increases in muscle strength and power (140, 328, 379), increased anaerobic enzyme activity (7, 263), shifts in proportion of fibre type (7, 155, 263, 411), enhanced muscle fibre recruitment and synchronisation (7, 158, 297, 378, 411) and changes in stride parameters (140, 335, 378, 379). These adaptations contribute to a delay in muscular fatigue, improved uphill running and also enable the athlete to sprint in the final stages of a race; all factors that improve running performance (390, 456, 491).

The effect of muscle strength on endurance performance was investigated by Hickson *et al.* (203). In this study, heavy resistance exercise (in order to increase leg strength) was added to the training regime of well-trained endurance athletes already in a steady state level of performance. Following ten weeks of training, leg strength was increased by approximately 30%, but there were none of the expected concomitant increases in both thigh girth and cross sectional area of *vastus lateralis* muscle fibres as well as no changes in citrate synthase activity. This led the authors to the conclusion that the accumulation of strength post-training may have reflected the improvement of activation of motor units and motor unit recruitment patterns rather than intramuscular biological and biochemical changes (203). However, there were limited intramuscular biological and biochemical variables tested so this finding is inconclusive. The conclusions reached, however, are in agreement with Moritani *et al.* (334), who stated that the first line of evidence for neural involvement in muscular strength gains is when it is observed that there is no concurrent muscle hypertrophy with the strength gains (158), as was the case in the study of Hickson *et al.* (203).

Additional muscle mass from resistance training would be detrimental to endurance running performance (41, 491) and so when undertaking strength training it is important to be mindful to limit the volume and intensity of this type of training (41). Ultimately, it is advantageous to incur strength gain from exercise in which the muscle movements mimic the movements and velocities of running. In this regard, Paavolainen *et al.* (376) demonstrated that 5 km run time improved by approximately 30 seconds in well-trained endurance runners when plyometric strength training was

introduced into the runners' training programme whilst concurrently decreasing training volume. Additionally, foot contact time measured by a force plate decreased by 7% (376). Plyometric strength training allows movements and velocities that are similar to that of running and so it is possible that by increasing the rate of force production in active muscles, stride rate or length may be improved, thereby improving running performance (41), however, in the aforementioned study of Paavolainen *et al.* (376), stride length and $VO_{2\text{ max}}$ both remained unchanged.

A running stride is defined as the cycle from contact of one foot to the next contact of the same foot (235). Increased stride frequency and length, as well as decreased contact and flight time are associated with the ability to run at higher speeds (234, 271, 335, 376, 378) and are indirect measures of neuromuscular control (376). Numella *et al.* (371), found that improvements in 5 km running time were associated more with an increase in stride length than with higher stride frequency in well-trained runners. Conversely, in a study examining the effect of eight weeks of strength and endurance training in recreational runners, the stride frequency tended to increase with significant increases in leg strength, while no changes in stride length were observed (140).

Surface electromyography (sEMG) is a method commonly used to evaluate and record the electrical activity in skeletal muscle. Early strength gains from resistance exercise are associated with an increase in the amplitude of sEMG activity and this has been interpreted as an indication of increased neural drive, thus increasing the magnitude of efferent neural output from the central nervous system to the active muscle fibres (1-3, 158, 181-183, 222, 224, 225, 348). However, sEMG is a global measure of muscle activity and therefore there are other underlying factors which will impact on the signal, such as motor unit firing patterns, including firing rate and motor unit synchronisation (158, 330, 426). Creer *et al.* (106) investigated the effects of four weeks of high intensity sprint training combined with endurance training on sEMG and cycling performance in well-trained cyclists. They found that the combination of sprint and endurance training significantly increased motor unit activation, as recorded during four 30-second sprints, and total work output, compared to endurance training alone. Other research has come to similar conclusions that the overall magnitude of muscular activation, as measured by sEMG, is increased with training (31, 56, 158, 241, 455).

1.4 Training techniques commonly employed to improve endurance performance in well-trained individuals

Once submaximal endurance training becomes habitual, and running performance seems to have plateaued, it is often not possible to further increase training volume. Therefore, different training stimuli are needed to further enhance performance (118, 190, 205, 296). These could include altitude training, the incorporation of a period of reduced training or taper prior to competition, fine tuning of pacing strategies for an athlete's specific race distance, or the addition of sprint, resistance or interval training into an athlete's existing training programme.

1.4.1 Altitude training

The effect of altitude training on endurance performance has been comprehensively researched (21, 22, 28, 68, 79, 122, 156, 166, 176, 253, 289, 306, 391, 448), but to date few studies have been done to investigate the effect of altitude exposure on running economy in highly trained distance runners. Altitude acclimatisation leads to both central and peripheral adaptations that improve oxygen delivery and utilisation, which could potentially lead to improvements in an athlete's running economy (79, 289, 306, 450, 492). Three studies (253, 254, 417) have shown improved running economy following differing simulations of altitude in highly trained distance runners. Gore *et al.* (166) demonstrated that simulated hypoxic exposure using intermittent hypobarica of 4500 m for three hours a day over 14 days improved running economy by 2.6% and that this improvement accounted for 37.0% of the improvement observed in 3000 m running performance. There were similar results when well-trained endurance runners were exposed to normobaric hypoxia (12.3% oxygen) (254). Furthermore a study by Saunders *et al.* (417) found that sleeping at simulated altitude (2000 – 3100 m) whilst training near sea level (600 m) for 20 consecutive days, significantly improved running economy in elite distance runners with no concomitant changes in cardiorespiratory measures or red cell mass. Further research suggests that increased dependence on glucose metabolism during hypoxia results in greater efficiency due to there being a higher yield of adenosine tri-phosphate (ATP) per mole of oxygen in glycolysis compared to fatty acid utilisation (176, 398). Furthermore, Green *et al.* (176) suggest the increased yield in

ATP decreases the need to maintain hydrolysis at the same rate to that prior to altitude exposure resulting in greater efficiency in energy production.

1.4.2 The effect of reduced training (taper) on endurance performance in well-trained individuals

The taper is a technique that is widely used to improve performance before a competitive event and is characterised by a marked reduction in training load in the days leading up to the event (63, 98, 98, 230, 342, 344, 346) (for extensive reviews, see references (226, 228, 337, 351)). Coaches and athletes often face this period of training with apprehension as it is of paramount importance to balance the recovery from fatigue due to prior training against the risks of the negative effects of detraining (161, 229, 344, 350, 461). Training volume, intensity and frequency are altered to varying degrees. The strategy was largely dependent on a trial and error approach from coaches (344). However, in the last decade, sports science has described the physiological changes associated with the taper period and also the effects on performance of different reduction strategies (344).

1.4.2.1 Physiological changes associated with taper

There are numerous physiological changes associated with reduced training involving neuromuscular (376, 406, 479), cardiorespiratory (33, 98, 245, 494), metabolic (33, 98, 245, 342, 346, 350, 352), haematological (341, 342, 350, 465) and psychological (216, 351, 488, 489) variables, most of which have been associated with concomitant performance enhancements.

Evidence suggests that short-sprint performance, representative of muscle power, is greatest following a taper period (406) as there appears to be a notable adaptation toward an increase in the number of MHC Type IIb muscle fibres with rest (406). Similarly, whole muscle power increased with significant enlargements in MHC Type IIa muscle fibres following a 21-day reduction in training volume in well-trained swimmers (465) and both isokinetic leg strength along with cycling performance were enhanced following a two-week taper in well-trained cyclists (312).

Various studies have described changes in the activities of numerous enzymes involved in skeletal muscle metabolism following a taper period (98, 231, 298, 350). Other metabolic changes following a period of taper include increased peak blood lactate concentration (98, 245, 341, 342, 352) and decreased or unchanged blood lactate at submaximal intensities (229). A reduction in daily energy expenditure has also been observed (227, 230) as well as a slightly reduced or stable respiratory exchange ratio at the same work load (343). Muscle glycogen concentrations and muscle oxidative capacities have been shown to increase progressively during the taper (98, 226, 227, 231, 350, 428, 428) and changes in hormonal markers such as testosterone (216, 341, 342), cortisol (216, 342), insulin-like growth factor-1 and growth hormone (343) have been shown to occur during the taper period and sometimes correlated to performance changes (216).

Possible haematological changes associated with an increase in performance during the taper period include increased blood and red cell volume (67, 94, 95, 345, 428), haemoglobin concentration, haematocrit and decreased red cell distribution and red cell width (305, 345). These changes suggest a positive balance between haemolysis and erythropoiesis (67, 94, 95, 305, 340, 345, 346) indicating possible recovery from fatigue of prior training, as during fatigue more haemolysis is observed. Specifically, Shepley *et al.* (428) reported increased total blood volume following three different seven-day tapers with concomitant improvements in running time-to-exhaustion. Mujika *et al.* (341), however, found decreased erythrocyte count, mean corpuscular volume, haemoglobin concentration and mean erythrocyte haemoglobin content following both reductions in low- and high-intensity training volumes by 50 and 75% over six days, with no significant changes being found in 800 m running performance.

Numerous studies have described positive psychological effects during the taper period (216, 393, 488, 489). Wittig *et al.* (488) found pre-race and weekly global mood states to be improved following a three-week period of 70% reduction in training volume in well-trained runners. Their results were based on the Profile of Mood States (POMS) and Physical Self-Efficacy Scale. Similarly, Raglin *et al.* (393) used the same scales when investigating a taper period in collegiate women swimmers and found that mood disturbance was elevated above baseline levels during peak training and peak swimming power was significantly reduced below

baseline levels. Following a period of taper of 72% reduction in training volume, these variables then returned to baseline levels. It is perhaps not surprising, therefore, that Hooper *et al.* (216) found the results of the POMS to be able to predict changes in performance before and after a taper period in elite swimmers.

There are mixed results with regards to the effects of a taper period on $\text{VO}_2 \text{max}$ and running economy in well-trained athletes. It is widely accepted that changes in these parameters are seldom observed in well-trained athletes, as they are already approaching the maximal limits for these parameters (378, 379). Nevertheless, one study has described improvements in these measures following a taper period (230), whereas the majority of studies describe no change (216, 226, 227, 229, 245, 320, 351, 352, 428) or even reductions in these parameters (204, 352). Other changes in the cardiorespiratory system may include blood pressure and ventilatory function as well as resting, maximal and submaximal heart rate changes (80, 346).

1.4.2.2 Types of training-reduction strategies

To date, no optimum approach to the taper has been described that can be prescribed to all athletes, although numerous studies have described various techniques of applying a taper that have resulted in performance enhancements. For comprehensive reviews see references (63, 270, 270, 337, 338, 344, 344, 351).

The reduction in training load can be implemented in either a progressive manner or a single-step standardised protocol (344, 461). As mentioned previously there are three variables which can be manipulated during the taper period to reduce training load, namely: training volume, intensity and frequency (338).

1.4.2.2.1 Progressive and step taper protocols

A progressive taper strategy involves a reduction in training over a certain amount of time. Either exponential or linear progressive tapers are described. A step-wise reduction protocol is where the training volume, intensity or frequency are reduced in one or more defined steps, usually as a percentage reduction of pre-training values.

There is evidence that both progressive and step tapers have been linked with the maintenance and improvement of a number of performance-related measures and physiological adaptations of the training implemented prior to the taper period (204,

207, 227, 229, 320, 337, 344), although in general, progressive style tapers are believed to be more beneficial compared to step-wise (33, 270, 337). Specifically, in a study involving triathletes, Zarkadas *et al.* (493), reported a greater improvement of 12% in 5 km running time trial performance when training volume was reduced in a progressive manner compared to only a 3% improvement in the same criterion when a single-step reduction in training volume was applied. Banister *et al.* (33) also compared a 14-day progressive reduction in volume to a single-step reduction in triathletes and reported no change in 5 km running time trial performance following the single-step taper, but a significant 4% improvement following the progressive taper. A cycle ramp test-to-exhaustion was also performed in this study and it was found that the progressive taper resulted in a larger significant improvement in this test compared to the single-step taper (5.2% and 1.4%, respectively). The sample size in the latter study was very small, including only three participants in the step taper reduction group and six participants in the progressive reduction group, which suggests the significance of the results should be interpreted with caution. Houmard *et al.* (230), additionally reported a 3% improvement in 5 km running time trial performance following an 85% progressive reduction in training volume over seven days in distance runners, however no comparison was made to a step taper protocol in this study.

The majority of studies involving a step-wise reduction in training load have reported the maintenance of pre-taper values in aerobic variables as well as performance (206, 227, 229, 320). Specifically, Hickson *et al.* (206) investigated the responses of a single-step 33% and 66% volume reduction in training (whilst maintaining training frequency and intensity) over 15 weeks and found that $VO_{2\text{ max}}$, peak lactate concentration and 5-minute exercise (combination of running and cycling) performance were all maintained in both groups. Similarly, Houmard *et al.* (227) found no change in 5 km time trial performance or $VO_{2\text{ max}}$ following a three-week single-step 70% reduction in training volume with a concomitant 17% reduction in training frequency. Additionally, aerobic capacity was maintained following both steps of a two-step volume reduction in training in well-trained runners in a separate study by the same author (229). In another study, McConell *et al.* (320) examined the effects of a single-step 66% volume reduction taper with a concomitant 50% reduction in frequency of training on 5 km running performance in distance runners

and reported that $VO_{2\text{ max}}$, resting plasma volume and resting heart rate were all maintained following four weeks of taper. Conversely, though, 5 km time trial performance significantly declined in the latter study.

It therefore appears that a progressive style taper may be more beneficial to an improvement in running performance compared to step taper protocols. The findings of the meta-analysis of Bosquet *et al.* (63), are in agreement with this, as they found higher performance improvements following a progressive style taper and indeed 80% of the subjects analysed across the 27 studies were involved in this style of taper as opposed to a step taper. It is however, thought that the latter is technically easier to administer.

1.4.2.2.2 Training intensity and volume during the taper period

There is a consensus in the literature that training intensity needs to be maintained during the taper period to prevent a decline in performance and associated aerobic enhancements from training prior to the taper (204, 206, 207, 270, 488, 489). Hickson and Rosenkoetter (207) and Hickson *et al.* (204, 206) conducted a three-part series of studies examining the effects of 33% or 66% reductions in either training intensity (204), training frequency (207) or training volume (206). The results indicated that $VO_{2\text{ max}}$ was maintained over the 15-week reduction in training in both 33% and 66% reduction groups when training frequency was manipulated (207). Similar results were found when training volume was reduced, as $VO_{2\text{ max}}$ and five-minute exercise performance were maintained in both the 33% and 66% volume reduction programmes. However, when training intensity was reduced by 33%, $VO_{2\text{ max}}$ was not maintained but still remained higher than pre-training levels, while in the 66% reduction group, $VO_{2\text{ max}}$ declined to an even greater extent. Furthermore, five-minute exercise performance was maintained in the 33% reduction group, whereas it was markedly reduced in the 66% reduction group. Moreover, two-hour cycling performance was significantly reduced in the latter group by a greater amount compared to the 33% intensity reduction group (30% and 21%, respectively).

Wittig *et al* (488, 489) conducted two studies to investigate the effects of a taper period on well-trained distance runners. The comparison of these two studies suggests that maintenance of training intensity is vital during a period of taper. In

one of the studies of Wittig *et al.* (488) the runners ($n = 10$) reduced their training volume by 70% for three weeks and it was found that 5 km race performance was maintained during the taper period. The second study (489) was also conducted using well-trained distance runners ($n = 10$), except this time the training volume was reduced by 66% with a concomitant reduction in training intensity so that all training was carried out at below 70% $VO_{2\text{ max}}$. The results indicated a significant decline of approximately 1% in 5 km race performance from 16:36 to 16:48 (min:s). In a study comparing taper periods of differing intensities, Shepley *et al.* (428) found that exercise performance was improved following a period of taper involving a higher training intensity compared to one with a lower training intensity. Similarly, Houmard *et al.* (230) determined the effects of an 85% reduction in training volume on 5 km race performance in well-trained distance runners. Approximately 6% to 10% of the pre-taper total weekly training volume consisted of interval sessions and / or racing at high intensity. During the taper period, habitual training was replaced with intervals of high intensity running at 90% $VO_{2\text{ max}}$ with the result that 5 km race performance was significantly improved by 3% from 17:18 to 16:48 (min:s).

A meta-analysis by Bosquet *et al.* (63), which analysed 27 studies involving swimming, cycling and running investigations, also confirmed that performance improvement was maximal with a total reduction in training volume of 41 – 60%. The authors further find that training intensity is key in the maintenance of training-induced adaptations during the taper which is in agreement with the findings in the literature.

1.4.2.2.3 Training frequency during the taper period

It has been suggested that certain sports, such as swimming, require a minimum frequency of training during a taper period (270). Various studies have been conducted to investigate this factor in swimmers (206, 228, 245, 352). This was investigated by Bryntesson and Sinning (71) in cyclists and it was concluded that training at least three days a week, was required to maintain pre-taper fitness gains. Similarly, Hickson and Rosenkoetter (207), described reductions in training frequency in well-trained runners and found that both a 33% and 66% reduction in training frequency were able to maintain pre-taper $VO_{2\text{ max}}$ values. Bosquet *et al.* (63), however, report that a decrease in training frequency does not result in

performance improvement from the analysis of 27 studies in the literature. The authors do recognise that each moderated variable (frequency, volume, intensity and style of taper) often interacts closely with other variables and so it is difficult to precisely isolate each variable's effect on performance and other tested parameters.

1.4.3 The effect of pacing strategy on endurance performance in well-trained individuals

The way that an athlete distributes work and energy throughout an exercise task is referred to as a 'pacing strategy' (5, 115, 150, 151, 167, 291, 441, 469). It is well documented that this strategy can impact on performance, as it is the aim of the pacing strategy to regulate speed to delay fatigue and reach the end point of an event in the fastest time possible (10, 150, 151, 167, 184).

A variety of different pacing strategies have been described in the literature, the selection of which depends on the race type and duration (5, 116, 201, 467). These include positive, negative and even pacing strategies, as well as 'all-out', parabolic-shaped and variable pacing strategies (5). A graphic representation of these strategies is shown in Figure 1.1.

i) Positive pacing strategy

A positive pacing strategy is one where the athlete reaches a peak speed and then gradually slows over the duration of an event (5). It has been shown that this strategy results in an increased volume of oxygen inspired (VO_2) due to increased running speed (413, 463), greater blood lactate accumulation (463, 464) and increased ratings of perceived exertion (RPE) (463) during the early stages of an event. In response to these signals, speed may then be reduced progressively in order to prevent failure of one or more physiological systems (276, 365-367). This strategy has been observed during the 100 m and 200 m breaststroke swimming events (462), 800 m track running (413) as well as ultra-endurance events (> four hours) (6, 277, 282, 283, 375).

ii) Negative pacing strategy

In contrast to the latter strategy, a negative pacing strategy is one where there is a progressive increase in speed over the duration of an event (5). This pacing strategy

leads to improvements in endurance performance by lowering the rate of carbohydrate depletion (4), reducing VO_2 (413) and lowering the accumulation of fatigue-related metabolites (4, 314, 400) in the early stages of an event (5). Certainly Mattern *et al.* (314), reported significantly lower blood lactate accumulation during the first nine minutes of a 20 km cycling time trial combined with significant improvements in time trial performance when a negative pacing strategy was enforced compared to self-paced time trials. A negative pacing strategy is often observed in middle distance events (5) and it has been suggested that the ability to further increase speed or power output in the final stages of an event may be the result of an increase in motor unit recruitment (470) and the use of 'anaerobic' energy reserve (147).

iii) Even and 'All-out' pacing strategies

It has been suggested that under stable environmental conditions, an even pace, represented by minimal acceleration and deceleration from the chosen pace, is optimal for performance in events of less than two minutes (115, 463, 464). However, an 'all-out' pacing strategy is often observed during short distance events (< 30 seconds), where it has been demonstrated that 50% – 60% of the event is spent in the acceleration phase (5).

iv) Parabolic and variable pacing strategies

A parabolic-shaped pacing strategy is characterised by a U, J or reversed J-shaped curve, where speed may be progressively reduced during the first stages of an event, followed by a progressive increase in speed in the later stages of the event (160, 470). Garland (160), investigated the pacing strategy employed during the 2000 m rowing event and found that the first 500 m of the race was performed in the fastest time, followed by a slower middle 1000 m and then an increase in speed again in the final 500 m of the race (reverse J-shape curve). It has been suggested that this pacing strategy could be the result of a combination of positive and negative pacing strategies (5). A variable pacing strategy is different to this, however, as it is characterised by continual fluctuations in power output or work rate and is usually adopted in response to inconsistent environmental conditions (24, 452). This has been demonstrated in cyclists, where reduced power output has been observed in

downhill sections of a race compared to increased power output during uphill sections, resulting in the maintenance of a more constant speed and improvements in overall cycling performance (452).

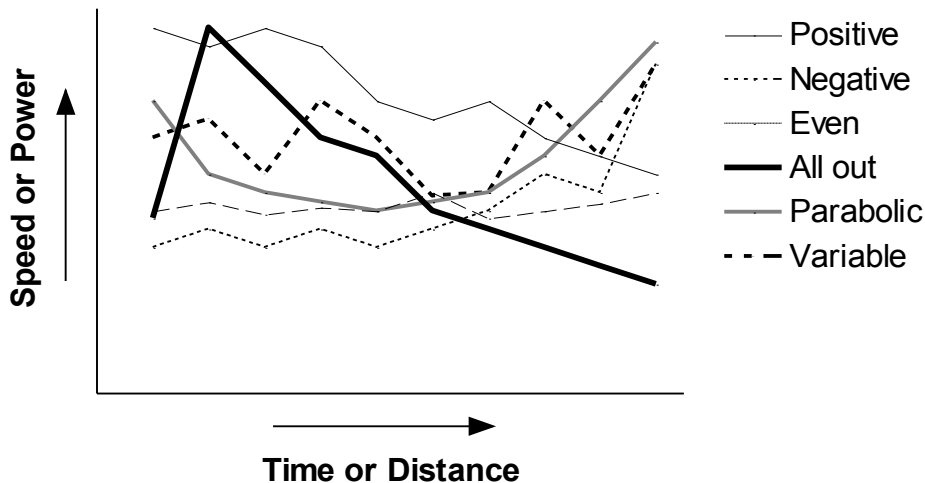


Figure 1.1 A graphic representation of the various pacing strategies described in the literature.

Notes: The data represented above are theoretical for descriptive purposes.

The variable pacing strategy would be representative of power fluctuations and not speed as the end goal is ultimately the maintenance of speed.

1.4.3.1 Determination of an optimal pacing strategy

There are numerous studies in the literature that have been performed to assess which of the aforementioned strategies is optimal for different types of exercise bouts, the results of which are inconclusive. De Koning *et al.* (115) found that an all-out strategy over the entire distance was optimal for a 1000 m track cycling time trial, however, an all-out start followed by a constant power output for the remainder of the trial, was more beneficial for a 4000 m track cycling time trial. Bishop *et al.* (52) investigated the effectiveness of different pacing strategies on a two-minute kayaking laboratory time trial and found that an all-out strategy resulted in superior results compared to an even pacing strategy. Furthermore, Foster *et al.* (146) examined different pacing strategies during cycling time trials of different durations and found that all cyclists started with an initial high power output, then subsequently

decreased power output for the middle section before increasing power output again in the final section of all of 500 m, 1000 m, 1500 m and 3000 m distance laboratory cycling time trials. Similarly, Ansley *et al.* (17) found that both sEMG and power output were increased in the final 60 seconds of a 4 km cycling time trial. According to St Clair Gibson *et al.* (441), it appears that each individual might have a uniquely optimal pacing strategy for different athletic events. They further suggest that additional research is needed to determine which pacing strategy might be optimal to athletic events of differing durations and indeed whether there is no single optimal pacing strategy (441).

1.4.3.2 Models of fatigue

As previously mentioned, the delay of fatigue development during an endurance athletic event is of utmost importance, thus making the pacing strategy employed a key factor in the determination of success. There are two main theories describing the initiation of fatigue during endurance exercise. The 'peripheral fatigue' theory is related to fatigue produced by changes in metabolite concentrations at, or distal to, the neuromuscular junction (159). It is suggested that accumulation of certain intramuscular metabolites inhibits the contractile process in the muscles, so resulting in fatigue and the eventual inability to continue exercising (29, 82, 259, 487). The second theory, termed 'central fatigue', involves a reduction in neural drive to the muscles, thus resulting in a decline in muscle force production, which is suggested to be independent to changes in skeletal muscle contractility (37, 129). The underlying mechanisms influencing the regulation of pace are unclear; however, models based on the aforementioned theories of fatigue have been developed and investigated in a number of studies. Ulmer (473) developed a theory of 'teleoanticipation' where, before the start of exercise, the body calculates the optimal amount of exertion required to finish the desired exercise bout without early fatigue. It was suggested that there is a central programmer which works backwards from a known end point. In an extension of this theory, termed the central governor model, it is proposed that afferent peripheral feedback results in the sensation of fatigue by a central governor in the brain (276, 365, 366, 443). Skeletal muscle motor recruitment is then continuously adjusted resulting in an observed pacing strategy, the object of which is to prevent physiological failure (276, 367, 443). The majority of evidence to support

the central regulation of pacing strategies is based on exercise in the heat (357, 372, 470) or at altitude (84, 365, 367, 388).

Measurement of sEMG changes in exercising muscles is also used in investigations into central fatigue based on the assumption that changes in this parameter are a reflection of changes in neural drive (443). According to peripheral theories, muscle recruitment should progressively increase to compensate for a decrease in muscle contractility from metabolite accumulation. According to the central theories, however, muscle recruitment should decrease concurrently, indicating that the decreased work output is related to reduced motor unit recruitment rather than contractility. Indeed St Clair Gibson *et al.* (444) had well-trained cyclists perform a 100 km cycling time trial during which 1 km and 4 km high intensity bouts were performed. They found that reductions in sEMG of *rectus femoris* and *vastus lateralis* paralleled a decline in power output during these repeated bouts. Conversely, Hettinga *et al.* (201) found that sEMG of *vastus lateralis* and *biceps femoris* increased or remained the same despite a decline in power output towards the end of a 4 km cycling time trial, irrespective of the use of a positive, negative or even pacing strategy.

1.4.3.3 Ratings of perceived exertion and pacing strategies

The perception of effort during exercise and its relation to fatigue has been investigated in many studies (188). There are various scales that have been developed to quantify this perceived exertion, however, Borg's 15 point RPE scale is the most widely used. RPE are frequently used to investigate the setting of a pacing strategy dependent on perceived exertion and affiliated sensations of fatigue (240). Tucker and Noakes (469) propose an anticipatory-RPE model where the brain will generate a conscious RPE based on afferent information and produce a range of RPE templates which are then compared against each other. Accordingly, distance knowledge and distance feedback are integral to the working of this process (469).

1.4.3.4 The effects of distance knowledge and feedback on pacing strategy

To test the importance of prior distance knowledge and distance feedback during an event on the effectiveness of a pacing strategy and subsequent performance, Albertus *et al.* (10) designed an experiment where well-trained cyclists performed

five 20 km cycling time trials. The cyclists were informed of the distance they would be covering in each time trial, however, during the subsequent trials they received either correct or incorrect distance feedback every kilometre. During the incorrect trials, the distance feedback was up to 250 m longer or shorter per kilometre than actuality. It was found that the overall performance, pacing strategy and RPE were not different from that found in the correct feedback trial. This finding supports the hypothesis that the pacing strategy is set prior to the onset of exercise, based on the anticipated exercise duration and that this strategy is unaffected by discrepancies in distance feedback of this magnitude. It has been suggested that if the discrepancy between actual and informed distance had been larger or if the participants had known of the mismatch, that their strategy may have changed based on to these conscious cues (469).

In another study, Nikolopoulos *et al.* (358) misleadingly informed well-trained cyclists that they would be performing four 40 km cycling time trials, when the distance was actually either 40 km or 15% less or more than this (34 km and 46 km, respectively) for the first three time trials. The first three time trials were performed randomly, and the fourth in the sequence was always a distance of 40 km. It was found that performance (average power and heart rate) and pacing strategy during the 34 km, 40 km and 46 km time trials were all similar. Furthermore, when participants were then correctly informed of the distance to be covered, no differences were found in both performance and pacing strategy in two subsequent time trials of the same distances (34 km and 46 km, respectively). These two results together possibly indicate that the distance discrepancy was perhaps not large enough to cause the participants to alter their pacing strategy (469). Interestingly, in this study the participants were provided with distance feedback during the time trial which indicated the percentage of the distance remaining. As suggested by Tucker and Noakes (469), this type of feedback would have allowed the pacing strategy to be constantly readjusted with respect to the endpoint. A study design where participants are given no feedback or incorrect feedback (as in the aforementioned study of Albertus *et al.* (10)) may be more effective in determining the importance of distance knowledge to a pacing strategy and subsequent performance.

A further study of Ansley *et al.* (16) informed cyclists that they would be performing a 30-second bout of supra-maximal cycling, when in fact they performed a 36-second

bout. It was found that the power output in the final six seconds of the 'deception 36-second bout' was significantly slower than the final six seconds of a 36-second bout when participants were correctly informed of the distance to be covered prior to onset. It is suggested that the decline in performance when the anticipated duration was exceeded by 20% could indicate that physiological resources were incorrectly allocated, adding evidence to the hypothesis that a pacing strategy is based on anticipated duration resulting from previous experience of the distance (469).

The study of Lima-Silva *et al.* (291) examined the influence of performance level on 10 km time trial performance in distance runners. The participants were divided into either a low-performance group or high-performance group, based of their 10 km running time trial performance (> 39 minutes and < 36 minutes, respectively). The results demonstrated that the two groups adopted different pacing strategies during the 10 km time trial. Specifically, the low-performance group adopted a more even pacing strategy with no significant difference found between running speed during any stage of the race, whereas the high-performance group adopted a classic U-shaped pacing strategy.

1.4.4 The effect of resistance and strength training on endurance performance in well-trained individuals

Resistance and strength training were not a focus of this thesis; for comprehensive reviews on this topic see references (143, 491). Historically, resistance and strength training have been avoided by runners due to concerns of the negative effects of muscle hypertrophy on factors such as capillary density and mitochondrial function (143, 302). However, there are reports in the literature that resistance training resulted in improved neuromuscular adaptation (411), increases in the lactate threshold (308) and that there is no negative change in $VO_{2\text{ max}}$ (265, 308, 319), but rather increases in running economy (39, 265, 377, 405) in well-trained endurance athletes following this type of training.

1.4.4.1 Effects of resistance training on running economy

There are several mechanisms by which resistance training could increase running economy: (i) an increase in muscle strength may lead to improved muscle co-ordination, motor recruitment patterns and general mechanical efficiency (35, 411,

447), (ii) the conversion of MHC type IIx fibres into more fatigue resistant MHC Type IIa fibres (405), (iii) relative intensity could be reduced with improved muscular strength and co-ordination (212, 447), or (iv) improvements in whole body strength could lead to changes in running style becoming more physiologically efficient. Consequently, types of resistance training have been incorporated into endurance training regimes as it has been shown to improve distance running performance (327, 329, 376, 440). Specifically, Paavolainen *et al.* (376) investigated the effects of explosive strength training (plyometric training) and running performance and found that 5 km running performance, muscle power and running economy were all improved after training.

1.4.5 The effect of short-sprint training on endurance performance in well-trained individuals

Short-sprint training (less than ten seconds) often involves repetitions of brief maximal intensity sprints interspersed with either long or short recovery periods (162, 406). There appears to be a general consensus among leading coaches that two to three maximal intensity sessions per week is optimal to improve performance in middle to long distance events (389). This observation is in accordance with the scientific literature as it has been shown that daily sprint training did not improve cycling performance, whereas training every third day significantly improved both peak and mean cycle sprint power (385). Short-sprint training has also been shown to be beneficial to endurance running performance as Dawson *et al.* (114) found that six weeks of short-sprint training (mean of 16 sprint sessions consisting of 20 to 40 sprints in each session over the six-week period) improved endurance, sprint and repeated sprint ability in well-trained runners with an increase in MHC Type IIa muscle fibres.

The adaptations of skeletal muscle to sprint training can be divided into morphological and metabolic changes. Muscle contraction speed and strength are largely determined by morphological adaptations such as muscle fibre type, muscle cross-sectional area and sarcoplasmic reticulum adaptations (406). The maximal unloaded shortening velocity of MHC Type IIa and IIb fibres is approximately ten times faster than MHC Type I fibres (64), making an increased expression of the former more advantageous for improved sprint ability. Indeed, sprint training has

been shown to induce increased expression of MHC Type IIa fibres in skeletal muscles bi-directionally from both MHC Type I and Type IIb isoforms (13). Furthermore, sprint performance has been correlated with the percentage of MHC Type II fibres (114, 119, 131, 323). It has been observed that eight weeks to eight months of sprint training results in significant increases in the fibre area of both MHC Type I and Type II fibres (81, 433) and additionally Sharp *et al.* (427) demonstrated that skeletal muscle buffer capacity was increased following eight weeks of highly intense cycle sprint training in well-trained cyclists.

The metabolic adaptations to short-sprint training have been extensively reviewed (406). These adaptations are associated with an enhanced ability of the muscle to produce energy through enzymatic adaptations in the various pathways involved in skeletal muscle metabolism. In general, key regulatory enzyme activity is increased, enhanced substrate storage is made possible and increased ability to decrease accumulation of metabolites associated with muscular fatigue is achieved (406).

1.4.6 The effect of high intensity interval training on endurance performance in well-trained individuals

Whereas short-sprint training is generally comprised of short duration sprints of only a few seconds, HIIT can be prescribed to involve intervals of high intensity for longer duration, making this type of training more appropriate for endurance events, as the training not only involves adaptations to the neuromuscular and anaerobic system but the aerobic energy system as well (281, 301, 401, 430).

1.4.6.1 Definition of high intensity interval training and development of training programmes

HIIT can be broadly defined as the repetition of specific exercise at an intensity greater than the lactate threshold which is carried out in bouts of short to moderate duration with periods of recovery between (44, 73, 74, 109, 194, 281). The idea behind HIIT is to stress the physiological systems used during endurance exercise to a greater extent than that required during the activity (44, 281). The length and intensity of individual work bouts and duration of training stimulus are factors which are debated in the literature, however, to date no optimal HIIT programme has been defined to improve endurance running performance.

HIIT has a long history and was incorporated into training regimes before there was any scientific knowledge on this topic. Emil Zatopek was a Czech long distance runner who is the only person to win three long distance gold medals, in the 5000 m, 10 000 m and marathon at a single Olympics (1952). Later, in 1954, he became the first person to break the 29-minute barrier for 10 km and is thus widely regarded as one of the greatest runners of the 20th century. Interestingly, he was also well known for the type of training which he employed, as this was different to that which was popular at this time. He was one of the pioneering athletes to use HIIT to improve his distance running performance (44). Zatopek calculated the critical speed at which he ran his intervals from his personal best speed achieved in 3 km to 10 km events. It is recorded that, per HIIT session, he repeated up to 100 x 400 m intervals at a pace of about 20 km·h⁻¹ with a recovery run of 200 m at a pace close to that of “hard work” (44). Following him, various other successful long distance runners made use of varying HIIT programmes such as Gordon Pirie, Sigfried Hermann and Vladimir Kutz.

Prior to the first scientific studies on HIIT, the runners and trainers who used this type of training largely based the intensity of intervals on the runners’ best previous performance at a specific distance, with the range of speed requirements of a race being of utmost importance. This is also evidenced by the fact that the final lap of a 10 km race is currently run in less than one minute (greater than 24 km·h⁻¹) which is well above a runner’s speed at $VO_{2\text{ max}}$. Subsequently, following the success of these athletes, many more runners began to incorporate HIIT into their endurance training regimes with the first scientific description of HIIT being published in 1959 by Reindell and Roskamm (395). The inclusion of science into HIIT programmes led to the intensity of intervals being based on the velocity achieved at $VO_{2\text{ max}}$.

The majority of studies in the literature pertaining to HIIT have been conducted on untrained individuals (30, 42, 76, 77, 89, 152, 267, 295, 301, 303, 321, 495) but, as stated previously, it is known that already well-trained individuals respond differently to training compared to untrained individuals and therefore the results of these studies cannot necessarily be applied when dealing with well-trained athletes. There are comparatively fewer studies involving well-trained athletes addressing the effects of HIIT on running (117, 139, 261, 399, 423, 424, 437, 438) than there are

investigating cycling (106, 177, 243, 285, 286, 293, 384, 404, 425, 445, 446, 453, 481, 483)

1.4.6.2 High intensity interval training intervention studies involving well-trained cyclists

Lindsay *et al.* (293) and Weston *et al.* (483) both examined the effects of four weeks of HIIT on performance measures in well-trained cyclists. The cyclists in these studies replaced $15 \pm 2\%$ of their $300 \text{ km}\cdot\text{wk}^{-1}$ with six HIIT sessions over the 28-day period, each consisting of six to eight 5-min repetitions at 80% of peak power (as established from baseline peak power tests prior to training), separated by one minute of recovery. Westgarth-Taylor *et al.* (481), studied the effects of 12 sessions of HIIT over a six- to seven-week period with each session consisting of six to nine 5-min repetitions, also, at 80% peak power output (PPO) with one minute of recovery in between. It was reported that PPO, 40 km time trial performance and absolute and relative workloads during the 40 km time trial were all significantly improved following the HIIT programme in both the studies of Westgarth-Taylor *et al.* (481) and Lindsay *et al.* (293). Furthermore, in the study of Weston *et al.* (483), skeletal muscle buffering capacity was found to be correlated significantly with 40 km time trial performance prior to HIIT and the relationship between the change in skeletal muscle buffering capacity and the change in 40 km time trial was close to significance, indicating that this variable responded positively to the six sessions of HIIT over a 28-day period.

In another study, Jemma *et al.* (243) investigated the effects of three weeks of HIIT on sEMG and 40 km time trial performance in well-trained cyclists. As in the previous studies cited, the participants replaced 15% of their weekly endurance training with six sessions of HIIT over the three-week period with each session being comprised of eight 5 min work bouts at 82% PPO with one-minute active recovery at 100 W. It was reported that 40 km time trial performance was significantly improved and that the mean power frequency of the sEMG was decreased after three weeks of HIIT. The frequency of sEMG is a measure of muscle fatigue where a decreased frequency is indicative of a reduced degree of fatigue in the muscles in which it is measured. The authors suggested that this reduced degree of fatigue was possibly due to the recruitment of additional slow-twitch motor units (243).

Creer *et al.* (106) also conducted a study to determine the effects of a HIIT programme on performance and sEMG in well-trained cyclists. In this study, the four weeks of HIIT comprised bi-weekly sessions of a series of 30-second all-out sprints separated by four minutes of active recovery at 50 W and cadence less than 75 revolutions per minute. The first week consisted of four 30-second all-out sprints, with an additional two being added each subsequent week, until there were ten 30-second sprints being performed in week four. Following the HIIT programme, there was a significant increase in both total work output and motor unit activation.

Stephens *et al.* (445), designed a study to attempt to ascertain the best training stimulus to improve 40 km time trial performance in well-trained cyclists. Participants were randomly assigned to one of five HIIT groups: 12 x 30 seconds at 175% PPO, 12 x 60 seconds at 100% PPO, 12 x 2 min at 90% PPO, 8 x 4 min at 85% PPO or 4 x 8 min at 80% PPO. It was concluded that maximal enhancement in 40 km cycle time trial performance was observed after work bouts of four minutes and an intensity of approximately 85% PPO. Similarly, Laursen *et al.* (285, 286) also aimed to determine the effects of different HIIT programmes on certain variables including performance in well-trained cyclists. Participants were randomly assigned to one of three training groups, all with varying work to recovery intervals and varying intensities based on either a percentage of PPO or time-to-exhaustion measured during a progressive cycle test to determine PPO (T_{PPO}). The study found that 40 km time trial performance improved significantly in all training groups and accordingly the authors recommended the inclusion of a variety of exercise intensities, durations and recoveries into the training programmes of elite cyclists. Specifically, the HIIT group performing eight intervals per session at 60% T_{PPO} with a 1 : 2 work to recovery ratio over the four-week training period (two HIIT sessions per week) resulted in a greater significant improvement in 40 km time trial performance compared to the control group who continued with low-intensity base training throughout the experimental period.

In a study to determine the effects of HIIT by heart rate or power on well-trained cyclists, Swart *et al.* (453) designed HIIT programmes consisting of eight repetitions of four minutes at either 80% PPO (power group) or at the heart rate coinciding with 80% of PPO (heart rate group) with rest periods of 90 seconds. Forty km time trial performance was significantly improved in both interval training groups, however,

there was no significant difference between the groups. Interestingly and contrary to the literature, when the data in the aforementioned study were analysed using magnitude-based effects, the heart rate group showed a greater probability to improve PPO than the power group.

In a more recent study, Seiler *et al.* (425) compared the effects of three different seven-week interval training programmes on well-trained recreational cyclists. The training programmes were matched for effort but all varied in interval duration. Specifically, the three different interval groups performed two sessions per week of either 4 x 4 min intervals, 4 x 8 min intervals or 4 x 16 min intervals. All three groups performed an additional two-to-three unsupervised low intensity bouts per week. Additionally, a control group trained four-to-six sessions per week at a low intensity. The interval sessions in the three experimental groups were prescribed at the maximal tolerable intensity to be able to complete all intervals within a session. This resulted in the training being performed at $88 \pm 2\%$ of HR_{max} in the 4 x 16 min group, $90 \pm 2\%$ in the 4 x 8 min group and $94 \pm 2\%$ in the 4 x 4 min group. The 4 x 8 min training intervention induced greater overall gains in VO_{2max} , power at VO_{2max} and power at 4 mM blood lactate as well as improved time-to-exhaustion at 80% of pre-intervention peak aerobic power in comparison to all other groups involved in the study. The authors conclude that accumulating 32 min of work at 90% HR_{max} resulted in greater adaptive gains than accumulating 16 min of work at 94% HR_{max} or accumulating 64 min of work at 88% HR_{max} . The findings suggest that a vital interaction exists between work duration and intensity of interval sessions and that it is possible to determine the optimum combination of these to induce maximal physiological adaptations in endurance athletes performing interval training.

1.4.6.3 High intensity interval training intervention studies involving well-trained runners

i) Research assessing time trial performance (closed loop) following high intensity interval training

As previously mentioned in section 1.2, tests employing a closed loop protocol yield markedly better CV's compared to open loop tests (34, 51, 202, 383, 436). CV's

ranging from 1.0 – 2.7% have been observed for these types of tests in well-trained runners making them highly reliable as a performance measure (280, 410, 419).

One of the first investigations into the physiological adaptation from increased training intensity on well-trained distance runners was conducted by Acevedo and Goldfarb (8). In this study, participants took part in eight weeks of higher intensity training, where each week consisted of three high intensity sessions (Monday, Wednesday and Friday) with the remaining days comprising of 8 – 19 km per day consistent with training prior to testing (intensity and exact duration of these runs are not reported), so that weekly mileage remained constant before and during the testing period. One of the HIIT sessions comprised intervals run at 90 to 95% of maximal heart rate (HR_{max}) with limited recovery between the intervals (the next interval was started when heart rate returned to 120 $beats \cdot min^{-1}$). The other two HIIT sessions consisted of 'Fartlek' sessions covering a total distance of approximately 10 – 16 km. The faster bouts were run at a pace "slightly below to faster than 10 km race pace" (the exact pace is not reported) with a slower pace between these bouts allowing minimal recovery. Ten-kilometre race time was assessed on an outdoor course before and after the training intervention. It was found that 10 km running performance was significantly improved by approximately 3% from 35:27 to 34:24 (min:s). Although this is a substantial performance improvement, a potential weakness is that not all the participants were tested on the same course before and after the training intervention.

In contrast to the findings of the latter study of Acevedo and Goldfarb (8), Iaia *et al.* (238) found no change in 10 km time trial performance following the HIIT intervention in their study. Participants in this study were randomly assigned to either a HIIT group or to a control group, with testing taking place before and after the four-week training intervention in both groups. All training was completed on a 400 m track. The control group completed moderate intensity ($13.0 \pm 0.4 \text{ km} \cdot \text{h}^{-1}$) regular endurance training throughout the study, which amounted to a session of $52.3 \pm 2.4 \text{ min} \cdot \text{day}^{-1}$ four times a week with a total distance of $42.2 \pm 5.1 \text{ km} \cdot \text{wk}^{-1}$. The HIIT group replaced the ordinary training with interval sessions on alternate days consisting of eight to twelve 30-second running bouts, separated by three minutes of rest. The intensity of the runs was $22.4 \pm 0.4 \text{ km} \cdot \text{h}^{-1}$, corresponding to 93% of the speed achieved in an 'all-out' 30-second sprint. This intensity was

modified accordingly over the course of the training period so that relative intensity was maintained. Alternate days consisted of low-intensity running amounting to $9.9 \pm 0.3 \text{ km}\cdot\text{wk}^{-1}$. The 10 km time trial was performed on a 400 m track and, as previously mentioned, no change in performance was observed in either the HIIT group ($40:52 \pm 1:09$ vs $40:49 \pm 1:30$ (min:s)) or the control group ($40:53 \pm 2:41$ vs $40:36 \pm 2:27$ (min:s)). The HIIT sessions employed in the two aforementioned studies are very different in terms of their duration and intensity of intervals and it would appear from these results that longer intervals of high intensity are more beneficial to 10 km running performance than shorter high speed sprints. It is interesting to note the findings of other studies that have investigated the effects of differing HIIT interventions on shorter distance time trials with regard to whether a similar pattern was observed.

One such study compared the effects of two different four-week long HIIT programmes on 3 km and 5 km running performance in well-trained distance runners (437). The intensity of the HIIT sessions was based on the speed at which $\text{VO}_{2\text{ max}}$ was elicited in a $\text{VO}_{2\text{ max}}$ test ($V_{\text{ max}}$) and the duration of the HIIT sessions was based on the length of time that $V_{\text{ max}}$ could be sustained ($T_{\text{ max}}$). Both HIIT programmes consisted of two sessions per week over the four-week period, with the one programme consisting of six intervals at 60% $T_{\text{ max}}$ per session (60% $T_{\text{ max}}$ group) and the other programme, five intervals at 70% $T_{\text{ max}}$ per session (70% $T_{\text{ max}}$ group). The 3 km and 5 km time trials were performed on a synthetic track before and after the training intervention. There was a significant improvement in 3 km time trial performance time (10:17 (min:s) or 617 s) vs 10:00 (min:s) or 600 s) in only the 60% $T_{\text{ max}}$ group following the four-week HIIT programme and no significant improvement in 5 km time trial performance following either training programme.

Interestingly, another study by Kohn *et al.* (261) based the HIIT regime in their study on the aforementioned study of Smith *et al.* (437), however, some modifications were made. For example, the interval speed was calculated as 94% of peak treadmill running speed (PTRS) as attained from the maximal test previously administered, whereas in the study by Smith *et al.* (437) the intensity of the intervals was based on $V_{\text{ max}}$, as attained from the same maximal test. When the data are analysed in these two studies it is, however, observed that the intensities of the intervals was very similar. An additional modification was that only a 60% $T_{\text{ max}}$ group was compared to

a control group in the study of Kohn *et al.* (261). In this study it was found that there were no significant changes in 10 km time trial performance following the HIIT intervention. In agreement with our previous observation, this specific interval programme where the intervals are based on an intensity and duration of V_{\max} and 60% T_{\max} , respectively, seems better suited to improve shorter distance (3 km) time trial performance as opposed to that of the longer distances (5 km and 10 km). In comparison to the study of Acevedo and Goldfarb (8), the interval intensity is higher, but the duration of the intervals much shorter. It is interesting though, based on this observation, that the longer interval duration of 70% T_{\max} was unable to elicit 5 km performance improvements in the study of Smith *et al.* (437).

Similarly, Denadai *et al.* (117) analysed the effects of four weeks of two different HIIT programmes on 1500 m and 5000 m running performance in well-trained distance runners. Participants were randomly assigned to either a 95% V_{\max} group or a 100% V_{\max} group, where two HIIT sessions of four intervals per session were performed per week in conjunction with four submaximal runs (45 – 60 min at 60 – 70% V_{\max}) per week. Total weekly volume was recorded as 77.5 ± 3.8 km in the 95% V_{\max} group and 78.2 ± 3.9 km in the 100% V_{\max} group and distance covered during each HIIT session was 6.4 ± 1.5 km and 6.1 ± 1.9 km, respectively. The results showed a significant improvement in 5000 m time trial performance in both groups post-training, as well as a significant improvement in 1500 m time trial performance in the 100% V_{\max} group only. The authors postulate that it is possible that the 100% V_{\max} group may have experienced a greater overload to the cardiovascular and aerobic enzymatic systems for an extended time compared to the 95% V_{\max} group, which may have contributed to the greater performance benefits observed over the shorter distance (1500 m).

ii) Research assessing run-to-exhaustion performance (open loop) following high intensity interval training

It is important to reiterate (from section 1.2) that CV's ranging from 13.2 – 17.0% have been reported for open loop tests, such as run-to-exhaustion tests, in well-trained runners (49, 280). Accordingly, these tests are not seen to be as reliable or valid as closed loop tests (202, 244, 266, 387).

The aforementioned study by Acevedo and Goldfarb (8), also assessed run time-to-exhaustion on a treadmill before and after their prescribed HIIT intervention as previously described. Intensity for the run-to-exhaustion test was set at 15 seconds more than the initial 10 km pace time for each participant and at a 2% gradient. Run time-to-exhaustion was improved significantly by 3:53 (min:s) from 19:25 ± 2:06 to 23:18 ± 2:28 (min:s), representing a 20% improvement in performance for this test. However, as stated previously, it is important to consider whether this is a meaningful difference or not, based on the large CV's observed in this kind of test.

In another study, Roberts *et al.* (399) investigated the effects of a five-week HIIT programme on running performance, of well-trained distance runners, as measured by an open loop treadmill test at 16 km·h⁻¹ and 15% gradient. The participants were tested before and after the five-week HIIT training programme. This programme consisted of 16 sessions over the training period (three to four sessions per week) with each session comprising eight x 200 m runs at 90% of maximal running speed over 200 m (as previously determined for each participant), separated by rest periods of two minutes. Following the training programme there was a significant improvement in performance time in the treadmill test (40 ± 1 s vs 49 ± 1 s).

Enoksen *et al.* (130) examined the effects of ten weeks of either high-intensity, low-volume (HILV) or low-intensity, high-volume (LIHV) interval training programmes on performance in well-trained distance runners. Both groups participated in six training sessions per week. The LIHV group performed 33% of the total training volume at 82 – 92% HR_{max} and 67% at 65 – 82% HR_{max} and ran an average of 70 km·wk⁻¹, whereas the HILV group performed 13% of the total training volume at 82 – 92% HR_{max} and 87% at 65 – 82% HR_{max} and ran an average of 50 km·wk⁻¹. Running performance was assessed via a running test to exhaustion at V_{max} (as previously determined for each participant) on a treadmill. No differences in performance were found in either group before and after the training intervention.

Ferley *et al.* (139) addressed a different aspect of HIIT and compared uphill and level grade HIIT programmes in well-trained distance runners. Participants were randomly divided into either an uphill HIIT programme (G_{hill}), a level grade HIIT programme (G_{flat}) or a control group (G_{control}). Both testing groups performed two high intensity sessions per week and two sessions per week of continuous level

running at 75% V_{\max} for 45 – 60 min, whereas the G_{control} continued their normal weekly training programme of 5 days \cdot wk⁻¹ and 270 \pm 82 min \cdot wk⁻¹. The G_{hill} programme consisted of completing ten to 14 bouts of running at V_{\max} for 30 seconds (\sim 13.5% T_{\max}) on a treadmill with a 10% grade per session. The level grade HIIT programme (G_{flat}) consisted of completing four to six bouts at V_{\max} for a duration of 60% T_{\max} on a treadmill with a 1% grade. Running performance was assessed by determining T_{\max} using a run to exhaustion test at V_{\max} on a treadmill set at 1% gradient. The results indicated that both G_{hill} and G_{flat} HIIT programmes resulted in significant improvement in T_{\max} from pre- to post-training with no significant changes observed in G_{control} . Interestingly, G_{flat} elicited greater performance gains pre- to post-training compared to G_{hill} (61.9 \pm 32.5% change in G_{flat} compared to 31.7 \pm 16.0% change in G_{hill}). In contrast to this, a study by Barnes *et al.* (34) found that five different uphill HIIT programmes of different intensities were all able to significantly improve 5 km time trial performance with a mean improvement over all intensities of 2.0% \pm 0.6%, however no comparison to level grade HIIT programmes was made in this study.

iii) Research assessing physiological parameters and metabolic markers following high intensity interval training

Acevedo and Goldfarb (8) assessed $VO_{2\max}$ using a continuous progressive treadmill test, maintaining speed while increasing the gradient by 2% every two minutes. $VO_{2\max}$ was measured as the highest value recorded during the test. $VO_{2\max}$ was measured before and after the HIIT intervention and no changes in this parameter were observed. Blood lactate concentration was also measured before and after the HIIT intervention. Blood samples were obtained at six submaximal intensities (65, 70, 71, 75, 80, 85 and 90% of $VO_{2\max}$) within three days of the $VO_{2\max}$ test before and after the HIIT intervention. A progressive discontinuous protocol was used where participants ran on the treadmill for five minutes at each of the specified submaximal intensities. Blood lactate concentration at rest and at $VO_{2\max}$ remained unchanged before and after the training intervention, whereas blood lactate at submaximal intensities of 85% and 90% of $VO_{2\max}$ were observed to be lower than pre-training values. Furthermore, a significant correlation was found

between the changes in lactate concentration at these intensities and the improvement in 10 km race time.

Ferley *et al.* (139) determined $VO_{2\text{ max}}$ using a different method to that of the latter study in their HIIT study. In this study, $VO_{2\text{ max}}$ was determined on a treadmill set to 1% gradient, where the speed was increased by $0.8\text{ km}\cdot\text{h}^{-1}$ every two minutes until volitional exhaustion. Each participant's lactate threshold was defined as the speed which elicited a $1\text{ mmol}\cdot\text{L}^{-1}$ rise above baseline values. As previously described, participants were divided into three groups; G_{flat} , G_{hill} and G_{control} . No changes in $VO_{2\text{ max}}$ were observed in any group over the course of the six-week training intervention, nor were there any significant changes in V_{max} or lactate threshold in any group. In contrast to these findings, Enoksen *et al.* (130) found significant increases in V_{max} and vLT in the HILV group, as previously described in their study.

The aforementioned study by Kohn *et al.* (261) focused on examining fibre type changes and lactate dehydrogenase (LDH) activity following their six week HIIT intervention. Plasma lactate concentrations, muscle morphology, MHC content and various enzyme activities were all analysed before and following the HIIT intervention. No changes were observed in fibre type, citrate synthase and 3-hydroxyacetyl co-enzyme-A dehydrogenase (markers of muscle oxidative capacity) activities. LDH activity, however, was significantly increased by 9.3% in MHC Type IIa fibre pools in the homogenate following the HIIT intervention. This finding suggested that more MCH Type IIa fibres were recruited during the HIIT intervention, thereby increasing the demand for rapid ATP production (261). No change in $VO_{2\text{ max}}$ was reported, however, PTRS increased significantly following the HIIT programme from $21.0 \pm 0.8\text{ km}\cdot\text{h}^{-1}$ to $22.1 \pm 1.0\text{ km}\cdot\text{h}^{-1}$ (261). The previously mentioned study by Roberts *et al.* (399) also had a focus on the investigation of various enzyme activities following a HIIT intervention. There were significant increases observed in the activities of phosphorylase, phosphofructokinase (PFK), glyceraldehyde phosphate dehydrogenase, LDH and malate dehydrogenase, all key enzymes involved in aerobic energy production. The largest relative increase of approximately 100% in activity was in PFK, involved in the rate limiting step of glycolysis.

iv) Research investigating performance prediction ability of high intensity interval sessions

In an interesting study, Babineau and Leger (27) investigated whether running performance during three different HIIT sessions could be correlated with 5 km time trial performance and whether the performance in these HIIT sessions could be used as predictors for 5 km time trial performance. The results of these were then compared to the correlation of $VO_{2\max}$ to 5 km time trial performance. A group of well-trained endurance runners took part in a series of three standardised HIIT sessions with a work to rest ratio of five to one; 12 x 400 m (15 s rest), 6 x 800 m (30 s rest) and 3 x 1600 m (60 s rest), all performed at maximal cruising speed, which was the highest maximal speed that could be maintained over all work intervals of a single session. The times taken to complete these were correlated against 5 km time trial performance and it was found that the correlation coefficients for all three sessions were as high as that found for $VO_{2\max}$ and 5 km time trial performance. The 6 x 800 m interval produced the highest correlation with 5 km time trial performance. The authors therefore concluded that these standardised sessions are as capable of predicting 5 km time trial performance as the standard laboratory measure of $VO_{2\max}$. This is interesting as two of these sessions (12 x 400 m and 3 x 1600 m) are the same as those used for the training study in this thesis.

1.4.6.4 Summary of high intensity interval training methods

While, for the most part, the above studies indicate that HIIT has been proven to be an effective strategy to improve distance running performance over a variety of distances, the majority of the training studies have prescribed an interval training intensity which is based on laboratory measures such as % HR_{\max} , V_{\max} , T_{\max} , PTRS and % $VO_{2\max}$. Historically, the interval prescription in the first HIIT programmes used by world class runners were designed by incorporating the runner's best time at the specific distance. This reference point was used to determine the speed at which the intervals should be run. To our knowledge no HIIT programme has been published in which the design of the intervals is based on this easy to use measure.

There is paucity in the literature as to the effects of HIIT programmes on 10 km running performance and to our knowledge there is no published investigation into the effects of four weeks of continuous HIIT training on 10 km running performance. Furthermore, there are no data available pertaining to the effects of a training programme consisting of HIIT sessions of 400 m intervals, 1600 m intervals and, particularly, a combination of the two, on subsequent 10 km running performance. Specifically, no study has reported the effects of a programme of intervals consisting of two different distances as all previous studies have used only one length of interval for the training intervention. Since the demands during a 10 km race are variable, with no single speed being used throughout the distance, it is reasonable that training sessions should stress different physiological systems and also incorporate different intensities over different distance intervals. Interestingly, coaches in the field often combine sessions of shorter and longer intervals in a training week.

1.5 Summary and conclusions of the literature review

The 10 km run is a standard race distance on both track and road, as evidenced by the high prevalence of 10 km road and track events worldwide. In addition, the 10 km distance has been shown by Noakes *et al.* (364) to be one of the best predictors of performance at 21.1 km, 42.2 km and 90.0 km ($r = 0.91 - 0.98$) in specialist marathon and ultra-marathon runners. The 10 km race is therefore an important distance in running and consequently warrants investigation and scrutiny as to methods to improve performance at this distance.

To adequately measure performance benefits of any training intervention, it is first imperative to design a measurement protocol that is both reliable and valid (91, 107, 218-220). Open loop time-to-exhaustion testing protocols have yielded far lower reliability (CV's ranging from 13.2 – 17.0% in well-trained runners) compared to closed loop protocols, such as time trials (CV's ranging from 1.0 – 2.7% in well-trained runners) (49, 280, 410, 419). Accordingly, a clear recommendation is given that to test a training intervention in a sport such as running, it is advisable to make use of a time trial protocol as this is a more valid and reliable protocol (107).

Following training interventions, the importance of improvements in VO_2 max, running economy, the lactate threshold and neuromuscular factors should not be ignored, but for athletes in competition, the most important variable is race time or performance. Combined with this, the complexity of the variables of training adaptation and individual differences in athletes makes the transfer of knowledge from laboratory to coach to athlete more challenging. In a country such as South Africa, it is realistic to assume that the majority of the running population are found in lower income groups who may not have exposure to scientific research or access to scientists, laboratories and even formal coaching. It is therefore a necessity to present training programmes to improve running performance that are easily applied and understood and not reliant on laboratory-measured physiological variables. It is for these reasons that we have chosen to base the HIIT programmes administered in this thesis on the athletes' current 10 km performance time. This measure was used by coaches and athletes prior to the scientific study of HIIT programmes, yielding success with many athletes at the time and we feel that for the aforementioned reasons this is a method that could be beneficial from a practical perspective.

1.6 Objectives of the thesis

The primary objective of this thesis was to examine the effects of three different HIIT programmes on physiological determinants of running performance and to determine whether these programmes improve 10 km running performance time in well-trained endurance runners.

In order to achieve this objective, it was first imperative to design a testing protocol that was both reliable and valid to adequately determine the effects of the training programmes on the variables measured and indeed to confirm whether this measurement has sufficient precision to detect small meaningful changes in performance. Therefore, the first objective of this thesis was to investigate the reliability and validity of a 10 km TTT to be used in the subsequent training study. (Chapter Two)

The subsequent chapters (Four to Seven) are based on a large training study, making use of the same participants throughout, with data collected systematically over the course of the training period using the 10 km TTT as a performance

measure. Each chapter addresses a specific question or performance related parameter and the effects of three different HIIT programmes on these parameters.

The following questions are addressed in the training study:

- i) What 10 km running performance change (if any) is observed following the three different HIIT programmes? Furthermore, are there associated changes in $VO_{2\max}$, running economy, running economy as % $VO_{2\max}$, PTRS, 20 m sprint time, and average heart rate as a percent of HR_{\max} , following any of the HIIT programmes? (Chapter Four)
- ii) What is the effect of a period of reduced training (taper) on the 10 km running performance and physiological variables measured? Specifically, is there an optimal duration of the taper and does the preceding training regime affect the effectiveness of the taper period? (Chapter Five)
- iii) Do different HIIT programmes result in any changes to the pacing strategy during a 10 km TTT and if so, are any changes in pacing strategy associated with 10 km TTT performance? (Chapter Six)
- iv) Are there any changes observed in neuromuscular characteristics such as muscle strength, sEMG and stride parameters following the three different HIIT programmes? Furthermore, can any observed changes be associated with 10 km TTT performance? (Chapter Seven)

To our knowledge, this study is novel because; (i) it examines the reliability and validity of a 0% grade 10 km TTT that has not been preceded by a pre-load run, (ii) the interval training programme involves two different training intensities and distances in one training programme, (iii) pacing strategies during a specific event following HIIT programmes are studied.

It is anticipated that addressing these questions will add to the body of knowledge on the effects of HIIT on running performance. In addition, answers to these questions will provide a training technique that is inexpensive, easy to administer and valid for coaches to use in the development of training programmes for 10 km runners. Furthermore, answers will provide scientists with a testing protocol which is both

valid and reliable with precision to detect meaningful changes in running performance.

CHAPTER TWO – RELIABILITY AND VALIDITY OF A SELF-PACED 10 KM TREADMILL TIME TRIAL IN WELL-TRAINED MALE DISTANCE RUNNERS

2.1 Introduction

Performance tests are one of the most important and commonly used measures in sports science, a good test being one that is both valid and reliable (55, 107, 217, 218). A valid test is one that is designed to most closely resemble the performance being tested. The reliability of a test refers to the variation within a protocol when it is administered more than once (107, 418). Reliability is a key consideration when deciding on a tests' utility, especially when the test is to be administered on two or more occasions to the same participant. In research that involves an intervention that may affect the performance outcome, reliability impacts on the power of the test to detect meaningful changes in performance (55, 91, 418, 420) and the validity impacts on the actual practical applications of such an intervention.

Reliability is usually expressed as a coefficient of variation (CV), describing the within-participant variation expressed as a percentage of the participants' mean test score (25, 55, 220, 355, 418, 420). There are two broad categories of endurance tests; those that involve the study participant exercising at a constant intensity until exhaustion (open loop) and those that require the participant to complete a set amount of work in a given time, or a set distance in as fast a time as possible (closed loop) (107). Reliability of performance in tests such as the former (open loop), has been shown to be poor (244, 410, 420) with CV's ranging from 13 – 27% having been reported for these tests (202, 244, 266, 280, 387). However, tests employing a closed loop protocol have yielded markedly better CV's (51, 202, 280, 383, 436). For example, Laursen *et al.* (280) directly compared the reliability of time-to-exhaustion tests (open loop) versus treadmill time trials (TTT) of 5000 m and 1500 m (closed loop) in well-trained distance runners and found the TTT's to have a significantly higher reliability compared to the time-to-exhaustion tests at both distances (CV = 2% vs 15% (5000 m) and 3% vs 13% (1500 m); open vs closed). Additionally, Palmer *et al.* (383) instructed cyclists to complete simulated 20 and 40 km time trials on a cycle ergometer in as fast a time as possible, and reported

CVs of 1.1 and 1.0%, respectively. Similarly, Hickey *et al.* (202) reported CVs of 0.95 – 2.40% when cyclists were required to perform several fixed amounts of work as quickly as possible. The CV for a one-hour endurance performance test in trained female cyclists, reported by Bishop (51), was somewhat higher, at 2.7%.

There are fewer studies focusing on reliability of performance tests for distance runners compared to those investigating cycling performance tests (418). The only relevant research studies for distance runners on such tests are:

- the aforementioned study by Laursen *et al.* (280),
- a closed loop study by Schabort *et al.* (420), in which runners were asked to run as far as possible in 60 minutes (CV = 2.7%),
- an open loop study of running time-to-exhaustion at maximal oxygen uptake ($VO_{2\max}$) by Billat *et al.* (49) (CV = 10%, calculated from their data by Schabort *et al.* (420)),
- a study by Doyle and Martinez (123) where runners completed a fixed distance TTT, with the distance calculated as the distance travelled during a 30 min constant intensity run prior to the TTT (CV = 4.4%),
- one by Rollo *et al.* (403) assessing the reliability of a 60 min running TTT (CV = 1.4%) and,
- one by Russel *et al.* (410) which investigated the reliability of a 10 km TTT that was preceded by a 90 min pre-load run at 65% of $VO_{2\max}$ (CV = 1.0%).

The 10 km run is a standard race distance on both track and road, evidenced by the high prevalence of 10 km road and track events worldwide. In addition, the 10 km distance has been shown by Noakes *et al.* (364) to be one of the best predictors of performance at 21.1 km, 42.2 km and 90 km ($r = 0.91 - 0.98$) in specialist marathon and ultra-marathon runners. The training study in this thesis therefore used a 10 km TTT as a performance measure. Accordingly, the aim of the first study was to determine whether the time taken to complete a self-paced 10 km TTT on a motorised treadmill is a reliable performance measure. The second aim of this study was to assess the validity of the test by comparing TTT performance to time taken to run a 10km time trial on an outdoor track (TRTT).

2.2 Methods

2.2.1 Participants

Eight endurance-trained male runners participated in this study, which was approved by the Human Research Ethics Committee of the Faculty of Health Sciences of the University of Cape Town. To qualify for the study, participants had to be training consistently (at least three times per week and $\geq 30 \text{ km}\cdot\text{wk}^{-1}$ over the preceding six months), be familiar with treadmill running and have completed a 10 km road race in ≤ 40 min within the six months prior to participating in the study. A further requirement was that the participants were not to have included any HIIT in their training regime in the last three months before the start of the study. Prior to the start of the trial all participants were informed of the purpose of the investigation, as well as the protocol involved and their written informed consent was obtained (Appendix 1). Body composition measurements included mass (kg) and height (cm), seven skinfolds, three girths and the sub-gluteal to above knee height. The biceps, triceps, abdominal, subscapular, supra-iliac, mid-thigh and calf skinfolds (mm) formed the 'sum of seven skinfolds' measurement (mm) (256). The same investigator performed all measurements to avoid inter-tester measurement errors. The descriptive characteristics of the participants are shown in Table 2.1.

Table 2.1 Descriptive and training characteristics of participants.

	Mean \pm SD (n = 8)
Age (yr)	30 \pm 7
Height (cm)	175 \pm 10
Mass (kg)	69.4 \pm 10.3
S7 (mm)	55.6 \pm 12.2
PTRS (km·h⁻¹)	20.5 \pm 0.8
HR_{max} (beats·min⁻¹)	185 \pm 10
Weekly distance (km)	52 \pm 17
Frequency (days·wk⁻¹)	5 \pm 1

Abbreviations: S7 – Sum of seven skinfolds; PTRS – Peak treadmill running speed; HR_{max} – Maximal heart rate.

2.2.2 Preliminary testing

On their initial visit to the laboratory, participants performed a maximal test-to-exhaustion on a motor driven treadmill (Quinton Instruments, Seattle, WA, USA), in order to determine peak treadmill running speed (PTRS) and maximum heart rate (HR_{max}). PTRS was defined as the highest speed at which a participant was able to complete a full 30-second stage during the maximal test-to-exhaustion. After a five- to ten-minute self-paced warm-up on the treadmill, the test started at a speed of 12 km·h⁻¹. This speed was maintained for the first 60 seconds, after which it was increased by 0.5 km·h⁻¹ every 30 seconds until volitional exhaustion. Heart rate was measured continuously throughout the test using a Polar Vantage XL heart rate monitor (Polar Electro, Kempele, Finland).

Body composition and anthropometric data were collected from the study participants, including age, height, weight, and seven skinfold measurements for calculation of the sum of seven skinfolds (S7).

2.2.3 Ten kilometre time trials

Subsequent to the preliminary testing, participants were required to complete four 10 km TTT's on the same motorised indoor treadmill used during the preliminary testing and two 10 km TRTT's on a standard 400 m outdoor track. The first trial for all participants was always a TTT, which was used as a familiarisation trial. These trials were not used in the final analysis unless specifically mentioned. The remaining three TTTs and two TRTTs were run in a randomised order and separated by seven to ten days, such that testing spanned five weeks. Each TTT for a given participant was performed at the same time of the day under standard laboratory conditions (~20°C, 55% relative humidity). Likewise, all TRTT's were performed at the same time of day as the TTT's. Participants were instructed to maintain the same training regime for the duration of the study. They were also requested to maintain the same diet for the three days prior to each time trial and a training diary and dietary record was kept for those periods to assess their adherence to these criteria. All participants adhered to these criteria. In addition, participants were asked not to perform any hard training on the day prior to a time trial.

Immediately prior to all time trials, heart rate monitors were attached to the study participants who were then allowed a five- to ten-minute self-paced warm-up on the treadmill for the TTT or the equivalent time and intensity warm-up around the track for the TRTT. Each individual's warm-up procedure was noted at their first time trial and the same procedure was followed for each subsequent time trial. Participants were requested to complete each time trial in the fastest possible time; the only feedback given was the total distance covered at any time. They were not informed of their finishing times until completion of the study and were not allowed to wear a watch during any of their time trials. During the TTT, the treadmill speed was controlled by the runner, using a pair of lightweight hand-held micro-switches which increased or decreased the speed of the treadmill via telemetry. The gradient of the treadmill for all tests was 0%. Participants were allowed to consume water *ad libitum* during all time trials. The position of the treadmill remained unchanged for the duration of the study and a large industrial fan was positioned to cool the participants during all TTT's.

Time taken to complete all time trials, as well as the 400 m and 1000 m split times were recorded. Heart rate was measured continuously and ratings of perceived exertion (RPE) were recorded after each kilometre using the 15 point Borg scale (Appendix 2) (57-59).

No metabolic monitoring, such as the volume of oxygen inspired (VO_2), was carried out during either the maximal testing for PTRS or the 10 km time trials, as the runner's performance (speed and time to complete a time trial) was the primary consideration and such interventions would have the potential to negatively impact on this.

2.2.4 Statistical analysis

The data were analysed with STATISTICA version 12.0 (Stat-soft Inc., Tulsa, OK, USA) for any statistical significance at the 95% confidence level ($p < 0.050$). All data are expressed as mean \pm standard deviation. A dependent t-test was used to compare differences between TTT's and TRTT's for mean time, mean speed, percentage of mean HR_{max} sustained, as well as mean heart rate between the two TRTT's. One-way analysis of variance (ANOVA) was used to compare mean times and mean heart rate of the four TTT's. Repeated measures ANOVA was used to compare RPE values and pacing during the course of all time trials. Where significant differences were indicated, a Tukey's honestly significant difference *post hoc* test was utilised to identify the sources of the overall difference. Reliability for each variable was also assessed by calculating interclass correlation coefficients (ICC) and the 95% confidence intervals (476). Differences between all TTT's (i.e. the second and the first (test 2-1), the third and the second (test 3-2) and the third and the first (test 3-1)) were calculated to determine the typical error of measurement (TEM). TEM and typical percent error (TEM % or CV), expressed as a percentage of the mean score, were calculated with 95% confidence intervals, using a spreadsheet designed for this purpose and downloaded from www.newstats.org (54).

2.3 Results

Of the eight volunteers recruited for the study, two were unable to complete all of the TRTT's due to injury. One of these participants completed one TRTT, while the other was unable to participate in either. Thus $n = 8$ for all of the measures relating to the TTT's and $n = 6$ for all references to and comparisons with the outdoor TRTT's.

For performance times in all time trials, see Table 2.2. Comparison of the time taken to complete the three experimental TTT's revealed no significant differences between the trials ($n = 8$; $p = 0.999$), and when including the familiarisation trial the result was similar ($n = 8$; $p = 0.911$). Table 2.2 shows the time taken by each runner to complete each of the three TTT's as well as those performed on the track, together with mean times and CV. The familiarisation TTT was not significantly different compared to the first experimental TTT ($n = 8$; $p = 0.543$). Similarly, there were no significant differences between the time taken to complete the TTT's compared to the TRTT's (mean TTT = $37:20 \pm 2:44$ (min:s) and mean TRTT = $37:45 \pm 2:29$ (min:s); $n = 6$; $p = 0.675$) (Table 2.2).

The overall mean speed for the TTT's was $16.1 \pm 1.1 \text{ km}\cdot\text{h}^{-1}$ ($3:44$ (min:s) per km) ($77.8 \pm 5.5\%$ of PTRS; Range 69.5 – 88.4%) compared to a mean speed of $16.0 \pm 1.0 \text{ km}\cdot\text{h}^{-1}$ ($3:45$ (min:s) per km) ($76.9 \pm 4.8\%$ of PTRS; Range 69.9 – 85.4%) for the outdoor TRTT's ($p = 0.637$). Participants ran on average at $91.7 \pm 2.3\%$ (Range 87.9 – 96.1%) and $92.9 \pm 3.6\%$ (Range 86.9 – 98.4%) of their HR_{max} for the TTT's and TRTT's, respectively ($p = 0.289$).

Performance time between the TRTT's was not different ($p = 0.909$) (Table 2.2) and neither were the pacing strategies employed ($p = 0.876$).

Table 2.2 Times taken to complete all 10 km time trials.

Participant	1	2	3	4	5	6	7	8	Group mean	Group SD
TTT 1	35:00	41:15	43:22	34:39	35:37	36:50	40:34	41:16	38:34	03:24
TTT 2	35:15	42:07	43:23	33:56	36:00	36:55	40:26	40:59	38:38	03:31
TTT 3	34:57	41:15	44:19	34:56	36:02	36:34	39:48	41:16	38:38	03:30
Individual mean	35:04	41:32	43:41	34:30	35:53	36:46	40:16	41:10	38:37 [#]	03:19
Individual SD	00:10	00:30	00:33	00:31	00:14	00:11	00:25	00:10		
CV (%)	0.5	1.2	1.2	1.5	0.6	0.5	1.0	0.4		
TRTT 1	35:24	41:53	-	35:07	35:17	38:02	41:21	-	37:51	03:07
TRTT 2	35:44	39:51	-	36:17	36:02	37:59	40:07	-	37:40	01:58
Mean	35:34	40:52	-	35:42	35:39	38:00.5	40:44	-	37:45	02:29
SD	00:14	01:26	-	00:49	00:32	00:02	00:52	-		
CV (%)	0.7	3.5	-	2.3	1.5	0.1	2.1	-		

Individual time trial data, as well as the means \pm standard deviation, are presented as minutes and seconds (min:s).

[#] The mean TTT time for participants who completed both the TTT's and TRTT's (n = 6) is 37:20 \pm 2:44 (min:s).

Abbreviations: TTT – Treadmill time trial; TRTT – Track time trial; SD – Standard deviation; CV – Coefficient of variation.

Neither mean heart rate for the three TTT's (TTT 1 = 169 \pm 8 beats·min⁻¹; TTT 2 = 170 \pm 8 beats·min⁻¹; TTT 3 = 169 \pm 10 beats·min⁻¹; n = 8; p = 0.936) nor mean heart rate for the two TRTT's (TRTT 1 = 176 \pm 9 beats·min⁻¹ and TRTT 2 = 174 \pm 9 beats·min⁻¹; n = 6; p = 0.739) were significantly different between the respective trials. Mean TTT heart rate was not different to that for the TRTT (TTT's = 173 \pm 6 beats·min⁻¹ and TRTT's = 175 \pm 9 beats·min⁻¹; n = 6; p = 0.404). RPE values were also not different between the TTT's and the TRTT's (p = 0.983; Figure 2.1).

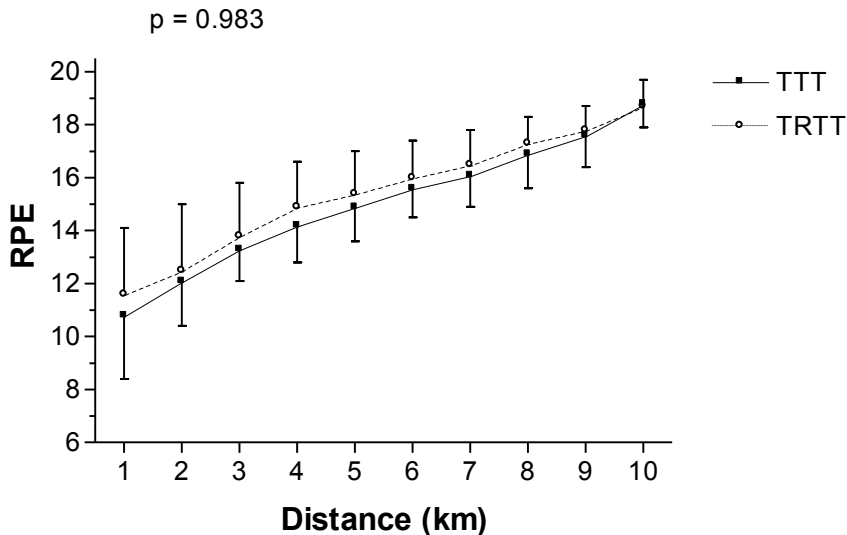


Figure 2.1 Ratings of perceived exertion values for all treadmill time trials combined compared to all track time trials combined.

Data are presented as the mean \pm standard deviation ($n = 6$). The p -value on the graph represents group by time (distance) interaction effect, as determined by a repeated measures ANOVA.

Abbreviations: TTT – Treadmill time trial; TRTT – Track time trial; RPE – Ratings of perceived exertion.

Pacing strategies of the TTT's were compared with those of the TRTT's. Despite the relatively small sample size for the outdoor TRTT's it was possible to show differences in pacing strategies between time trials performed on the treadmill and track, as there was a significant time by group interaction effect ($p < 0.001$). *Post hoc* analysis indicates that the average speed of the first kilometre was significantly different between the TRTT's and the TTT's, with all runners, without exception, completing the first kilometre on the track faster than that on the treadmill ($n = 6$; $p = 0.037$, Figure 2.2). The final kilometre of the TTT's was significantly faster than kilometres one, two and five to nine of the same trial, whereas the final kilometre of the TRTT's was only significantly faster than kilometre number eight. However, the first kilometre of the TRTT's was significantly faster than kilometres three to ten during those trials. Both the TRTT's and TTT's displayed the 'end-spurt' profile as described in a number of studies on endurance pacing (86, 87, 192, 358).

Weather conditions (with particular reference to temperature and wind speed) were similar for all TRTT for all participants as observed subjectively by the researcher. Only subjective ratings of wind speed of 'no wind' and 'light wind' were accepted for

testing to take place in order to be able to compare these conditions to the treadmill conditions. Temperature was measured and a range of 21 to 27 °C was recorded. The mean temperature for all trials of all participants combined was 24 ± 3 °C. It is important to note that the temperature was within 3 °C for each trial for each participant.

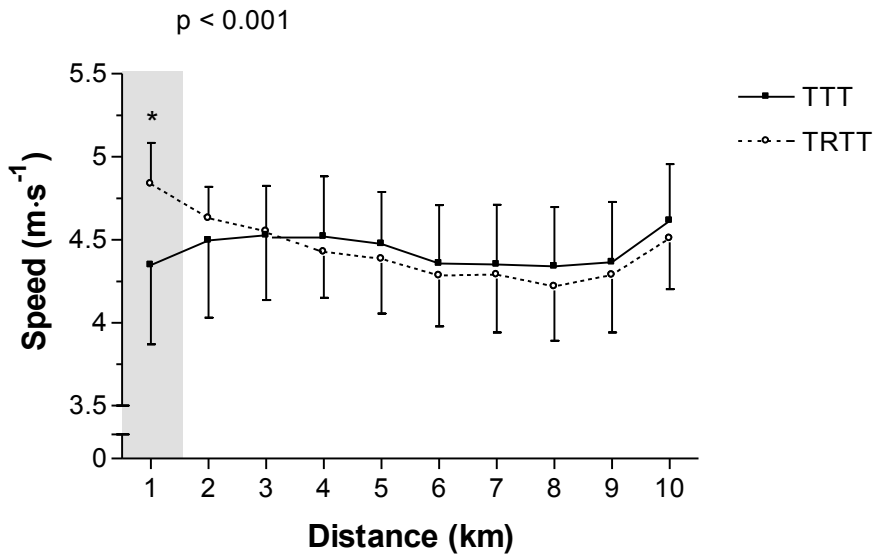


Figure 2.2 Pacing profiles of the treadmill time trials compared to the track time trials.

Data are presented as the mean \pm standard deviation ($n = 6$). The p -value on the graph represents group by time (distance) interaction effect, as determined by a repeated measures ANOVA.

* Significant difference in speed of the first kilometre between TTT and TRTT ($p = 0.037$).

Abbreviations: TTT – Treadmill time trial; TRTT – Track time trial.

Pacing profiles were not different between the three experimental TTT's ($p = 0.976$) as shown in Figure 2.3.

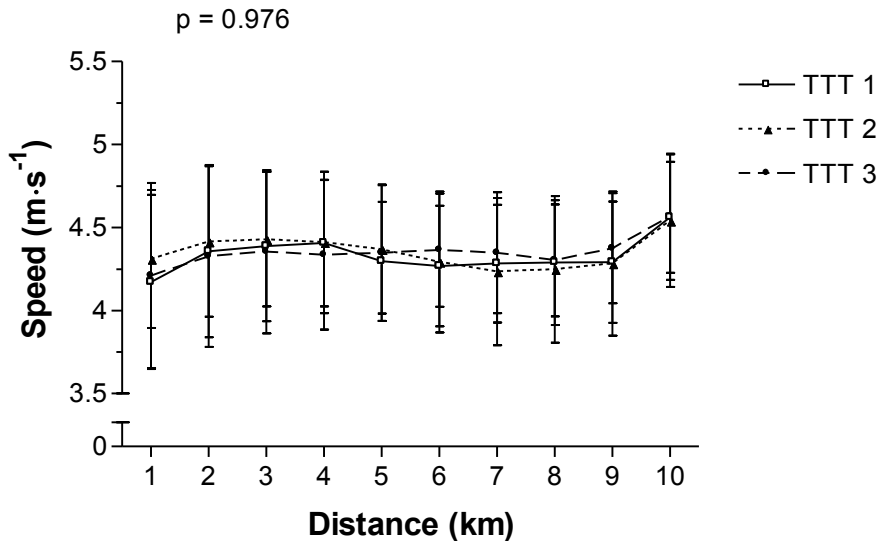


Figure 2.3 Pacing profiles of all three experimental 10 km treadmill time trials.

Data are presented as the mean \pm standard deviation ($n = 8$). The p -value on the graph represents group by time (distance) interaction effect, as determined by a repeated measures ANOVA.

Abbreviation: TTT – Treadmill time trial.

The TEM's for the 10 km TTT's are expressed as absolute and relative values (percentages) and are shown in Table 2.3. The mean TEM for the time taken to complete the 10 km TTT's was 23.8 s (1.0%) with a mean TEM for mean speed during the TTT of 0.2 km·h⁻¹ (1.0%). Mean heart rate was more variable than the measures mentioned above, with a mean TEM of 4 beats·min⁻¹ (2.2%). RPE values during all 10 km TTT's remained relatively unchanged between trials with a TEM of 0.6.

Table 2.3 Typical error of measurement for time, speed, heart rate and ratings of perceived exertion of all experimental treadmill time trials.

10 km treadmill time trials					
	Variable	Test 2-1 [‡]	Test 3-2 [#]	Test 3-1 [§]	Mean
TEM	Time (s)	20.0 (13.2 – 40.6)	29.2 (19.3 – 59.4)	21.2 (14.0 – 43.1)	23.8 (18.3 – 34.0)
TEM %	Time (%)	0.9 (0.6 – 1.8)	1.3 (0.8 – 2.6)	0.9 (0.6 – 1.8)	1.0 (0.8 – 1.5)
ICC	Time	0.99 (0.97 – 1.00)	0.99 (0.94 – 1.00)	0.98 (0.92 – 1.00)	0.99 (0.97 – 1.00)
TEM	Mean speed (km·h ⁻¹)	0.1 (0.1 – 0.3)	0.2 (0.1 – 0.4)	0.1 (0.1 – 0.3)	0.2 (0.1 – 0.2)
TEM %	Mean speed (%)	0.9 (0.6 – 1.8)	1.3 (0.8 – 2.6)	0.9 (0.6 – 1.8)	1.0 (0.8 – 1.5)
ICC	Mean speed	0.99 (0.97 – 1.00)	0.99 (0.94 – 1.0)	0.99 (0.93 – 1.0)	0.99 (0.98 – 1.0)
TEM	Mean HR (beats·min ⁻¹)	3 (2 – 7)	3 (2 – 5)	5 (3 – 9)	4 (3 – 6)
TEM %	Mean HR (%)	2.1 (1.4 – 4.3)	1.5 (1.0 – 3.2)	2.8 (1.8 – 5.7)	2.2 (1.6 – 3.4)
ICC	Mean HR	0.86 (0.47 – 0.97)	0.95 (0.77 – 0.99)	0.67 (0.01 – 0.92)	0.87 (0.66 – 0.97)
TEM	RPE (units)	0.5 (0.3 – 1.0)	0.4 (0.2 – 0.7)	0.8 (0.5 – 1.6)	0.6 (0.4 – 0.8)

Data are expressed as typical error of measurement, typical percent error (%) and the intra-class correlation coefficient ($n = 8$). Data in parentheses are the 95% confidence intervals of that variable.

Heading explanations: [‡] TEM and TEM % between time trial 2 and time trial 1, [#] TEM and TEM % between time trial 3 and time trial 2, [§] TEM and TEM % between time trial 3 and time trial 1.

Abbreviations: TEM – Typical error of measurement; TEM % – Typical percent error (%); ICC – Intra-class correlation coefficient; HR – Heart rate; RPE – Ratings of perceived exertion.

2.4 Discussion

Intervention studies on athletic performance require a measure of performance change that accurately simulates the physical demands of the athletes' competitive event (i.e. it is valid), is relatively easy to administer, has sufficient sensitivity to detect any meaningful changes in performance and most importantly, is reliable (107, 218, 220, 418). Although there are a number of studies available on the reliability and validity of cycling performance testing protocols (51, 91, 202, 244, 284, 381, 383, 387, 419, 436) there are notably fewer that address endurance running performance (123, 249, 403, 410, 420).

The most important finding of this study was that the self-paced 10 km TTT was highly reliable, as indicated by the small TEM of 1% for time to complete the TTT's (23.8 s) (Table 2.3). It has been reported by Hopkins and Hewson (219) that variation in competitive performance of well-trained distance runners in shorter endurance events (less than half marathon distance) is approximately 1.5%. Therefore, a performance test to track meaningful differences, beyond that of standard variation, needs a TEM % similar to or preferably less than this value (107, 219, 387). Accordingly, the TEM % in the present study meets this criterion, as it falls below 1.5%. Thus, the self-paced 10 km TTT protocol employed has sufficient precision to detect small changes in performance in well-trained male runners who are able to complete a 10 km road race in a time of 40 minutes or faster. The TEM % of the present study compares favourably with those of other studies for both running and cycling where values of 1.4% (403), 5.4% (91) and 2.7% (420) have been reported. The TEM % of the present study is in fact the lowest recorded for a running performance protocol along with that from a study by Russell *et al.* (410) who reported values of $1.00\% \pm 0.25\%$ in a sample of eight well-trained male and female distance runners.

It is important to note that there are a few methodological differences between the latter and the present study. The first is that Russell *et al.* (410) included a 90-minute 'pre-load' run prior to the 10 km TTT, which seemed to make TTT performance time less variable compared to that during actual road races. This is an interesting finding as, 'pre-loaded' time trials have actually been found to be less reliable than those without a 'pre-load' (123). The rationale behind the inclusion of a

'pre-load' is that it allows for the achievement of a metabolic 'steady-state' which is of importance in studies measuring gas exchange or making use of isotopes in assessing altered substrate diets on performance (410). The presence of the 90 min 'pre-loaded' run does not however, represent what would occur in reality as an athlete would not warm up for this length of time before competing in a 10 km race or time trial. Therefore when assessing the reliability of a protocol for extrapolation to race performance in the field, the protocol should resemble the actions in the field as closely as possible. For this reason, the athletes in the present study were allowed to warm up at their chosen pace for five to ten min prior to the start of the time trial. Findings from the present study indicate that similar reliability is achievable without any 'pre-loaded' run.

Secondly, both male and female participants were used and thirdly, not all TTT's were performed under the same conditions during the Russell *et al.* (410) study. All participants who ran the TTT in less than 40 minutes had to perform the time trial at a gradient of between two and three percent as the maximum speed of the treadmill was not sufficient. Thus the gradient was not consistent for all participants. This is not ideal for assessing inter-individual performance, as the differences in gradient will alter aspects such as the athletes' gait, energy expenditure and run time (249). The gradient of the treadmill was maintained at 0% for all TTT's for the present study.

How closely a protocol resembles the performance that is being simulated is termed its validity (217). In the studies that follow in this thesis, we intend to infer that laboratory measured 10 km TTT performance is comparable to competitive 10 km race performance in well-trained runners. As discussed and shown in Table 2.2, there were no significant differences in performance between the TTT's and TRTT's in the present study. This, in conjunction with the lack of a significant difference in heart rate and RPE data for all time trials, indicates that this self-paced TTT is a valid measure of 10 km track running performance. Interestingly, in a study in which physiological responses during a 5 km time trial performed under laboratory conditions were compared to those during a competitive race, Foster *et al.* (148) also showed no physiological difference between the two scenarios. In contrast to these findings, however, Heesch and Slivka (196) found 10 km TTT performance to be faster than 10 km TRTT's performed on an indoor 200 m track. The authors attribute

the difference in performance times to be due to different pacing strategies or the difference in the metabolic cost between treadmill and track running. However, the differences in the performance time in their study in comparison to no difference in performance time in the present study, could merely be explained by the tighter corners experienced in the 200 m indoor track compared to a standard 400 m track. This is also evidenced by the current world records for all middle and long distance running events being faster on an outdoor 400 m track compared to an indoor 200 m track.

Interestingly, a gradient of 1% for TTT's has been recommended by Jones and Doust (249) in order to replicate the energy expenditure of over-ground running. However, as mentioned, we found no significant difference between performance time or speed for TTT's at 0% grade compared to TRTT's. If energy expenditure was a key determinate of performance it would be expected that the TRTT's would be slower than those on the treadmill, because to achieve the same time compared to the treadmill, energy expenditure would be higher. Without data such as VO_2 it is difficult to postulate the possible reasons for the lack of the expected difference between the TTT and TRTT's. However, given the extremely low CV and error of measurement with the 0% grade, these results suggest that it is not necessary to try to replicate energy costs when assessing running performance of trained runners under time trial conditions on a treadmill by setting the gradient at 1%. This is anecdotally supported by the fact that two participants in the current study participated in competitive 10 km road races shortly before participation in the study, and their times closely matched all their time trial performance times (Runner 1: Race = 35:00 (min:s) vs. mean of three TTT = 35:04 \pm 00:10 (min:s), mean of two TRTT = 35:24 \pm 00:14 (min:s) and Runner 2: Race = 35:54 (min:s) vs. mean of three TTT = 35:53 \pm 00:14 (min:s), mean of two TRTT = 36:02 \pm 00:32 (min:s)).

Although this study has shown overall performance is the same for all time trials, the pacing strategies the study participants used to achieve these results were different between those on the treadmill and the track. Without exception, all runners started all 10 km TRTT's faster than they did for any performed on the treadmill (Figure 2.2). Lack of experience cannot be used as an explanation for this as all participants had several years of experience of running on both a treadmill and the road. In addition to this, a familiarisation TTT was performed by all participants. Despite the obvious

inherent perceived differences between running on a motorised treadmill compared to that of over-ground running, it is difficult to explain these differing pacing strategies. Perhaps the first kilometre of the TTT is slower as the runners are more subconsciously concerned about balancing on the treadmill. However, for the purpose of pure performance testing the reliability of the 10 km TTT is once again illustrated as pacing for all TTT's was not significantly different (Figure 2.3).

In conclusion, the TEM % of this study indicate that performance in a well controlled 10 km TTT is highly reliable and valid, and indicates that this test is sensitive enough to detect small but meaningful changes in performance (~1%) in well-trained distance runners under laboratory conditions, making it a practical and valid method to assess performance differences resulting from training or other interventions.

CHAPTER THREE – METHODS FOR CHAPTERS FOUR TO SEVEN

3.1 Introduction

All data for the subsequent chapters were collected during the course of a large training study. The data were analysed and are presented in Chapters Four to Seven.

All methods sections in subsequent chapters will refer back to the relevant sections of this chapter.

3.2 Methods

3.2.1 Participants

A total of 37 well-trained male runners participated in this training study, which was approved by the Human Research Ethics Committee of the Faculty of Health Sciences of the University of Cape Town. To qualify for the study, participants had to be run training regularly (at least three times a week and $\geq 30 \text{ km}\cdot\text{wk}^{-1}$ consistently over the preceding six months), be familiar with treadmill running and have completed a 10 km road race in ≤ 40 min within the previous six months. A further requirement was that they were not to have included any specific high intensity interval training (HIIT) in their training programmes in the last three months. Before the start of the trial all participants were informed of the purpose of the investigation and the protocol involved. In addition, their written informed consent was obtained (Appendix 3). Participants were then randomly assigned to one of three training interventions, either a 400 m, 1600 m or mixed (combination of both 400 m and 1600 m sessions on separate days within the same week) HIIT group ($n = 10$ for each group) or a control group ($n = 7$). Participants were assigned to groups in the order of recruitment to the study, i.e. the first participant recruited was assigned to the 400 m group, the next participant to the 1600 m group, the next to the mixed group. This was repeated until each experimental group reached a total of ten participants. Thereafter, participants recruited were assigned to the control group.

Minimal sample size for this study for each of the groups was determined using the reliability data from Chapter Two. Assuming the smallest meaningful difference to be

27 s and a standard deviation of 13 s, the sample size required for the training intervention study, in order to achieve a statistical power of 90% and a significance level of 5% was therefore, $n = 7$ per group (12).

3.2.1.1 Control group

It was decided prior to the start of this training study that if the first post-HIIT 10 km TTT data for the control group was not significantly different to the pre-HIIT measurements, then the group would not be tested again. This decision was in accordance with the findings of Chapter Two. The control group from this training study and the participants in the reliability study (Chapter Two) were not different with respect to weekly training frequency, weekly mileage and the fact that they were not performing HIIT for at least three months before the start of either study. In Chapter Two it was shown that over a five-week period, without any change to the participants training regime apart from the inclusion of a higher intensity session in the form of a 10 km treadmill time trial (TTT) once a week (included without any increase in weekly mileage as the TTT formed part of the original mileage), there were no TTT performance changes. Therefore, any further testing for this training study would effectively be a repeat of the study already performed in Chapter Two as training for the control group would be unaltered as per the participants in Chapter Two (See also Chapter Four, section 4.3).

3.2.2 Experimental design

All participants in the training intervention groups were required to attend 16 sessions over a nine-week period. Eight of the 16 sessions were laboratory based time trials and assessments and the other eight were HIIT sessions performed on a 400 m outdoor athletics track. Those in the control group attended five sessions only (Chapter Four) as they did not participate in the supervised HIIT track sessions, nor the final three laboratory based sessions. All participants attended all required sessions in order to be included in the data analysis. A schematic of the experimental design for the training study is shown in Figure 3.1.

	Session No	Session	Notes
Week 1	1	10 km TTT	<ul style="list-style-type: none"> • Informed consent • 10 km TTT familiarisation
Week 2	2	10 km TTT	<ul style="list-style-type: none"> • Pre-HIIT 10 km TTT
	3	Max Testing Day 1 (two days following the 10 km TTT)	<ul style="list-style-type: none"> • Body composition assessment • PTRS and $VO_{2\max}$ test • RE test • MVC • 20 m sprint test & sEMG testing
Week 3	4 & 5	Track HIIT	<ul style="list-style-type: none"> • 400 m and 1600 m supervised HIIT track session depending on group • HR monitoring
Week 4	6 & 7		
Week 5	8 & 9		
Week 6	10 & 11		
START OF TAPER PERIOD			
Week 7	12	10 km TTT (three days following the last HIIT session)	<ul style="list-style-type: none"> • 1st post-HIIT 10 km TTT
	13	Max Testing Day 2 (two days following the 10 km TTT)	<ul style="list-style-type: none"> • PTRS and $VO_{2\max}$ test • RE test • MVC • 20 m sprint test & sEMG testing
Week 8	14	10 km TTT	<ul style="list-style-type: none"> • 2nd post-HIIT 10 km TTT
Week 9	15	10 km TTT	<ul style="list-style-type: none"> • 3rd post-HIIT 10 km TTT
	16	Max Testing Day 3 (two days following the 10 km TTT)	<ul style="list-style-type: none"> • PTRS and $VO_{2\max}$ test • RE test • MVC • 20 m sprint test & sEMG testing

Figure 3.1 Schematic representation of the testing protocol used in this study.

Abbreviations: TTT – Treadmill time trial; Max Testing Day – refers to a single day when all other testing was carried out other than the TTT; PTRS – Peak treadmill running speed; $VO_{2\max}$ – Maximal oxygen uptake; RE – Running economy; MVC – Maximal voluntary contraction; sEMG- Surface electromyography; HR – Heart rate; HIIT – High intensity interval training.

3.2.3 Ten kilometre treadmill time trials

All participants in the training intervention groups for the study were required to complete five 10 km TTT's on a motor driven treadmill (Quinton Instruments, Seattle, WA, USA). The first two TTT's were completed before the HIIT intervention and were separated by seven days. The third, fourth and fifth TTT's were completed in the first, second and third week, respectively, following the completion of the four weeks of HIIT. All participants had three full days between their last training session on the track and the first post-HIIT TTT. All post-HIIT TTT's were separated by seven days. The first session for all participants was always a TTT which was used as a familiarisation trial, as it has previously been shown that a significant learning effect may exist between an initial and subsequent performance trial (420). This learning effect was not significant in Chapter Two, although the difference between the familiarisation TTT and the subsequent TTT did demonstrate the largest time difference of all TTT's in that study. These familiarisation TTT's were not used in the final analysis unless specified. Each TTT for a given participant was performed at the same time of the day under standard laboratory conditions (~20°C, 55% relative humidity) and participants were instructed to maintain the same training regime for the duration of the study (see also section 3.2.5). Participants were requested to maintain the same diet and training for the three days before each time trial and a training diary and dietary records were kept over that time to assess their adherence to these criteria. In addition, participants were asked not to perform any hard training on the day prior to a TTT.

Prior to all TTT's, athletes were fitted with a heart rate monitor (Polar® Xtrainer Plus, Polar Electro, Kempele, Finland) and allowed a five- to ten-minute self-paced warm-up on the treadmill. Each individual's warm-up procedure was noted at their first TTT and the same procedure was followed for each subsequent TTT. Participants were requested to complete each TTT in the fastest possible time. As in the reliability study (Chapter Two), the only feedback given was the total distance covered at any time. Participants were not informed of their finishing times until completion of the study. During each TTT the treadmill speed was controlled by the participant, using a pair of lightweight hand-held micro switches which increased or decreased the speed of the treadmill via telemetry. The gradient of the treadmill for

all tests was 0%. Participants were allowed to consume water *ad libitum* during all TTT's. The position of the treadmill remained unchanged for the duration of the study and a large industrial fan was positioned to cool the participants during TTT's.

Split times were recorded at 400 m and 1000 m intervals. Overall time taken to complete all TTT's was recorded, heart rate was measured continuously and ratings of perceived exertion (RPE) were recorded after each kilometre using the 15 point Borg scale (Appendix 2) (57-59).

3.2.4 Maximal testing day

All participants in the training intervention groups were required to complete three maximal testing days in the laboratory. The control group participated in the first two of these sessions only. The first maximal testing day was two days following the second TTT, but before the start of the four weeks of HIIT (Figure 3.1). This included anthropometrical measurements, a maximal oxygen uptake ($VO_{2\text{ max}}$) and peak treadmill running speed (PTRS) test, a running economy test, isometric voluntary contraction tests, a 20 m sprint test as well as surface electromyography (sEMG) testing, in the order described. The second maximal testing day was completed two days following the first post-training TTT (five days following the final HIIT session). The third maximal testing day was completed two days following the third post-HIIT TTT (19 days following the final HIIT session). The control group did not perform the 20 m sprint test or participate in the sEMG testing.

3.2.4.1 Anthropometry

Body composition measurements included mass (kg) and height (cm), seven skinfolds, three girths and the sub-gluteal to above knee height. The biceps, triceps, abdominal, subscapular, supra-iliac, mid-thigh and calf skinfolds (mm) formed the 'sum of seven skinfolds' measurement (mm) (256). The sub-gluteal, mid-thigh and above knee girths as well as the sub-gluteal to above knee height (cm) were used to determine lean thigh volume (cm^3) (407). The same investigator performed all measurements to avoid inter-tester measurement errors.

3.2.4.2 Maximal treadmill test

Participants were required to perform a maximal treadmill running test to determine PTRS, $VO_{2\text{ max}}$ and $HR_{\text{ max}}$. After a five- to-ten minute self-paced warm-up on the treadmill, the test started at a speed of $12\text{ km}\cdot\text{hr}^{-1}$. Each individuals' warm-up procedure was noted at their first maximal test and the same procedure was followed for all subsequent tests. The initial speed was maintained for the first 60 seconds, after which it was increased by $0.5\text{ km}\cdot\text{hr}^{-1}$ every 30 seconds until volitional fatigue. PTRS was defined as the highest speed at which a participant was able to complete a full 30-second stage.

Heart rate was measured continuously throughout the test using a Polar® Xtrainer Plus heart rate monitor (Polar Electro, Kempele, Finland) to determine $HR_{\text{ max}}$. This monitor recorded the average heart rate for each five-second period of the test and $HR_{\text{ max}}$ was noted as the highest value recorded.

VO_2 measurements were recorded during the test using an Oxycon Alpha analyser system (Jaeger-Mijnhart, Bunnik, Netherlands). The Oxycon Alpha system captures breath by breath data and displays this as an average in ten second periods. Before each test the analyser volume was calibrated with a Hans Rudolph 3 L syringe (Vacumed, Ventura, CA) and the oxygen and carbon dioxide (CO_2) analysers were calibrated with room air and a certified 4% CO_2 : 96% nitrogen gas mixture. $VO_{2\text{ max}}$ was recorded from the highest value measured during any ten-second period during the test. The following criteria were used to determine if indeed $VO_{2\text{ max}}$ was obtained; an RER (respiratory exchange ratio) greater than 1.1, peak heart rate similar to age predicted $HR_{\text{ max}}$, RPE at maximum of 20 on Borg's 15 point RPE scale as well as the subjective perception of an experienced tester who conducted all the $VO_{2\text{ max}}$ tests.

3.2.4.3 Running economy test

The running economy test was performed after the maximal test following ten minutes of complete recovery. Before the running economy test, study participants completed the same warm-up protocol as that performed prior to the maximal test. The test was performed at 70% of the PTRS attained during the preceding maximal test to determine oxygen uptake and percentage uptake at this participant-specific

relative speed for comparisons during the course of the study. The test was terminated once the participant had maintained a steady state VO_2 for more than four minutes (i.e. the VO_2 reading did not shift by more than $\pm 5\%$ during a four-minute period).

3.2.4.4 Isometric maximal voluntary contractions

Approximately 20 minutes after the running economy test, all HIIT intervention participants performed a standardised ten-minute warm-up of low intensity 'shuttle' runs and stretches for the lower body on an indoor running track. Following this, participants were seated on a seated leg press apparatus (NAMS unit; Zest Manufacturing PTY (Ltd) and University of Cape Town, Cape Town, South Africa) to perform two separate types of isometric voluntary contractions (MVC). For the leg press, the knee flexion angle was set to 95 degrees and a seat angle of 155 degrees. For the calf press, the participants were seated on the same leg press apparatus, however the seat angle was adjusted to 105 degrees and knees were fully extended. These angles were measured and set using a goniometer and were always measured by the same researcher. Their hips were strapped firmly to the seat to prevent any lifting of the pelvis and to help to further isolate the lower limb muscles during the MVC's that followed. Adjustable shoulder stoppers were positioned to add further stability and limit whole body movement under load. After a further warm-up of five sub-maximal five-second contractions against the footplate, each individual performed three five-second MVC's separated by 60 seconds of complete rest. Participants were requested to exert maximal force against the footplate (full foot on the plate for the leg press and only forefoot for the calf press) for five seconds. Verbal encouragement and a countdown of time were given by the principal investigator to all participants. The contraction that produced the highest force ($N \cdot m^{-1}$) was used for further analysis to detect changes in upper leg (quadriceps) and lower leg (calf) strength following the different training interventions. This method to determine peak force during the MVC's has been shown to be repeatable with an ICC of 0.96 which equates to a CV of 5.4% as previously determined (475).

3.2.4.5 Maximal 20 m sprint and sub-maximal standardised 20 m run test

Immediately after the MVC test, participants in the training intervention groups performed a sub-maximal standardised 20 m run test followed by three maximal 20 m sprints on an indoor running track. The 20 m sprint and 20 m submaximal run tests were used primarily for maximal and submaximal dynamic sEMG measurement of specific muscles to detect any changes in these measures following the HIIT interventions. The 20 m sprint was also used to normalise the sEMG data as it was shown by Albertus-Kajee *et al.* (11) to be a reliable method for normalisation. Additionally, 20 m sprint time performance was also compared following the HIIT interventions. The sub-maximal test was based on a set time of five seconds, during which the participants had to cover the 20 m distance at a constant pace finishing as close to five seconds as possible. Acceptable tolerance for this was prescribed to be 5.0 ± 0.1 seconds based on practicalities of this testing from pilot trials. Whether or not the pace was considered even was a subjective decision based on the opinion of two separate experienced observers. Once these two criteria had been met for the sub-maximal run, the participants then performed the maximal 20 m sprints.

For the 20 m sprints, participants were given a 20 m running start to ensure a normal and maximal running gait throughout the subsequent timed 20 m section of the sprint. Each sprint was separated by a recovery period of one minute, during which the participant would move back to the starting point. The fastest of the three sprints was used for further analysis. Twenty metre running time for both the sub-maximal run described above and maximal sprint test was measured using four photocell gates separated by no more than two metres and connected to an electronic timer accurate to one hundredth of a second (Newtest, LTD, Oulu, Finland).

3.2.4.6 Surface electromyography and stride parameter measurements

The sEMG activity of the *vastus lateralis*, *vastus medialis*, *biceps femoris* and *gastrocnemius medialis* muscle of the right leg was recorded bipolarly during the sub maximal 20 m run and 20 m sprint described above. A single reference electrode was placed on the tibial tuberosity of the same leg. The sEMG and footswitch sensor signals were recorded using a telemetric sEMG system (Telemetry Research System 900, Noraxon, Arizona, USA).

Prior to electrode placement, hair and dead skin cells were removed from the electrode sites by dry shaving and then rubbing a patch of skin ($\pm 100 \text{ cm}^2$ around the site) with fine sandpaper. The site was then cleaned with alcohol swabs to minimise surface interference. Two surface electrodes (Blue Sensor, Medicotest, Denmark) were positioned with their centres approximately 2 cm apart, parallel to the muscle fibre direction along the centre of each individual muscle belly and carefully strapped. The placement and location of these electrodes was in accordance with the recommendations by SENIAM (Surface EMG for Non-invasive Assessment of Muscles) (200). The strapped electrodes and their leads were secured to the leg using reusable elasticised straps. These five leads plugged into a telemetric transmitter unit, which was strapped to the waist of the participant. The electrode pairs recorded the sEMG activity (μV) of the underlying muscle via the telemetric transmitter unit at a sampling rate of 2000 Hz.

A footswitch (Norswitch bilateral telemetric footswitch system, Noraxon, Arizona, USA) was taped to the right foot of all participants for the collection of stride parameter data. The 20 m sprint is a common method used to evaluate these stride parameters (371, 376, 378, 379). Four pressure sensors in total were taped to the underside of the right foot. One sensor was secured to the bottom of the distal phalange of the right hallux, at the point where the toe lifts off the ground. Sensors two and three were secured to the underside of metatarsal one and five, and the fourth was secured similarly to the middle of the posterior tip of the calcaneus. All sensors were firmly secured with tape, followed by the participant replacing his sock and shoe. The footswitch lead was plugged into the telemetric transmitter unit and recorded heel-strike and toe-off simultaneously with sEMG from the *vastus lateralis*, *vastus medialis*, *biceps femoris* and *gastrocnemius medialis* muscles during both the sub maximal 20 m run and maximal 20 m sprints .

3.2.4.7 Data analysis for stride parameters

The footswitch trace in Noraxon's MyoResearch software (version 2.11.90.81.200, Noraxon, Arizona, USA) was used for the manual determination of the exact points of heel-strike and toe-off for both the 20 m sub-maximal run and fastest maximal sprint test. For the purposes of this study, contact time (CT) is defined as the period from heel-strike to toe-off of the same foot, and flight time (FT) is the period from toe-

off of the right foot to heel-strike of the left. A step is defined as the contact time plus the subsequent flight time of the same leg. A stride is defined as the step of the right leg plus the following step of the left leg and stride time (ST) is the time taken to complete a stride. Stride frequency (SF) is the number of strides taken in one-second and stride length (SL) is the distance covered in one stride.

Using the heel-strike (HS) and toe-off (TO) times, the following equations were used to calculate the stride parameters of the 20 m maximal sprint test:

$$\begin{aligned} \text{CT (ms)} &= \text{TO time} - \text{HS time} \\ \text{FT (ms)} &= [(\text{right foot HS time (n + 1)} - \text{right foot HS time (n)}) - \text{CT}] / 2 \\ \text{ST (ms)} &= [\text{HS time (n + 1)} - \text{HS time (n)}] \\ \text{SF (strides}\cdot\text{s}^{-1}) &= 1 / (\text{ST} / 1000) \\ \text{SL (m)} &= \text{running speed} / \text{SF} \end{aligned}$$

3.2.4.8 Data analysis for surface electromyography

Noraxon MyoResearch software (version 2.11.90.81.200, Noraxon, Arizona, USA) was used to process the raw digital sEMG signal and the data were analyzed further using Microsoft Excel. The raw signal was first passed through a 50 Hz notch filter to remove any possible electrical interference from an external source. Following this a 15 – 500 Hz bandpass filter was used to remove any noise or movement artefacts (signals below 15 Hz) and non-physiological signals above 500 Hz. Once filtered, the signal was then smoothed using the root mean square method over 50 ms windows. An integrated EMG value (iEMG; $\mu\text{V}\cdot\text{s}$) was calculated for both the pre-activation phase and the contact time of a step in both the sub-maximal 20 m run and the fastest maximal sprint. These were then time-normalised to one second ($\mu\text{V}\cdot\text{s}\cdot\text{s}^{-1}$). Pre-activation phase was defined as the 100 ms period prior to heel-strike.

The pre-activation phase and the contact time phase of the sub maximal run were then normalised to the fastest maximal sprint and expressed as a percent of this maximal activity. It has previously been shown by Albertus-Kajee *et al.* (11), that the sprint method of normalisation is both reliable and sufficiently sensitive for detecting

change over repeated trials. The authors further recommended that the sprint method of normalisation should be utilised for running trials as it is the method that best represents the dynamic muscle activity of trials of that nature (11).

Arsenault *et al.* (20) have shown that the reliability of as few as three strides of sEMG data per participant are as reliable as that of 12 during gait studies. The final normalised sEMG data, represented as a percent of the fastest 20 m sprint, were the average and standard deviation of at least four strides of data.

3.2.5 Training intervention

All participants were personally interviewed at the start of the study to obtain a detailed account of their current training schedule. Importantly, all HIIT sessions were then incorporated into their schedules, ensuring that there was no increase in their weekly training distance or frequency. As previously mentioned, none of the participants had performed any form of HIIT for at least three months before the start of the study.

The training intervention consisted of two HIIT sessions per week for four weeks, performed on an outdoor grass track, beginning the first week after the initial maximal testing day. Participants were randomly assigned to either a 400 m, 1600 m, or mixed (combination of both 400 m and 1600 m sessions) HIIT training group or a control group. The control group continued with their normal training, as recorded at their initial interview, during the four week period. The 400 m group performed twelve 400 m intervals twice a week at a speed 13% faster than their current 10 km time trial pace which was determined from the first experimental 10 km TTT. Training sessions for all groups were always separated by two full days. A work to recovery ratio of 1 : 2 was utilised for these 400 m sessions. The 1600 m group followed the same routine but performed three 1600 m intervals at a speed 4% faster than their current 10 km time trial pace with a work to recovery ratio of 2 : 1. The mixed group performed one of each of these sessions per week at the same intensities as previously mentioned, with the 400 m interval session always being performed first in the week, followed by the 1600 m interval session on the subsequent HIIT day. All HIIT sessions covered the same training distance of 4800 m and were supervised on a one-to-one basis, always by the primary investigator. A Polar® Xtrainer Plus heart rate monitor (Polar Electro, Kempele, Finland) was worn

by all participants during all training sessions and interval times were recorded. An example of actual data from both a 400 m and 1600 m HIIT session is shown in Figure 3.2.

The decision about the intensity and work-to-rest ratios of the 400 m and 1600 m interval sessions was made following consultation with coaches and athletes. This ensured that athletes were able to complete both of the interval sessions while maintaining the same distance of 4.8 km. Pilot testing was done with athletes where perception of effort was noted as the criteria for the intensity of the sessions was that both sessions were found difficult to complete but were still achievable.

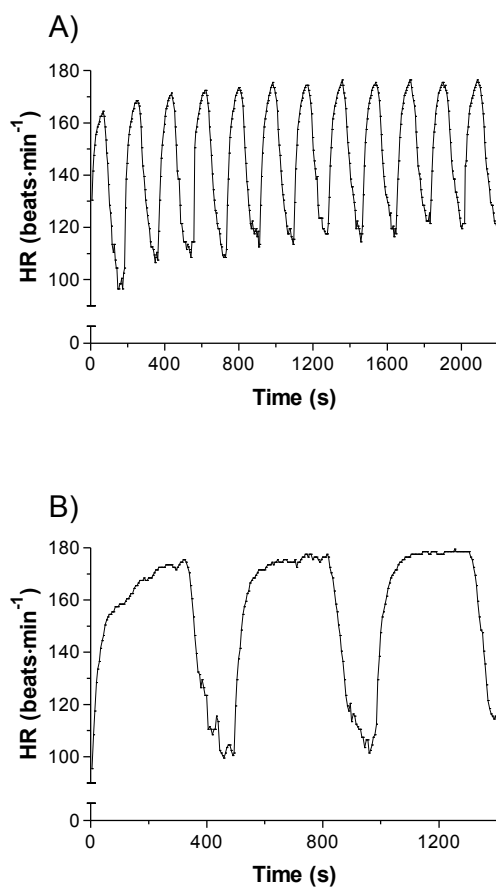


Figure 3.2 Examples of actual heart rate curves for A) a 400 m and B) a 1600 m high intensity interval training session.

Abbreviations: HR – Heart rate.

3.2.6 Taper

Following the eighth and final HIIT session, a period of reduced training (taper) was implemented. This consisted of a single-step reduction in total weekly training volume of 30%. All participants had a one-on-one meeting with the principal investigator, where this taper was explained to them and details about the required changes for their individual training over the following three weeks were provided. Participants were instructed to maintain their frequency of training. Although they no longer performed HIIT sessions, a weekly high intensity session was still included during the taper period as all participants performed a 10 km TTT once a week. The three 10 km TTT scheduled for the three weeks of the taper period were included in the training volume calculations. Participants were requested to keep a record of their training during this period and all were personally interviewed before each TTT to ensure adherence to this requirement.

3.2.8 Statistical analysis

The data were analysed with STATISTICA version 12.0 (Stat-soft Inc., Tulsa, OK, USA) for any statistical significance at the 95% confidence level ($P < 0.050$). All data are expressed as means \pm standard deviation. One-way analysis of variance (ANOVA) was used to compare differences in the descriptive characteristics of participants between groups, as well as the pre-HIIT values for the descriptive performance characteristics. Repeated measures ANOVA were used for all pre- and post-HIIT comparisons of descriptive performance characteristics as well as for comparisons of pre- and post-HIIT performance times, RPE, pacing and neuromuscular data. Where significant differences were indicated, a Tukey's honestly significant difference *post hoc* test was utilised in order to identify the sources of the overall difference. A dependent t-test was used to compare differences in the control group between pre- and post-HIIT values for TTT times, PTRS and $VO_2 \text{ max}$. Assumption criteria were assessed and verified prior to all statistical analyses.

CHAPTER FOUR – THE EFFECT OF DIFFERENT HIGH INTENSITY INTERVAL TRAINING PROGRAMMES ON 10 KM TREADMILL TIME TRIAL PERFORMANCE AND ASSOCIATED PHYSIOLOGICAL PARAMETERS

4.1 Introduction

High intensity interval training (HIIT) is a method commonly used as an effective means of improving performance in athletes (73, 261). This type of training is characterised by repeated short-to-long (duration can vary from seconds to minutes) bouts of high-intensity exercise interspersed with periods of recovery (44, 45, 73, 279, 281). It has been suggested that in the case of well-trained athletes, HIIT may be one of the only ways to further improve performance (44, 117, 194, 237, 279, 281, 453), making this an important topic for further scientific research.

A relatively large volume of research has been conducted on the physiological adaptations of previously untrained or recreationally active individuals to HIIT (23, 30, 42, 76, 77, 89, 134, 152, 267, 278, 295, 301, 303, 304, 321, 397, 399, 425, 495), however, comparatively less has been done on the responses of well-trained athletes to four to six weeks of sustained HIIT (270, 286). This is most likely due to the difficulty in persuading well-trained athletes to alter their training programmes for the purposes of scientific research (270, 281). Hence, most of the current knowledge and advice that scientists can give coaches or athletes is either based on training studies involving previously untrained individuals or subjective observations and anecdotal evidence from coaches and athletes in the field (194, 324).

The optimum duration and intensity of intervals has been the focus of a number of previous studies. For example, Acevedo and Goldfarb (8) found that 10 km running performance was increased by approximately 3% when well-trained distance runners were exposed to eight weeks of HIIT at 90 to 95% of maximal heart rate (HR_{max}). Additionally, Sandbakk *et al.* (414) concluded that longer five- to ten-minute duration aerobic HIIT led to greater improvements in maximal oxygen uptake (VO_{2max}) in 12 km roller-ski skating time trial performance than shorter intervals of two to four minutes and Enoksen *et al.* (130) found that VO_{2max} of well-trained middle-distance runners was improved to a greater extent when the HIIT was performed closer to

their lactate threshold as opposed to at a lower intensity. Similarly, in a study performed on well-trained recreational cyclists, Seiler *et al.* (425) found that a slightly higher work intensity of 90% HR_{max} and interval session of a shorter duration of 32 min (comprised of 4 x 8 min intervals) induced greater physiological adaptations compared to an intensity approximating the lactate threshold (88% HR_{max}) and longer 62 min duration (comprised of 4 x 16 min intervals). Additionally, this 90% HR_{max} group was also found to induce greater overall adaptive effects in comparison to another group performing intervals at an intensity approximating VO_{2 max} (94% HR_{max}) with a shorter 16 min work duration (4 x 4 min intervals), which is in agreement with the aforementioned study of Sandbakk *et al.* (414).

It is noted that in the above research, as with most training and performance research, the training variables (such as interval duration and intensity) are largely determined by a number of measured physiological determinants of performance. Consequently athletes and coaches are urged to target these physiological determinants in their training in view of enhancing performance by an improvement in these variables (324). The key physiological determinants of endurance performance have long been identified and are usually listed as VO_{2 max}, lactate threshold and running economy (41, 324, 325). Together these are understood to explain greater than 70% of the inter-individual variance in endurance performance of runners (324).

The velocity at VO_{2 max} (V_{max}) and the length of time this velocity can be sustained for (T_{max}), have been previously identified as measures that could be used to improve athletic performance (46, 48-50, 209, 242, 437). Indeed some of the pioneering research on VO_{2 max} concluded that it was the most important determinant of potential for endurance performance (96, 100, 144, 145, 364, 412, 490). Furthermore, the manipulation of training intensity has been regarded as the most important means of enhancing VO_{2 max} (66, 324, 451, 485). Although the role of lactate in fatigue is debated in the literature (32, 70, 83, 292), it is still widely accepted by scientists that an increase in the lactate threshold is associated with improved endurance performance (194, 324, 457). Finally, improvements in running economy have been linked with improvements in distance running performance in a number of studies (281, 286, 415, 424).

It is important to note that when dealing with highly trained competitive athletes, changes or improvements in these key physiological determinants may not necessarily translate into meaningful performance advantages needed at this level (41, 45, 324). For example, $VO_{2\max}$ is already high in well-trained athletes, where small improvements may not translate into a performance enhancement. At this level, an emphasis needs to be placed on training techniques that will generate a meaningful improvement in performance. In addition to this, these physiological determinants are not necessarily practical measures for the majority of athletes as they may not have the access to facilities or finances to obtain these laboratory measures. This is of particular relevance in a country such as South Africa where, generally, most of the proficient distance running talent in the population falls within a low income bracket. Therefore, $VO_{2\max}$ and other laboratory measures are of very little utility as a training tool in these circumstances. Accordingly, the determination of training intensity for the present study was based on the participants' most recent time for a 10 km time trial or race. This is a measure which is easily obtained, requires no laboratory and has a relatively low monetary cost.

The aim of the present study was to assess the effects of varying duration and intensity of intervals over four weeks of HIIT on 10 km running performance in well-trained runners by using an easily obtained determinant (10 km time trial time) for the prescription of intensity and duration of the interval session in the HIIT intervention.

4.2 Methods

4.2.1 Participants

The participants for this study were described in section 3.2.1.

4.2.2 Experimental design

A schematic of the experimental design for the entire training study is shown in Chapter Three, section 3.2.2, Figure 3.1. All participants assigned to a HIIT group were required to attend the first 13 sessions (Figure 3.1) of the training study over a seven-week period to be included in this component of the thesis. Five of these sessions were laboratory based sessions (sessions 1 – 3, 12 and 13) and the other eight were HIIT sessions (sessions 4 – 11) performed on an outdoor athletics track. The participants in the control group were required to attend the first five laboratory sessions only (sessions 1 – 3, 12 and 13). In order to be included in the data analysis, participants needed to have 100% compliance.

4.2.3 Ten kilometre treadmill time trials

These were conducted as described in Chapter Three, section 3.2.3.

4.2.4 Maximal testing days

These have been described in Chapter Three, section 3.2.4.

4.2.5 Training

The training protocols employed are described in Chapter Three, section 3.2.5.

4.2.6 Statistical analysis

Analyses were as described in Chapter Three, section 3.2.8.

4.3 Results

Thirty-seven volunteers were recruited for the training study. Five were unable to complete the study: two sustained injuries and were unable to do any further training, one became ill during the course of the training and two had to withdraw because of other commitments. Thus, the resulting numbers for the groups were $n = 10$ for the mixed group, $n = 8$ for the 1600 m group and $n = 7$ each for the 400 m and control groups.

As described in Chapter Three, section 3.2.5, the intensity (speed) of all HIIT sessions was prescribed based on the individuals' current 10 km TTT time as established in the pre-training TTT (i.e. 13% and 4% faster for 400 m and 1600 m sessions, respectively). The average duration of each HIIT session from the beginning of the first interval to the end of the recovery of the last was $38:03 \pm 2:20$ (min:s) and $25:09 \pm 1:25$ (min:s) for the 400 m and 1600 m sessions, respectively. Of this time, a total of $15:13 \pm 0:52$ (min:s) (40% of total time) and $16:46 \pm 0:55$ (min:s) (67% of total time) was the actual average time taken to complete the 4800 m of intervals for the 400 m and 1600 m sessions. The respective average individual interval time was $1:16 \pm 0:04$ and $5:35 \pm 0:18$ (min:s) for the 400 m and 1600 m intervals, respectively, which corresponds to a 10 km TTT equivalent to $31:41$ (min:s) (13.2% faster than the pre-HIIT TTT and equivalent intensity of $81 \pm 3\%$ HR_{max}) and $34:55$ (min:s) (4.3% faster than the pre-HIIT TTT and equivalent to $90 \pm 2\%$ HR_{max}), respectively. The average heart rate for an entire session (recovery periods included), as a percentage of HR_{max}, was $77\% \pm 4\%$ for a 400 m interval session and $84\% \pm 2\%$ for a 1600 m interval session.

4.3.1 Descriptive characteristics of participants

The descriptive and training characteristics of the four groups are presented in Table 4.1. There were no differences between the groups for all variables except for age, for which the control group was older than the three experimental HIIT groups. Descriptive performance characteristics (percentage of HR_{max} sustained during the pre-HIIT intervention treadmill time trial (TTT), VO_{2 max}, running economy, running economy as a percent of VO_{2 max}, peak treadmill running speed (PTRS) and 20 m

sprint time; Table 4.2) were not significantly different between the three HIIT groups prior to the training intervention.

Table 4.1 Descriptive and training characteristics of participants prior to training.

	Control (n = 7)	1600 m (n = 8)	400 m (n = 7)	Mixed (n = 10)	p-values
Age (yr)	33 ± 6 *	27 ± 5	26 ± 5	25 ± 3	0.005 (0.538)
Height (cm)	180 ± 8	179 ± 7	176 ± 6	176 ± 9	0.635 (0.674)
Mass (kg)	72.3 ± 5.5	68.1 ± 8.2	68.7 ± 8.0	71.9 ± 6.7	0.543 (0.518)
S7 (mm)	51.0 ± 15.7	46.4 ± 9.0	48.5 ± 11.2	51.2 ± 14.9	0.864 (0.716)
LTV (cm³)	4180 ± 371	4029 ± 493	4107 ± 453	4170 ± 506	0.910 (0.833)
PTRS (km·h⁻¹)	20.0 ± 1.0	20.5 ± 1.3	20.5 ± 0.9	21.0 ± 0.8	0.198 (0.397)
VO_{2 max} (ml·kg⁻¹·min⁻¹)	58.1 ± 3.8	63.3 ± 2.8	64.4 ± 5.7	64.3 ± 6.9	0.086 (0.907)
HR_{max} (beats·min⁻¹)	187 ± 6	187 ± 6	190 ± 9	187 ± 9	0.740 (0.616)
Weekly distance (km)	51 ± 19	57 ± 27	55 ± 18	53 ± 23	0.962 (0.921)
Frequency (days·wk⁻¹)	5 ± 1	5 ± 1	5 ± 1	5 ± 1	0.932 (0.872)

Data are presented as the mean ± standard deviation. The p-values represent differences between all four groups as determined using a one-way ANOVA. The p-values in parentheses represent differences between the three experimental HIIT groups only.

* Significant difference between the control group and the 400 m ($p = 0.034$), 1600 m ($p = 0.048$) and mixed ($p = 0.003$) groups, respectively.

Abbreviations: 1600 m – 1600 m interval group, 400 m – 400 m interval group, Mixed – Mixed interval group, S7 – Sum of seven skinfolds, LTV – Lean thigh volume, PTRS – Peak treadmill running speed, VO_{2 max} – Maximal oxygen uptake, HR_{max} – Maximal heart rate.

4.3.2 Comparison of treadmill time trial time between pre- and post-high intensity interval training intervention

Pre-HIIT intervention TTT performance was not significantly different between groups (36:17 ± 1:53 (min:s) for control group; 37:03 ± 2:35 (min:s) for mixed group;

35:23 ± 3:41 (min:s) for 1600 m group; 36:58 ± 2:36 (min:s) for 400 m group; p = 0.568).

It was found that only the mixed group showed a significant 3.3 ± 2.0% improvement in TTT performance between the pre- and post-HIIT TTT (p = 0.001) (Figure 4.1). Additionally, there was a significant trial effect when data for all three HIIT groups were combined showing an improvement of 36.2 s or 1.7% in TTT performance between the pre- and post-HIIT TTT (p = 0.003).

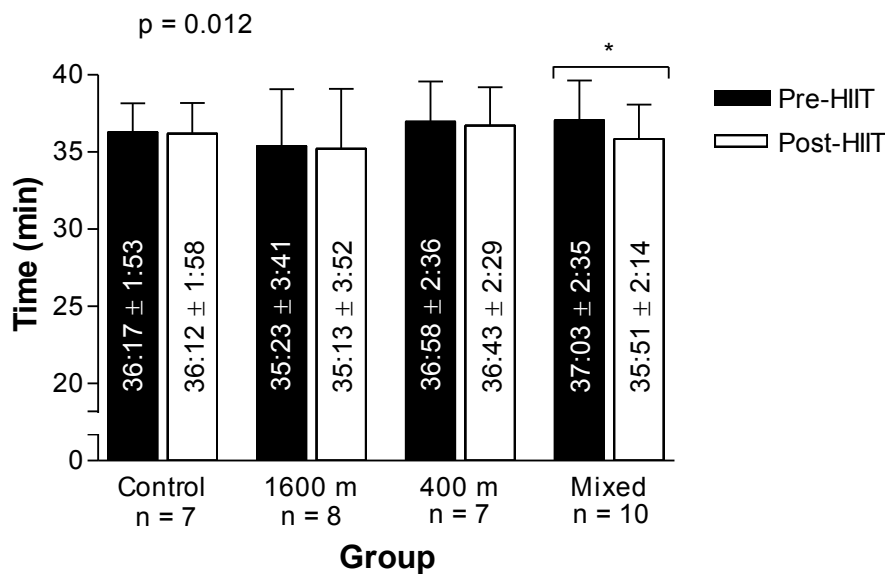


Figure 4.1 Treadmill time trial time for all training intervention groups pre-compared to post-high intensity interval training intervention.

Data are presented as the mean ± standard deviation. The actual mean time in minutes and seconds (min:s) has been included within each bar. The p-value on the graph represents group by trial interaction effect, as determined by a repeated measures ANOVA.

* Significant improvement compared to the pre-HIIT intervention TTT in the mixed group only (p = 0.001).

Abbreviations: TTT – Treadmill time trial, HIIT – High intensity interval training, 1600 m – 1600 m interval group, 400 m – 400 m interval group, Mixed – Mixed interval group.

The percentage improvement of the mixed group was significantly greater than that of the control and 1600 m groups (3.3 ± 2.0% vs. 0.2 ± 1.6% for the mixed vs. control group; p = 0.028 and 3.3 ± 2.0% vs. 0.5 ± 2.6% for the mixed vs. 1600 m group; p = 0.037). The same trend was evident in comparison to the 400 m group, although

not significantly so ($3.3 \pm 2.0\%$ vs. $0.6 \pm 1.9\%$ for the mixed vs. 400 m group; $p = 0.068$) (Figure 4.2).

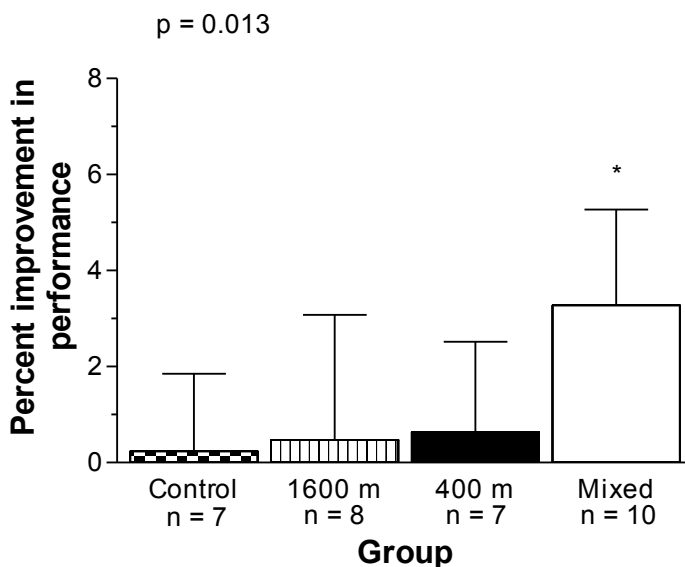


Figure 4.2 Percentage change in 10 km treadmill time trial performance for all training intervention groups pre-high intensity interval training intervention compared to post-high intensity interval training intervention

Data are presented as the mean \pm standard deviation. The p -value on the graph represents the difference between all four groups, as determined using a one-way ANOVA.

* Significantly greater improvement in performance compared to the control and 1600 m groups ($p = 0.028$ and $p = 0.037$, respectively).

Abbreviations: 1600 m – 1600 m interval group, 400 m – 400 m interval group, Mixed – Mixed interval group.

4.3.3 Comparison of descriptive performance characteristics of participants between pre- and post-high intensity interval training

Comparison of all groups indicated that running economy for the control group was lower compared to the 400 m ($p = 0.033$) and mixed ($p = 0.020$) HIIT groups prior to the HIIT intervention (Table 4.2). There were no significant differences between groups for all other descriptive performance characteristics post-HIIT intervention or within individual groups when comparing these data to those of pre-HIIT intervention (Table 4.2). There was, however, a significant trial effect improvement in both PTRS ($p < 0.001$, Figure 4.3) and $VO_{2\text{ max}}$ ($p = 0.011$, Figure 4.4) between pre- and post-HIIT, when the data for the groups were combined.

Table 4.2 Descriptive performance characteristics for all groups before (pre-) and after (post-) the four week high intensity interval training intervention.

	Control (n = 7)	1600 m (n = 8)	400 m (n = 7)	Mixed (n = 10)	p-values
Mean % of HR_{max} sustained during the TTT					
Pre-HIIT	92.5 ± 2.9	92.9 ± 3.4	92.4 ± 2.6	92.4 ± 2.8	0.982 (0.921)
Post-HIIT	92.3 ± 2.6	93.5 ± 2.6	91.9 ± 2.2	92.7 ± 1.2	
Δ	-0.2	0.6	-0.5	0.3	0.770 (0.673) [#]
VO_{2 max} (ml·kg⁻¹·min⁻¹)					
Pre-HIIT	58.1 ± 3.8	63.3 ± 2.8	64.4 ± 5.7	64.3 ± 6.9	0.086 (0.907)
Post-HIIT	59.9 ± 3.4	67.7 ± 3.8	67.1 ± 8.5	65.4 ± 6.3	
Δ	1.8	4.4	2.7	1.1	0.490 (0.393) [#]
RE (ml·kg⁻¹·min⁻¹)					
Pre-HIIT	43.9 ± 4.2 *	48.3 ± 3.8	50.1 ± 3.9 *	50.1 ± 4.0 *	0.018 (0.584)
Post-HIIT	45.4 ± 3.7	51.9 ± 4.0	52.8 ± 8.9	49.8 ± 5.0	
Δ	1.5	3.6	1.7	-0.3	0.339 (0.262) [#]
RE as % of VO_{2 max}					
Pre-HIIT	75.7 ± 5.2	76.4 ± 5.4	78.1 ± 6.4	78.3 ± 5.7	0.759 (0.781)
Post-HIIT	76.0 ± 7.3	77.0 ± 7.7	78.8 ± 11.4	76.5 ± 5.0	
Δ	0.3	0.6	0.7	-1.8	0.757 (0.582) [#]
PTRS (km·h⁻¹)					
Pre-HIIT	20.0 ± 1.0	20.5 ± 1.3	20.5 ± 0.9	21.0 ± 0.8	0.198 (0.397)
Post-HIIT	20.0 ± 0.9	21.5 ± 1.5	20.5 ± 0.7	21.5 ± 0.9	
Δ	0.0	1.0	0.0	0.5	0.120 (0.225) [#]
20 m Sprint Time (s)					
Pre-HIIT	-	2.54 ± 0.11	2.55 ± 0.09	2.53 ± 0.14	(0.959)
Post-HIIT	-	2.56 ± 0.14	2.57 ± 0.09	2.55 ± 0.16	
Δ	-	0.02	0.02	0.02	(0.997) [#]

Data are presented as the mean ± standard deviation. The p-values represent differences between all four groups as determined using a one-way ANOVA. The p-values in parentheses represent differences between the three experimental HIIT groups only.

[#] The p-value represents the differences from pre- compared to post-HIIT for all groups, as determined using a repeated measures ANOVA.

* Significant difference in pre-HIIT intervention values only between the control group and the 400 m (p = 0.033) and mixed group (p = 0.020), respectively.

Abbreviations: TTT – Treadmill time trial, HIIT – High intensity interval training, 1600 m – 1600 m interval group, 400 m – 400 m interval group, Mixed – Mixed interval group, VO_{2 max} – Maximal oxygen uptake, RE – Running economy at 70% of PTRS, PTRS – Peak treadmill running speed.

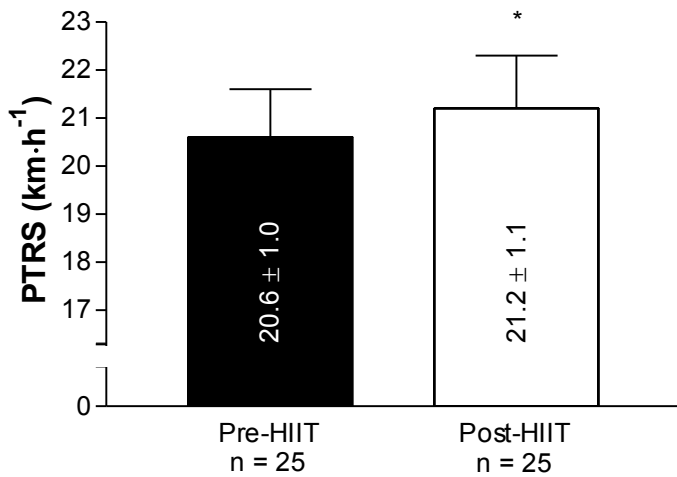


Figure 4.3 Peak treadmill running speed for all training intervention groups combined (i.e. excluding the control group) pre- compared to post-high intensity interval training intervention.

Data are presented as the mean ± standard deviation. The actual mean speed in km·h⁻¹ has been included within each bar.

** Significant improvement compared to pre-HIIT intervention value (p < 0.001).*

Abbreviations: HIIT – High intensity interval training, PTRS – Peak treadmill running speed.

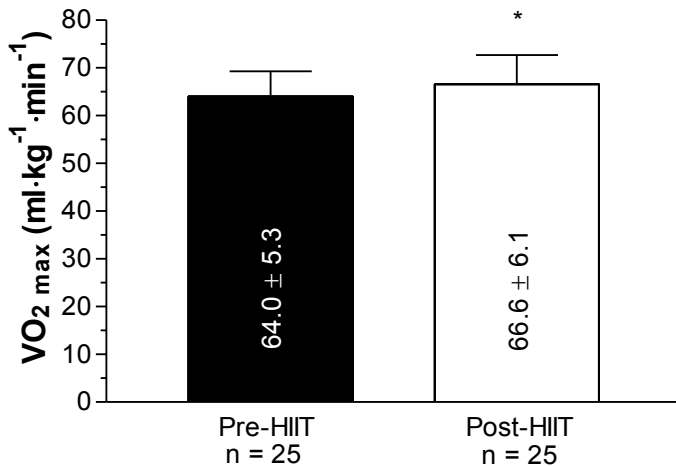


Figure 4.4 Maximal oxygen uptake for all training intervention groups combined (i.e. excluding the control group) pre- compared to post-high intensity interval training intervention.

Data are presented as the mean \pm standard deviation. The actual mean $VO_{2\max}$ value in ml·kg⁻¹·min⁻¹ has been included within each bar.

* Significant improvement compared to pre-HIIT intervention value ($p = 0.011$).

Abbreviations: $VO_{2\max}$ – Maximal oxygen uptake, HIIT – High intensity interval training.

4.3.3 Control group

An analysis of the control group's performance data revealed no significant differences between pre- and post-HIIT values for TTT times ($p = 0.704$), PTRS ($p = 0.569$) or $VO_{2\max}$ ($p = 0.249$) and the typical error of measurement (TEM) (time) and typical percent error (TEM %) (time) of this group fell comfortably within the range of values reported in Chapter Two (TEM: 24.8 s for the control group vs. 20.0 s to 29.2 s and TEM %: 1.1% vs. 0.9% to 1.3% reported in Chapter Two, Table 2.3). In conjunction with this, the descriptive and training characteristics of the control group were not different to that of the participants assessed in the reliability chapter (Chapter Two) both prior to the start of the study as well as during the training intervention period. No differences were found in age ($p = 0.271$), height ($p = 0.309$), mass ($p = 0.515$), S7 ($p = 0.533$) and PTRS ($p = 0.236$). Furthermore, both groups of participants for both studies were matched for weekly training distance ($p = 0.962$) and frequency ($p = 0.914$) and neither were performing HIIT.

It was therefore assumed that this group's performance response to a further two weeks of one 10 km TTT per week, with no alteration in training, would show no significant change as performance was shown to be highly reliable and not significantly different under the same conditions in Chapter Two. As per the methods section 3.2.1.1 it was decided that no further testing would be required for the control group.

4.4 Discussion

The purpose of this study was to compare the effects of three HIIT programmes of differing intensity and duration on 10 km running performance in well-trained male runners. More specifically, these were intervals of 400 m duration at an intensity of 13.2% faster than current average 10 km TTT pace, 1600 m intervals at an intensity of 4.3% faster than current average 10 km TTT pace and a mixed group of four sessions of 400 m intervals and four sessions of 1600 m intervals again at an intensity of 13.2% and 4.3% faster than current average 10 km TTT pace, respectively. To ensure that the effects of the training programme could be differentiated from inherent physiological variability, it was necessary to demonstrate the reliability of the testing procedure to evaluate changes in 10 km TTT performance. It was shown in the study reported in Chapter Two that the 10 km TTT's are highly reproducible (TEM % = 1%) in well-trained runners ($VO_{2\max}$: 56.9 – 78.3 ml·kg⁻¹·min⁻¹ and PTRS: 19 – 23 km·h⁻¹). Furthermore, the participants in the three different HIIT groups were similar and comparable with respect to anthropometry and performance characteristics prior to any intervention. All the runners were of a similar calibre prior to training and so it is reasonable to infer that any changes in performance could be attributed to their different exposures to the different HIIT programmes.

Hence, the first relevant finding was that the mixed HIIT group (400 m and 1600 m) showed a significant 3.3% improvement in 10 km TTT performance, whereas both the 1600 m and 400 m groups showed only non-significant improvements in performance (Figure 4.1 and 4.2).

The second finding was that, as shown in Table 4.2, there was no significant difference between pre- and post-HIIT values for any of the descriptive performance characteristics measured in any of the individual groups, namely: $VO_{2\max}$, percentage of HR_{max} sustained during the TTT, running economy, running economy as a percent of $VO_{2\max}$, PTRS and 20 m sprint time.

Interestingly, there was a significant improvement in both $VO_{2\max}$ and PTRS when data were combined for all groups, suggesting that the HIIT had an effect on all runners in terms of the maximum speed that they could reach on the treadmill and

maximal oxygen uptake during a maximal test after the HIIT intervention, regardless of the nature of the training intervention (Figures 4.3 and 4.4).

This is curious as it has been shown that PTRS is a good predictor of endurance running performance (364), so one might have expected that an improvement in PTRS would have been observed in the mixed group as they had a significant improvement in performance following the training intervention. The grouped improvement in PTRS actually appears to be driven predominantly by a large non-significant improvement in the PTRS of the 1600 m group, although this group did not demonstrate a significant improvement in performance. It is also, however, observed that the average PTRS of the mixed group also increased, although not significantly so. It could be that PTRS is not sensitive enough to be an indicator of a change in 10 km running performance unless the magnitude of change is greater than that shown in this study.

The trial effect improvement for $VO_{2\max}$ appears to be driven by a non-significant change in the 1600 m group with very little change observed in this parameter in the mixed group that showed the performance improvement. Although many investigations have reported an increase in $VO_{2\max}$ following HIIT, such studies, for the most part, have used previously sedentary (42, 112, 152, 301), recreationally active (495, 497) or moderately-trained individuals (132, 179, 197, 374). One such study which reports an improvement in $VO_{2\max}$ following different HIIT programmes and which makes use of a similar design to the present study was conducted by Seiler *et al.* (425). This study however, tested the effects of different interval training programmes on well-trained recreational cyclists and not runners. Specifically, male and female recreationally active cyclists were randomly divided into four groups; a control group, a 4 x 4 min interval group, 4 x 8 min interval group and a 4 x 16 min interval group. The intervention took place over a seven week period. The control group trained for four to six unsupervised sessions per week at a low intensity, whereas the three intervention groups performed two interval sessions per week as well as two to three additional low intensity session per week. The 4 x 4 min interval group performed the interval sessions with a two min recovery between intervals and the intervals were performed at an intensity approximating $VO_{2\max}$ (corresponding to 94% HR_{\max}). The 4 x 8 min interval group performed the interval sessions with the same recovery between intervals, however, the intervals were performed at an

intensity corresponding to 90% HR_{max}. Finally, the 4 x 16 min group performed the interval sessions with a three min recovery between intervals and the intervals were performed at an intensity approximating lactate threshold intensity (corresponding to 88% HR_{max}). In this study the examiners aimed to match the effort of the interval sessions by varying the duration of the intervals and consequently the intensity of the sessions varied between the different groups. In the present study the interval groups were matched for distance (4.8 km was run in each interval session) and a relative intensity was prescribed for the different interval sessions such that the 400 m intervals were run at an intensity of $81 \pm 3\%$ HR_{max} and the 1600 m intervals were run at an intensity of $90 \pm 2\%$ HR_{max}. In the study of Seiler *et al.* (425), all three intervention sessions induced an improvement in VO_{2 max}, with the 90% HR_{max} group showing the greatest improvement in comparison to all other groups in the study. Interestingly the 1600 m group in the present study, who performed only 1600 m intervals and produced the largest improvement in VO_{2 max} (although not significant), ran these intervals at same % HR_{max} as the group which produced the greatest improvement in VO_{2 max} in the aforementioned study of Seiler *et al* (425). Although these studies are each investigating a different type of exercise, it would seem that more investigation is warranted making use of intervals performed at 90% HR_{max} as this relative intensity appears to induce greater improvements in VO_{2 max} in both of these investigations.

Notably, it has been suggested previously that changes in VO_{2 max} may only have a significant influence on performance in previously untrained individuals (324). The results of the present study are not the first to show improvements in performance without concomitant changes in physiological measures such as VO_{2 max} in well-trained athletes (8, 96, 99, 111, 130, 311). Specifically, a study conducted by Acevedo and Goldfarb (8) found that eight weeks of HIIT (at 90 – 95% of HR_{max}) improved both 10 km running performance and exercise time to fatigue at supra-maximal running speed, without any improvement in VO_{2 max} in well-trained distance runners.

Improvements in VO_{2 max} can occur through improvements of both oxygen delivery to and / or oxygen utilisation by active muscles (69) and this improvement is dependent on, amongst other factors, the duration of the training programme (281). In the present study, the 1600 m group took part in eight sessions of 1600 m intervals

compared to the mixed group which took part in only four 1600 m intervals (and four 400 m intervals). On average an individual 400 m interval in this study was 77% shorter than a 1600 m interval ($1:16 \pm 0:04$ vs $5:35 \pm 0:18$ (min:s), respectively). Franch *et al.* (153) reported a 6% increase in $VO_{2\max}$ following longer duration intervals (4 min) compared to only a 3% increase in $VO_{2\max}$ following an interval of 94% shorter duration (15 s). It is conceivable that an interval of longer duration requiring substantially higher oxygen delivery, may induce increased adaptations to the oxygen delivery system and hence more of an increase in $VO_{2\max}$ (69, 132) which could explain the large change observed in this parameter in the 1600 m group compared to the 400 m group.

Running economy is a measure of efficiency and has been shown to be well developed in well-trained individuals (149, 153, 482). It is, however, usually measured at a fixed speed when comparing pre- and post-values in an intervention study. We did not think that this was necessarily the correct way to establish an improvement in efficiency following any form of training intervention. For example, if the cross-over effect for substrate utilisation described by Brooks (69) is considered, shifts in utilisation are often seen when comparing measurements taken at the same absolute intensity pre- vs post-intervention. However, when comparing these measures at the same relative intensity the same is often not true. Therefore, if an athlete's performance improves following an intervention, then the absolute intensity as measured prior to the intervention is no longer the same relative intensity at the time following the intervention, so the likelihood of an improvement is obviously very high. In the present study we performed the running economy test at 70% of PTRS as this is more comparable pre- to post-intervention at a relative intensity compared to if the same fixed speed was used. A number of studies have shown an improvement in running economy following HIIT in well-trained runners (117, 130, 376, 437), however, we are unable to fully compare our data to theirs due to this difference in measurement methodology. For example, Smith *et al.* (437) determined running economy from an incremental running test to exhaustion, where running economy was defined as the average VO_2 at $14 \text{ km}\cdot\text{h}^{-1}$. Dendai *et al.* (117) made use of an eight-minute submaximal constant-intensity test at $14 \text{ km}\cdot\text{h}^{-1}$ and VO_2 was averaged in the sixth and seventh minute of the test to determine running economy. In the present study running economy was measured at $14.4 \pm 0.7 \text{ km}\cdot\text{h}^{-1}$

before the training intervention and $14.9 \pm 0.8 \text{ km}\cdot\text{h}^{-1}$ following the training intervention. Furthermore, the fact that we measured running economy at a relative intensity, would more than likely explain the lack of any significant difference in running economy, especially in the mixed group where performance improved by more than a minute or greater than 3%.

The effect of HIIT on the lactate threshold has been researched in a number of studies (8, 132, 495). For example, Esfarjani *et al.* (132) investigated the effects of two different HIIT interventions on 3000 m running performance and the lactate threshold over a period of ten weeks in a group of moderately trained runners. The study participants were divided into the separate HIIT groups; one group performed eight bouts per session at an intensity of $100\% V_{\max}$ and duration of $60\% T_{\max}$, whereas the other group performed twelve sessions at an intensity of $130\% V_{\max}$ and duration of 30 seconds. There was a significant performance improvement in 3000 m running performance in both groups and this performance improvement was significantly related to velocity at the lactate threshold (v_{LT}) ($r = -0.67$). Additionally, a study by Acevedo and Golfarb (8) investigated the effects of eight weeks of a HIIT intervention on 10 km running performance and plasma lactate concentrations in a group of well-trained endurance runners. Three interval sessions were performed each week with one session comprised of intervals run at 90 to 95% of HR_{\max} with limited recovery between the intervals (the next interval was started when the heart rate returned to $120 \text{ beats}\cdot\text{min}^{-1}$). The other two HIIT sessions were Fartlek sessions covering a total distance of approximately 10 – 16 km. The faster bouts were run at a pace “slightly below to faster than 10 km race pace” (the exact pace is not reported) with a slower pace between these bouts allowing minimal recovery. It was found that 10 km running performance was significantly improved by approximately 3% from 35:27 to 34:24 (min:s) and a significant correlation was found between 10 km time trial performance and changes in plasma lactate concentration at 85% and 90% $VO_{2\max}$ ($r = 0.69$ and 0.73 , respectively). Lactate threshold, however, was not measured in the present study as the blood sampling during the $VO_{2\max}$ trial would have interfered with the performance indicator (PTRS), which we deemed more important for the purposes of this study. The possibility that the athletes in the present study may have had an increase in the lactate threshold following the HIIT

intervention, which could have contributed to an improvement in performance, therefore remains unknown.

Parameters such as running economy and $VO_{2\text{ max}}$ are near their maximum limit in well-trained athletes, with only small changes in these parameters being possible (324). Thus, improvements in athletic performance in highly-trained individuals may be independent of increases in $VO_{2\text{ max}}$ and running economy (96, 311). As it was observed in this study that the mixed training group improved their performance with no concomitant changes in $VO_{2\text{ max}}$ and running economy, it is likely, therefore, that other factors influenced the performance outcome. Some factors associated with performance improvements after HIIT described in the literature are: (i) Enhanced skeletal muscle blood perfusion (267, 321); (ii) Metabolic parameter changes (30, 76, 77, 112, 152, 295, 301, 399); (iii) The psychological effects of training (293, 453, 483) and (iv) Various neuromuscular adaptations (106, 382), examples of all of which are discussed below.

(i) Muscle oxygenation reflects the balance of oxygen delivery to, and consumption in, working muscles (185). It has been suggested that the utilisation of available oxygen in muscle is limited by the activity of rate-limiting enzymes and the provision of oxidative substrate to the mitochondrial tricarboxylic acid cycle and electron transport chain (233). These factors are directly linked with blood flow and oxygen availability (168). An increase in blood flow or perfusion would therefore lead to an increased ability of the applicable muscle to utilise oxygen and therefore increase the ability of the muscle to do work (69). Adaptations in microvascular blood flow following HIIT have been reported to be associated with an increase in exercise performance in recreationally active individuals (267, 321). The aforementioned studies have been conducted mainly on untrained or only moderately-trained individuals. The improvements of these variables in well-trained individuals are not as well documented with very few research studies showing concomitant performance improvements with changes in these variables. We can therefore assume that these were most likely not the reason for performance enhancement in this study.

(ii) An increase in mitochondrial density following a HIIT intervention, associated with a reduced reliance on carbohydrate as a substrate, has been reported to improve

exercise performance in untrained individuals (76, 77, 295). However, Houston and Thomson (232), Costill *et al.* (99) and Lindsay *et al.* (293) have all shown no changes in these parameters following a HIIT intervention in well-trained athletes. Specifically, Lindsay *et al.* (293) concluded that the aforementioned factors may not explain the improvement in performance after six HIIT sessions in highly-trained cyclists as they found no change in the muscle glycolytic or oxidative capacities. Similarly, Westgarth- Taylor *et al.* (481) showed that carbohydrate oxidation was similar pre- and post-HIIT at the same relative intensities, indicating that the improvements in cycling time trial performance observed in their study were unrelated to rates of carbohydrate oxidation, implying that there must be other mechanisms that allowed the highly-trained athletes to sustain higher work rates following HIIT. Conversely, Weston *et al.* (483) found that skeletal muscle buffering capacity was improved after just six sessions of HIIT in well-trained cyclists which closely correlated with 40 km cycling time trial performance ($r = -0.82$).

(iii) Lindsay *et al.* (293) discuss the demands of a sudden increase in training load on disturbances in mood states (393). It is acknowledged that any training intervention programme may have an impact on exercise performance, merely due to there being a change, as athletes tend to be very suggestive to new training regimes that they believe are intended to improve performance (HIIT being one of these) (293). In an effort to negate this factor, a study was designed by Stepto *et al.* (445), where cyclists were randomly assigned to one of five different interval training sessions (12 x 30 s at 175% peak power output (PPO), 12 x 60 s at 100% PPO, 12 x 2 min at 90% PPO, 8 x 4 min at 85% PPO, or 4 x 8 min at 80% PPO). It is unlikely that one group would have more of a psychological input (in terms of training novelty) than another and participants would not have been able to predict the performance outcomes of the different types of HIIT sessions they were requested to perform in comparison to the others. Hence, any performance changes could be explained by changes in the different HIIT sessions. The same could be said for the present study as the three different training groups were not informed of what training the other groups were involved in. It is, however, not easy to determine the extent to which psychological factors may be responsible for an improvement in performance (293) so we cannot rule out a psychological aspect to the improvement seen in this study.

iv. During strength training, neural adaptations have been shown to precede morphological adaptations, such as increased muscle fibre recruitment, firing rate and motor unit synchronisation; all resulting in the ability of a muscle to exert more force (106, 264, 334, 411). A study by Hickson *et al.* (203) showed a running endurance improvement of 11 and 13% with a concomitant 30% improvement in leg strength in both well-trained cyclists and runners, respectively, following the addition of strength training to their endurance training regimes. Additionally, Creer *et al.* (106) found total work output (as derived from four sprint trials) to be improved by 7% in conjunction with a significant increase in motor unit activation following four weeks of HIIT in trained cyclists. It was postulated that the improvement in repeated sprint work following the HIIT intervention was partly due to improvement in neural activation (106). Improvements in maximal voluntary contraction of major muscle groups involved in running (140, 328, 379), improved pre-activation of muscle groups (7, 158, 297, 378, 411) and stride parameters such as reduced contact time, increased stride frequency and stride length (140, 335, 378, 379) are all parameters which could possibly explain the performance difference that we observed in this study following the HIIT intervention. Accordingly, these neuromuscular parameters and the possibility that they contributed to the observed performance increase following the HIIT intervention in the mixed interval training group will be discussed in Chapter Seven of this thesis.

Most research centred on explaining performance changes is conducted to examine physiological parameters such as those described previously. One aspect that is comparatively less studied, but of great interest to coaches, is that of pacing and how this could impact race performance. The ability of an athlete to correctly pace themselves according to race distance is of vital importance to their performance and cannot be underestimated. It has been suggested that PTRS, running economy and the lactate threshold appear to be important determinants of the chosen pacing strategy (291). Furthermore, Mauger *et al.* (316) investigated the pacing strategy disturbance of exercise of a set duration when a bout of exercise of different distance was included and the authors concluded that further research is needed to investigate the effects of interchanging distances during training on subsequent pacing strategies for a specific event. This raises the question as to whether performance can be improved following HIIT due to an improved pacing strategy

owing to more exposure to actual race pace or higher than race pace intensities. The question is raised as to whether the performance enhancement observed in the mixed interval training group was due to the development of a more efficient pacing strategy, as they were exposed to intervals of mixed intensity and therefore, could adapt to different intensities during a 10 km TTT after this training exposure, to a better degree than the other two interval groups (who were exposed to only one intensity during their training). Another factor to investigate is whether an enhanced perception of effort from exposure to HIIT could have enabled a superior pacing strategy in the mixed interval training group that could have led to the observed improvement in performance. These are factors that are addressed in Chapter Six of this thesis.

It is clear from the data in the present study that the mixed interval training group had the greatest performance enhancement after the four-week HIIT intervention. Furthermore, we have also shown that the prescription of the intensity of intervals based on previous 10 km TTT performance is effective in producing a training programme capable of generating performance enhancements. What is also evident is that this performance enhancement was not associated with any changes in the physiological variables that were investigated.

We therefore conclude that a HIIT session including both 400 m at intensity of 13.2% faster than current average 10 km TTT pace and 1600 m at an intensity of 4.3% faster than current 10 km TTT pace, significantly improves 10 km TTT performance and that this change in performance was not associated with any changes in $VO_{2\text{ max}}$, running economy, running economy as a percent of $VO_{2\text{ max}}$, PTRS and 20 m sprint time.

This leaves the question of what could have been the cause of this performance improvement immediately following this specific interval training programme in comparison to the other programmes. Additionally, the question is raised as to whether any further improvements in performance in the mixed group would be observed following a taper period and indeed whether a performance enhancement or deterioration would be observed in the other training groups during this period. Accordingly, Chapter Five will address this question and investigate both changes in running performance and various physiological parameters over a taper period

following the end of the training intervention. As mentioned, Chapters Six and Seven of this thesis will then aim to address whether other factors can be associated with any performance improvements both immediately following the end of the training intervention, as well as during the taper period. Chapter Six will focus on pacing strategies and RPE and Chapter Seven will investigate specific neuromuscular characteristics and whether these are associated with changes in running performance immediately following the training intervention and during the subsequent taper period.

Practical application to coaches

The findings of this chapter suggest that, for the 10 km distance, an interval training programme should include a variation of intensity and duration to achieve greater performance improvements compared to a non-varied training programme. Specifically, coaches should consider an interval programme that includes both a 400 m and 1600 m interval session, each week. It was also shown that basing the intensity of intervals on previous 10 km TTT performance is easy to implement and effective in the design of a training programme to produce performance enhancements.

CHAPTER FIVE – THE EFFECT OF A SINGLE-STEP 30% REDUCTION IN TRAINING VOLUME (TAPER) FOLLOWING FOUR WEEKS OF HIGH INTENSITY INTERVAL TRAINING ON 10 KM TREADMILL TIME TRIAL PERFORMANCE AND ASSOCIATED PHYSIOLOGICAL PARAMETERS.

5.1 Introduction

In the final days before an important event, athletes will often reduce their training load in an effort to optimise their performance (226, 229, 339, 344, 351, 428, 465). This reduction in training load is referred to as the taper (227, 230, 337, 339, 344, 428, 494) and can be achieved through the alteration of several training components (63), such as training volume, intensity and frequency (338). Additionally, the pattern of the taper and its duration can differ. Progressive tapers are either linear or exponential in nature and, in addition, exponential tapers can involve either a fast or slow time constant of decay (344). Non-progressive or step tapers involve a standardised reduction in training load (344, 461), as is described in this component of the training study in this thesis. Progressive and step tapers have both been linked with the maintenance and improvement of a number of performance-related and physiological adaptations of prior training (204, 207, 227, 229, 320, 337, 344).

In the taper stage of training, athletes, coaches and sports scientists face the challenge of finding the balance between maximising performance by reducing accumulated fatigue and avoiding the negative effects of detraining (229, 344, 350, 461). The relationship between taper-induced performance enhancements and the associated neuromuscular (312, 465), cardiorespiratory (33, 98, 245, 494), metabolic (33, 98, 245, 342, 346, 350, 352), haematological (341, 342, 350, 465) and psychological (216, 351, 488, 489) changes has become a focus of research into tapering techniques, resulting in a better understanding of the complex relationships between these variables (344, 346). While mathematical modelling has been used as a method to determine optimum tapering strategies (142, 336, 339, 461), the majority of tapering studies have involved the experimental manipulation of taper programmes with athletes of varying competitive levels (33, 341, 342, 342, 350, 428, 494). According to Costill *et al.* (227), a large proportion of the metabolic

adaptations that increase performance from continuous swimming training are lost in one to four weeks of inactivity, possibly highlighting that physical activity is certainly required during the taper period (98, 227). It is the degree to which the different training characteristics should be altered that remains the subject of many investigations.

5.1.1 The influence of training characteristics on adaptations during tapering

Hickson *et al.* (204, 206) and Hickson and Rosenkoetter (207) conducted a three-part series of studies focusing on a period of reduced training and the effect of reduction of training intensity (204), reduction of training volume (206) and reduction of training frequency (207) on various physiological and performance parameters. In this series it was established that the maintenance of training intensity during reduced training is integral to the preservation of training induced adaptations in moderately trained individuals taking part in running and cycling (204).

5.1.1.1 Influence of training intensity

In the study by Hickson *et al.* (204), which investigated the effect of training intensity during a prolonged reduction in training, a reduction of intensity of 33% and 66% (while maintaining training volume and frequency) over 15 weeks was examined. It was found that the 33% intensity reduction group showed a lesser decline in maximal oxygen uptake ($VO_{2\text{ max}}$) than the 66% intensity reduction group.

Furthermore, short-term cycling endurance was maintained over the 15-week period in the former group whereas it declined after five weeks in the latter group. It has been suggested that the effect of training intensity could be somewhat explained by the role of exercise intensity on fluid retention hormone regulation and activity (63, 94, 95, 337), as it has been shown that a reduction in $VO_{2\text{ max}}$ during detraining in untrained individuals is related to decreases in both blood and stroke volume (103, 104, 351). This suggestion is also supported in well-trained individuals, as a study by Shepley *et al.* (428) compared rest-only seven day tapers, high-intensity low-volume and low-intensity moderate-volume tapers in well-trained middle-distance runners and found haematological, metabolic and performance markers to be optimised in the high-intensity low-volume taper only (428). Specifically, whole blood

and red cell volumes as well as citrate synthase activity (a marker of aerobic oxidative potential) increased significantly after the high-intensity taper. Furthermore, an increase of 22% in running time-to-exhaustion was found in the high-intensity taper compared to no change in the other two tapers. In a review of the topic, Mujika (337) suggests that while maintaining training intensity during the taper period is clearly important, there needs to be a simultaneous reduction in other training characteristics, including volume and frequency, to ensure that sufficient recovery from prior training is possible in the athlete.

5.1.1.2 Influence of training volume

i) Step volume reductions

Hickson *et al.* (206) investigated the responses of a single-step 35% and 68% volume reduction in training (whilst maintaining training frequency and intensity) over 15 weeks and found that $VO_{2\text{ max}}$, peak lactate concentration and 5 min exercise performance were all maintained in both groups, whereas cycling time-to-exhaustion at 80% $VO_{2\text{ max}}$ was decreased significantly in the 68% reduction group from 139 to 123 min, or by 10%. In another study, McConell *et al.* (320) examined the effects of a single-step 66% volume reduction with concomitant 50% reduction in frequency of training on 5 km running performance in distance runners. $VO_{2\text{ max}}$, resting plasma volume and resting heart rate were all maintained following four weeks of reduced training, however 5 km time trial performance significantly declined. Conversely, Houmard *et al.* (227) found no change in 5 km time trial performance or $VO_{2\text{ max}}$ following a three-week single-step 70% reduction in training volume with concomitant 17% reduction in training frequency. However, interestingly, there was a significant increase of 10% in time-to-exhaustion during the $VO_{2\text{ max}}$ test following the taper period. An increase in time-to-exhaustion suggests an increase in total work output during the maximal test suggestive of enhanced performance capability in a similar way that an increase in peak treadmill running speed (PTRS) is viewed as a good predictor of endurance performance (364). The authors were unable to explain this finding, in light of the fact that there was no associated improvement in 5 km time trial performance (227). Finally, Houmard *et al.* (229) examined the physiological effects of a two-step volume reduction in training on well-trained distance runners. The runners underwent a ten-day 27% volume reduction taper followed by a further

50% volume reduction taper of an additional ten days. The results indicated that aerobic capacity was maintained following both steps of the taper. Other than the aforementioned study by Hickson *et al.* (206), there are minimal data available of the effects of single-step-wise volume reduction tapers lower than 50% in well-trained runners (488).

ii) Progressive volume reductions

In a study involving triathletes, Zarkadas *et al.* (493), reported a 12% improvement in 5 km time trial performance when training volume was reduced in a progressive manner over a 10-day taper compared to a 3% improvement when a single-step reduction in training volume was employed. Similarly, Houmard *et al.* (230), reported a 3% improvement in 5 km time trial performance following an 85% progressive reduction in training volume over seven days in distance runners. In a review compiled by Mujika (337), it is suggested that progressive tapers seem to have more of a positive effect on athletic performance compared to step tapers, however, step tapers are easier to administer and are often easier to quantify by athletes than progressive tapers.

5.1.1.3 Influence of training frequency

Several studies have been conducted to determine the minimum training frequency required to maintain the aerobic enhancements from prior training (71, 169, 207, 229, 337, 352). Hickson and Rosenkoetter (207) described reductions in training frequency from six days per week to four and two days per week and found that both were able to maintain pre-reduction $VO_{2\max}$ values in well-trained runners, however no running performance variables were reported. In another study, Bryntesson and Sinning (71) investigated the effects on a reduction in training frequency on cycling performance. Training frequency was decreased from five to four, three, two and one days per week and it was concluded that training at least three days per week was required to maintain pre-taper fitness gains. Various studies have been conducted on swimmers, for example, Neuffer *et al.* (352) examined the effect of reduced training frequency over a period of four weeks in well-trained swimmers. The study participants were divided into one of three groups; a three day per week training group, a one day per week training group or a no-training group. Whilst

swim power was reduced in all the groups, $\text{VO}_2 \text{ max}$ was maintained only in the three days per week training group. In another study, Johns *et al.* (245), investigated the effect of a ten-day taper consisting of a 50% reduction in training frequency (from 12 sessions per week to six sessions per week) on well-trained swimmers. No significant changes were observed in the volume of oxygen inspired (VO_2), however, swim power during a tethered sprint swim increased significantly by 5% following the taper period.

5.1.1.4 Influence of taper duration

The importance of training intensity, volume and frequency during the taper period has been highlighted in various reviews (63, 270, 337, 338, 344, 344, 351), but certainly one of the most difficult challenges is assessing the optimal duration of taper for each individual athlete, particularly as the time frame separating the benefits of the taper from the negative consequences of detraining has not been established (229, 341, 343, 351). According to the literature, taper durations of 4 – 28 days appear to result in beneficial physiological adaptations and improved performance across various sports (63, 287, 344, 350, 488). Specifically, studies involving middle- and long-distance runners show a taper duration of 6 – 14 days to be effective in enhancing performance (63, 341, 342, 428).

5.1.2 Rationale and aims pertaining to the taper used in the training study

Further research is needed to quantify the optimum characteristics of a taper to best enhance performance-related adaptations for 10 km running and so improve performance at this distance (406). In this aspect of the present study, in accordance with the suggestions in the literature, training frequency during the taper period was maintained at similar levels to the training phase before the onset of the taper and intensity of training during the taper period was also somewhat maintained by the inclusion of high intensity 10 km time trials and maximal tests. It is possible that a single-step taper of lower reduction in volume may be more psychologically attractive to athletes as they are able to quantify the reduction and furthermore, as previously mentioned, there are minimal data available on the effects of step reduction tapers of below 50% on distance runners. Therefore, a single-step 30% volume reduction taper was chosen for this aspect of the present study.

The aim of this aspect of the study is three part; first to determine if a single-step 30% volume reduction taper will improve 10 km running performance and selected physiological variables ($VO_{2\text{ max}}$, running economy, % $HR_{\text{ max}}$, running economy as a percent of $VO_{2\text{ max}}$ and 20 m sprint time) following four weeks of high intensity interval training (HIIT); secondly, to investigate whether a shorter (ten-day) or longer (17-day) duration for this specific taper better maximises running performance enhancement; and thirdly, to assess if the training programme prior to taper influences the effectiveness of the taper.

5.2 Methods

5.2.1 Participants

The same study participants were used for the three HIIT groups as previously described in Chapter Three; section 3.2.1. As reported in Chapter Four (section 4.3; Table 4.1 and 4.2), there were no significant differences between the HIIT groups in terms of descriptive characteristics of participants and descriptive performance characteristics such as percentage of HR_{max} sustained during the pre-HIIT intervention treadmill time trial (TTT), VO_{2 max}, running economy, running economy as a percent of VO_{2 max}, PTRS and 20 m sprint time or TTT performance prior to commencing the training and subsequent taper intervention.

One participant in the mixed group sustained an injury prior to completion of the final TTT and maximal testing day, therefore there were nine participants in the mixed group at the third post-HIIT TTT and second post-HIIT maximal testing day compared to ten participants in all previous trials. The aforementioned participant sustained a calf muscle strain and it is uncertain as to whether this was related to participation in the study. This injury was, however, not sustained during any testing or training in the study and occurred during the participant's personal training time between testing days.

5.2.2 Experimental design

The detailed design has already been described in Chapter Three, section 3.2.2 and Figure 3.1. All HIIT intervention participants were required to attend all sessions for the full nine-week period in order to be included in this component of the study. A summary of the experimental design more specific to this component of the study is presented in Figure 5.1.

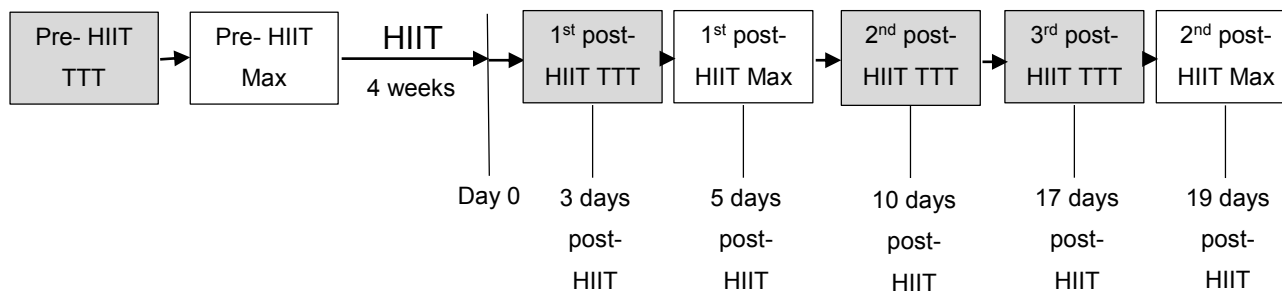


Figure 5.1 Summary of the testing protocol, indicating the number of days following the end of the high intensity interval training and the commencement of the taper period.

Note: TTT's have been highlighted in grey for ease of reference.

Abbreviations: TTT – Treadmill time trial, HIIT – High intensity interval training, Max – Maximal testing day when all other physiological measures were measured and recorded.

5.2.3 Ten kilometre treadmill time trials

These were conducted as described in Chapter Three, section 3.2.3.

5.2.4 Maximal testing days

These were conducted as described in Chapter Three, section 3.2.4, with particular reference to sub-sections 3.2.4.1 to 3.2.4.5 for this component of the study.

5.2.5 Training

The training protocols employed are described in Chapter Three, section 3.2.5.

5.2.6 Taper

This consisted of a single-step 30% reduction in weekly training volume as described in Chapter Three, section 3.2.6.

5.2.7 Statistical analysis

Analyses were as described in Chapter Three, section 3.2.8.

5.3 Results

5.3.1 Treadmill time trial performance changes during the taper period

The TTT performance changes are reported below by means of two comparisons. All post-HIIT TTT's are firstly compared to the performance values obtained prior to the HIIT intervention. In the second comparison, the performance of the second and third post-HIIT TTT's are compared to that of the first post-HIIT TTT, when the taper period began.

5.3.1.1 Performance changes in comparison to the pre-high intensity interval training treadmill time trial

As previously described, the mixed group showed a significant improvement in performance time in the first post-HIIT TTT compared to the pre-HIIT TTT (see Chapter Four, section 4.3, Figures 4.1 and 4.2). As reported previously, this TTT was also significantly faster compared to the pre-HIIT TTT (36.2 s or 1.7%) when the data for all groups were combined. These data were recorded three days following the cessation of interval training, early in the taper period which had begun following the final HIIT session.

When comparing the second post-HIIT TTT (ten days after completion of the HIIT intervention) to the pre-HIIT TTT, a $4.5 \pm 2.5\%$ significant improvement in performance time was found in the mixed group ($p < 0.001$) (Figure 5.2). There was also a significant trial effect when the experimental groups were combined when comparing the second post-HIIT TTT to the pre-HIIT TTT ($p < 0.001$), as well as when comparing the third post-HIIT TTT (17 days after completion of the HIIT intervention) to the pre-HIIT TTT ($p = 0.003$) (Figure 5.3). No group by trial interaction was found when comparing the third post-HIIT TTT to the pre-HIIT TTT ($p = 0.538$).

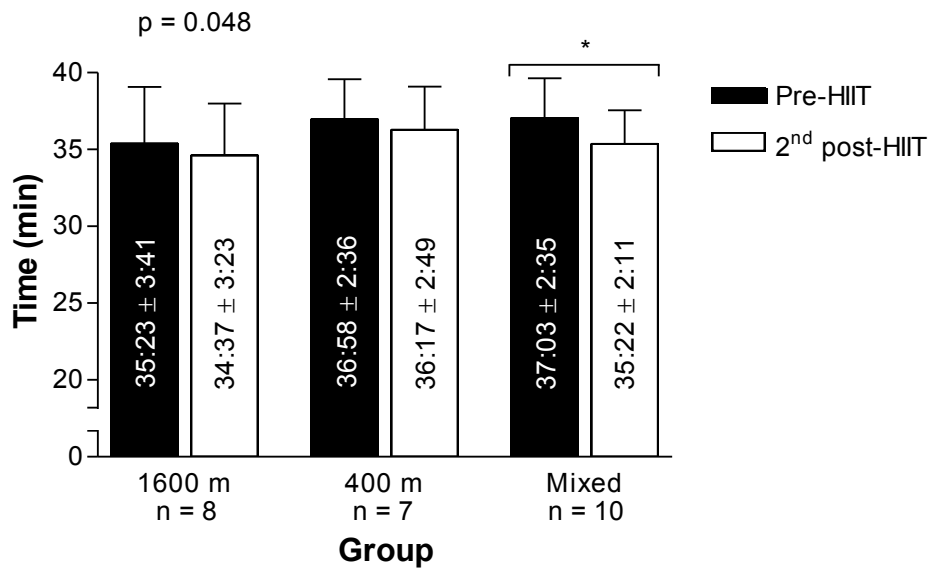


Figure 5.2 Treadmill time trial time for all training intervention groups pre-compared to second post-high intensity interval training intervention (ten days following the start of the taper)

Data are presented as the mean \pm standard deviation. The actual mean time in minutes and seconds (min:s) has been included within each bar. The p-value on the graph represents group by trial interaction effect, as determined by a repeated measures ANOVA.

* Significant improvement compared to the pre-HIIT TTT value ($p < 0.001$).

Abbreviations: TTT – Treadmill time trial, HIIT – High intensity interval training, 1600 m – 1600 m interval training group, 400 m – 400 m interval training group, Mixed – Mixed interval group.

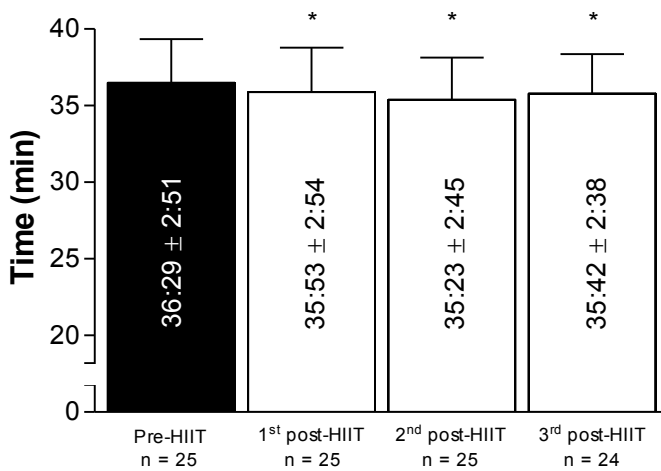


Figure 5.3 Comparison of 10 km treadmill time trial time for all training intervention groups combined pre- compared to first post- (three days following the start of the taper), second post- (ten days following the start of the taper) and third post-high intensity interval training intervention (17 days following the start of the taper).

Data are presented as the mean \pm standard deviation. The actual mean time in minutes and seconds (min:s) has been included within each bar.

* Significant improvement compared to the pre-HIIT TTT value ($p = 0.003$, $p < 0.001$, and $p = 0.003$ for the first, second and third post-HIIT TTT, respectively).

Abbreviations: TTT – Treadmill time trial, HIIT – High intensity interval training.

The percentage change in performance within the three HIIT groups between the pre-HIIT TTT and the second and third post-HIIT TTT's shows a descriptive picture of the pattern of change (Figure 5.4). All the groups show a similar trend of improvement in performance from the pre-HIIT TTT to the first post-HIIT TTT, followed by a larger improvement to the second post-HIIT TTT and then a trend towards a smaller improvement at the third post-HIIT TTT. As mentioned previously, the mixed group was the only group to show a significant improvement between the pre-HIIT TTT and both the first and second post-HIIT TTT ($p = 0.001$ and $p < 0.001$, pre- compared to first and second post-HIIT TTT, respectively).

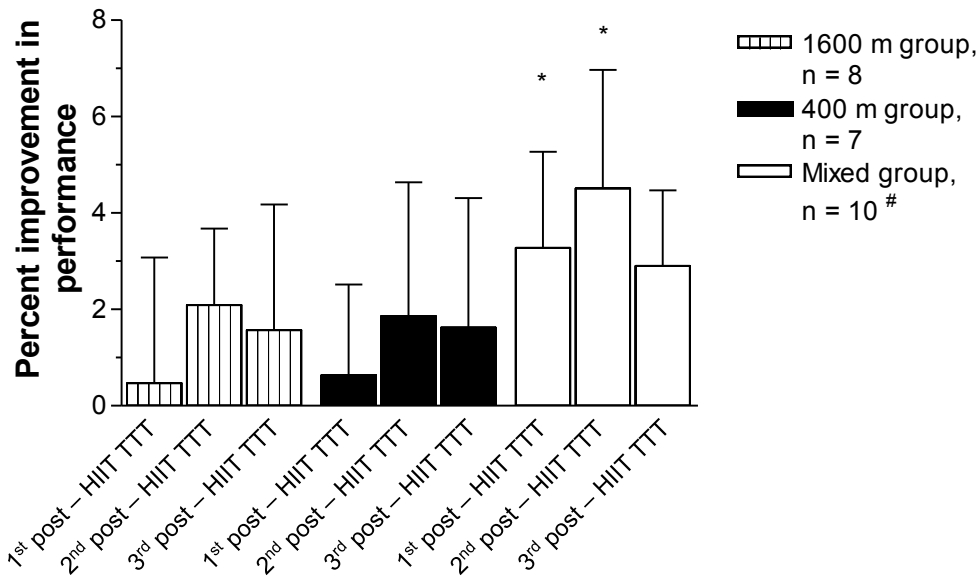


Figure 5.4 Percentage change in performance for all training intervention groups and all post-high intensity interval training treadmill time trials (three, ten and 17 days following the start of the taper) compared to the pre-high intensity interval training intervention values.

Data are presented as the mean \pm standard deviation.

[#] n = 9 for the 3rd post-HIIT TTT.

* Indicates where the significant performance improvements took place for the mixed group as mentioned previously.

Abbreviations: TTT – Treadmill time trial, HIIT – High intensity interval training, 1600 m – 1600 m interval group, 400 m – 400 m interval group, Mixed – Mixed interval group.

5.3.1.2 Performance changes in comparison to the first post-high intensity interval training treadmill time trial (three days following the start of taper)

When comparing the performance time of the second and third post-HIIT TTT's to that of the first post-HIIT TTT (three days following start of the taper), there were no significant differences between any groups ($p = 0.927$ and $p = 0.490$, respectively). There was, however, a significant trial effect when comparing the first post-HIIT TTT to the second post-HIIT TTT, representing a 30-second or 1.4% improvement ($p = 0.013$) when the data for the three HIIT groups were combined. No trial effect was evident when comparing the first post-HIIT TTT to the third post-HITT TTT ($p = 0.475$) (Figure 5.5).

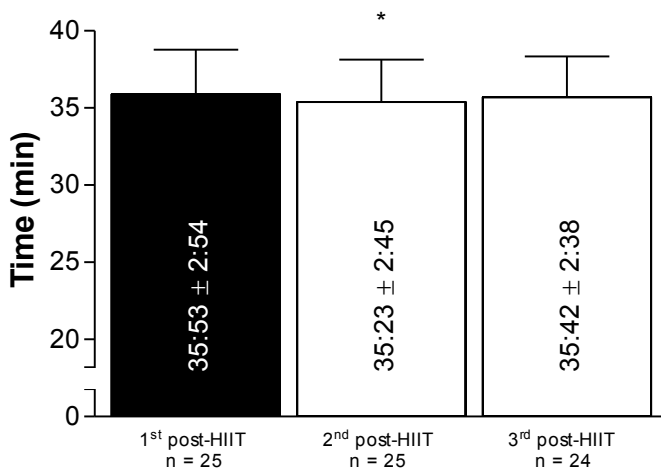


Figure 5.5 Comparison of 10 km treadmill time trial time for all training intervention groups combined first post-high intensity interval training intervention (three days following the start of the taper) compared to the second post- (ten days following the start of the taper) and third post-high intensity interval training intervention (17 days following the start of the taper).

Data are presented as the mean \pm standard deviation. The actual mean time in minutes and seconds (min:s) has been included within each bar.

* Significant improvement compared to the 1st post-HIIT TTT value ($p = 0.013$).

Abbreviations: TTT – Treadmill time trial, HIIT – High intensity interval training.

5.3.2 Maximal testing day descriptive performance measures during the taper period

As reported in Chapter Four (section 4.3 and Table 4.2), there were no significant differences between the HIIT groups for the descriptive performance characteristics at the first post-HIIT maximal testing day (five days following start of the taper). However, there was a significant improvement in both $VO_{2\max}$ and PTRS when data from all HIIT groups were combined (see Chapter Four, section 4.3 for detail). Descriptive performance characteristics second post-HIIT maximal testing day (19 days following the start of the taper period), yielded similar results to those reported above (Table 5.1). There were no significant differences between groups or within the individual groups when comparing these data to those of pre-HIIT. There was, however, again a significant trial effect for both PTRS ($p < 0.001$, Figure 5.6) and $VO_{2\max}$ ($p = 0.009$, Figure 5.7) when data from all HIIT groups were combined.

Table 5.1 Descriptive performance characteristics for all groups pre-high intensity interval training intervention, five days post- (1st post-) and 19 days post- (2nd post-) the four-week high intensity interval training intervention.

	1600 m (n = 8)	400 m (n = 7)	Mixed (n = 10 #)	p-values
Mean % of HR_{max} sustained during the TTT				
Pre- HIIT TTT	92.9 ± 3.4	92.4 ± 2.6	92.4 ± 2.8	0.921 [§]
1 st post-HIIT TTT	93.5 ± 2.6	91.9 ± 2.2	92.7 ± 1.2	0.673
2 nd post-HIIT TTT	94.2 ± 2.4	93.0 ± 2.5	92.2 ± 2.2	0.726
3 rd post-HIIT TTT	93.2 ± 2.3	92.0 ± 1.2	91.2 ± 1.5	0.391
VO_{2 max} (ml·kg⁻¹·min⁻¹)				
Pre-HIIT	63.3 ± 2.8	64.4 ± 5.7	64.3 ± 6.9	0.907 [§]
1 st post-HIIT	67.7 ± 3.8	67.1 ± 8.5	65.4 ± 6.3	0.393
2 nd post-HIIT	66.5 ± 2.8	66.2 ± 5.7	65.2 ± 6.9	0.416
RE (ml·kg⁻¹·min⁻¹)				
Pre-HIIT	48.3 ± 3.8	50.1 ± 3.9	50.1 ± 4.0	0.584 [§]
Post- HIIT	51.9 ± 4.0	52.8 ± 8.9	49.8 ± 5.0	0.262
2 nd post-HIIT	50.7 ± 4.9	54.7 ± 6.0	49.9 ± 3.6	0.085
RE as % of VO_{2 max}				
Pre-HIIT	76.4 ± 5.4	78.1 ± 6.4	78.3 ± 5.7	0.781 [§]
1 st post-HIIT	77.0 ± 7.7	78.8 ± 11.4	76.5 ± 5.0	0.683
2 nd post-HIIT	76.5 ± 8.9	82.8 ± 8.2	76.8 ± 4.5	0.101
PTRS (km·h⁻¹)				
Pre-HIIT	20.5 ± 1.3	20.5 ± 0.9	21.0 ± 0.8	0.397 [§]
1 st post-HIIT	21.5 ± 1.5	20.5 ± 0.7	21.5 ± 0.9	0.225
2 nd post-HIIT	21.5 ± 1.4	21.0 ± 1.0	21.5 ± 1.2	0.254
20 m Sprint Time (s)				
Pre-HIIT	2.54 ± 0.11	2.55 ± 0.09	2.53 ± 0.14	0.959 [§]
1 st post-HIIT	2.56 ± 0.14	2.57 ± 0.09	2.55 ± 0.16	0.997
2 nd post-HIIT	2.54 ± 0.11	2.58 ± 0.12	2.56 ± 0.18	0.626

Note: Mean % HR_{max} sustained during a TTT were measured during the TTT's and not on the maximal testing days.

Therefore, the 1st post-HIIT TTT is measured at 3 days, 2nd post-HIIT TTT at 10 days and 3rd post-HIIT TTT at 17 days following the training intervention.

Data are presented as the mean ± standard deviation. The p-values represent differences between the three groups compared to pre-HIIT values, as determined using a repeated measures ANOVA.

[§] The p-value represents pre-HIIT differences between the three groups, as determined using a one-way ANOVA.

n = 9 for the final measurement of each characteristic reported in this table (i.e. 3rd post-HIIT TTT and all 2nd post-HIIT).

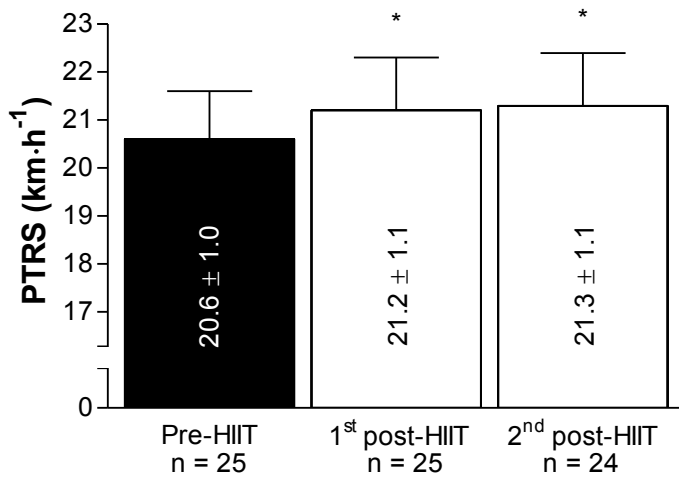


Figure 5.6 Comparison of peak treadmill running speed for all groups combined between the pre-high intensity interval training intervention values and the first post- (five days following the start of the taper) and second post-maximal testing days values (19 days following the start of the taper).

Data are presented as the mean \pm standard deviation. The actual mean speed in $\text{km}\cdot\text{h}^{-1}$ has been included within each bar.

** Significant improvement compared to pre-HIIT intervention values ($p < 0.001$ for both 1st and 2nd post-HIIT compared to pre-HIIT)*

Abbreviations: HIIT – High intensity interval training, PTRS – Peak treadmill running speed.

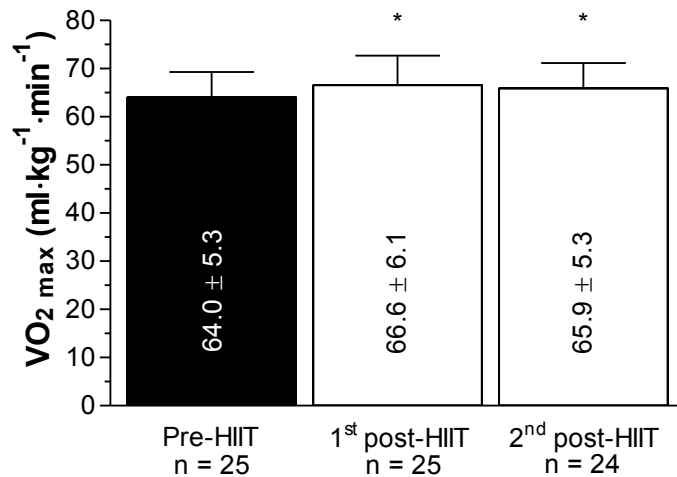


Figure 5.7 Comparison of maximal oxygen uptake for all groups combined between the pre-high intensity interval training intervention values and the first post- (five days following start of the taper) and second post-maximal testing day values (19 days following the start of the taper).

Data are presented as the mean \pm standard deviation. The actual mean $VO_{2\max}$ value in ml·kg⁻¹·min⁻¹ has been included within each bar.

* Significant improvement compared to pre-HIIT intervention values ($p = 0.011$ and $p = 0.009$ for 1st and 2nd post-HIIT compared to pre-HIIT, respectively)

Abbreviations: HIIT – High intensity interval training, $VO_{2\max}$ – Maximal oxygen uptake.

5.4 Discussion

The taper is a vital period prior to competition, when an athletes' training load is reduced before competition with the goal of achieving peak performance at a specific time (230, 344, 461). Importantly, this reduction in training should never be detrimental to training-induced adaptations from prior to the start of the taper (229, 344). Consequently, there were various aims to this aspect of the study. Firstly, to determine whether a single-step 30% volume reduction taper would improve 10 km running performance following four weeks of HIIT; secondly to investigate whether a shorter (ten-day) or longer (17-day) duration for this specific taper would better enhance or maintain running performance; and thirdly to assess if the type of HIIT programme prior to taper influences the effectiveness of the taper.

As previously reported in Chapter Four, the mixed group showed a $3.3 \pm 2.0\%$ improvement in 10 km TTT performance time at three days post-HIIT intervention when compared to the pre-HIIT TTT (section 4.3, Figures 4.1 and 4.2). The first finding of this chapter is that the mixed group showed an even further significant improvement in TTT performance at ten days post-training compared to the 10 km TTT prior to the HIIT intervention. This resulted in a significant ($p < 0.001$) improvement of $4.5 \pm 2.5\%$ in 10 km TTT time at ten days post-HIIT. Both the 1600 m and the 400 m groups showed no significant improvement in TTT time at the same time point in the taper period.

It is interesting to note that, without exception, every participant in the mixed group improved their performance time at the ten days post-HIIT TTT compared to the pre-HIIT TTT. The range of improvements was 1.2 – 10.4%. Furthermore, the four highest improvements in TTT performance across the entire study were found in the mixed group at 10 days post-HIIT. It is also worth noting that one of the fastest participants at the onset of the study with a time of 31:56 (min:s) demonstrated the second largest improvement in performance of 5.8% or 1:51 (min:s). This is interesting as it is normally expected that the fastest athletes at the start of an intervention will demonstrate smaller improvements than their slower counterparts.

As it was shown in Chapter Two that the 10 km TTT used in this study is highly reliable (TEM = 1%), it is possible to therefore conclude that these improvements in performance are indeed significant. In contrast to the finding of a significant

performance improvement following this taper, it is interesting to note that a number of studies have shown no improvement in running time trial performance of differing lengths following single-step reduction tapers of between 35 to 70% of training volume after HIIT (227, 229, 488). Specific examples are, Wittig *et al.* (488) and Houmard *et al.* (227) who found that single-step reduction tapers of 70% of training load ($81 \text{ km}\cdot\text{wk}^{-1}$ to $24 \text{ km}\cdot\text{wk}^{-1}$) over a time period of three weeks post-HIIT had no effect on 5 km time trial performance, nor any physiological parameters such as $\text{VO}_2 \text{ max}$ and running economy in well-trained runners. Similarly, Hickson *et al.* (206) found that a 35% single-step reduction in training volume over a ten-day period following HIIT resulted in no change in 5 km time trial performance in well-trained runners. It is unclear why these studies show no improvement in 5 km time trial performance, however, one possibility may be that the performance tests that were utilised were not sensitive enough to detect the changes in performance. Hopkins and Hewson (219) report that variation in competitive performance of well-trained distance runners in shorter endurance events (less than half marathon) is approximately 1.5%. Therefore, a performance test to track meaningful differences needs a TEM similar to, or preferably less than this value (107, 219, 387). The TEM in the present study meets this criterion, as it falls below 1.5% and is therefore able to detect small changes in 10 km running performance, however, the reliability of the performance tests used in the aforementioned studies is not reported so it is not clear as to whether this could be a reason that performance improvements were not observed in any of these studies.

The second finding of this chapter is that a taper duration of ten days appears to be optimal in enhancing 10 km running performance. At this time point, performance time was most significantly enhanced in the mixed group (the 1600 m and 400 m groups showed the same trend although not significantly so) as can be seen in Figure 5.2. Furthermore, Figure 5.3 illustrates a significant trial effect at the same time point when data for the experimental groups were combined, whereas there is no significant trial effect at the next time point (17 days post-HIIT or third post-HIIT TTT). This point is illustrated in Figure 5.4, when the percentage improvement in performance between the pre-HIIT TTT was compared to all TTT's post-HIIT intervention. It is observed that there is a percentage improvement in performance in the first post-HIIT TTT, followed by a larger percentage improvement at the

second post-HIIT TTT (10 days) and then a smaller percentage improvement at the third post-HIIT TTT (17 days) when compared to the pre-HIIT TTT. Although the mixed group is the only group to show significant improvements in TTT time at both the first and second post-HIIT TTT's, the other groups show a similar trend. We acknowledge the limitation that only specific days were measured and so the peak in performance may have occurred slightly earlier or later than at ten days. However, the optimal taper period of around ten days agrees with the literature where it has been suggested that a taper period of 6 – 14 days may be optimal to enhance performance in middle- and long-distance runners (8, 63, 342, 428). Specifically, a meta-analysis by Bosquet *et al.* (63) report a taper duration of 8 – 14 days to be optimal in increasing running performance from data gathered from 27 studies involving competitive athletes. However, Mujika *et al.* (341, 342) and Shepley *et al.* (428) all show a taper duration of six to seven days to be effective in enhancing running performance in well-trained middle-distance runners, however it must be noted that these studies and the majority of those involved in the meta analysis used progressive tapers and the aforementioned studies of Mujika *et al.* (341, 342) made use of a larger training volume reduction than that used in this thesis.

The third finding of this study was that there was no significant change in any of the physiological parameters ($VO_{2\ max}$, PTRS, running economy and running economy as a percent of $VO_{2\ max}$) that were measured at five and 19 days (first and second post-HIIT maximal testing day) post-HIIT intervention (Table 5.1) despite a significant improvement in TTT time performance in the mixed interval training group (Figure 5.2). Various other studies report similar findings of no changes in physiological parameters such as $VO_{2\ max}$ and running economy during a taper period following HIIT (227, 229, 320, 428). Furthermore, it has been suggested that there is an adaptation threshold which must be surpassed in order to enhance any of the physiological determinants of long distance running performance, such as $VO_{2\ max}$ and running economy (324). This adaptation threshold comprises both a training intensity and duration threshold (324). It could be that the intensity and duration of the HIIT programmes in this study were not sufficient to surpass this adaptation. However, as we have previously discussed, the reason for these parameters remaining unchanged in the mixed group is more likely due to the already high

training status of the individuals being tested where parameters such as running economy and $VO_{2\text{ max}}$ are already approaching their upper limit (324).

PTRS has been shown by Noakes *et al.* (364) to be a better predictor of performance than measures of $VO_{2\text{ max}}$, however, in the present study, it is observed that there is a trial effect when the data for the HIIT groups are combined for improvements in both $VO_{2\text{ max}}$ and PTRS between the pre-HIIT measurements and the first and second post-HIIT maximal testing day measurements at five and 19 days following the HIIT intervention, respectively. Furthermore, when data for the groups were combined, there was a significant trial effect for improvement in TTT time at both ten days post-HIIT and 17 days post-HIIT compared to the pre-HIIT intervention TTT, indicating that all groups combined were able to run faster during the taper period compared to the pre-HIIT intervention period. It should also be noted that although $VO_{2\text{ max}}$ improved by approximately $2.6\text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ when the data for the groups were combined, it has been shown that there is inherent variability in $VO_{2\text{ max}}$ measurements of around 5.6% (257), which brings into question how meaningful this change is.

It has been observed that performance gains following a taper period are more closely related to a reduction in accumulated fatigue from training as opposed to the positive effects of training during this period (245, 339). The authors of these studies therefore suggest that the athlete should have achieved most physiological training adaptations before the start of the taper and that these adaptations are then more apparent once the fatigue has been removed, even by a small degree (339). As previously stated, in the present study, a HIIT programme involving mixed intervals of 1600 m and 400 m yielded the greatest significant percentage increase in performance at both three and ten days post-HIIT. The 1600 m and the 400 m interval groups, however showed no significant improvement in performance at either of these time points. From these data we are able to infer that not only does an interval programme of mixed duration and intensity improve 10 km running performance directly post-HIIT, as was concluded in Chapter Four of this thesis, but it also further enhances performance during the taper period. It is postulated that a mixed HIIT programme consisting of both 400 m and 1600 m intervals is able to elicit improvements in power (45) from the shorter duration 400 m sessions as well as enhanced ability to run longer at a higher intensity (44, 281) from the 1600 m

intervals. The combination of the two seems to be the most effective in improving performance during the taper period when fatigue is lessened from a decrease in training load. This would agree with the literature in which it has been suggested that the training period before the taper can also affect the efficacy of the taper (270, 338). Indeed, when investigating tapering strategies of elite endurance runners, Spilsbury *et al.* (439) recently highlighted the importance of athlete specific tapers that take into account the specifics of the training programmes performed before the taper as well as the target event to follow the taper.

According to Kubukeli *et al.* (270), single-step reduction tapers are only effective in maintaining exercise performance, while progressive reductions may improve performance. Similarly, according to Mujika *et al.* (342), 800 m running performance was improved following a six-day 80% progressive reduction in HIIT whereas resting every third day did not improve performance. Furthermore, the authors of a study comparing progressive and step-tapers in triathlon athletes concluded that the progressive taper was more beneficial to performance than the single-step taper (33, 344, 494). In the latter study, 5 km TTT performance was improved by 12% following a ten-day progressive taper compared to a 3% improvement following a single-step protocol. In the present study, a single-step protocol was used where training volume was reduced by 30% following the HIIT programmes. As mentioned previously, a single-step taper of lower reduction in volume was administered as it was thought that this may be more psychologically attractive to athletes as they are able to quantify the reduction as well as being easier to administer than a progressive taper. Although performance enhancements were found at both three and ten days post-HIIT in the mixed interval group, it is conceivable, based on previous studies, that a progressive taper might have enabled an enhanced performance above that of the single-step taper that was used in this study.

A study involving highly trained middle-distance runners found that a volume reduction taper as high as 75% was more beneficial than one of 50% in optimising adaptations (341). Contrary to this, Hickson *et al.* (206) found that $VO_{2\text{ max}}$, peak lactate concentration and 5 min exercise performance were all maintained in both a 35% and 68% single-step volume reduction, however, cycling time-to-exhaustion at 80% $VO_{2\text{ max}}$ was decreased significantly in the 68% reduction group from 139 to 123 min (10% reduction). Similarly, Houmard *et al.* (229) examined the effects of a

two-step volume reduction of first 27% for ten days, followed by 50% for an additional ten days. The results indicated that aerobic capacity was maintained following both steps of the taper in well-trained distance runners. A volume-reduction of 30% was administered in the present study, as there are minimal data available on the effects of volume reduction tapers of less than 50% on well-trained runners (488). Furthermore, as this is a period during which athletes are concerned that too much of a reduction in volume may cause detraining, it was proposed that a lower percentage reduction would be more agreeable to the athletes participating in the study.

Tapering is not only important for the recovery of the body physically to ensure the athlete is well rested before the race, but it also appears to be important in resetting the pacing strategy of the athletes. In the present study it was observed that the 400 m HIIT group started faster in the first TTT three days post-HIIT intervention compared to their TTT pre-HIIT. Their pacing strategy then reverted back to the same as the pre-HIIT TTT strategy after their first 10 km TTT post-HIIT. This is discussed in Chapter Six of this thesis. This suggests that the type of training and intensity of the sessions prior to the taper need to be considered when planning the structure of the taper leading up to a key event. It is possible that it is necessary to simulate the race distance at least once during the taper period especially when the athletes have been performing much shorter duration intervals compared to their race distance. This could be done by the inclusion of a time trial of the race distance as was done in the present study.

It has also been suggested that from a neuromuscular perspective, a period of taper can result in increased muscular strength and power which has been associated with performance gains during this period (215, 312, 349, 393, 465). According to a study involving power athletes, it appears that power performance is well maintained and sometimes increased as result of a 14-day to three-month period of reduced training (223). Furthermore, the size and contractive properties of single muscle fibres improve during a period of taper (349, 465). The effects of the different HIIT programmes and subsequent taper on neuromuscular factors such as whole muscle strength (quads and calf), stride parameters and muscle activity will be discussed in Chapter Seven of this thesis.

In conclusion, a single-step, 30% volume-reduction taper following HIIT is effective in improving 10 km TTT performance. Specifically, a HIIT programme of mixed duration and intensity (400 m and 1600 m intervals) resulted in a larger performance benefit at three and ten days post-HIIT than a HIIT programme of only 400 m intervals or only 1600 m intervals. Furthermore, a taper duration of ten days appears optimal to improve 10 km TTT performance in well-trained runners.

CHAPTER SIX – THE EFFECT OF DIFFERENT HIGH INTENSITY INTERVAL TRAINING PROGRAMMES ON PACING STRATEGY AND RATINGS OF PERCEIVED EXERTION DURING A 10 KM TREADMILL TIME TRIAL

6.1 Introduction

It is well documented that to reach the end of a race in the fastest time possible and avoid early fatigue, athletes must regulate their speed or power output for the duration of the set distance (10, 150, 151, 167, 184, 291). This regulation of the distribution of speed by varying the rate of energy utilisation is termed the 'pacing strategy' (6, 115, 146, 150, 201, 291, 402, 469) and is of particular importance in athletic events regarded as closed loop, including running time trials.

During a competitive event, there are a number of different pacing strategies that can be used. The selection of which strategy is used is dependent on a variety of factors, which include race duration, course profile, prevailing environmental conditions, tactics of the competitors (38, 459), as well as the motivation, prior experience, and physiological capacity of the athlete (5, 441, 469). Pacing strategies have been broadly categorised into six categories (5, 150) as follows:

1. An 'all-out' pacing strategy involves the athlete utilising maximal effort from the onset of the event to the end-point. Peak speed or power output is achieved very early in the event followed by a gradual decline in these variables for the remainder of the distance (5, 484). This strategy is optimal for short duration sprint events of less than 30 seconds (5, 52, 474).
2. A 'negative pacing' or 'slow start' strategy is one during which speed is observed to increase over the duration of the event. This strategy is commonly seen in simulated and competitive individual time trial events, where the power output and speed are increased close to the end point (10, 192, 314, 358, 396, 470).
3. An 'even paced' strategy is where a constant submaximal rate is maintained for the duration of the event. It has been suggested that this strategy is optimal when external conditions are constant and during prolonged events

- (> 2 min), where the starting pace has a reduced effect on overall performance outcome (5, 115, 146, 150, 215, 380, 463, 484).
4. A 'positive pacing' strategy is one where the athletes' speed declines throughout the duration of the event (146, 160, 413, 463). This is often the strategy used during middle-distance events lasting between 1.5 to 2.0 min (5, 472), as well as ultra-endurance events (> 4 hours duration) (5, 6, 277, 282, 283, 353, 354, 375).
 5. The 'parabolic-shaped' pacing strategy is characterised by a decrease in speed or power output during the middle portion of the event, compared to the starting values, followed by a significant increase or 'end-spurt' in the final stages (5, 469). This strategy is generally associated with exercise of > 4 min duration (10, 160, 291, 309, 316, 468, 470).
 6. A 'variable pacing' strategy is different from those above, as it is solely based on research into the changes in the power output profiles of athletes and not changes in velocity or split times (5, 24, 26, 290). Athletes will seldom experience constant external conditions during outdoor competition and thus a variable strategy may be optimal to counteract fluctuating environmental conditions in an attempt to maintain a constant speed (5, 24, 309).

One pattern that seems to be present in most observed pacing strategies is the 'end-spurt' phenomenon (87, 192, 358, 396). This is categorised by a marked increase in power output or speed observed in the final 10% of a race (86, 87, 358). The occurrence of the 'end-spurt' points to questions about what might regulate a pacing strategy as to allow a surge in work in the final stages.

There are two broad theories (peripheral fatigue and central fatigue) explaining the onset of fatigue during endurance exercise. Two proposed models concerning the regulation of pacing during an event have evolved from these theories (315). The "peripheral fatigue" theory defines the onset of fatigue resulting from changes in metabolite concentrations at, or distal to, the neuromuscular junction (159). According to this theory, the changes in metabolite concentrations, specifically the rising of blood lactate concentrations and the development of a critically low muscle pH, in turn, result in inhibitions to the contractile process in the working muscle. This results in a reduction in power output or speed and the eventual cessation of

exercise (47, 101). This peripheral model of fatigue does not, however, explain the phenomenon of the 'lactate paradox' (258, 361, 362, 473) where it is observed that exercise is terminated at low blood lactate concentrations at extreme altitude (211, 449), nor can it explain the 'end-spurt', as it would not be possible to produce a surge in work if a build-up of metabolic waste products are impairing muscle function.

In contrast, a second model of fatigue, termed "central fatigue", involves a reduction in neural drive to the working muscles, which in turn results in a decline in force development, independent of changes in muscle contractility (37, 129). The theory that the central nervous system regulates athletic performance was first proposed over a century ago (478) and subsequently there are various models and investigations pertaining to the involvement of a central regulator of pacing strategy, as it has come to be known (15, 150, 362, 365, 441, 442, 466, 468-470, 473). Indeed, Ulmer (473) proposed a theory of 'teleoanticipation', where before an exercise bout, the body anticipates the optimal distribution of work to avoid fatiguing before reaching the end point of the exercise bout. In this theory, it is proposed that there must be a central programmer that focusses on the end point of the task and works backward to regulate work output during the task (315, 473). Similar to, and an extension of 'teleoanticipation', the central governor model, as proposed by Noakes *et al.* (365), hypothesises that physical activity is controlled by a central governor in the brain which adjusts skeletal muscle motor recruitment based on afferent feedback from the periphery. In this theory, fatigue is proposed to be interpreted as a sensation by this central governor, based on the afferent feedback, with the primary aim of ensuring physiological homeostasis is maintained and premature termination of exercise is prevented (125).

To quantify the conscious awareness of developing fatigue during an exercise task, subjective sensations of exertion can be recorded and analysed using Borg's 15 point ratings of perceived exertion (RPE) scale (59, 188, 260). This scale has proven to be an effective tool when investigating the setting of a pacing strategy (260, 469) and RPE have been shown to increase in a linear manner as a function of the proportion of an event completed (116, 133, 137, 146, 250, 363, 454). Tucker and Noakes (469) proposed an anticipatory-RPE model where the brain generates a

conscious RPE based on afferent information and produces a range of RPE templates which are then compared against each other. This suggests that an athlete is continuously comparing how they are feeling at a given time to how they expect to feel based on the distance remaining. If RPE are higher or lower than expected, power output is changed accordingly to ensure that the end point is reached before the onset of fatigue (116). This model is proposed based on the findings of several studies in which interventions, such as high temperature (126, 310, 373, 468, 470), altered substrate availability (78, 85, 394) and oxygen content (18, 365), have been found to influence pacing strategy during exercise. For example, Nybo and Nielsen (373) investigated whether cycle exercise in hot (40°C) compared to temperate (18°C) conditions would result in changes in a sustained isometric maximal voluntary contraction (MVC) following the bout of cycling. Study participants in the hot trial cycled at 60% maximal oxygen uptake ($VO_{2\text{ max}}$) until exhaustion, whereas the participants in the temperate trial group cycled for one hour at the same intensity as the participants in the hot trial group. The study showed that force production and voluntary activation percentage in the exercised muscles (as measured by the MVC) was lower following the exercise bout in the hot environment. However, when electrical stimulation of the femoral nerve was superimposed on voluntary contraction (to distinguish between central and peripheral fatigue), force production remained unchanged. This indicated that the decreased force production following the exercise in the hot environment was caused by reduced central activation of the motor units and not from a reduced capacity of the muscle to produce force. Furthermore, RPE was associated with increases in core body temperature as well as cerebral activity and not muscular activity during the trial, indicating that the RPE was linked to central fatigue rather than peripheral fatigue (373).

It has been proposed that distance knowledge prior to the start of an exercise task, feedback during the task and prior experience of the specific task are all integral to this model (136, 367, 473). The importance of these factors in the development of a pacing strategy has been the focus of numerous studies (10, 16, 291, 315, 316, 358). Indeed, Mauger *et al.* (315) demonstrated that distance knowledge (of the total distance to be covered or total amount of work to be done) and prior experience (in completing the distance or amount of work to be done) are more important than

distance feedback (of the distance covered thus far) during an event for the generation of a successful pacing strategy in well-trained cyclists. In this study, distance feedback during a 4 km cycling time trial provided in conjunction with prior distance knowledge before the time trial in well-trained experienced cyclists, did not alter performance compared to when no distance feedback was provided during the trial. Similarly, Albertus *et al.* (10) found that 20 km cycling time trial performance, pacing strategy and RPE remained unchanged when participants were given either correct or incorrect distance feedback during the time trial while having knowledge of the length of the time trial before the onset, again suggesting that distance knowledge prior to the onset of the trial was more important than feedback given during the trial. A further study of Ansley *et al.* (16) found that by misleading cyclists into thinking they would be performing a 30-second bout of supra-maximal cycling, when in fact they performed a 36-second bout, resulted in the final six seconds being significantly slower compared to when they were correctly informed of the time they were required to perform for. The aforementioned studies provide evidence that a pacing strategy is set prior to the onset of exercise, based on the anticipated exercise duration in well-trained experienced athletes.

To determine whether performance level at a certain distance influences the pacing strategy employed, Lima-Silva *et al.* (291) compared the pacing strategies of a high performance (10 km time trial performance < 35:36 (min:s)) and low performance (10 km time trial performance > 39:06 (min:s)) group during a 10 km running track time trial. They found that the low-performance group adopted a more even pacing strategy with no significant difference found between running speed during any stage of the race, whereas the high-performance group adopted a classic U-shaped pacing strategy (291). In accordance with this, Mauger *et al.* (315) found that as more experience was gained at a previously unknown distance, so a greater improvement was observed in the pacing strategy, resulting in better performance times. A further study (316), by the same authors, was designed to determine whether a pacing strategy of a certain distance would be retained if an exercise bout of a different distance was introduced during a testing period. Specifically, four cycling time trials were performed by each participant; two 4 km time trials and two 6 km time trials. The highly trained cyclists were divided into control and experimental groups, where the control groups performed both distances in a sequential order (first the two 4 km

time trials, then the two 6 km time trials or vice versa) and the experimental groups performed the time trials in a variable order (either, 4, 6, 4, 6 km or 6, 4, 6, 4 km), with each time trial separated by 17 min of active recovery in all groups. Distance knowledge was provided before the trial, but no distance feedback was provided during the trials. The authors hypothesised that the experimental groups would display less improvement in completion time in the same distance time trial, as findings of previous studies indicated that previous experience was reasonably plastic and could be interfered with by bouts of similar exercise (316). It was found, however, that there were no differences between or within the groups for completion time at either distance. There was, however, an interesting finding in that the experimental groups started their second 4 km time trial at a lower power output compared to other trials. This 4 km time trial was performed following a 6 km time trial, where the power output was generally low towards the end of the trial. In fact, the power output at the end of the 6 km time trial and the power output at the start of the second 4 km time trial were almost the same (279 vs 288 W) and interestingly this effect was not observed in the control groups. The authors suggest that further research is warranted to investigate the effect of interchanging distance during training on the subsequent pacing strategy employed during a specific distance event. It seems from this result, that preceding exercise intensity impacts on the pacing strategy that is employed during a subsequent exercise bout requiring a differing intensity. In the case of this study it appears that there was an error in recall in the previous 4 km time trial due to the interrupting bout of 6 km which caused the intensity of exercise in the initial section of the 4 km time trial to be based on the preceding 6 km time trial.

To our knowledge, there is no study examining the effect of a preceding training stimulus on the pacing strategy employed in the specific event following four weeks of continuous training at a set different distance. Specifically, there are no data available on the effect of high intensity interval training (HIIT) programmes of differing duration and intensity intervals on subsequent pacing and 10 km running performance. In theory, the well-trained runners participating in the current study should all undertake a similar pacing strategy during the 10 km time trials, as they will all be provided with prior distance knowledge, will be provided with distance feedback during the time trials and all possess similar experience levels at this

distance. However, partly based on the findings in the study of Mauger *et al.* (316), we posed the question as to whether the duration and intensity of intervals in a training programme might impact on subsequent pacing during an event of longer duration compared to the intervals trained at. Therefore, the aim of this study was to examine this question and determine whether a HIIT programme of either 400 m intervals, 1600 m intervals or a combination of the two might have an influence on the adopted pacing strategy and RPE reported in 10 km treadmill time trials (TTT) following these different HIIT training programmes. A further aim was to ascertain whether a change in pacing strategy could explain performance differences following the HIIT intervention.

6.2 Methods

6.2.1 Participants

The study participants described in section 3.2.1 were involved in this component of the training study.

6.2.2 Experimental design

The detailed design is described in Chapter Three, section 3.2.2 and Figure 3.1. All HIIT intervention participants were required to attend all sessions for the full nine-week period in order to be included in the pacing component of the study.

6.2.3 Ten kilometre treadmill time trials

These were conducted as described in Chapter Three, section 3.2.3, but the focus for this component of the study was on the 400 m split times that were recorded and the RPE values that were recorded every kilometre.

6.2.4 Maximal testing days

Although these were performed by all study participants and conducted as described in Chapter Three, section 3.2.4, the data were not utilised for this component of the study.

6.2.5 Training

The training protocols are described in Chapter Three, section 3.2.5.

6.2.6 Taper

This was conducted as described in Chapter Three, section 3.2.6.

6.2.7 Statistical analysis

The statistical analysis was performed as described in Chapter Three, section 3.2.8.

6.3 Results

6.3.1 Ten kilometre treadmill time trial pacing strategy and ratings of perceived exertion profile for all groups prior to the high intensity interval training intervention

The pacing strategy between groups was not significantly different prior to the training intervention (time by group interaction effect $p = 0.999$) (Fig 6.1 A).

However, there was a significant time effect when data for all groups was combined ($p = 0.001$), with 400 m laps 1 –3, 12, 14 – 18 and 20 – 23 all significantly slower compared to the 25th and final lap (Lap 23, $p < 0.050$; Lap 3 & 22, $p < 0.04$; Lap 12, 14, 18 & 20, $p < 0.03$; Laps 1, 2, 15 – 17 & 21, $p < 0.01$) (Figure 6.1 B). As shown in Figure 6.1 B by the overall average pace line (-----) in comparison to the individual average 400 m split times, the strategy adopted was that of a slower start followed by a relatively even pace for the majority of the TTT with an ‘end-spurt’ in the final 400 m. The split times barely deviate from the overall average pace for the entire TTT.

There was no significant difference between the groups for RPE scores ($p = 0.266$) (Figure 6.1 C), which increased on average from 12.3 ± 1.1 for the first kilometre to 17.6 ± 1.7 on completion of the TTT ($p < 0.001$).

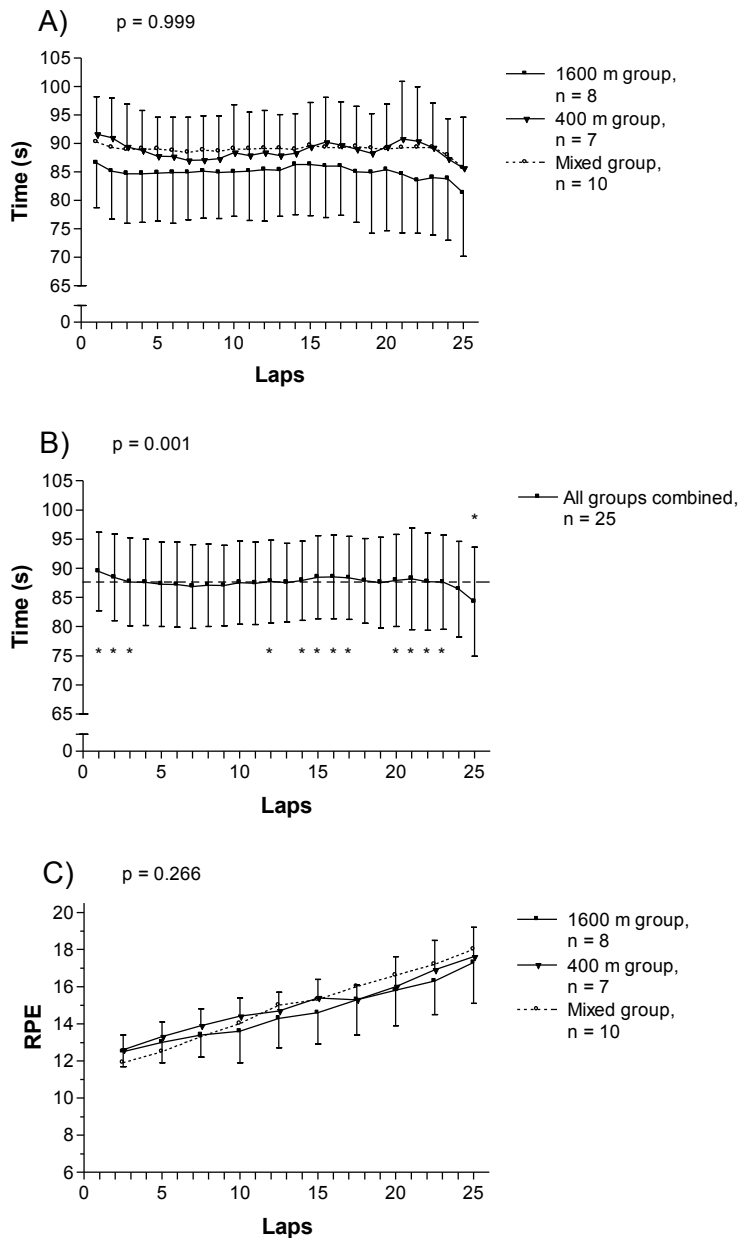


Figure 6.1 Pacing data and ratings of perceived exertion scores for all groups during the pre-high intensity interval training 10 km treadmill time trial: A) Comparative pacing data for individual groups, B) All pacing data combined for all groups and C) Comparative ratings of perceived exertion scores for individual groups.

Data are presented as the mean \pm standard deviation. The p-values on the graphs represent group by time (distance) interaction effect (A & C) and time effect only (B), as determined by a repeated measures ANOVA.

* Significant difference between lap 25 and laps 1–3, 12, 14–18 and 20–23.

----- Average pace per lap for the TTT (graph B)

Abbreviations: TTT – Treadmill time trial, 1600 m – 1600 m interval group, 400 m – 400 m interval group, Mixed – Mixed interval group.

6.3.2 Pacing strategy and ratings of perceived exertion profiles following high intensity interval training for the mixed group only

As already established in Chapter Four, only the mixed group showed a significant improvement in overall 10 km TTT performance in the first post-HIIT 10 km TTT ($37:03 \pm 2:35$ (min:s) pre- vs $35:51 \pm 2:14$ (min:s) post-; $p = 0.001$). This represents an improvement of $3.3 \pm 2.0\%$. As indicated in Figure 6.2 A, this improvement in performance was achieved using a virtually identical pacing strategy from pre-HIIT TTT to the first post-HIIT 10 km TTT (time by trial interaction effect $p = 1.000$). There was, however, a significant time effect when the data for both trials were grouped together ($p < 0.004$), with *post hoc* analysis revealing that laps 1 to 23 were all significantly slower compared to the 25th and final lap (Figure 6.2 B) (Lap 7, $p < 0.03$; Lap 3, 6, $p < 0.02$; Lap 1, 2, 4, 5, 8 – 23, $p < 0.01$). As illustrated in the pre-HIIT TTT previously, a predominantly even pacing strategy with an ‘end-spurt’ is again observed in Figure 6.2 B for the first post-HIIT TTT.

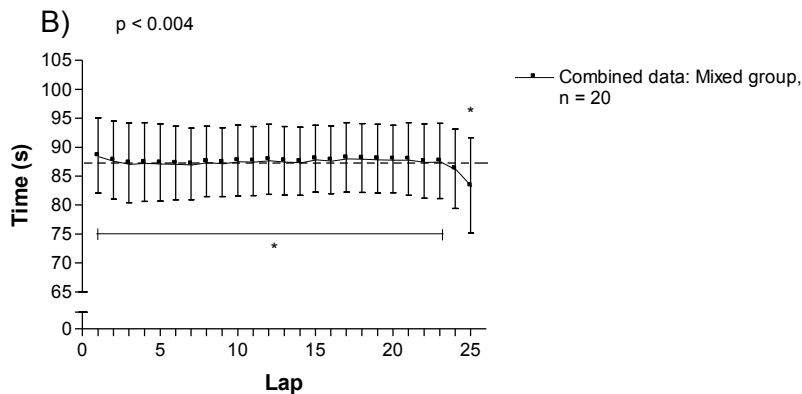
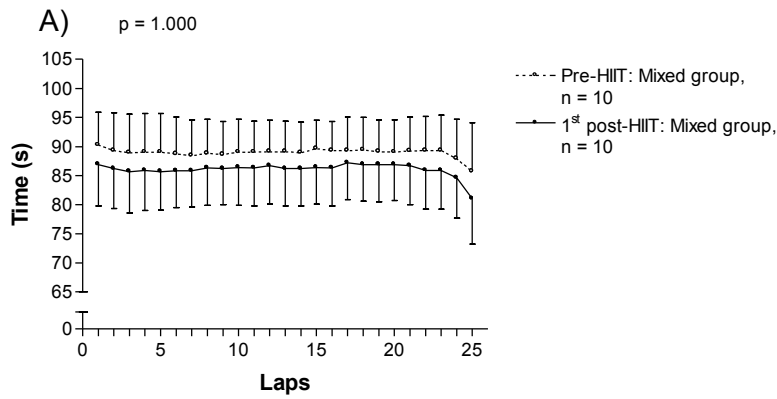


Figure 6.2 Pacing data for the mixed high intensity interval training group during the pre-high intensity interval training treadmill time trial and the first post-high intensity interval training treadmill time trial: A) Comparison of pacing data pre- compared to first post-high intensity interval training time trial and B) All data combined for both trials.

Data are presented as the mean \pm standard deviation. The p-values on the graphs represent trial by time (distance) interaction effect (A) and time effect only (B), as determined by a repeated measures ANOVA.

—*— Significant difference between lap 25 and laps 1 – 23.

----- Average pace per lap for the TTT (graph B)

Abbreviations: TTT – Treadmill time trial, Mixed – Mixed interval group.

The same pattern was also evident when comparing the pacing strategy and RPE profile of the pre-HIIT TTT to that of the second post-HIIT TTT (Figure 6.3 A and B).

Moreover, as discussed in Chapter Five, performance in the second post-HIIT TTT improved significantly by $4.5 \pm 2.5\%$ ($p < 0.001$) when compared to the pre-HIIT TTT.

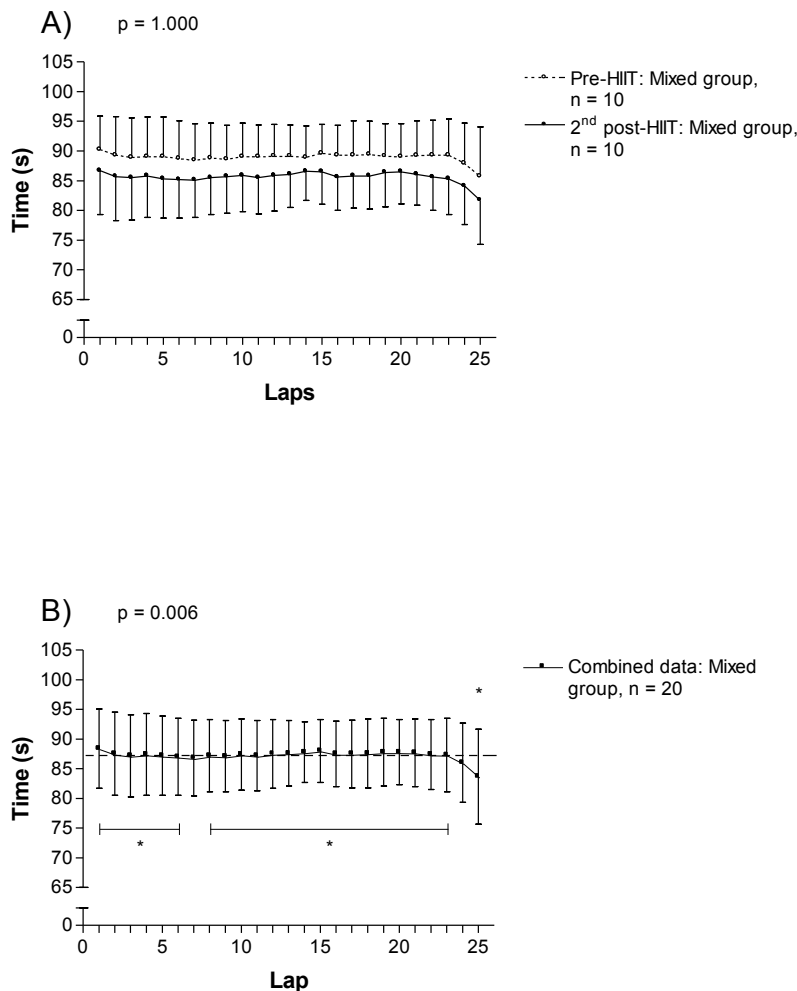


Figure 6.3 Pacing data for the mixed high intensity interval training group during the pre-high intensity interval training treadmill time trial and the second post-high intensity interval training treadmill time trial: A) Comparison of pacing data pre- compared to the second post-high intensity interval training time trial and B) All data combined for both trials.

Data are presented as the mean \pm standard deviation. The p-values on the graphs represent trial by time (distance) interaction effect (A) and time effect only (B), as determined by a repeated measures ANOVA.

* Significant difference between lap 25 and laps 1 – 6 and 8 – 23.

----- Average pace per lap for the TTT

Abbreviations: TTT – Treadmill time trial, Mixed – Mixed interval group.

6.3.3 Pacing strategy and ratings of perceived exertion profiles for all groups during the first post-high intensity interval training 10 km treadmill time trial

The first post-HIIT TTT revealed a significant time by group interaction effect when comparing all groups ($p < 0.001$) (Fig 6.4 A). *Post hoc* analysis showed that this difference was predominantly due to the 400 m group (Fig 6.4 B). In this group, laps 2 – 8 were all significantly faster compared to laps 18 ($p < 0.02$) and 19 ($p < 0.01$). Laps 5 – 7 were significantly faster compared to laps 20 - 21 ($p < 0.01$), lap 22 ($p < 0.03$) and lap 23 ($p < 0.04$). This indicates a far more variable pacing pattern tending towards a parabolic strategy by comparison to the even paced pre-HIIT TTT for this group and indeed for all the other groups both pre- and post-HIIT.

There was no significant difference between the groups for RPE scores ($p = 0.315$) (Figure 6.4 C), which increased on average from 12.8 ± 1.5 for the first kilometre to 18.1 ± 1.1 on completion of the TTT ($p < 0.001$). The 400 m group, however, did tend towards significance when the pre-HIIT TTT was compared to the first post-HIIT TTT RPE scores ($p = 0.088$) (Figure 6.4 D). The highlighted area (grey) in Figure 6.4 D indicates the period from lap 10 to 20 where the RPE values appear to be increased in comparison to the pre-HIIT values. This coincides with a progressive increase in lap times (i.e. a reduction in speed) during the same period (Figure 6.4 B) in the post-HIIT TTT which was not evident during the pre-HIIT TTT. The variance in pace during this period (i.e. the difference between the fastest and slowest lap) was more than three and half times greater during the post-HIIT TTT compared to that of the pre-HIIT (6.6 s for the post-HIIT vs. 1.8 s for the pre-HIIT).

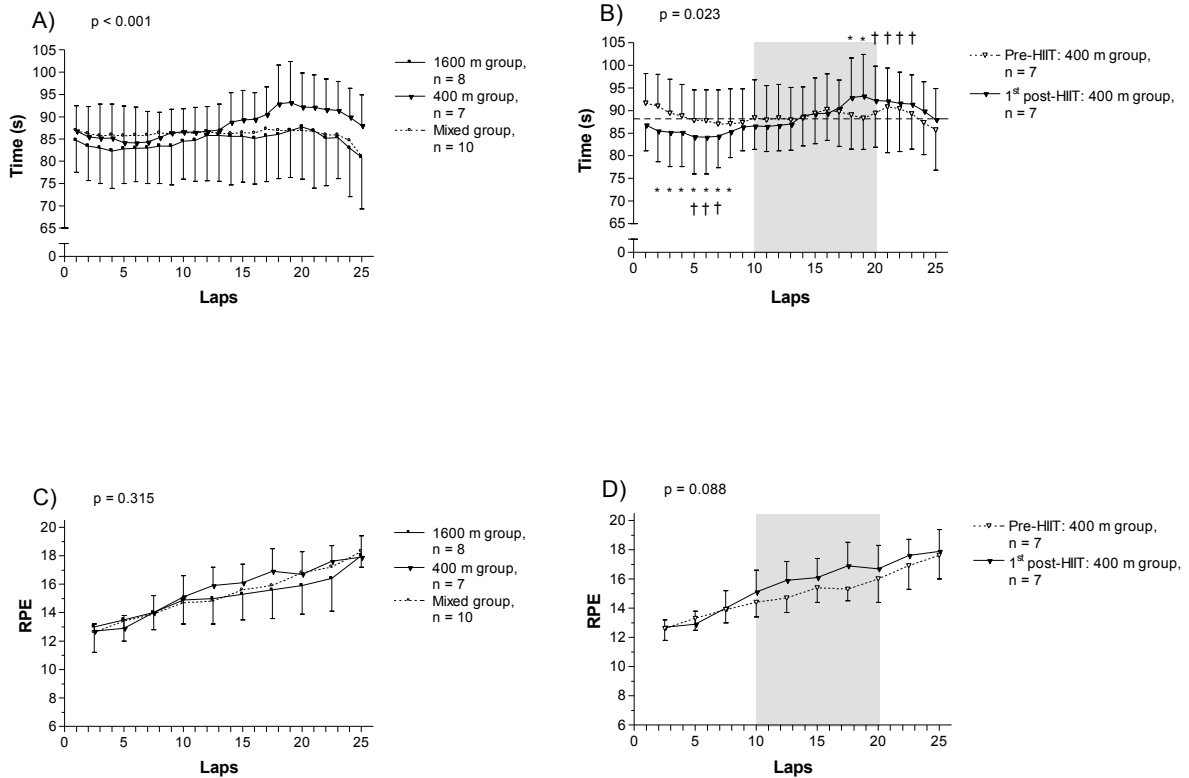


Figure 6.4 Pacing data and ratings of perceived exertion scores for all groups during the first post-high intensity interval training treadmill time trial: A) Comparative pacing data for individual groups, B) A comparison of pacing during the pre- versus that during the first post-high intensity interval training treadmill time trial for the 400 m group only, C) Comparative ratings of perceived exertion scores for every kilometre for individual groups and D) A comparison of ratings of perceived exertion scores during the pre- versus those of the first post-high intensity interval training treadmill time trial of the 400 m group only.

Data are presented as the mean \pm standard deviation. The p-values on the graphs represent group by time (distance) interaction effect (A & C) and trial by time (distance) interaction effect (B and D), as determined by a repeated measures ANOVA.

* Significant difference between laps 18 –19 and laps 2 – 8 in the 1st post-HIIT TTT.

† Significant difference between laps 20 – 23 and laps 5 – 7 in the 1st post-HIIT TTT.

----- Average pace per lap for the TTT.

Abbreviations: TTT – Treadmill time trial, HIIT – High intensity interval training, 1600 m – 1600 m interval group, 400 m – 400 m interval group, Mixed – Mixed interval group.

6.3.4 Pacing strategy and ratings of perceived exertion profiles for all groups during the second post-high intensity interval training 10 km treadmill time trial

There was no significant time by group interaction effect for the second post-HIIT TTT ($p = 0.915$) (Fig 6.5 A), indicating that all groups had once again paced themselves in a similar way compared to the pre-HIIT TTT. However, there was a significant time effect ($p < 0.001$) with *post hoc* analysis highlighting laps five to seven were all significantly faster compared to lap one (lap five, $p < 0.050$; lap six, seven, $p < 0.02$) and lap 20 (lap five, $p < 0.02$; lap six, seven, $p < 0.01$). Lap eight was also significantly faster than lap 20 ($p < 0.04$). Laps one to three and 11 – 23 were all significantly slower compared to the final lap (lap two, 12, 23, $p < 0.01$; lap one, 13 – 22, $p < 0.001$; lap three, 11, $p < 0.04$) (Figure 6.5 B). An even pacing strategy with a significant ‘end-spurt’ over the final 400 m is once again demonstrated when the data for all groups were combined.

There was no significant difference between the groups for RPE scores ($p = 0.748$) (Figure 6.5 C), which increased on average from 12.6 ± 1.5 for the first kilometre to 18.4 ± 1.6 on completion of the TTT ($p < 0.001$).

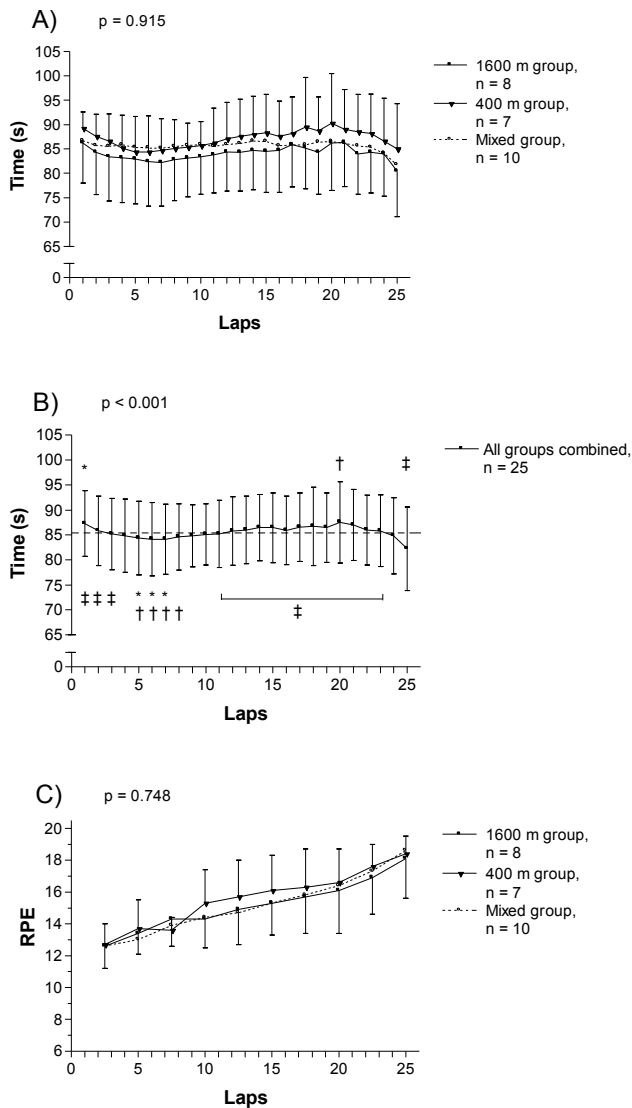


Figure 6.5 Pacing data and ratings of perceived exertion scores for all groups during the second post-high intensity interval training treadmill time trial: A) Comparative pacing data for individual groups, B) All pacing data combined for all groups and C) Comparative ratings of perceived exertion scores for individual groups.

Data are presented as the mean \pm standard deviation. The p-values on the graphs represent group by time (distance) interaction effect (A & C) and time effect only (B), as determined by a repeated measures ANOVA.

* Significant difference between lap 1 and laps 5 – 7.

† Significant difference between lap 20 and laps 5 – 8.

‡ Significant difference between lap 25 and laps 1 – 3 and 11 – 23.

----- Average pace per lap for the TTT (graph B)

Abbreviations: TTT – Treadmill time trial, 1600 m – 1600 m interval group, 400 m – 400 m interval group, Mixed – Mixed interval group.

6.3.5 Pacing strategy and ratings of perceived exertion profiles for all groups during the third post-high intensity interval training 10 km treadmill time trial

The third or final post-HIIT TTT also yielded no significant time by group interaction effect ($p = 0.551$) (Figure 6.6 A). However, there was again a significant time effect ($p < 0.001$) with *post hoc* analysis highlighting laps seven and 9 - 25 were all significantly faster compared to lap one ($p < 0.050$). Laps two to ten, 12, 14 – 15 and lap 20 were all significantly slower than lap 24 ($p < 0.04$). Lap 25, the final lap, was significantly faster than all the other laps (laps 1 – 24; $p < 0.003$) (Figure 6.6 B). As with the previous TTT's, apart from the 400 m group in the first post-HIIT TTT, an even paced strategy with a significant 'end-spurt' was employed for this final TTT, when the data for all groups were combined.

RPE scores were not significantly different between the groups ($p = 0.964$) (Figure 6.6 C), and increased on average from 12.5 ± 1.9 for the first kilometre to 18.2 ± 1.7 on completion of the TTT ($p < 0.001$).

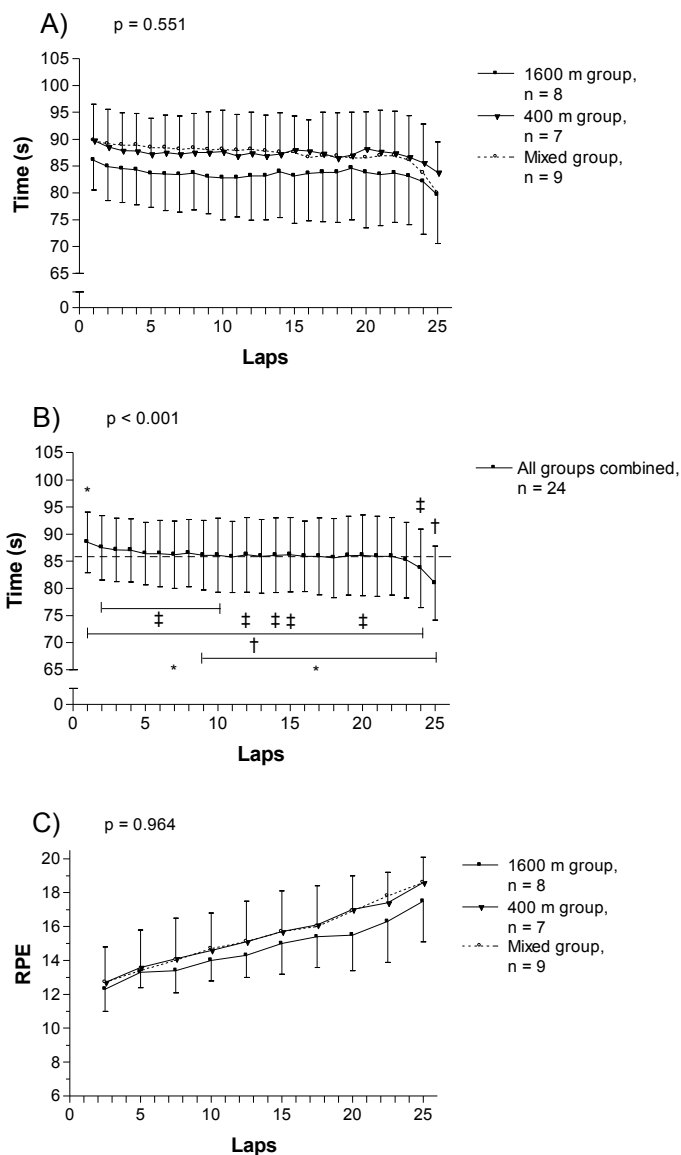


Figure 6.6 Pacing data and ratings of perceived exertion scores for all groups during the third post-high intensity interval training treadmill time trial: A) Comparative pacing data for individual groups, B) All pacing data combined for all groups and C) Comparative ratings of perceived exertion scores for individual groups.

Data are presented as the mean \pm standard deviation. The p-values on the graphs represent group by time (distance) interaction effect (A & C) and time effect only (B), as determined by a repeated measures ANOVA.

- *— Significant difference between lap 1 and laps 7 and 9 – 25.
- †— Significant difference between lap 25 and laps 1 – 24.
- ‡— Significant difference between lap 24 and laps 2 – 10, 12, 14 – 15 and 20.
- Average pace per lap for the TTT (graph B)

Abbreviations: TTT – Treadmill time trial, 1600 m – 1600 m interval group, 400 m – 400 m interval group, Mixed – Mixed interval group.

6.3.6 Pacing strategy of all the experimental groups combined compared to the pacing strategy of the last ten men's 10 km track event world records

An analysis was done of the 1 km split times for the last ten world records in the men's 10 km track event (Figure 6.7) with the data spanning the last 21 years. The split times for the records were averaged and plotted in comparison to the pacing data for all the groups combined prior to the start of the different HIIT interventions. The pacing strategy of the combined experimental groups in this study was similar to that observed in the world records.

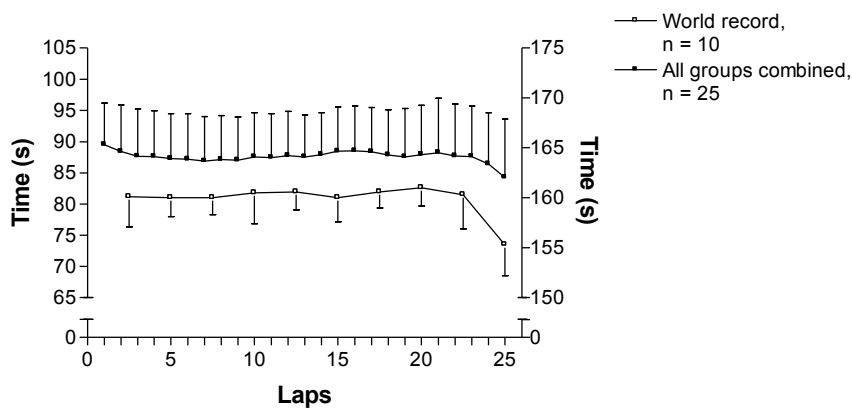


Figure 6.7 Pacing data for all groups combined for the pre-high intensity training treadmill time trial compared to the averaged pacing data for the last ten men's 10 km track event world records.

The left hand Y axis indicates time in seconds per 400 m lap of the TTT and the right hand Y axis indicates the time in seconds per kilometre for the world record data.

6.4 Discussion

The aim of this component of the training study was to determine whether a four-week HIIT programme of either 400 m intervals, 1600 m intervals or a combination of the two might have an influence on the pacing strategy employed and RPE reported in subsequent 10 km TTT's.

There was no difference found in the pacing strategies in any of the groups in their pre-HIIT TTT with all groups showing an even pacing strategy for the majority of the TTT with a significantly faster final lap (Fig 6.1 A), often referred to as the 'end-spurt'. However, the primary finding was that a significant difference was found in the 400 m group between their pre-HIIT TTT pacing strategy and their first post-HIIT TTT strategy. Specifically, this group started faster than the average pace for the first post-HIIT TTT, slowed towards the end to a pace slower than the average pace and then sped up to match the average pace for their final lap, whereas all the other groups in all other TTT's (pre- and post-HIIT) started slower than the average pace for the TTT, then displayed an even pacing strategy tracking the average pace for the entire time trial, before an 'end-spurt' in the final lap. Furthermore, no difference in pacing strategy was observed in any of the groups (including the 400 m group) between their pre-HIIT pacing strategy and their second and third post-HIIT strategies. Therefore, it appears as if the pacing strategy of the 400 m group reverts back to 'normal' and it is postulated that the first post-HIIT TTT was needed in order to 'reset' this pacing strategy back to the way it was prior to the intervention. The study of Mauger *et al.* (316) was designed to test the retention of a pacing strategy and the robustness of a stored pacing schema. The study design is outlined in section 6.1. To reiterate, there was no difference in completion time between any of the time trials in both groups. Yet, interestingly, the experimental groups started their second 4 km time trial at a lower power output compared to their first trial with this power output was very similar to the power output at the end of the previous 6 km time trial, an occurrence not found in the control groups. This is a similar finding in some ways to that in the present study. For example, the training intervention of shorter duration 400 m intervals between the 10 km TTT's seems to have 'interrupted' the pacing strategy, with this group now starting faster as they would be more inclined to do in a 400 m exercise bout. When analysed individually

in the first post-HIIT TTT, five out of seven participants started faster and on average the group started 5.3% faster than during the pre-HIIT TTT. Interestingly, Hauswirth *et al.* (192) demonstrated that when triathletes began the 10 km run leg of a standard triathlon at a pace 5% faster than that achieved during a controlled 10 km run, slower overall performances were observed compared to those who began at a pace 5% slower. In the present study, however, there is no significant difference in 10 km TTT performance with the faster start. Conversely, Gosztyla *et al.* (167) found that a 6% faster start during a 5 km TTT, resulted in an improved TTT performance in 73% of their study participants. It appears that a faster start during shorter distance events is more beneficial to performance.

The HIIT programme consisting of only 400 m intervals was the most dissimilar compared to the other two programmes in terms of duration and intensity and to the demands of a 10 km TTT. For example, the average pace during a 36:29 (min:s) 10 km TTT was approximately $16.4 \text{ km}\cdot\text{h}^{-1}$ and the average pace during a 1600 m interval of 5:35 (min:s) duration was approximately $17.2 \text{ km}\cdot\text{h}^{-1}$, whereas the average pace during a 400 m interval lasting only 1:16 (min:s) was closer to approximately $19.0 \text{ km}\cdot\text{h}^{-1}$. The pace during the 1600 m interval sessions would translate to a 10 km TTT time of approximately 34:55 (min:s), which is 4.3% faster than the time in the 10 km TTT the athletes could perform, whereas the average pace during the 400 m intervals would translate into a 10 km TTT time of 31:41 (min:s) which is 13.2% faster than the time in the 10 km TTT that the athletes were actually able to perform. It appears that a programme consisting of only these shorter intervals is least favourable in terms of the retention of a pacing strategy for 10 km. However, the change in pacing strategy was not mirrored with any performance changes within the 400 m group (Chapter Four) as was similarly found in the aforementioned study of Mauger *et al.* (316). Conversely, the mixed group in the present study showed no change in pacing strategy between their pre-HIIT TTT pacing strategy and the first (Figure 6.3) or second post-HIIT TTT (Figure 6.4) strategies. However, there was a significant performance enhancement in both their TTT's following the training intervention, as discussed in Chapters Four and Five. It can therefore be concluded that their performance enhancement post-HIIT was not due to a superior pacing strategy.

According to St Clair Gibson *et al.* (441), there is a 'brain centre' which designs a mathematical algorithm incorporating various intrinsic and extrinsic factors to set a particular optimal pacing strategy for a particular exercise bout. They further postulate the concept of an internal clock that uses relative rather than absolute time scales (441). Ulmer describes the process of 'teleoanticipation', where knowledge of the end point or expected duration of the exercise bout serves as the initial controller for creating this algorithm (473). Once the athlete begins the exercise bout, afferent input provides information about the physiological changes associated with the chosen pace to the pacing centre in the brain (276, 394, 408, 441, 470). If the algorithm indicates that the pace is either too fast or too slow to reach the end point optimally, then efferent neural commands are modified to either increase or decrease the chosen pace (441). This concept appears to be demonstrated in our study as it seems that the 400 m group started too fast and therefore needed to reduce their pace in the later stages of the TTT to reach the end without premature failure (Figure 6.5).

Another factor, which is integral to the setup of the algorithm determining pace, is prior experience of the particular distance. According to Patterson and Marino (386), for the 'teleoanticipatory' centre to utilise a relative internal clock, the scaling mechanism must be based on previous experience at the specific distance. As more repeated training bouts are performed at a specific distance, the relative internal clock becomes more accurate. Indeed, another study of Mauger *et al.* (315), found that as more experience was gained at a previously unknown distance, a greater improvement was observed in the pacing strategy employed. In their study, well-trained cyclists were divided into either control or experimental groups. The control group was informed that they would be performing four consecutive 4 km time trials, whereas the experimental group was only informed that they would be performing four consecutive time trials of the same distance, but were not informed of what that distance would be. The experimental group was significantly slower than the control group in the first time trial, but then the completion time difference reduced linearly over the course on the remaining three time trials, such that in the final time trial the experimental group was only two seconds slower than the control group. The more experience that the cyclists gained at the unknown distance, the more robust their relative perception of the distance became. In the present study, the fact that just

one exposure to a 10 km TTT is able to 'reset' the pacing strategy provides evidence to support the robustness of a stored pacing schema. In agreement, although using a different study design, the study of Albertus *et al.* (10), provides further evidence as to the robust nature of the internal clock. In this study, despite deception in distance feedback during 20 km cycling time trials, the time to complete each time trial was similar. Similarly, Nikolopoulos *et al.* (358) informed well-trained cyclists that they would be performing 40 km time trials, when in fact the distances were actually 34, 40 and 46 km. The pacing strategy during the 34 km, 40 km and 46 km time trials were all similar. On first examination, these results seem to contradict the importance of prior distance knowledge. However, on closer inspection, the participants in this study were provided with distance feedback during the time trial, which specified the percentage of the distance remaining. This indicates the pacing strategies were based on the individuals' perceived distance rather than the absolute distance. Similarly, the 'end-spurt' phenomenon provides evidence of this relative distance judgement as participants engaged in different tasks of different duration all increased their activity or output in the final 10% of the task irrespective of task type or length (86, 87, 192, 358, 396, 441).

The second important finding was that when comparing RPE scores during the TTT's, the RPE scores for the 400 m group during the first post-HIIT TTT diverge from those of the pre-HIIT TTT (Figure 6.5 D). It has been suggested that the perception of effort with fatigue is regulated by the same subconscious brain control centre that regulates the pacing strategy during an event (188, 326). Tucker and Noakes (469) propose an anticipatory-RPE model where the brain generates a conscious RPE based on afferent information and produces a range of RPE templates which are then compared against each other in order to alter pacing strategy to optimise performance and prevent potentially damaging disturbances to any physiological systems. The higher RPE scores in the 400 m group are observed over the same time period that the group is observed to slow down. It is interesting to speculate whether, due to their faster start in their first 10 km TTT post-HIIT in comparison to their pre-HIIT TTT (Figures 6.5 B and D), that afferent feedback was received by the brain centre that the pace was too fast at this time. This afferent feedback would then be translated into a conscious awareness of effort resulting in efferent feedback to reduce pace in order to reach the end point optimally and avoid

premature fatigue. During this time period the variance in time to complete a 400 m lap is 6.6 s (86.6 ± 5.2 s to 93.2 ± 9.2 s) for the post-HIIT TTT compared to only 1.8 s for the same period during the pre-HIIT TTT. No changes were observed in the RPE scores between the groups during the second and third post-HIIT TTT's in agreement with there being no differences in the pacing strategies between the groups and a 're-setting' of the pacing strategy of the 400 m group back to 'normal'.

To put the pacing strategies in this study into context compared to the pacing strategy observed in competitive events, an analysis was done of the 1 km spilt times for the last ten world records in the men's 10 km track event (Figure 6.7). It is clear that the pacing strategy of the combined experimental groups in this study was similar to that observed in the world records, with the exception that the TTT's in this study start at a slower pace before adopting an even pacing strategy (equivalent to the average pace for the entire time trial as shown in Fig 6.1 B) for the majority of the TTT before the 'end-spurt'. As discussed in Chapter Two a different pacing strategy was observed between the TRTT's and the TTT's and the results presented in this chapter are in line with this. Specifically, there was a significant difference between the starting pace in the first kilometre of the TRTT's compared to the TTT's, where the TTT's started significantly slower in comparison to the TRTT's. Indeed the study of Lima-Silva *et al.* (291) show a classic U-shaped pacing strategy for well-trained runners (10 km time trial performance < 35.6 min) when completing a 10 km TRTT. The runners in the latter study ran the first and last 400 m at a faster pace compared to the rest of the time trial which was run at an even pace (as is similar to what is observed in the results of the TRTT's of the present study).

In conclusion, it appears from these results that the type of interval session used during the training phase leading up to an event has a significant influence on the pacing strategy adopted during the event if no other similar distance experiences are permitted prior to the event. Specifically, it appears that for a distance of 10 km, a HIIT programme consisting of mixed intervals, or intervals of longer duration (1600 m intervals), will have no negative effects on the athletes' pacing strategy in 10 km events following training. Shorter intervals of 400 m appear to have a potentially negative effect on 10 km race pacing strategy immediately following training. It is therefore advised that the athlete participates in, at the very least, a simulated race situation of similar duration to that of the target event following the completion of a

short interval HIIT programme and prior to the target competition. As discussed, an exposure of this nature appears to 'reset' the athlete's perception of pacing. Further research should aim to determine if this disruption in pacing occurs in events of other distances and if there is indeed an optimal interval length during a HIIT programme to ensure that pacing strategy for the target event is retained.

The performance improvement at both the first and second post-HIIT TTT observed in the mixed group cannot be explained by changes in pacing strategy, as no significant difference was observed in the pacing strategy in this group during either of these trials in comparison to their pre-HIIT pacing strategy. Therefore, there must be other factors contributing to this performance improvement and accordingly Chapter Seven will investigate whether specific neuromuscular factors could explain the performance improvement in the mixed group.

CHAPTER SEVEN – THE EFFECT OF DIFFERENT HIGH INTENSITY INTERVAL TRAINING PROGRAMMES ON NEUROMUSCULAR CHARACTERISTICS AND STRIDE PARAMETERS IN WELL-TRAINED MALE RUNNERS

7.1 Introduction

It has been discussed previously in this thesis that maximal oxygen uptake ($VO_{2\max}$), lactate threshold, running economy and other physiological variables are important determinants of distance running performance. However, in Chapter Four it was shown that there was a significant improvement in 10 km treadmill time trial (TTT) performance in the mixed high intensity interval training (HIIT) group, although there were no concomitant changes in $VO_{2\max}$ and running economy measured in this group or any other group. Furthermore, Chapter Six revealed that differences in pacing strategy could not explain the performance improvement, as no changes in the pacing strategy adopted by the mixed group pre- and post-training were found. This raises the possibility of other factors contributing to the observed improvement in performance in these well-trained runners. As other studies have also shown endurance performance to improve without any changes in $VO_{2\max}$ (117, 203, 230, 308, 319, 377, 428), it has indeed been the observation of coaches and sports scientists that athletes thought to be reaching their maximal limit for $VO_{2\max}$ and running economy need to find other ways to further improve running performance (378, 379). Various research has suggested that endurance performance may not only be limited by central factors related to aerobic capacity, but also by neuromuscular characteristics contributing to increased muscle strength and power (175, 376, 379).

Neural adaptation has been shown to precede morphological adaptations in strength training (264, 334, 411). These neural adaptations include increased muscle fibre recruitment, firing rate and motor unit synchronisation (128, 264, 297, 330, 378), all contributing to an increased ability to generate more force in the active muscles (140, 141, 234, 308, 319, 328, 377, 379). Additionally, changes in stride parameters during running, such as an increased stride frequency and length and decreased ground contact and flight time (140, 335, 378, 379), have also been associated with

an ability to run at higher velocities. Also, it was found that 5 km running performance, but not $VO_{2\text{ max}}$, was improved following the inclusion of explosive-type strength training to both sprint and endurance training in well-trained runners (376). The authors concluded neuromuscular characteristics were more likely the main contributors to improved running performance.

A running stride is defined as the cycle from contact of one foot to the next contact of the same foot (235). Running speed is the product of stride length and frequency. Therefore, increased stride frequency and length, as well as decreased contact and flight time are all associated with improvements in sprint running performance (234, 335). Interestingly, Numella *et al.* (371), found that improvements in 5 km running speed were associated *more* with an increase in stride length than with higher stride frequency in well-trained runners. While some researchers have come to the same conclusion (322, 323), others have suggested that both stride length and frequency are equally needed to improve running speed (19, 234). Despite these varying opinions, a general consensus exists that stride parameters effect running speed (235). The 20 m sprint is a common method used to evaluate these stride parameters (371, 376, 378, 379).

In addition to changes in stride parameters during running at higher speeds, a study conducted by St Clair Gibson and Noakes (443), demonstrated that an increase in spatial and temporal recruitment of motor units occurred when running at higher speeds. Electromyography (EMG) is defined as the recording and analysis of the electrical activity of skeletal muscle tissue, either using electrodes attached to the surface overlying the muscle fibres (surface EMG (sEMG)) or inserted into the muscle directly (needle or fine wire EMG). EMG recordings of muscle activity pre- and post-training have been shown to be effective in evaluating neural adaptation to training (31, 411). The degree of muscle fibre activity during different phases of the stride is directly related to the amount of force that the muscle is able to produce. Higher skeletal muscle recruitment leads to an increased ability to produce force (69). During a gait cycle, the phase of contraction of muscle 100 ms prior to heel-strike in the stride is referred to as pre-activation. This phase is important as it increases the muscle's stiffness in preparation for ground contact. This enables the muscle to be able to tolerate the high impact load and subsequent toe-off (378). A muscle's ability to absorb impact forces can be changed with alterations in muscle

stiffness, thereby modifying the ability of the muscle to store and utilise elastic energy (356). It has been suggested that a higher pre-activity allows faster transition from braking to propulsion phase, thereby leading to faster running times (60, 262, 272, 370). The latter is supported by Paavolainen *et al.* (378) who suggested that higher pre-activation and lower agonist EMG activities could indicate that neural control in the stretch-shortening cycle and the storage and utilisation of elastic energy contribute to outcomes observed in 10 km performance in well-trained runners with similar $VO_{2\text{ max}}$ values. Additionally, a study by Creer *et al.* (106) suggests that high speed sprint training in cyclists improved motor unit recruitment and synchronisation resulting in improved cycling performance. Furthermore, various other cycling sprint training studies have shown increases in muscle power and improved cycling performance following sprint interval training sessions (13, 106, 114, 191, 427, 434).

A number of key muscle groups are commonly investigated in running studies, including *vastus lateralis*, *vastus medialis*, *biceps femoris* and *gastrocnemius medialis*. Improvements in strength of these muscles have been shown to be associated with improvements in running performance (140, 241, 273, 328, 376, 379, 477). An isometric leg press has been shown to be an effective means to measure leg strength and specifically *quadriceps* strength (273, 288, 444). Similarly an extended leg calf press is used to quantify *gastrocnemius* muscle strength (273). As the speed of running increases, so does the muscle activation, as measured by sEMG, of the *biceps femoris*, *vastus lateralis*, *vastus medialis* and *gastrocnemius medialis*, indicating that these muscles are associated with greater force production during higher speed running (307, 331). The 10 km race is one which is run at a relatively high speed over the course of the race with the average pace for current men's world record being 2 min 38 s per km ($6.34\text{ m}\cdot\text{s}^{-1}$) (as calculated based on the current world record). This high running speed emphasises the important role that the aforementioned neuromuscular characteristics have in races of 10 km (376, 378, 379).

There are two studies to our knowledge which examine the impact of HIIT on neuromuscular parameters. Firstly, Jemma *et al.* (243) studied the effects of three weeks of laboratory based HIIT on sEMG in well-trained cyclists and found improved 40 km time trial performance as well as increased muscle activity following training.

Secondly, Smith *et al.* (435) examined the effects of cycle HIIT on recreationally trained men with a specific focus on neuromuscular markers of fatigue. Participants in the trial were randomly assigned to placebo or beta-alanine supplementation (beta-alanine is known to increase muscle carnosine levels which aids in the delay of muscle fatigue) groups, with both groups undertaking six weeks of HIIT. The authors suggested that adaptations from HIIT may be more influential in delaying fatigue. Both groups demonstrated significant improvements in electromyographic fatigue threshold (the load a muscle can withstand without being effected by neuromuscular fatigue) and efficiency of electrical activity post-HIIT training. Less motor units therefore needed to be recruited due to reduced fatigue of the motor units in use, with the beta-alanine supplementation group not showing any more significant improvements compared to the control group.

The effects of HIIT on these neuromuscular parameters in well-trained runners are not well established, with no studies to our knowledge having the direct focus of four weeks of continuous HIIT on neuromuscular characteristics associated with a change in 10 km running performance. Therefore, the aim of this component of the training study was to investigate whether various neuromuscular factors such as muscle strength, sEMG and specific stride parameters would be influenced differently by three different HIIT programmes and more specifically whether changes in any of these neuromuscular characteristics could be associated with, or contribute to, a change in 10 km running performance following the different HIIT programmes.

7.2 Methods

7.2.1 Participants

The study participants described in section 3.2.1 participated in this component of the training study.

7.2.2 Experimental design

The detailed design is described in Chapter Three, section 3.2.2 and Figure 3.1. All HIIT intervention participants were required to attend all sessions for the full nine-week period to be included in this component of the study. A summary of the experimental design more specific to this component of the study is presented in Figure 7.1.

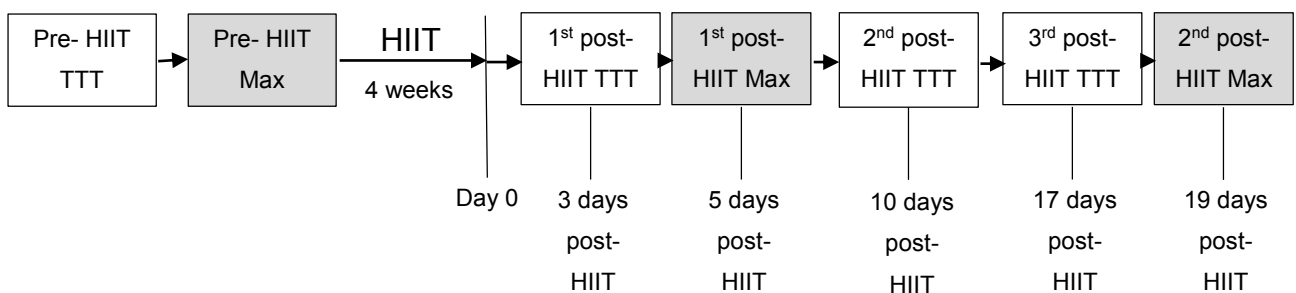


Figure 7.1 Summary of the testing protocol, indicating the number of days following the end of the high intensity interval training and the start of the taper period.

Note: The maximal testing days, when the stride parameters and sEMG data were recorded, have been highlighted in grey for ease of reference.

Abbreviations: TTT – Treadmill time trial, HIIT – High intensity interval training, Max – Maximal testing day when all other physiological measures were recorded.

7.2.3 Ten kilometre treadmill time trials

These were conducted as described in Chapter Three, section 3.2.3.

7.2.4 Maximal testing days

These were conducted as described in Chapter Three, section 3.2.4, with particular reference to sub-sections 3.2.4.4 to 3.2.4.6 for this component of the study.

7.2.5 Training

The training protocols employed are described in Chapter Three, section 3.2.5.

7.2.6 Taper

This was conducted as described in Chapter Three, section 3.2.6.

7.2.7 Data analysis

The analysis of stride parameters and the raw sEMG signal are described in Chapter Three, section 3.2.4, sub-sections 3.2.4.7 and 3.2.4.8, respectively.

7.2.8 Statistical analysis

Analyses were as described in Chapter Three, section 3.2.8.

7.3 Results

The same participants were used for the three experimental study groups as already described in Chapter Three (section 3.2.1). The descriptive characteristics of participants and their descriptive performance characteristics are reported in Chapter Four, section 4.3; Table 4.1 and 4.2, respectively.

7.3.1 Isometric maximal voluntary contractions

There were no significant differences between groups pre-HIIT intervention to post-HIIT intervention with respect to maximal force generation during a seated leg press ($p = 0.058$ and $p = 0.058$ for the individual group data or all data combined, respectively) (Figure 7.2). As the level of significance was so close to $p = 0.050$, we opted to do a *post hoc* analysis. This showed that the tendency for difference can be attributed to the 1600 m group, particularly between the second and last trial ($p = 0.058$).

There was, however, a significant group by trial interaction effect for the maximal seated calf press ($p = 0.021$) (Figure 7.3). *Post hoc* analysis indicated that the difference was a result of the 400 m group, where the final trial was significantly improved compared to the first trial from prior to HIIT ($2160 \text{ N}\cdot\text{m}^{-1}$ vs. $1957 \text{ N}\cdot\text{m}^{-1}$, respectively; $p = 0.030$). This represents an improvement of 10.4% compared to pre-HIIT.

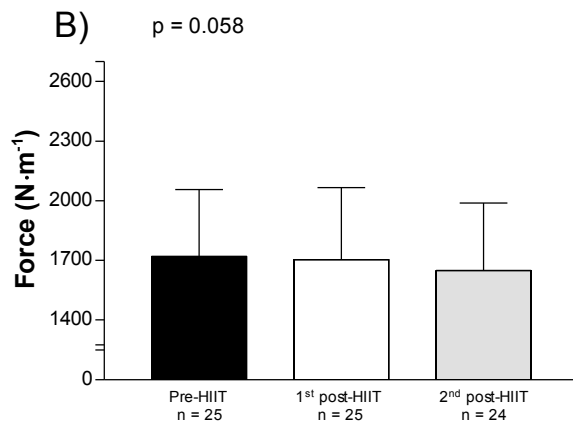
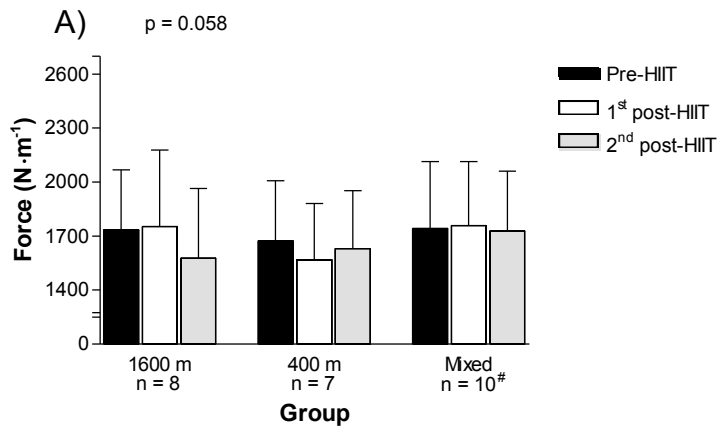


Figure 7.2 Maximal force generated during a seated isometric leg press: A) All data for individual groups pre- and post-high intensity interval training intervention and B) All data combined for all groups pre- and post-high intensity interval training intervention.

Data are presented as the mean \pm standard deviation. The p -values on the graphs represent group by trial interaction effect (A) and trial effect only (B), as determined by a repeated measures ANOVA.

[#] $n = 9$ for the final measurement in the mixed group (i.e. 2nd post-HIIT).

Abbreviation: HIIT – High intensity interval training, 1600 m – 1600 m interval group, 400 m – 400 m interval group, Mixed – Mixed interval group.

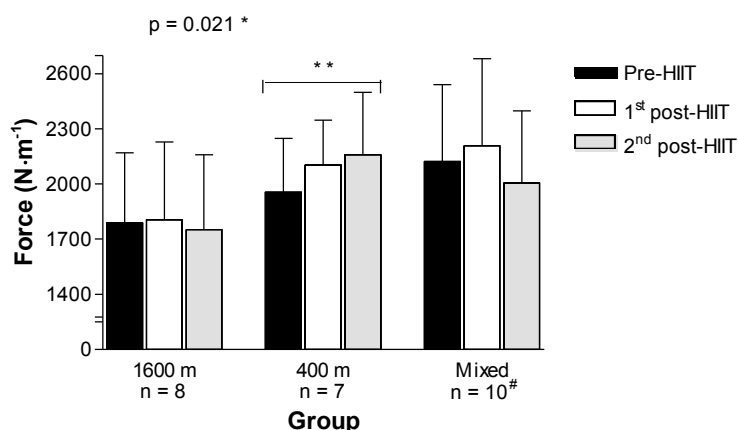


Figure 7.3 Maximal force generated during a seated isometric calf press for individual groups pre- and post-high intensity interval training intervention.

Data are presented as the mean \pm standard deviation. The p -value on the graph represents the group by trial interaction effect, as determined by a repeated measures ANOVA.

$n = 9$ for the final measurement in the mixed group (i.e. 2nd post-HIIT).

* Significant interaction effect between group and trial.

** Significant difference within the 400 m group. Pre-HIIT significantly different compared to 2nd post-HIIT ($p = 0.030$).

Abbreviation: HIIT – High intensity interval training, 1600 m – 1600 m interval group, 400 m – 400 m interval group, Mixed – Mixed interval group.

7.3.2 Surface electromyography

Figure 7.4 (*biceps femoris*) shows a group by trial interaction effect for the contact time phase sEMG of the *biceps femoris* muscle ($p = 0.037$). The mixed group shows a progressive increase in sEMG activity during this phase, although *post hoc* analysis does not indicate significantly so ($p = 0.135$ for the second post- vs. the pre-HIIT values). There were no further significant interaction effects for sEMG in the other three muscles during this phase or for any of the four muscles measured during the pre-activation phase.

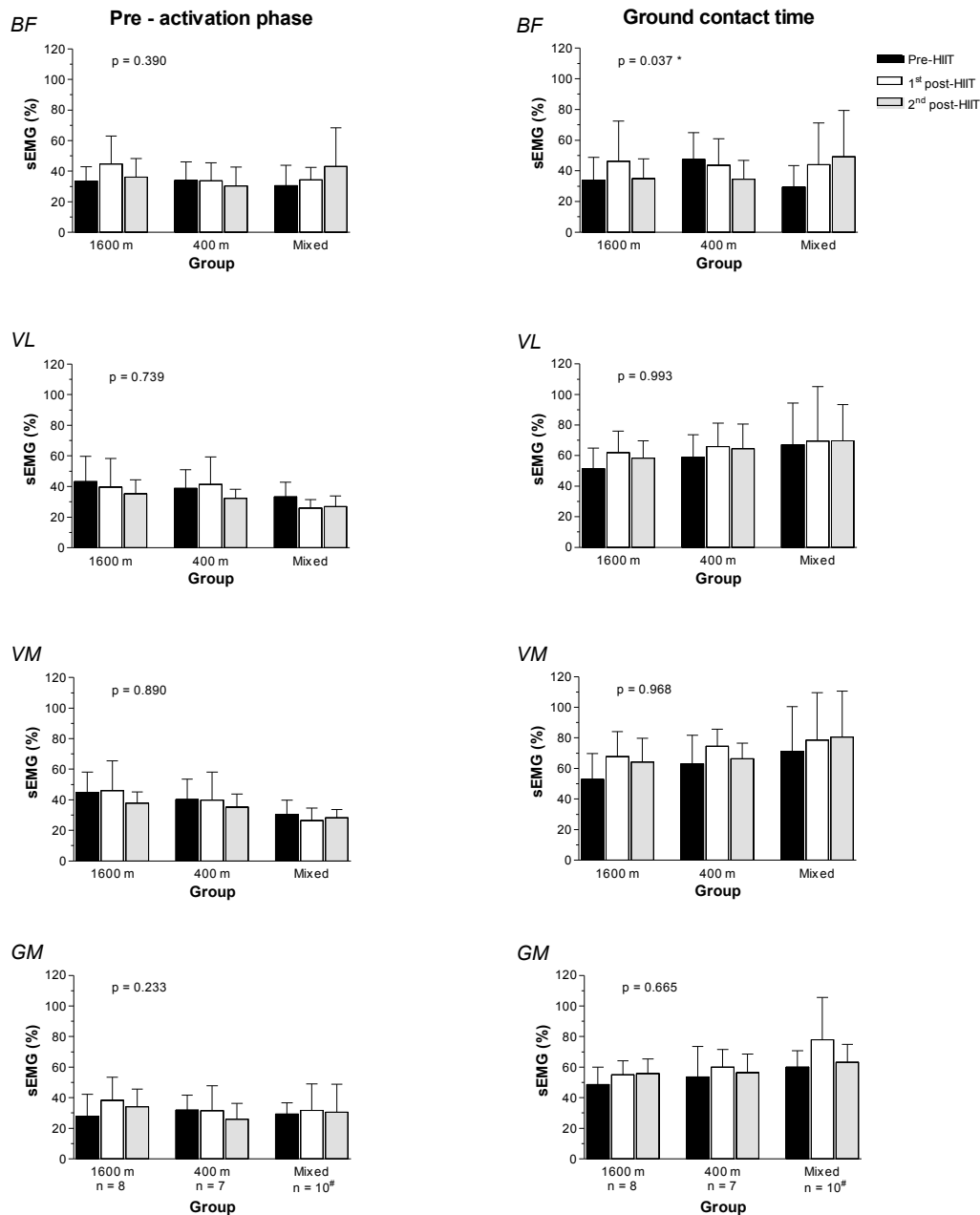


Figure 7.4 Surface electromyography characteristics for all groups. Pre-activation phase and ground contact phase sEMG (%) for: *biceps femoris*, *vastus lateralis*, *vastus medialis* and *gastrocnemius medialis*.

Data are presented as the mean \pm standard deviation. The p-values on the graphs represent the group by trial interaction effect, as determined by a repeated measures ANOVA.

n = 9 for the final measurement in the mixed group (i.e. all 2nd post-HIIT).

* Significant interaction effect between group and trial.

Abbreviations: HIIT – High intensity interval training, 1600 m – 1600 m interval group, 400 m – 400 m interval group, Mixed – Mixed interval group, sEMG – Surface electromyography, BF – Biceps femoris, VL – Vastus lateralis, VM – Vastus medialis, GM – Gastrocnemius medialis.

7.3.3 Stride parameters

Repeated measures ANOVA revealed no significant group by trial interaction effects for the stride parameters reported in this study, namely contact time, flight time, stride length and stride frequency (Figure 7.5). Stride frequency demonstrated a tendency towards significance, however, with a p-value of 0.074. As indicated in Figure 7.5, the 1600 m group only appears to show a non-significant increase in stride frequency in both the second and last trial compared to the first trial prior to HIIT. The other two groups appear almost completely unchanged for this parameter by comparison.

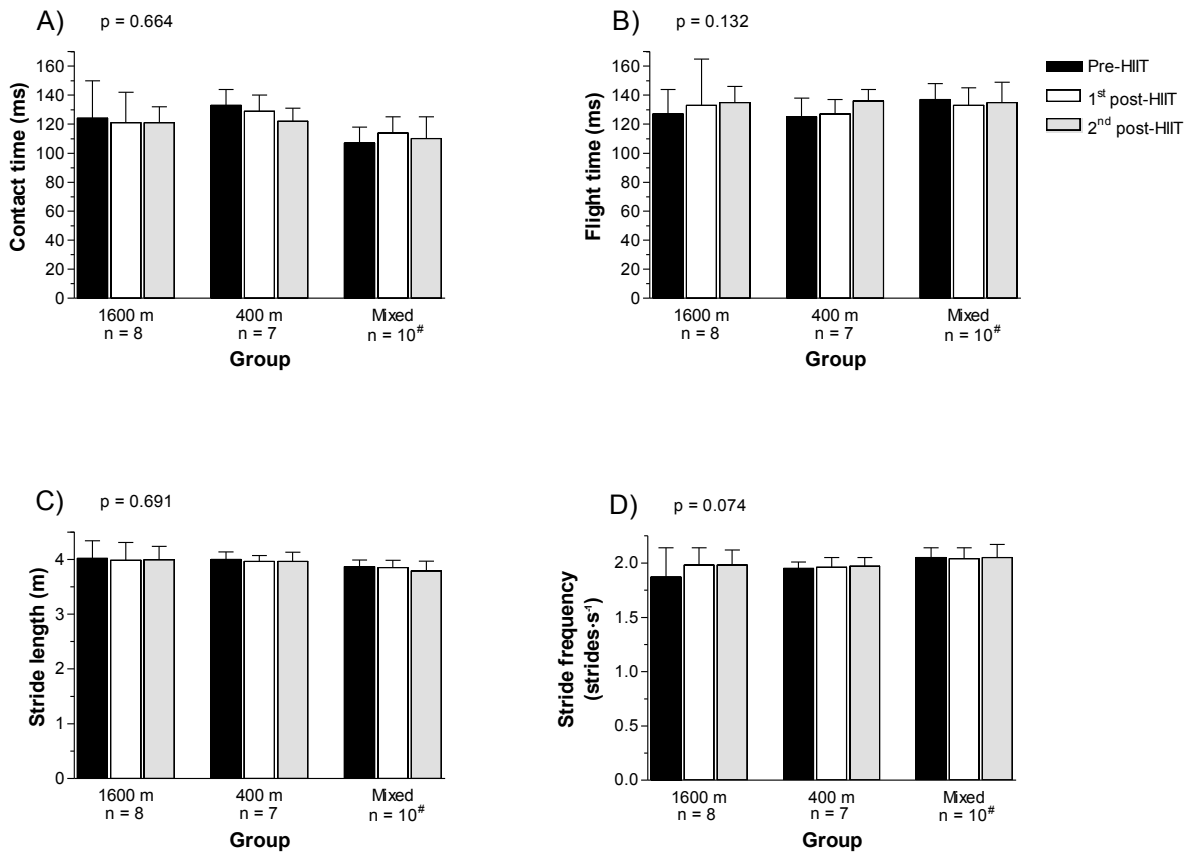


Figure 7.5 Stride parameters for all groups pre- and post-high intensity interval training: A) Contact time, B) Flight time, C) Stride length and D) Stride frequency.

Data are presented as the mean \pm standard deviation. The p-values on the graphs represent the group by trial interaction effect, as determined by a repeated measures ANOVA.

[#] n = 9 for the final measurement in the mixed group (i.e. all 2nd post-HIIT).

Abbreviations: HIIT – High intensity interval training, 1600 m – 1600 m interval group, 400 m – 400 m interval group, Mixed – Mixed interval group, sEMG – Surface electromyography, BF – Biceps femoris, VL – Vastus lateralis, VM – Vastus medialis, GM – Gastrocnemius medialis.

7.4 Discussion

The aim of this study was to answer the question posed in the previous chapter: could there be neuromuscular changes that could contribute to or explain the improvement in performance of the mixed interval training group immediately following the training intervention and during the taper period? It has been suggested that neuromuscular characteristics leading to increased muscle strength, power and fibre recruitment are associated with improvements in performance in the case of highly-trained athletes who are reaching their maximal aerobic capacity (175, 360, 378, 379, 444). Specifically, the aim of the present study was to establish whether there were any changes in muscle force, muscle activity and stride parameters after completion of three different HIIT programmes and whether any changes in these factors were associated with the 10 km TTT performance improvement in the mixed group following the HIIT intervention.

It is important to note that, as already established, the participants in the three different HIIT groups were similar and comparable with respect to anthropometry and performance characteristics prior to any intervention.

The first relevant finding of this study was that the 400 m group showed a significant 10.4% improvement in maximal calf force production 19 days post-HIIT (Fig 7.3). It is of interest that the group which showed no performance improvement in the 10 km TTT was the only group to show significant improvement in muscle strength, as reports in the literature suggest that a period of taper increases muscular strength leading to associated performance gains (215, 312, 349, 393, 465). The improvement in calf strength could be explained by the fact that the 400 m intervals were run at a higher speed compared to the 1600 m intervals. Higher speed sprint performance has been shown to result in greater increases in muscle strength especially in those muscles directly involved in the toe-off propulsion phase of the stride such as the *gastrocnemius* and *soleus* muscles, which comprise the calf muscle (53, 77, 301). In conjunction with this, the running style of the runner will contribute to the strength improvements of different muscle groups. Runners that run more on their toes, as seen with higher speed running, will typically develop stronger calves and hamstrings than those runners who strike more with their mid- or hindfoot (53, 77, 301). Therefore, the repetition of these high speed 400 m intervals

could have contributed to this observed improvement in calf strength in this group compared to the other groups. We are unable to confirm if this could be a factor, as running styles in this study were not monitored or recorded in the different groups. However, given the fact that participants were randomly assigned to groups, it is unlikely that all participants in a group would have had the same running style. The fact that the increase in calf muscle strength did not translate into performance improvements within this group could also point to the possibility that strength gains are not a major contributor to distance (10 km) running performance as it is observed that top runners for this distance do not have high muscle mass. This also highlights a key issue in sports physiology; that no single factor can be used to explain performance in isolation, but it is rather a more complex explanation involving an integration of many factors.

There were no significant differences in any of the groups for maximal force generation in the leg press. In the present study the leg press was designed to isolate the *quadriceps* muscles (VL, VM and BF) as much as possible. Therefore, it seems that none of the HIIT programmes elicited improvements in force production in the *quadriceps* muscles.

The second important finding of this component of the training study was that there were no significant changes in muscle activity after the training programmes in the *vastus lateralis*, *vastus medialis* and *gastrocnemius medialis* during pre-activation or contact phase in any of the HIIT groups post-HIIT intervention. There was, however, a significant difference in *biceps femoris* activity between groups and trials during contact phase following the HIIT intervention, however, no differences between or within the individual groups in *biceps femoris* activity post-HIIT. The *biceps femoris* muscle is most active during the stance phase of running (331) so the fact that the activity of this muscle has changed during the contact phase of running following a training intervention, is not surprising. The finding that there are no differences in *biceps femoris* activity between or within the individual groups, could be due to the small sample size, resulting in the inability to statistically detect differences.

Interestingly, in the *post hoc* analysis, the mixed group showed a tendency of increased muscle activity of *biceps femoris* in the contact phase following the training intervention, and the 400 m group showed a tendency towards decreased *biceps femoris* activity (Figure 7.4).

The mixed interval group was the only group to show a significant improvement in performance three days post-HIIT. It is possible that an improvement in strength in the *biceps femoris* muscle could have contributed towards the performance enhancements, however *biceps femoris* strength was not measured in the present study and so this cannot be confirmed. It is however, unclear as to why the 400 m group, who ran their intervals at a relatively higher speed compared to the other groups, would have showed a tendency towards decreased activation in this muscle as the *biceps femoris* is associated with higher speed running and is often the first to become injured in higher speed running activities (208, 307, 421). It is possible that this finding could be associated with an increase in muscle fibre strength in *biceps femoris* alluded to previously. This increase in strength could mean that the muscle fibres are more efficient and therefore less muscle activity is needed to produce the same performance.

The amount of force a muscle can produce is dependent on the rate and force of myofibrillar cross-bridge cycle activity as well as the ability to effectively store and release elastic energy during stretch-shortening cycle exercises such as the 20 m sprint, as was used in this component of the training study (60, 127, 262). This ability to utilise stored energy is in turn influenced by the level of pre-activation and the time between eccentric and concentric phases of contraction (60). It has been suggested that the more a muscle is able to use the stored elastic energy, the less muscle fibre recruitment and activation is needed during the propulsion phase (307, 368). In the present study, there were no differences in recruitment in any muscle groups during the pre-activation phase, suggesting that increased muscle stiffness and the concomitant energy storage and release do not explain the performance improvements observed in this study.

The final finding was that there were no significant differences or group by trial interactions in stride parameters for any of the groups. A potential limitation of this component of the present study is that the stride parameters were not measured during the 10 km TTT but rather during a maximal 20 m sprint. The 20 m sprint has been used in previous studies for extrapolation of endurance performance (72, 371, 376, 378, 379) and since perspiration and movement artefacts during prolonged exercise are known to make results less reliable, the 20 m sprint was chosen for this study. Performance was the key measure in these studies, and the presence of

electrodes, footswitches, cables and transmitter boxes could interfere with running performance in the 10 km TTT's. Additionally it was decided that data from a maximal test would be more comparable between runners than a submaximal 10 km run, as the latter would be run at different intensities amongst the participants.

In conclusion, it should be noted that as a consequence of a relatively high variance in sEMG measurements (178, 189, 359) and considering the sample sizes in each group, there is a risk of a Type II error having occurred (i.e. an inability to detect meaningful differences that were in fact present). However, based on the study design it is concluded that none of the neuromuscular measurements were associated with improvements in the 10 km TTT performance following HIIT. Although there was a tendency towards increased *biceps femoris* activation during the contact phase in the mixed interval training group, this was not significant, and therefore the impact this has on 10 km TTT performance remains uncertain.

CHAPTER EIGHT – SUMMARY AND CONCLUSIONS

8.1 Overview

The first objective of this thesis was to analyse the reliability and validity of a 10 km treadmill time trial (TTT) in measuring the performance of 10 km running and to confirm whether this measurement has sufficient sensitivity to detect small meaningful changes. This 10 km TTT was then used as a performance measure during the subsequent training study involved in the second objective of this thesis, which was to investigate the effect of three different high intensity interval training (HIIT) interventions on 10 km running performance and associated physiological parameters immediately following the training intervention and during a taper period.

8.1.1 Chapter Two: Reliability and validity of a self-paced 10 km treadmill time trial in well-trained male distance runners

Performance tests need to be both reliable and valid, especially in a study design where the effects of an intervention are assessed (107). The reliability of a performance test will impact on the power of the test to assess changes in performance that may arise as a result of the intervention (25, 217, 220, 280). It was therefore imperative that a performance test be designed and tested to determine whether it was both reliable and valid for use in the training component of this thesis. To this end, the 10 km TTT designed for this study was examined and assessed in terms of its reliability and validity.

In summary, the data showed that:

- i) The 10 km TTT was highly reliable, demonstrating a typical percent error (TEM %) of 1%.*
- ii) As the TEM % for this performance test was below 1.5%, it was concluded that this test was sensitive enough to measure meaningful performance changes.*
- iii) The 10 km TTT was also valid, as no significant differences were observed in performance time, heart rate and ratings of perceived exertion (RPE)*

between the 10 km time trials performed on the treadmill compared to those run on a 400 m outdoor track.

In conclusion, the 10 km TTT was found to be both reliable and valid for use as a performance measure to detect meaningful changes in 10 km running performance following a training intervention.

8.1.2 Chapters Four to Seven: Training intervention study

HIIT is a method commonly used to improve performance in well-trained athletes (73, 261). Although the effects of different HIIT programmes have been examined in well-trained athletes, the majority of these studies have been conducted on cyclists (106, 177, 243, 285, 286, 293, 384, 404, 425, 445, 446, 453, 481, 483), with far fewer studies examining the effects of HIIT on running performance (117, 139, 261, 399, 423, 424, 437, 438). Of the studies examining running performance, few have focused on the 10 km distance, specifically, and importantly none, to our knowledge, have investigated the performance effects of a HIIT programme involving high intensity intervals of two different intensities and durations in one programme. Furthermore, the intensity of training sessions reported in the literature are prescribed based on laboratory-determined physiological measures, such as, percentage of maximal heart rate (HR_{max}), velocity at which maximal oxygen uptake (VO_{2max}) is achieved (V_{max}), length of time that V_{max} can be sustained (T_{max}), peak treadmill running speed (PTRS) and maximal speed over a specific interval distance, whereas the interval intensity in the sessions in this study were based on the participants' current 10 km TTT performance time. To our knowledge, there are no studies in the literature that have designed and tested the impact of a HIIT program that prescribes the intensity of an interval based on this easy to use measure on performance in a 10 km running event.

The aim of this training study, as a whole, was to determine the effects of different HIIT programmes on 10 km running performance and associated physiological parameters immediately following the training intervention as well as during a three-week taper period. It was a further aim to determine what physiological parameters, if any, could be associated with any performance changes observed in order to ascertain what may have contributed to the performance changes.

Accordingly, each chapter addressed a different aspect of analysis of the performance and physiological measures obtained during and following this training intervention.

8.1.2.1 Chapter Four: The effect of different high intensity interval training programmes on 10 km treadmill time trial performance and associated physiological parameters

The aim of this component of the study was to determine the effect of three different HIIT programmes, (each with high intensity sessions of differing duration and intensity) on 10 km running performance, $VO_{2\text{ max}}$, running economy, PTRS, % $HR_{\text{ max}}$ sustained during a 10 km TTT, running economy as a percent of $VO_{2\text{ max}}$ and 20 m sprint time, immediately following the training intervention.

The main findings of this component of the study were:

- i) 10 km TTT performance was only improved in the mixed interval group ($3.3 \pm 2.0\%$), which performed one 400 m and one 1600 m interval session per week for four consecutive weeks.*
- ii) No changes were observed in $VO_{2\text{ max}}$, running economy, PTRS, % $HR_{\text{ max}}$ sustained during a 10 km TTT, running economy as a percent of $VO_{2\text{ max}}$ and 20 m sprint time in any of the three training groups.*
- iii) There was a significant trial effect when data for the groups were combined between pre- and post-HIIT intervention for both $VO_{2\text{ max}}$ and PTRS.*

In conclusion, the HIIT programme consisting of interval sessions of mixed duration and intensity (400 m and 1600 m intervals) was most effective in improving 10 km TTT performance. To our knowledge, this was the first study to investigate the effectiveness of a HIIT programme consisting of two different interval sessions. It is therefore recommended that HIIT programmes, designed to enhance 10 km running performance, should contain interval sessions of differing duration and intensity.

8.1.2.2 Chapter Five: The effect of a single-step 30% reduction in training volume (taper) following four weeks of high intensity interval training on 10 km treadmill time trial performance and associated physiological parameters

A period of taper is often used in the final days leading up to an event in an effort to optimise performance by reducing accumulated fatigue of prior training (229, 344, 350, 461). There are three key training components, namely training volume, intensity and frequency, which can be altered during the taper, and additionally the pattern and duration of the taper can differ.

The aim of this component of the study was three-part:

- i) To determine whether a single-step 30% volume reduction taper would improve or maintain 10 km running performance, $VO_{2\ max}$, running economy, PTRS and running economy as a percent of $VO_{2\ max}$, following a HIIT intervention.
- ii) To determine whether a shorter (ten-day) or longer (17-day) taper duration is optimal.
- iii) To determine whether HIIT sessions of differing intensity and duration prior to a taper would influence the effectiveness of the taper.

The main findings of this component of the study were:

- i) 10 km TTT performance in the mixed interval group was significantly improved ($4.5 \pm 2.5\%$) at day ten of the taper when compared to TTT performance prior to the training intervention.*
- ii) No changes were observed in $VO_{2\ max}$, running economy and running economy as a percent of $VO_{2\ max}$ in any of the three HIIT groups during the taper period.*
- iii) When the data for the three HIIT groups were combined, the following observations were made: Firstly, PTRS and $VO_{2\ max}$ were significantly increased during the taper period, at both day five and 19, when*

compared to prior to the training intervention. Secondly, time to complete a 10 km TTT was significantly improved at both day ten and 17 of the taper when compared to prior to the training intervention.

In conclusion, the single-step 30% volume reduction taper was able to further improve 10 km TTT performance in the mixed interval group at ten days following the start of the taper. Therefore, a taper duration of ten days was optimal for improvement of 10 km running performance following this HIIT programme. Furthermore, this taper programme was able to maintain $VO_{2\text{ max}}$, running economy and running economy as a percent of $VO_{2\text{ max}}$, over the course of three weeks in all training groups.

8.1.2.3 Chapter Six: The effect of different high intensity interval training programmes on pacing strategy and ratings of perceived exertion during a 10 km treadmill time trial

The pacing strategy during an event is known to have an impact on performance. There are a number of pacing strategies which have been broadly defined, the choice of which depends largely on the duration and profile of the event, as well as prior experience and the physiological capacity of the athlete (5, 441, 469). The aim of a pacing strategy is to delay fatigue during an event in order to maximise performance (10, 150, 151, 167, 184, 291).

One report in the literature (316) found that the addition of a time trial of different distance, between two time trials of the same distance, caused an interference in the pacing strategy during the following time trial. To our knowledge there are no reports pertaining to the effect of a HIIT intervention on the subsequent pacing strategy employed in a target event.

The aim of this component of the study was, therefore, firstly to determine whether preceding HIIT programmes (making use of intervals of differing duration and intensity) would have an effect on the pacing strategy employed during subsequent 10 km TTT's, and secondly whether pacing strategy could be associated with any changes in performance following the HIIT intervention.

The main findings of this component of the study were:

- i) *In the 400 m interval group (only), a significant difference was found in the pacing strategy in the first post-HIIT 10 km TTT, immediately following the cessation of the HIIT intervention, compared to the pacing strategy prior to the HIIT intervention. During the second post-HIIT 10 km TTT, the pacing strategy of this group was again no different to that which was employed prior to the HIIT intervention.*
- ii) *In the 400 m interval group (only), the RPE scores were observed to diverge during the first post-HIIT 10 km TTT compared to the RPE scores during the TTT prior to the HIIT intervention. Specifically, higher RPE scores were recorded during the same time period that the group was observed to slow significantly in the first post-HIIT 10 km TTT.*

In conclusion, changes in pacing strategy were not associated with the performance improvement measured in the group performing mixed interval sessions.

Furthermore, it appears that interval sessions of only 400 m intervals performed in the HIIT intervention had a potentially negative effect on the pacing strategy during the subsequent 10 km TTT, immediately following the cessation of the HIIT intervention. The pacing strategy then reverted to the same as it was prior to the intervention, once one 10 km TTT had been performed. It is therefore recommended that a simulated race situation of similar distance to the target event is completed following a HIIT programme, if the programme consists solely of shorter intervals run at a much faster pace than the trial pace (in this case, 400 m intervals which are run at approximately 13% faster than 10 km time trial pace). Further research is needed to determine the optimal interval intensity and duration, proportional to that of the target event, to ensure that pacing strategy is not negatively affected by prior training programmes.

8.1.2.4 Chapter Seven: The effect of different high intensity interval training programmes on neuromuscular characteristics and stride parameters in well-trained male runners

Endurance performance is limited by central factors relating to aerobic capacity, and also neuromuscular characteristics contributing to an increase in muscle strength,

activation or power (175, 376, 379). This is particularly important when dealing with well-trained athletes approaching their maximal limit for enhancements of $VO_2 \text{ max}$ or running economy, as further performance improvements may only be possible due to changes in other factors (378, 379).

Accordingly, the aim of this component of the study was to investigate whether any changes would occur in a number of neuromuscular factors, such as muscle strength, surface electromyography (sEMG) and certain stride parameters, following three different HIIT interventions and whether any changes in these factors could be associated with performance changes following the HIIT intervention. Specifically, muscle strength (as measured by an isometric maximal voluntary contraction (MVC) during a seated leg press and calf press), sEMG of *vastus lateralis*, *vastus medialis*, *biceps femoris* and *gastrocnemius medialis* and stride parameters were measured before the start of the HIIT intervention and then five and 19 days following the training intervention.

The findings were as follows:

- i) *The group performing intervals of 400 m only, had a significant improvement in calf muscle strength (as measured by an isometric MVC) 19 days following the HIIT intervention.*
- ii) *No significant changes were recorded in the muscle activity (as measured by sEMG) of vastus lateralis, vastus medialis and gastrocnemius medialis during pre-activation or the contact phase during running, following the HIIT intervention in any of the groups, nor when data for the groups were combined. There was, however, a significant group by trial interaction effect for the muscle activity of biceps femoris during the contact phase.*
- iii) *No significant differences were recorded in the stride parameters measured during the 20 m sprint test, following the HIIT intervention in any of the groups, nor when the data for the groups were combined.*

In conclusion, no significant changes in the neuromuscular factors examined showed changes consistent with the performance improvement measured in the group performing mixed interval sessions. Therefore, it seems unlikely that the

performance improvement observed in the mixed interval group was due to changes in the neuromuscular parameters measured.

8.2 Interpretation

The aim of the first component of this thesis was to design and test a performance measure for use in the nine-week training study which made up the second component of the thesis.

The study in Chapter Two was integral to the remainder of the thesis as it is important that investigations into the effects of training interventions make use of a testing protocol which is reliable, sensitive and valid to be able to detect meaningful changes in performance. Without the certainty that this test was reliable, it would not have been possible to make recommendations based on any performance changes in the remainder of the thesis. The testing protocol that was designed in Chapter Two, in the form of a self-paced 0% grade 10 km TTT, was found to be highly reliable with a TEM % of 1%. This result indicated that this test was also sensitive enough to detect meaningful changes in performance as it has been reported by Hopkins and Hewson (219) that the inter-individual variation in the competitive performance of well-trained runners in endurance events less than 21 km, is approximately 1.5%. Furthermore, the validity of this test was ascertained by comparing outdoor track time trials (TRTT) to the TTT's. As no differences were found between the performance times, RPE and heart rate, it was concluded that the TTT is indeed valid for extrapolation of 10 km running performance in the field. This study, therefore, provides a new reliable, sensitive and valid testing measure that will allow scientists to detect meaningful changes in 10 km running performance in the laboratory.

The nine-week training study made up the second component of this thesis. The training study was designed to investigate the effects of three different HIIT programmes on 10 km running performance and selected physiological variables.

Chapter Four showed that a HIIT programme consisting of intervals of mixed duration and intensity (400 m and 1600 m intervals, specifically) was effective in improving 10 km running performance, rather than a programme containing interval sessions of

only one type. This is the first investigation, to our knowledge, that tested this type of HIIT programme and the results of this have practical application for coaches and scientists. Certainly, in this study, a mixed interval programme comprised of 12 x 400 m intervals run at 13.2% faster than 10 km pace and 3 x 1600 m intervals run at 4.3% faster than 10 km pace, each performed once per week for four weeks, was able to enhance 10 km running performance significantly. It is tempting to suggest that mixed interval sessions might be beneficial to a range of other distance performances as well. The prescription of the intensity of the intervals based on current 10 km performance is an easy to use measure which does not require laboratory testing, an aspect that is advantageous when access to laboratory facilities is limited or non-existent.

As there were no changes in the measures of $VO_{2\text{ max}}$, running economy, running economy as a percent of $VO_{2\text{ max}}$, PTRS, % $HR_{\text{ max}}$ sustained during a 10 km TTT and 20 m sprint time following the HIIT programme comprised of mixed intervals, it is likely that none of these factors were associated with, or contributed to, the improvement in 10 km running performance observed in this group. Similarly, as shown in Chapter Seven, it is unlikely that changes in the measured neuromuscular factors contributed to the performance enhancement in the mixed interval group. The question arises as to what parameters, other than those measured, may have contributed to this improvement? It is possible that the participants in the mixed group were able to exercise at a higher % $VO_{2\text{ max}}$ thus allowing them to run at an increased speed following the training intervention. Another possibility is that the neuromuscular measurements were not sensitive enough to record any meaningful changes which in fact may have existed. Another interpretation is that there could have been improved motor-neuron synchronisation in the active muscles, which was not measured. It is also possible that changes in a combination of these variables although not significant on their own, could together have led to an improvement in performance.

A taper consisting of a single-step 30% reduction in training volume, while maintaining training frequency and somewhat maintaining intensity showed either a maintenance or improvement in 10 km running performance during the taper period in all the groups. Therefore it can be concluded that this specific taper programme was not detrimental to performance. Performance improvements were recorded in

the mixed interval group at ten days following the cessation of the HIIT intervention but not in the 1600 m and 400 m groups. This raised the issue of specificity of training for an event. The 1600 m intervals are run at an intensity of 4.3% faster than 10 km race pace, whereas the 400 m intervals were run at 13.2% faster than 10 km race pace and were 77% shorter in terms of duration per interval compared to the 1600 m intervals. Both the 400 m group and the 1600 m group showed no performance improvement up to ten days following the HIIT programme (second post-HIIT) and indeed at any stage following the HIIT intervention. Therefore, it seems that the duration and intensity of these intervals performed in isolation may have been too dissimilar compared to the demands during the actual target event of 10 km. It would be interesting to determine whether there is an optimal proportional intensity and duration for intervals based on the target event.

Reports in the literature deem progressive reduction protocols to be more effective than single-step reduction protocols (33, 270, 337). Nevertheless, a single-step reduction protocol was used for the taper in this study, as this was thought to be easier to administer by athletes and coaches and would be more accepted by the study participants. It is possible that the performance improvements observed during the taper period could have been enhanced if the 30% volume reduction was carried out in a progressive rather than a step-wise manner and possibly also if the volume reduction was greater than 30%.

An analysis of pacing strategy showed a novel and interesting finding in that the intensity (pace) and duration of interval sessions prior to the 10 km TTT's had an effect on the pacing strategy adopted during the TTT immediately post-training. The group performing only 400 m intervals during the HIIT intervention, had a different pacing profile in the first post-HIIT 10 km TTT, in comparison to the pacing profile observed in the TTT prior to the start of the intervention, as well as both subsequent TTT's following the training intervention (second and third post-HIIT). It seems that the study participants in this group may have become accustomed to running at a higher intensity so that when they began their first TTT immediately following training, they ran at a faster pace than before. They then needed to readjust their pace to complete the TTT. Interestingly, the exposure of one 10 km TTT seemed to reset the pacing strategy as they then started their second TTT at a pace no different to that which they ran before the training intervention. This concept is important to

consider when exposing athletes to HIIT. It follows that if the interval intensity for the training sessions is too high or dissimilar relative to the distance they are training for, there may be a risk that the pacing could be disrupted immediately following training, particularly if there is no exposure to a bout of exercise similar in intensity and duration as the target event. Practical advice from this finding is that athletes should simulate their target event at least once following a HIIT programme and before the target event.

8.3 Further research

Further research should be conducted on the effectiveness of HIIT on the performance of other race distances. In particular, the HIIT programmes should consist of interval sessions defined by mixed durations and intensities. Additionally, future studies should determine whether there is an optimum combination of intervals for varying race distances, as well as a proportional measure that could be determined for prescribing intensity and duration of intervals for specific race distances. The answer to this would assist coaches in the field in making objective decisions about the prescription of training sessions, particularly in well-trained athletes.

The use of the single-step taper protocol in this thesis was able to elicit maintenance and improvement of running performance over the taper period. A progressive style taper may be more effective than step tapers, so it would be interesting to determine whether the effectiveness of the 30% reduction in training volume would be affected if the reduction was carried out in a progressive, rather than step-wise fashion.

Further research is needed to investigate the effect of preceding interval training intensity on pacing strategies during longer events. In particular it is important to determine whether there is a threshold intensity or duration of sessions above which pacing is disrupted.

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APPENDIX 1 – INFORMED CONSENT FORM (CHAPTER TWO)

Reliability and validity of a self-paced 10 km treadmill time trial.

I, _____ agree to participate in a research project, conducted at the Sports Science Institute of South Africa, Department of human biology, Faculty of Health Sciences, at the University of Cape Town.

I understand that the project will involve five visits to the laboratory and two visits to an outdoor track. On the first occasion, I will perform a maximal test to volitional exhaustion on a treadmill in the laboratory, in order to determine my maximal oxygen uptake ($VO_2 \text{ max}$), maximum heart rate ($HR \text{ max}$) and peak treadmill running speed (PTRS). Heart rate will be recorded throughout the test with a heart rate monitor.

During my second visit to the laboratory I will be requested to perform a familiarization 10 km time trial (TT) on a motorised treadmill. I understand that my five subsequent visits to either the laboratory or the track will be randomised, and I'll be requested to perform a 10 km TT on each occasion. All of these TT's will be separated by seven to ten days and I will be allowed a five to ten minute self-paced warm up prior to each TT. Time taken to complete each TT as well as the 1 km split times will be recorded. Heart rate as well as ratings of perceived exertion (RPE) after each kilometre will also be measured during each TT.

I fully understand the risks of this project, which have been explained to me, and any questions that I may have had have been answered to my satisfaction. I understand that I am free to withdraw from this study at any stage of the project should I choose to do so.

Signature of participant

Investigator

Witness

Date: _____

APPENDIX 2 – BORG'S RATINGS OF PERCEIVED EXERTION SCALE

6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Borg's ratings of perceived exertion scale instructions

While exercising we want you to rate your perception of exertion (i.e. how heavy and strenuous the exercise feels to you). This perception of exertion depends mainly on the strain and fatigue in your muscles and on your feeling of breathlessness or aches in the chest.

Look at this rating scale; we want you to use this scale from 6 to 20, where 6 means "no exertion at all" and 20 means "maximal exertion".

- 9 corresponds to "very light" exercise. For a normal, healthy person it is like walking slowly at his or her own pace for some minutes.
- 10 on the scale is "somewhat hard" exercise, but still feels OK to continue.
- 11 "very hard" is very strenuous exercise. A healthy person can still go on, but he or she really has to push him- or herself. It feels very heavy, and the person is very tired.
- 12 on the scale is an extremely strenuous exercise level. For most people this is the most strenuous exercise they have ever experienced.

Try to appraise your feeling of exertion as honestly as possible, without thinking about what the actual physical load is. Don't underestimate it, but don't overestimate it either. It's your own feeling of effort and exertion that's important, not how it compares to other people's. What other people think is not important either.

Look at the scale and the expressions and then give a number.

APPENDIX 3 – INFORMED CONSENT FORM (CHAPTERS FOUR TO SEVEN)

Interval training: How does duration and intensity effect 10 km running performance?

I, _____ agree to participate in a research project, conducted at the Sports Science Institute of South Africa, Department of human biology, Faculty of Health Sciences, at the University of Cape Town.

I understand that this project will involve at least 16 visits to the laboratory or track. I also understand that I'll be required to perform the following tests during the course of this study:

- five 10 km treadmill time trials,
- three maximal testing days, with all of the tests that this includes (anthropometry, maximal treadmill test, running economy test, surface electromyography, maximal voluntary contraction test for both upper and lower leg as well as three maximal 40 m sprint tests), and
- eight interval training sessions of either 400 or 1600 m intervals, comprising no more than 4800 m of intervals per session.

I agree that all of the above tests have been explained to me in full and I completely understand what is going to be required of me in order to complete this study.

I fully understand the risks of this project, which have been explained to me, and any questions that I may have had have been answered to my satisfaction. I understand that I am free to withdraw from this study at any stage should I choose to do so.

Signature of participant

Investigator

Witness

Date: _____

APPENDIX 4 – DATA COLLECTION SHEET FOR A 10 KM TIME TRIAL (TREADMILL OR TRACK)

Name: _____ Trial: _____ Date: _____
 Time: _____

Distance	RPE	Actual time	1 km splits	400 m splits	
1				1	
				2	
				3	
2				4	
				5	
				6	
3				7	
				8	
				9	
4				10	
				11	
				12	
5				13	
				14	
				15	
6				16	
				17	
				18	
7				19	
				20	
				21	
8				22	
				23	
				24	
9				25	
10					

Ave speed: _____ Wind speed : _____
 Temp: _____
 Max speed: _____ Humidity : _____
 Ave HR _____ HR_{max}: _____

APPENDIX 5 – DATA COLLECTION SHEET FOR MAXIMAL TESTING DAYS

Name : _____ Date : _____ Trial : _____
 Mass (kg) : _____ Height (m) : _____ Age: _____

MVC			Support setup (Quad) 4 holes all round, (Calf) 6 all round		
QUAD					
Back rest:	<input type="text"/>	Head rest:	<input type="text"/>	Base:	<input type="text"/>
CALF					
Back rest:	<input type="text"/>	Head rest:	<input type="text"/>	Base:	<input type="text"/>
Norm time: _____ (5 seconds for 20m)					
Sprint 1:		Sprint 2:		Sprint 3:	
20 m	_____	20 m	_____	20 m	_____
40 m	_____	40 m	_____	40 m	_____

MAX TEST	
Max Time :	_____
PTRS :	_____
VO ₂ max (l·min ⁻¹) :	_____ (ml·kg ⁻¹ ·min ⁻¹) : _____
HR max (beats·min ⁻¹) :	_____

RE	5 minutes or until at least 4 minutes of stable VO ₂ readings (plateau)
Run time:	_____

Sum of skin folds (cm)		Lean thigh volume (cm)	
Triceps	_____	Sub-gluteal girth	_____
Biceps	_____	Mid-thigh girth	_____
Subcap	_____	Above knee girth	_____
Suprailiac	_____		
Abdom	_____	Sub-gluteal to	
Mid-thigh	_____	above knee height	_____
Calf	_____		
TOTAL:	=====		