The use of the self-paced exercise test in assessing cardiorespiratory fitness in runners

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Abstract

The aim of this thesis was to investigate the utility of the self-paced exercise test (SPXT) in assessing the cardiorespiratory fitness of runners. Traditionally, cardiorespiratory fitness is assessed via an open-ended graded exercise test (GXT) which utilises fixed increments of work-rate and involves the participant continuing until volitional exhaustion. The SPXT is a closed-looped 10 minute (min) test which is made up of 5 x 2 min stages in which intensity is clamped by ratings of perceived exertion (RPE). The test starts at RPE 11, and this increases in an incremental fashion to encompass RPE 13, 15, 17, and finally 20. The test is more time-efficient than traditional protocols due to not requiring a known starting speed. Additionally, the SPXT may be more valid for runners compared to the GXT in which test duration is unknown.

In study one, gradient and speed-based SPXT protocols were compared to a laboratory based GXT to investigate the validity of the SPXT in producing maximal oxygen uptake ($\dot{V}O_{2max}$). The gradient-based SPXT [which has not previously been investigated] produced higher $\dot{V}O_{2max}$ than the GXT (71 ± 4.3 vs. 68.6 ± 6.0 mL·kg^{-1}·min^{-1}, $P = .03$, ES $= .39$) but the speed-based SPXT produced similar $\dot{V}O_{2max}$ to the GXT (67.6 ± 3.6 vs. 68.6 ± 6.0 mL·kg^{-1}·min^{-1}, $P = .32$, ES $= .21$). Results also demonstrated that the oxygen (O_2) cost of ventilation may differ between the SPXT and GXT (26.4 ± 2.8 vs. 28.2 ± 2.8 mL·min^{-1}, respectively) ($P = .02$).

In study two, the oxygen cost of breathing during the SPXT was investigated. When assessed via separate ventilation trials, there were no differences in the oxygen cost of breathing between the SPXT and GXT (26.1 ± 5.3 vs. 26.9 ± 4.2 mL·min^{-1}, respectively) ($t_7 = -1.00$, $P = .34$,), and $\dot{V}O_{2max}$ was again similar between the SPXT and GXT ($Z = -.43$,

$P = .67,$). The mean velocity at RPE20 ($_v$RPE20) measured via the SPXT was also similar to the maximal velocity (V_{max}) derived from the GXT ($t_8 = .74$, $P = .48$).

In study three, the ability of the SPXT to provide novel parameters that could be used to prescribe six-weeks of running training for recreationally active runners was investigated. Results demonstrated that $_v$RPE20 was effective in improving $\dot{V}O_{2max}$ (6 ± 6 %), critical speed (3 ± 3 %) and lactate threshold ($7 \pm 8\%$) and these improvements were similar to a separate group who trained using GXT-derived parameters including V_{max} (4 ± 8, 7 ± 7, 5 ± 4 %, for $\dot{V}O_{2max}$, critical speed, and lactate threshold, respectively). Prescribing training via the SPXT may be beneficial as it does not require additional testing that is usually associated with the GXT.

In study four, the ability of the SPXT to accurately determine ventilatory thresholds (VT) was investigated. The first and second VT (VT1 and VT2, respectively) were not significantly different when measured as $\dot{V}O_2$ between the SPXT (4.03 ± 0.5 and 4.37 ± 0.6 L·min^{-1}, for VT1 and VT2, respectively) and GXT (4.18 ± 0.5 and 4.54 ± 0.7 L·min^{-1}, respectively) in highly trained runners. In recreationally trained runners VT1 was significantly different when measured via the SPXT and GXT (2.78 ± 0.5 vs. 2.99 ± 0.5 L·min^{-1}, respectively) ($t_{23} = -4.51$, $P < .01$, ES $= .42$) whilst VT2 was also significantly different (3.10 ± 0.6 vs. 3.22 ± 0.6 L·min^{-1}) ($t_{21} = -2.35$, $P = .03$, ES $= .20$). However, when calculated using different variables such as velocity, RPE, and HR, VT1 and VT2 were similar between protocols. This demonstrated that the SPXT can provide valid VT for runners.

The conclusion from this thesis is that the SPXT is a valid protocol for measuring $\dot{V}O_{2max}$

and can also be used to prescribe a programme of endurance training, and provide an accurate marker of VT.

Table of Contents

List of figures

List of tables

GXT and SPXT protocols for highly trained participants.

Abbreviations

ANOVA	Analysis of variance
a-vO$_{2diff}$	Ateriovenous oxygen difference
bpm	Beats per minute
CI	Confidence Interval
CS	Critical Speed
CP	Critical Power
ES	Effect Size
GPS	Global Positioning Satellite
G-VENT	GXT-based ventilation protocol
GXT	Graded exercise test
h	hours
HIIT	High intensity interval training
HR	Heart rate
HR$_{max}$	Maximal heart rate
ICC	Intraclass correlation coefficient
L·min^{-1}	Litres per minute
LoA	Limits of Agreement
LT	Lactate threshold
LT1	First lactate threshold
LT2	Second lactate threshold
m	Metres
min	Minutes
mL·kg^{-1}·min^{-1}	Millilitres, per kilogram of body weight, per minute
mL·min^{-1}	Millilitres per minute
mmol·L^{-1}	Millimoles per litre
m.s^{-1}	Metres per second
n	Number

η_p^2	Partial eta-squared
O_2	Oxygen
$P_{ET}O_2$	Partial end-tidal volume of oxygen
$P_{ET}CO_2$	Partial end-tidal volume of carbon dioxide
PO_{peak}	Peak power output
P	Significance level
PO	Power output
PRET	Perceptually regulated exercise test
$\dot{Q}$	Cardiac output
$\dot{Q}_{max}$	Maximal cardiac output
RAMP	Incremental ramp test
RER	Respiratory exchange ratio
RER_{max}	Maximal respiratory exchange ratio
RPE	Rating of perceived exertion
s	Seconds
SMD	Standardised mean difference
SPXT	Self-paced exercise test
SD	Standard deviation
SV	Stroke volume
S-VENT	SPXT-based ventilation protocol
SV_{max}	Maximal stroke volume
T_{max}	Time in which $V_{max}/_v\dot{V}O_{2max}$ can be maintained
TTE	Time to exhaustion
$\dot{V}CO_2$	Carbon dioxide production
$\dot{V}_E$	Minute ventilation
$\dot{V}_{Emax}$	Maximal minute ventilation
V_{max}	Maximal velocity
$\dot{V}O_2$	Volume of oxygen
$\dot{V}O_{2max}$	Maximal oxygen uptake
$\dot{V}O_{2peak}$	Peak oxygen uptake

$\dot{V}O_{2vent}$	Oxygen cost of breathing
V_{peak}	Peak Velocity
$_vRPE20$	Velocity at RPE20
VT	Ventilatory thresholds
VT1	Ventilatory threshold 1
VT2	Ventilatory threshold 2
$_v\dot{V}O_{2max}$	Velocity at $\dot{V}O_{2max}$
$\dot{V}O_{2VT1}$	$\dot{V}O_2$ at VT1
$\dot{V}O_{2VT2}$	$\dot{V}O_2$ at VT2
W	Watts
wk	Weeks
$W{\cdot}min^{-1}$	Watts increase per minute
Δ	Difference

Chapter 1: Introduction

1.1. Introduction

The graded exercise test (GXT) is a type, or collection of protocols, used to observe the dynamic relationship between exercise workload and integrated systems such as cardiovascular, pulmonary, musculoskeletal and neuropsychological (Albouaini et al., 2007). The most popular function of the GXT is to measure an individual's maximal oxygen uptake ($\dot{V}O_{2max}$), which is defined as the highest rate at which oxygen can be taken up and utilized by the body during severe exercise (Bassett & Howley, 2000). The origins of GXT date back to the 18th century (Beltz et al., 2016) and research regarding exercise tests to measure physiological parameters were first recorded in 1918 (Lambert, 1918). The most seminal of this early work was led by celebrated physiologist A. V. Hill et al (Hill et al., 1924; Hill et al., 1924a). Hill et al ran around an athletics track at multiple discontinuous increasing fixed intensities to plot the relationship between work-rate and oxygen uptake ($\dot{V}O_2$). They concluded four key points: 1) There is an upper limit to $\dot{V}O_2$ 2) There are interindividual differences in $\dot{V}O_{2max}$ 3) a high $\dot{V}O_{2max}$ is a prerequisite for success in middle and long distance running 4) $\dot{V}O_{2max}$ is limited by the ability of the cardiorespiratory system to transport oxygen (O_2) to the muscles.

Although the GXT is most predominately used for the identification of $\dot{V}O_{2max}$ it can also be used to identify ventilatory thresholds (VT). The GXT is recognised as arguably the most popular test in exercise sciences (Robergs, 2001; Noakes, 2008). Since the work of Hill et al over 100 years ago, the GXT and the study of $\dot{V}O_{2max}$ has gone through many seminal changes. This progression has been largely driven by the innovations in technology used [to measure $\dot{V}O_{2max}$] reaching new levels of sophistication.

Whilst the early tests for measuring $\dot{V}O_2$ were discontinuous in nature, the 1960's saw the rise of the continuous incremental protocol. This was largely related to the introduction of online gas analysers. These continuous incremental protocols were predominately designed for the primary purpose of measuring $\dot{V}O_{2max}$. These protocols became the crux for the GXT as we know it today. An important feature of the GXT, which separates this collection of protocols from the discontinuous protocols first tested by Hill and colleagues, is the $\dot{V}O_2$-workrate slope ($\dot{V}O_2$-WR). This refers to the relationship between the increase in intensity and the increase in $\dot{V}O_2$ during the exercise test. GXT protocols take the form of either a STEP or a RAMP. In a STEP, work-rate is increased periodically by a predetermined amount until exhaustion. In a RAMP, work-rate may increase by the same amount as the STEP, but is distributed over the entirety of each stage, creating a more linear progressive increase in intensity throughout the protocol.

Continuous STEP protocols were first prevalent in the 1960s and consisted of a number of well-known protocols: Balke; Bruce; Eleestad; and modified Astrand. All of these protocols are open-ended and combine different stage lengths and intensity alteration (velocity or gradient) with the participant continuing until they are unable to physically continue, or likewise they terminated the test due to fatigue, thereon defined as volitional exhaustion. These protocols were first compared comprehensively in the 1970's (Pollock et al., 1976) with it reported that the protocol itself is not necessarily a main contributing factor in $\dot{V}O_{2max}$ differences, if similar intensities and models are utilised. However, when protocol length, modality, and intensity increments (among other factors) are not similar, this can significantly alter $\dot{V}O_{2max}$. RAMP protocols may improve an individual's ability to reach $\dot{V}O_{2max}$ (Whipp et al., 1981; Davis et al., 1982; Beltz et al., 2016) but the small increases in work-rate may make it more difficult to verify a $\dot{V}O_2$ plateau (Midgley et al.,

2007a). Due to logistical limitations, such as some treadmills not being equipped with a ramp function, RAMP protocols are used less for treadmill protocols compared to cycling ergometers.

The GXT has been a key test in both clinical (McKelvie & Jones, 1989; Milani, 2004; Albouaini et al., 2007) and applied settings (Beltz et al., 2016) but how it relates to 'real-life' exercise has been questioned. South African physiologist and experienced ultra-endurance runner Tim Noakes (2008) has expressed three concerns regarding the current design of the GXT: 1) The test duration is unknown 2) The intensity increases incrementally from low to maximal 3) The participant has no control over regulation of the exercise intensity besides terminating the test. Noakes highlighted that all three of these concepts are foreign to real sporting performance as no sport exists within the confines of these rules.

In comparison to the GXT, in which intensity progressively increases until volitional exhaustion with no fixed end time, an exercise protocol that allows for a degree of self-pacing whilst remaining progressive and incremental may be favourable as it has the potential to address the concerns identified by Noakes (2008). Self-paced exercise has been shown to be less physiologically demanding than enforced paced exercise (Lander et al., 2009), most likely because fixed increments of intensity are an unnatural way of exercising for most athletes, as highlighted by Noakes (2008).

Mauger and Sculthorpe (2012) designed a novel maximal cycling exercise protocol named the 'self-paced $\dot{V}O_{2max}$ test' which will thereon be referred to as the 'self-paced exercise test' (SPXT). This protocol has a closed-loop design which is made up of 5 x 2 min stages.

Work-rate is self-regulated based on prescribed ratings of perceived exertion (RPE) (Borg, 1982; Borg, 1990). Participants must regulate their work-rate based on an RPE of 11, then 13, 15, 17 and then finally a maximal effort of 20 in the final 2 min. In doing so, the SPXT addresses the issues laid out by (Noakes, 2008). As intensity is clamped by RPE, participants can regulate their own work-rate, but an incremental test design remains due to the increasing RPE as the test progresses. The ability to self-regulate pace may make it more relevant for athletes. Additionally, the closed loop design means participants always exercise for 10 min, and due to the 'need to think' (Straub et al., 2014) during the protocol, increases the role of the brain. This protocol design could also be considered more efficient and practical due to it, unlike the GXT, not requiring the tester to estimate a starting velocity or power (PO). This also means the test can be easily adapted to a wide range of exercise modalities (Mauger et al., 2013). The definitive 10 min duration also means that the test is guaranteed to match the well-cited recommendation that $\dot{V}O_{2max}$ tests last for ~10 min (Yoon et al., 2007).

Whilst the test design of the SPXT makes it a popular alternative to the GXT, much interest has come from the findings of Mauger and Sculthorpe (2012) and their follow up study which introduced the treadmill-based SPXT (Mauger et al., 2013a). In both of these cycling and treadmill protocols, using untrained participants, they found that $\dot{V}O_{2max}$ was significantly higher in the SPXT protocols compared to the GXT counterparts. As mentioned earlier, whilst protocol differences can alter $\dot{V}O_{2max}$, much of the debate surrounded whether the self-paced nature of the SPXT was responsible for the differences in $\dot{V}O_{2max}$, with opinion very much divided (Mauger & Sculthorpe, 2012; Chidnok et al., 2013; Mauger, 2013; Mauger et al., 2013; Mauger et al., 2013a; Astorino, 2014; Eston et al., 2014; Poole, 2014). Since the height of this discussion, there has been a surge in

research regarding the SPXT in cycling and running across both applied and clinical settings (Straub et al., 2014; Astorino et al., 2015; Faulkner et al., 2015; Scheadler & Devor, 2015; Hanson et al., 2016; Jenkins et al., 2017; Jenkins et al., 2017a; Beltz et al., 2018). Variations of the SPXT have also been used that tend to utilise different RPE increments or stage lengths (Chidnok et al., 2013; Evans et al., 2014; Truong et al., 2017) compared to the protocol first used by Mauger and Sculthorpe (2012). To avoid confusion, study protocols that have utilised the test structure as described by Mauger and Sculthorpe (2012) (5 x 2 min stages with RPE increments of 11, 13, 15, 17, and 20) will thereon be termed 'SPXT' whereas studies that utilised a modified design will be described as having used a 'modified-SPXT'.

Reasons for potential differences in $\dot{V}O_{2max}$ in the SPXT have been hotly debated. Mechanistic investigations have predominately focused on the hemodynamic responses during both the GXT and SPXT, specifically looking at the role of O_2 delivery and extraction, and the role of cardiac output ($\dot{Q}$). Beyond $\dot{V}O_{2max}$, there have also been inconsistent findings regarding other physiological variables such as minute ventilation ($\dot{V}_E$), respiratory exchange ratio (RER) and heart rate (HR). One of the main criticisms of both GXT and SPXT testing is the lack of standardisation (Hutchinson et al., 2017), as this has been highlighted as an on-going issue (Beltz et al., 2016) with various researchers using slightly different methods which may confound progression towards an accepted consensus.

The attraction of the GXT is largely two-fold: 1) It is the most well-recognised method of directly measuring $\dot{V}O_{2max}$, which is itself the most widely tested parameter in sport and exercise science; and 2) it is a versatile test that can offer a wide range of data and

information to testers, clinicians, athletes, and coaches. Currently, the GXT can provide data on VT, exercise efficiency, $\dot{V}O_2$ kinetics, and as previously discussed, $\dot{V}O_{2max}$ (Poole & Jones, 2017). The GXT can also be used to identify both the velocity at $\dot{V}O_{2max}$ ($_v\dot{V}O_{2max}$) and the maximal velocity (V_{max}) which can be used by coaches and practitioners to prescribe interval training to athletes, recreationally active individuals, and clinical populations (Smith et al., 2003; Laursen & Jenkins, 2002; Esfarjani & Laursen, 2007; Manoel et al., 2017; Bacon et al., 2013). By prescribing training via these methods, significant improvements in $\dot{V}O_{2max}$, lactate thresholds (LT), VT, and the time in which $_v\dot{V}O_{2max}$ or V_{max} can be maintained (T_{max}), have been achieved (Smith et al., 2003; Denadai et al., 2006; Esfarjani & Laursen, 2007; Laursen & Jenkins, 2002; Manoel et al., 2017; Silva et al., 2017). Alternatively, the SPXT, whilst more ecologically valid and sport specific (Noakes, 2008; Poole & Jones, 2017) than the GXT, does not currently offer useful data beyond $\dot{V}O_{2max}$. If it could, this would make the SPXT potentially attractive to athletes and coaches.

Whilst the body of research on the SPXT is growing, gaps in the literature remain. The SPXT as a valid protocol of $\dot{V}O_{2max}$ is increasingly investigated; however, little has been done regarding highly trained athletes in relation to the SPXT. Of perhaps greater fundamental importance is what the SPXT can offer athletes and coaches, as the protocol was originally conceived to be more applicable to these populations. Accordingly, the aim of this thesis was to identify the utility and advantages of the SPXT in assessing cardiorespiratory fitness in runners.

Chapter 2: Literature Review

2.1. $\dot{V}O_{2max}$ and the factors that limit it

$\dot{V}O_2$ is the total amount of oxygen consumed per minute whereas $\dot{V}O_{2max}$ is defined as the highest rate at which oxygen can be taken up and utilised by the body during severe exercise (Bassett & Howley, 2000). $\dot{V}O_2$ can be expressed as an absolute value, as $L \cdot min^{-1}$, or, more commonly in endurance performance, normalised to body weight and expressed as $mL \cdot kg^{-1} \cdot min^{-1}$.

$\dot{V}O_2$ is measured via the Fick equation where $\dot{V}O_2$ = oxygen consumption; SV = stroke volume; HR = heart rate; CaO_2 = arterial oxygen content; CvO_2 = mixed venous oxygen content:

$$\dot{V}O_2 = (SV \text{ x } HR) \text{ x } (CaO_2 - CvO_2)$$

During maximal exercise the Fick equation can be displayed as such:

$$\dot{V}O_{2max} = (SV_{max} \text{ x } HR_{max)} \text{ x } (CaO_{2max} - CvO_{2max})$$

An individual's aerobic capacity is defined by the ability of the body to transport and use oxygen. An individual's aerobic capacity was first investigated by celebrated physiologist A.V. Hill et al (Hill et al. 1924; Hill et al. 1924a). They tested it by running around a track and measuring $\dot{V}O_2$. They speculated $\dot{V}O_2$ reached a point where no bodily effort could drive it higher, concluding there was an upper limit to oxygen consumption. Impressively, despite a lack of suitable equipment to make such measurements, Hill postulated that $\dot{V}O_{2max}$ was limited by the cardiovascular system's ability to supply O_2. Despite the great advancement in technology and techniques since the work of Hill et al, their findings still ring true today (Bassett & Howley, 2000). During incremental exercise, $\dot{V}_E$ and $\dot{Q}$ will increase ensuring there is greater O_2 delivery, so that blood is redistributed to muscles that

have a greater necessity for O_2. As such $\dot{V}O_{2max}$ and $\dot{Q}$ are higher in running exercise in comparison to cycling where O_2 is primarily required by the muscles of the legs. This is due to running being 'whole body' exercise as a result of the dual role of both the arms and legs during exercise. As $\dot{Q}$ and O_2 delivery to the muscles increases, oxygen is extracted from the arterial blood which then widens the arteriovenous oxygen difference (a-vO_{2diff}) further. Due to the complex nature of oxygen delivery and utilisation, any step in the pathway of O_2 from the atmosphere to the mitochondria could represent a potential impediment to $\dot{V}O_2$ (Bassett & Howley, 2000). It is also worth stressing that limiting factors can vary based on the population and exercise type (Robergs, 2001; Levine, 2008) and so the following sections of this thesis will focus on healthy individuals during whole-body exercise. As such, whilst this discussion alone could warrant an entire thesis, the most widely accepted and best-evidenced limitations concern the cardiorespiratory system's ability to maximally deliver oxygen to the working muscles (Bassett & Howley, 2000; Bergh et al., 2000; Mortensen et al., 2005; Brink-Elfegoun et al., 2007; Hawkins et al., 2007; Ferretti, 2014; Montero et al., 2015; Lundby et al., 2017).

As expressed by the Fick equation, $\dot{V}O_{2max}$ is governed by $\dot{Q}_{max}$, which is the product of maximal heart rate (HR_{max}) and SV_{max}, and the a-vO_{2diff}. However, $\dot{Q}$ is widely considered the primary limiting factor for $\dot{V}O_2$ in whole body exercise (Bergh et al., 2000; Bassett & Howley, 2000; Saltin, 2005; Astorino et al., 2015; Astorino et al., 2017; Lundby et al., 2017). During maximal incremental exercise in which hemodynamic responses were monitored using direct invasive techniques (Mortensen et al., 2005), $\dot{Q}$ increased linearly to 80 % of peak PO (PO_{peak}) and then plateaued due to a fall in SV, whereas HR continued to increase. Limb blood flow also increased until 80 % and then plateaued. Conversely, systemic a-vO_{2diff} and O_2 extraction increased until exhaustion, suggesting O_2 delivery, not

extraction, was the limiting factor (Mortensen et al., 2005). When participants had completed a GXT to assess $\dot{V}O_{2max}$, followed by blood donation, and then another GXT (48-72 hours (h) separating each visit) $\dot{V}O_{2max}$ significantly declined in the post-blood donation visit, suggesting that blood flow and O_2 delivery were the primary limiting factors (Gordon et al., 2014). $\dot{Q}_{max}$ and SV_{max} have been shown to increase with endurance training (~9 and 8 %, respectively), with a concurrent improvement in $\dot{V}O_{2max}$ (10 %) whilst a-vO_{2diff} did not improve (Astorino et al., 2017). Similar findings were reported by Ekblom (1968), further supporting this notion. In a meta-anaylsis investigating the effect of endurance training (ranging from $5 - 13$ weeks (wk)) on 130 untrained and moderately trained participants, $\dot{V}O_{2max}$ had a standardised mean difference (SMD) after training of 0.75. $\dot{Q}_{max}$ also improved (SMD = 0.64) whereas a-vO_{2diff} did not (SMD = 0.21) (Montero et al., 2015), further suggesting O_2 delivery has greater implications than O_2 extraction. As will be discussed later (see section 2.5.4), several studies have investigated hemodynamic responses during SPXT testing, however, these are typically performed with non-invasive methods, due to the difficulty of including invasive catheter techniques. As such, these methods should be considered estimative, as opposed to direct measurements.

2.2. Considerations for testing $\dot{V}O_{2max}$

2.2.1. Step and RAMP protocols

The early tests for measuring $\dot{V}O_2$ were discontinuous and intermittent in nature (Taylor et al., 1955). Continuous protocols became more prevalent in the 1960s, largely as a result of the increasingly widespread use of online gas analysers - these protocols became the crux for the GXT as we know them today. An important feature of the GXT, which separates

this collection of protocols from the discontinuous protocols that preceded them, is the $\dot{V}O_2$-WR slope. This refers to the relationship between the increase in intensity and the increase in $\dot{V}O_2$ during the exercise test.

The treadmill protocols that first used continuous incremental designs are: Balke; Bruce; Eleestad; and modified Astrand. All the tests are open-ended and combine different stage lengths and intensity alteration (velocity or gradient) with the participant continuing until they are unable to physically continue, or likewise they terminate the test due to fatigue [thereon defined as volitional exhaustion]. These protocols are considered a 'STEP' variation, as the work-rate increases periodically every stage, creating an incremental step effect. In a comparative study, Pollock et al (1976) investigated the aforementioned four protocols' ability to produce valid $\dot{V}O_{2max}$ using fifty-one healthy males (ranging from 35-55 years old). In all four protocols: Balke, Bruce, Ellestad and Astrand; $\dot{V}O_{2max}$ was not significantly different (39.4, 40.0, 40.7, and 41.8 mL·kg^{-1}·min^{-1}, respectively). Importantly, they highlight that the protocol itself, when similar intensities and models are used, is not necessarily the main contributing factor in $\dot{V}O_{2max}$ differences.

RAMP protocols have been suggested as an attractive alternative to step-protocols due to these protocols increasing work-rate in a more continuous fashion compared to STEP protocols. It has been proposed that the linear model of the RAMP may improve an individual's ability to reach a greater peak $\dot{V}O_2$ ($\dot{V}O_{2peak}$) (Whipp et al., 1981; Davis et al., 1982; Beltz et al., 2016). Buchfuhrer et al (1983) compared RAMP cycling protocols of different work rates (15 W·min^{-1}, 30 W·min^{-1}, and 60 W·min^{-1}) with five male volunteers and reported that 30 W·min^{-1} produced significantly the highest $\dot{V}O_2$ values ($P < 0.05$) compared to the 15 W·min^{-1} and 60 W·min^{-1} (3.77 ± 0.43 vs. 3.62 ± 0.40 vs. 3.35 vs. 0.38

L·min^{-1}, respectively). Although widely regarded as a seminal study, the small sample size (and thus low statistical power) renders the findings questionable on a larger scale (Yoon et al., 2007). In another comparative study, Zhang et al (1991) had eight sedentary males complete three cycling step protocols (stage durations of 1, 2, and 3 min) and a cycling RAMP. Intensities for each protocol were individualised to bring about exhaustion in approximately 12 min. $\dot{V}O_{2max}$ for the step protocols of 1, 2 and 3 min (3.35 ± 0.98 vs. $3.23 \pm .99$ vs. 3.22 ± 1.07 L·min^{-1}, respectively) did not significantly differ from that of the RAMP (3.25 ± 1.04 L·min^{-1}). This suggests that as long as stage duration and intensity are appropriately selected, $\dot{V}O_{2max}$ is likely to be similar between a STEP and RAMP protocol. Whilst both RAMP and step protocols continue to be used, preferences for protocol and stage duration vary widely with multiple methods reported to be valid. RAMP protocols may be preferable in situations where the highest possible $\dot{V}O_{2peak}$ is the primary goal, however due to the small increases in work-rate utilised in the RAMP, identifying the $\dot{V}O_2$ plateau is not feasible when analysing the differences in $\dot{V}O_2$ between stages, which is a clear disadvantage of the protocol. Alternatively, treadmill protocols are generally more suited to the STEP design as many treadmills do not have ramp function capabilities. As such, for the rest of the thesis step-dependent protocols will be referred to as GXT and ramp-orientated protocols referred to as RAMP.

2.2.2. Test duration

It is a common conception that exercise tests which aim to elicit $\dot{V}O_{2max}$ should have a time to exhaustion (TTE) of 8 - 12 min (Midgley et al., 2008). This notion largely comes from the findings of Buchfuhrer et al (1983). In that study, participants completed three RAMP cycling protocols and five treadmill protocols. These all had completion times of 5 - 26 min. In the shortest treadmill and cycling protocols (7 and 6 min, respectively) $\dot{V}O_{2max}$ was

significantly lower than those recorded in trials lasting between 8 − 17 min, and this was attributed to the test duration. While novel at the time of publication, the study is not without its limitations. First of all, as stated earlier, the small sample size (n = 5) means the results have a low statistical power. Secondly, only the shortest tests (6 and 7 min) showed a significant reduction in $\dot{V}O_{2max}$, with protocols longer than 17 min not being significantly different compared with those in the 'optimal' window of 8-17 min. More recent research has recommended a test duration of 8-10 min (Yoon et al., 2007). In that study, sixteen male and female University and club-level cyclists and triathletes completed four cycling RAMP protocols with estimated durations of 5, 8, 12, and 16 min. They found that for men, $\dot{V}O_{2max}$ was significantly higher in 8 min compared with all other durations ($P = .02$ for the 5 min; $P < 0.01$ for 12 and 16 min protocols). Of the eight male participants, seven achieved their highest $\dot{V}O_{2max}$ during the 8 min and one achieved it during the 12 min duration. There were no differences between protocols for women. This is further supported by Astorino et al (2004) who reported that participants achieved significantly lower $\dot{V}O_{2max}$ in a protocol lasting ~14 min compared with protocols of ~7 and 10 min durations (3.45 ± 0.79 vs. 3.56 ± 0.83 vs. 3.58 ± 0.83 L·min^{-1}, respectively). Shorter protocols of ~5 min might underestimate $\dot{V}O_{2max}$ due to the steeper $\dot{V}O_2$-WR slope creating a greater reliance on anaerobic energy systems (Beltz et al., 2016), which may be especially problematic in participants with lower fitness levels. Alternatively, as highlighted by Midgley et al (2008), longer protocols that underestimate $\dot{V}O_{2max}$ usually include excessive gradients ($\geq$ 15 %) and so it may be the poorly tolerated incline and related fatigue that results in the underestimated $\dot{V}O_{2max}$ as opposed to the actual protocol duration. Furthermore, Buchfuhrer et al (1983) stated that longer protocols have not been shown to offer any additional data of informative value compared with tests of durations of 8 − 12 min. Whilst Midgley et al (2008) made a recommendation to journal editors and

reviewers that they not judge manuscripts based on whether $\dot{V}O_{2max}$ protocols lasted between ~8-12 min, protocol duration is still being highlighted as a limitation ten years on. Based on the available evidence, as protocols as short as ~7 min have been shown to be valid, and longer protocols offer no additional valuable information, aiming for ~10 min protocols, as long as this is consistent throughout all protocols used, is most sensible, unless further research suggesting otherwise is presented.

2.2.3. Importance of the $\dot{V}O_{2max}$ plateau

The primary criterion for achieving a 'true' $\dot{V}O_{2max}$ is a small or no increase in $\dot{V}O_2$ despite an increase in work-rate. Taylor et al (1955) first reported the use of a plateau and defined it as an increase in $\dot{V}O_2$ of less than 150 mL·min^{-1} in response to an increase in treadmill gradient of 2.5 % at 7 mp·h^{-1}. This criteria was determined by halving the mean increase in $\dot{V}O_2$ per stage increment for all participants. A wide range of values have since been used to determine whether the plateau criteria have been satisfied, with a large majority of researchers failing to even report their plateau criteria (Robergs et al., 2010). Typically, various arbitrary (Midgley et al., 2007a) values ranging from the following have been used: <50, 100, 150, 200, 280 mL·min^{-1} (Taylor et al., 1955; Astorino et al., 2000; Kang et al., 2001; Astorino et al., 2005; Midgley et al., 2007a). Depending on the criteria used during a GXT, incidences of the plateau identification can vary widely between 8-100 % for adults (Astorino et al., 2000; Gordon et al., 2012; Beltrami et al., 2013). Midgley and Carroll (2009) highlighted that an arbitrary plateau threshold of 280 mL·min^{-1} would have been greater than the $\dot{V}O_2$-WR slope for 10 subjects [in their own study], meaning that plateau criteria would be satisfied for those participants regardless of whether a plateau had been legitimately achieved. In contrast, they highlight that a plateau threshold of 100 mL·min^{-1}, in the case of six out of twenty [of their participants], would have accounted for

nearly 33 % of the $\dot{V}O_2$-WR slope, rendering a plateau difficult to achieve. Consequently, such criteria should not be universally applied unless it is specific to the data set and expected rate of $\dot{V}O_2$ increase per unit of time in relation to the specific protocol design (Beltz et al., 2016). Furthermore, numerous factors that may affect the ability of the individual to obtain a plateau in $\dot{V}O_2$ have been identified: age; testing modality; data analysis methodology; non-contingent feedback; familiarisation; and female contraception (Robergs, 2001; Astorino, 2009; Gordon et al., 2012; Gordon et al., 2017; Gordon et al., 2017a; Beltz et al., 2016). However, the incidence of a plateau being verified may primarily be a methodological rather than a physiological issue (Astorino et al., 2005).

Interval sampling of $\dot{V}O_2$ data may be the main methodological limiter in achieving a $\dot{V}O_2$ plateau. In a substantial investigation with a cohort of 106 [recreationally active to competitive runners and triathletes] participants, plateau incidence was highest when using 15 seconds (s) sampling (91 % of participants), followed by 30 s (89 %), breath-by-breath (81 %) and finally 60 s intervals (59 %) (Astorino 2009). Smaller sampling intervals may increase the probability of a plateau being achieved due to allowing for better examination of small change (Astorino, 2009) increases in $\dot{V}O_2$ standard deviation (Myers et al., 1990) however an increase in data noise (Howley et al., 1995) may mean that a plateau has been detected due to calculation artefacts as opposed to physiological events (Beltrami et al., 2013). Whilst 15 s sampling may slightly increase the chance of a plateau being detected compared to 30 s interval sampling, 30 s sampling is still the most widely used (Robergs et al., 2010) and most commonly used for additional measurements such as the identification of the VT (Kuipers et al., 2003; Bergstrom et al., 2013; Gordon et al., 2017; Truong et al., 2017; Wang et al., 2017). For these reasons, either 15 or 30 s interval sampling should be used but 30 s may be preferable if the data is going to be used for VT measurement also.

Failure to register a plateau does not mean a true $\dot{V}O_{2max}$ has not been achieved or that it does not exist (Wagner, 2000; Day et al., 2003). Some participants may not be capable of achieving a plateau in $\dot{V}O_2$ despite a maximal effort being given, regardless of whether they are motivated or not (Midgley & Carroll, 2009) - perhaps due to the stress caused by the workload (such as too steep a work-rate increment being used, as discussed in section 2.2.2). Interestingly, Rossiter et al (2006) highlighted that based on the work of Taylor et al (1955), there was no implicit requirement of a plateau during a single bout of exercise, but that $\dot{V}O_2$ from a subsequent bout not be significantly higher. Whilst the detection of a plateau in the primary exercise bout is always preferable, and practitioners should attempt to select the best methodology to increase the probably of a valid plateau being detected [as discussed in 2.2.1], this is not always possible. As such, this would support the use of a secondary test or additional criteria to verify that a maximal effort, and thus a 'true' $\dot{V}O_{2max}$ has likely been achieved in the absence of a $\dot{V}O_2$ plateau being observed.

2.2.4. Secondary criteria

In instances where a plateau has not been achieved, a set of secondary criteria may be included to support whether a maximal effort has been given and a 'true' $\dot{V}O_{2max}$ attained. The use of such secondary criteria is currently recommended by ACSM (Riebe et al. 2018). A combination of maximal values for RER, HR, post-test lactate concentration, and RPE are used as evidence of a maximal effort having been given. Values used for secondary criteria can vary greatly, however the following have been widely adopted: RER (≥ 1.1); HR (within 10 bpm of age-predicted HR_{max}); RPE (≥ 17) (Edvardsen et al., 2014; Beltz et al., 2016; Riebe et al., 2018). Although secondary criteria are regularly used to support the attainment of $\dot{V}O_{2max}$, the validity of such criteria is widely debated. This is predominately due to large between-subject variation for the criteria being used (Midgley

et al., 2007a; Edvardsen et al., 2014; Beltz et al., 2016; Poole & Jones, 2017) which may then provide false confidence in attaining $\dot{V}O_{2max}$ or even incorrectly excluding participants who may otherwise have achieved a valid $\dot{V}O_{2max}$ or given a maximal effort (Poole et al., 2008). Despite the criticism of secondary criteria, they continue to be regularly reported, perhaps due to a lack of consensus on the alternatives. However, the increasing popularity of verification testing may result in a decrease in their use.

2.2.5. Verification stage to confirm $\dot{V}O_{2max}$

Due to the varying recommendations for $\dot{V}O_{2max}$ attainment criteria, it has become increasingly recommended to utilise a verification stage (Day et al., 2003; Midgley et al., 2006; Rossiter et al., 2006; Hawkins et al., 2007; Poole et al., 2008; Midgley & Carroll, 2009; Weatherwax et al., 2016; Astorino & DeRevere, 2017; Schaun, 2017). This usually takes the form of a 'square-wave' bout of exercise that follows the initial incremental test. The aim of a verification stage is to not simply achieve a similar $\dot{V}O_2$ to that attained in the preceding incremental test, but to create a platform which enables a higher $\dot{V}O_2$ to be reached if possible (Schaun, 2017). Intensities in the range of 5-10 % higher, or one stage higher than that achieved in the incremental are most common (Midgley et al., 2006; Poole et al., 2008; Mann et al., 2013; Sedgeman et al., 2013; Astorino et al., 2015; Astorino et al., 2017; Beltz et al., 2016; Murias et al., 2018). The required rest between the GXT and verification stage is considered less critical (Poole & Jones, 2017) and 10-20 min have been used effectively (Midgley et al., 2006; Mauger et al., 2013a; Lim et al., 2016; Weatherwax et al., 2016; Astorino & DeRevere, 2017). Nolan et al (2014) suggested that an intensity of 105 % of the maximal GXT workload and 20 min rest period may be the most optimal. They observed that a verification trial at 105 % confirmed a true $\dot{V}O_{2max}$ for all participants regardless of the recovery period allocated between the GXT and

verification trial, whilst a verification intensity of 115 % only confirmed $\dot{V}O_2$ in seven or eight participants [out of twelve] depending on recovery period used. It is possible that in the 115 % trials, the intensity limited the participants' ability to produce a maximal performance for a period long enough for $\dot{V}O_2$ kinetics to respond accordingly (Poole & Jones, 2017). Having the participants complete the incremental test and verification on the same day also has practical implications and may be more pragmatic for athletes and coaches compared to multiple lab visits.

Along with considering the intensity and recovery period of the verification stage, criteria for deciding whether the verification stage confirms that a 'true' $\dot{V}O_{2max}$ has been achieved is required. The most common method is that the verification stage $\dot{V}O_2$ must be no higher than 2-3 % than the incremental test, considering the measurement error of the equipment (Dalleck et al., 2012; Weatherwax et al., 2016; Astorino & DeRevere, 2017; Beltz et al., 2018). Fixed criteria such as < 50 mL^{-1}·min^{-1} have also been used (Scheadler & Devor, 2015) however it is considered important that verification criteria are more individualised (Schaun, 2017). It has been suggested that the verification stage may not be a valid method of confirming $\dot{V}O_{2max}$ from an incremental test (Mauger et al., 2013). This is largely based on the findings of (Hawkins et al., 2007) who reported that the verification stage confirmed $\dot{V}O_{2max}$ in all 156 tests conducted. However, Hawkins et al (2007) did not state what their criteria for $\dot{V}O_{2max}$ confirmation in the verification stage was. As with the GXT and plateau attainment, the criteria and methodology chosen is important. When using the criteria of ≤ 3 % ($\dot{V}O_{2max}$ from the GXT being less than the verification) $\dot{V}O_{2max}$ confirmation has varied from $87 - 100$ % (Dalleck et al., 2012; Weatherwax et al., 2016; Beltz et al., 2018) whilst out of 109 participants, Astorino and DeRevere (2017) reported that 11 % did not have $\dot{V}O_{2max}$ verified by the verification stage. Recently, Murias et al (2018) suggested that the

verification stage may not be necessary. They based this on their findings that there were no differences between a GXT and a verification, and that this meant that the verification stage does not prove an underestimation of $\dot{V}O_{2max}$ derived from the GXT. However, finding no differences between the protocols does not make the verification stage redundant, as they themselves concede that such findings could either suggest that the verification stage 'confirms' that a true $\dot{V}O_{2max}$ was achieved, or alternatively that the verification simply confirms the adequacy of the GXT. Either way, it is arguable that this still provides useful information, and the fact that past research has found that the verification can be significantly higher in some participants (Astorino & DeRevere, 2017) provides evidence that the verification stage is still beneficial. The current consensus is that the verification stage is still a useful component to verify $\dot{V}O_{2max}$ (Poole & Jones, 2017; Schaun, 2017) however the intensity [and thus the likely duration] and the criteria must be carefully selected, with the recovery [between the incremental and verification] less essential.

2.3. Additional parameters that can be obtained via the GXT

2.3.1. Velocity at $\dot{V}O_{2max}$ and maximal velocity

It is reasoned that to improve $\dot{V}O_{2max}$ it is important to train at velocities that would elicit it (Laursen & Jenkins, 2002). $_v\dot{V}O_{2max}$ is traditionally measured as the lowest speed which elicits $\dot{V}O_{2max}$ during an incremental test (Billat & Koralsztein, 1996; Billat et al., 2000; Laursen & Jenkins, 2002; Hanon et al., 2008; Esfarjani & Laursen, 2007; Manoel et al., 2017) and has been reported to have good repeatability across two repeated tests (intraclass correlation coefficient (ICC) = .93) (Merry et al., 2016). $_v\dot{V}O_{2max}$ has commonly been used

to prescribe interval training (Esfarjani & Laursen, 2007; Manoel et al., 2017; Denadai et al., 2006; Silva et al., 2017) (see section 2.6).

The terms $_v\dot{V}O_{2max}$ and V_{max} are often used interchangeably; however the difference between the two is small but significant. V_{max} is the maximal velocity [or peak, termed V_{peak}] achieved in a treadmill test (Jones & Carter, 2000), and so is not directly associated with $\dot{V}O_{2max}$. V_{max} is often calculated as the highest speed which is maintained for $30 - 60$ s at the end of the test (Noakes et al., 1990; Slattery et al., 2006; Stratton et al., 2009; McLaughlin et al., 2010; Smith et al., 2003). Numerous studies have found V_{max} to be highly correlated with running performance in distances ranging from 3-16 km (r = 0.83-0.97) (Noakes et al., 1990; Slattery et al., 2006; Stratton et al., 2009; McLaughlin et al., 2010; Machado et al., 2013). Both $_v\dot{V}O_{2max}$ and V_{max} have been shown to produce similar outcomes when used as part of high intensity interval training (HIIT) (Manoel et al., 2017) (see section 2.6) however, V_{max} may be more practical to coaches and athletes compared to $_v\dot{V}O_{2max}$ due to the relative ease in which it is obtained, as V_{max} does not require a measurement of $\dot{V}O_{2max}$ to calculate it.

2.3.2. Ventilatory thresholds

There are typically two ventilatory breakpoints that are passed during incremental exercise. During exercise the first threshold is typically identified via a first breakpoint in gas exchange or ventilation. The second threshold is typically identified as the point when a second breakpoint in gas exchange or ventilation occurs. There has been a series of contrasting and often conflicting terminology and definitions for exercise thresholds, which has caused considerable confusion in the field (Bosquet et al., 2002; Binder et al., 2008; Faude et al., 2009; Beneke et al., 2011; Hopker et al., 2011; Hall et al., 2016). To

avoid further confusion the VT will be referred to as the first ventilatory threshold (VT1) and the second ventilatory threshold (VT2), and these will be defined as the first and second break points in gas exchange or ventilation, respectively.

VT1 is characterised as the work-rate or $\dot{V}O_2$ just below the point in which anaerobic metabolism becomes a significant contributor to the increasing work rate and associated changes in gas exchange occur (Hopker et al., 2011) and typically occurs at 60-75 % $\dot{V}O_{2max}$ (Zhang et al., 1991; McClave et al., 2011; Bergstrom et al., 2013; Seiler & Sjursen, 2002; Nicolò et al., 2014; Rabadán et al., 2011; Esteve-Lanao et al., 2007; Cannon et al., 2009; Peinado et al., 2016). VT2 is characterised by a considerable increase in blood lactate accumulation and ventilation (Hopker et al., 2011; Morán-navarro et al., 2016) and is typically observed at 81-88 % $\dot{V}O_{2max}$ (Gordon et al., 2017; Seiler & Sjursen, 2002; Nicolò et al., 2014; Mermier, 2013; Rabadán et al., 2011; Esteve-Lanao et al., 2007; Black et al., 2014). VT1 is most commonly calculated using either the V-Slope or ventilatory equivalents (VEQ) methods. In V-Slope, VT1 represents the first break-point in the $\dot{V}O_2$ vs. $\dot{V}CO_2$ relationship (Beaver et al., 1986). In VEQ, VT1 occurs when there is a rise in $\dot{V}_E/\dot{V}O_2$ without a concurrent rise in $\dot{V}_E/\dot{V}CO_2$ (Beaver et al., 1986). A third method can be used which uses the first increase in $P_{ET}O_2$ with no concurrent fall in $P_{ET}CO_2$ (Beaver et al., 1986). As VT can be difficult to determine (Gaskill et al., 2001), authors sometimes utilise multiple methods to confirm where the threshold occurs. They use a primary method, typically either V-Slope or VEQ and then confirm the result using the remaining method and $P_{ET}O_2$ vs. $P_{ET}CO_2$ (Bergstrom et al., 2013; Gaskill et al., 2001; Nicolò et al., 2014; Jenkins et al., 2017a). VT2 can be identified using the following: the break-point in $\dot{V}_E$ vs. $\dot{V}CO_2$ relationship; first non-linear increase in $\dot{V}_E/\dot{V}CO_2$ with a continued rise in $\dot{V}_E/\dot{V}O_2$; and a fall in $P_{ET}CO_2$ (Beaver et al., 1986; Nicolò et al., 2014; Mermier, 2013;

Spurway et al., 2012; Rabadán et al., 2011; Esteve-Lanao et al., 2007; Bertuzzi et al., 2014; Black et al., 2014).

VT is typically identified visually by experienced researchers/laboratory technicians. Whilst this does allow for human error and subjectivity (Rabadán et al., 2011), this can be countered by having VT confirmed by a minimum of two researchers or technicians, to ensure agreement is found and to limit individual bias (Gaskill et al., 2001; Esteve-Lanao et al., 2007; Rabadán et al., 2011; Mermier, 2013; Black et al., 2014; Maturana et al., 2017; Peinado et al., 2016; Jenkins et al., 2017a; McNulty & Robergs, 2017; Truong et al., 2017). Automated calculations of VT built into online gas analysers can be used (Plato et al., 2008; Kang et al., 2001; Kuipers et al., 2003) however even these will sometimes require human correction as the software may not be able to account for individual differences or discrepancies in the test.

VT can be beneficial in prescribing exercise intensities and training zones for athletes (Esteve-Lanao et al., 2007; Seiler, 2010; Mora et al., 2016). The advantage of VT assessment over LT assessment is that VT can be detected via a GXT or RAMP (Kang et al., 2001; Plato et al., 2008; Mcnulty & Robergs, 2017; Jenkins et al., 2017a) without the need for additional lactate analysis equipment (Black et al., 2014). This is because VT is detected via ventilatory and gas exchange data that is synonymously collected when testing for $\dot{V}O_{2max}$ via online gas analysis. This potentially makes its desirable over LT, although how related LT and VT are, is debated (Hopker et al., 2011). As previously mentioned, VT is typically measured via a GXT or RAMP due to the linear increase in PO or velocity. However, a few studies have recently investigated the determination of VT within the SPXT. Truong et al (2017) reported a VT1 of 75 and 76 % in the GXT and SPXT

[respectively] amongst highly trained middle-distance runners. However, they utilised a modified SPXT that used 1 min stages (discussed more in section 2.5). Due to the very small increments in RPE, participants likely found it difficult to differentiate between RPE levels for each stage and so the RPE associated with VT1 may not be accurate. They also failed to identify VT2 in 8 out of 11 GXT tests which may suggest the 1 min stages made it difficult to get a valid ventilatory response. Similar findings were reported by Beltz et al (2018) with VT1 reported as 78 and 79 % in the SPXT and GXT [respectively] however unfortunately they did not measure VT2. Also, considering the relatively low fitness levels of the participants ($\dot{V}O_{2max}$ = ~47 mL·kg^{-1}·min^{-1}) ~78 % could be considered quite high compared to previous research. Whilst these are interesting findings, VT has yet to be investigated in a study that utilised both a well-trained population and an unmodified SPXT (2 min stages).

2.4. Rating of perceived exertion in exercise testing

Perceived exertion [or perception of effort] is the feeling of how heavy, strenuous and laborious exercise is, and plays a crucial role in endurance performance (Pageaux, 2016). This is predominately due to its strong relationship with exercise intensity (e.g. work, speed, power) (Eston, 2012; Eston & Thompson, 1997) and physiological factors such as HR, ventilation, blood lactate, and $\dot{V}O_{2max}$ (Hetzler et al., 1991; Eston & Williams, 1998; Pfeiffer et al., 2002; Eston et al., 2005; Green et al., 2006; Davies et al., 2007; Faulkner & Eston, 2007; Lambrick et al., 2009; Eston, 2012; Scherr et al., 2013; Dantas et al., 2015; Madrid et al., 2016; Nicolò et al., 2016). RPE is typically utilised in the form of a verbally anchored scale of which the most popular (Eston, 2012) is the Borg RPE 6-20 (Borg, 1982;

Borg, 1990). It is constructed as a 15-point scale from 6-20 where 6 represents 'no exertion at all' and 20 represents 'maximal exertion'. RPE 7 and 8 are considered extremely light, RPE 9 'very light', RPE 11 'light', RPE 12 'somewhat hard', RPE 15 'hard', RPE 17 'very hard' before the final aforementioned maximal effort of RPE 20. Participants are able to select numbers in between, and even decimal places if deemed necessary (Pageaux, 2016).

RPE is most commonly used as a dependent variable during a GXT where participants give a subjective estimation of their effort (estimation trial) (Eston & Thompson, 1997). Participants can then regulate subsequent exercise with RPE anchored to an intensity such as $\dot{V}O_{2max}$, HR, or blood lactate (Ceci & Hassmen, 1991; Faulkner et al., 2007; Kang et al., 2009). The latter is known as 'estimation-production'. Production procedures have been well utilised in the form of a perceptually regulated exercise test (PRET) (Eston et al., 2005; Eston et al., 2006; Faulkner et al., 2007; Eston et al., 2008; Eston et al., 2012; Smith et al., 2015). The exact methodologies of each PRET differ, however they generally consist of 4-5 stages (each being 2-4 min in length) in which work-rate is regulated by RPE values ranging between 9, 11, 13, 15, and 17. Eston et al (2005) reported that the predicted $\dot{V}O_{2max}$ from the PRET was not significantly different to that of a GXT (48.6 vs. 48.8 ± 7.1 mL·kg^{-1}·min^{-1}, respectively) with similar findings since reported (Eston et al., 2006; Faulkner et al., 2007; Eston et al., 2008; Eston et al., 2012; Smith et al., 2015). These studies however, did not use plateau criteria to verify $\dot{V}O_{2max}$ in the GXT, to ensure a true $\dot{V}O_{2max}$ was attained, which is important when the PRET is being validated against the GXT.

Whilst these findings are of interest, the PRET protocol is somewhat cumbersome, as at each RPE stage, the participant is required to regulate their RPE at the given intensity for

2-3 min, after which the intensity is clamped for a further 2-4 min. This raises two key issues: 1) if the PRET contains 5 stages, the participant could be exercising for up to 35 min, compared to ~15 min in a GXT containing 3 min stages (Eston et al., 2005); 2) by only allowing participants to regulate their intensity for the initial part of each stage, the test ceases to be continuously RPE-regulated, and simply becomes intensity-fixed. A potential argument for the use of a PRET is it may be safer to predict $\dot{V}O_{2max}$ via a submaximal protocol in clinical populations [although this has been disputed] (Noonan & Dean, 2000; Balady et al., 2010; Smith et al., 2015; Jenkins et al., 2017; Jenkins et al., 2017b; Selig et al., 2017). Regardless of this, as healthy participants have been used (Eston et al., 2005; Eston et al., 2006; Faulkner et al., 2007; Eston et al., 2012) it highlights whether it is worth using predictive $\dot{V}O_{2max}$ protocols at all, when it is just as practical [and actively quicker] to directly measure $\dot{V}O_{2max}$ via a GXT. The PRET does highlight, however, that RPE can be used effectively in production trials which may have an implication for RPE based training.

2.5. Self-paced exercise tests

2.5.1. RPE clamped self-paced exercise tests

The GXT has been notably criticised by Noakes (2008) for components which he describes as "being foreign" to all forms of freely chosen exercise. As no sports are performed in this fashion, it can be argued that the GXT does not represent the challenges of real sport and exercise. The SPXT was originally designed by Mauger and Sculthorpe (2012) as a novel method to assess $\dot{V}O_{2max}$ in cycling. Participants completed both a GXT and an SPXT protocol using a Computrainer cycle ergometer (RacerMate, Seattle, USA). The SPXT was

made up of 5 x 2 min stages, meaning it had a closed loop design and end-time of 10 min. Intensity was clamped via RPE values of 11, 13, 15, 17 and crucially a maximal effort at RPE 20, meaning that the first 2 min stage was completed at RPE 11, and then the next 2 min at RPE 13, and so on. Throughout the protocol PO could be freely regulated to match the required RPE of the given stage. In the GXT, the test commenced at a PO of 60 W and increased by 30 W every 2 min until either the participant reached volitional exhaustion or the cadence dropped to below 60 revolutions per minute, terminating the test. The SPXT produced significantly higher $\dot{V}O_{2max}$ values than those attained in the GXT (see table 2.1), which consequently represented an 8 % difference. This was despite a plateau being found in the majority of the tests, although no actual number is given by Mauger and Sculthorpe (2012) on what a 'majority' represents.

Table 2.1 Summary of thirteen studies that have used cycling or running RPE clamped exercise test protocols for the determination of $\dot{V}O_{2max}$. The studies are organised in descending order of publication date. $\dot{V}O_{2max}$ data is displayed as mean ± standard deviation (SD).

Study	Participants	Mode	Protocol	$\dot{V}O_{2max}$
Beltz et al. (2018)	Sixteen recreationally active males	Treadmill	2 x SPXT. RPE clamped, 5 x 2 min. 3 % gradient	47 ± 3 mL·kg⁻¹·min⁻¹
			RAMP. Speed increased by 0.16 km·h⁻¹ every 15 s. 3 % gradient	47 ± 3 mL·kg⁻¹·min⁻¹
Truong et al. (2017)	Eleven well trained male female athletes	Treadmill	Modified SPXT. RPE clamped, 10 x 1 min. 0 % gradient	70 ± 6 mL·kg⁻¹·min⁻¹
			GXT. Speed increased by 1 km·h⁻¹ every 1 min. 0 % gradient	68 ± 5 mL·kg⁻¹·min⁻¹
Jenkins et al. (2017a)	Twenty-two healthy male and female 18-30 year olds	Cycle ergometer	SPXT. RPE clamped, 5 x 2 min	50 ± 10 mL·kg⁻¹·min⁻¹*
			RAMP. 3 min baseline cycling at 20-100 W then 15-20 W min⁻¹	48 ± 10 mL·kg⁻¹·min⁻¹
Hanson et al. (2017)	Fourteen recreationally active males and females	Treadmill	SPXT 1. RPE clamped, 5 x 2 min Aggressive' pacing strategy	59 ± 9 mL·kg⁻¹·min⁻¹
			SPXT 2. RPE clamped, 5 x 2 min Conservative pacing strategy	58 ± 8 mL·kg⁻¹·min⁻¹
Hanson et	Thirteen recreationally	Treadmill	Treadmill SPXT. RPE clamped, 5 x 2 min. 8 % gradient	56 ± 5 mL·kg⁻¹·min⁻¹

al. (2016)	active males and females	& Cycle ergometer	Standard Bruce protocol	56 ± 7 mL·kg^{-1}·min^{-1}
Lim et al. (2016)	Fifteen recreationally-trained men	Treadmill and 400 m athletics track	SPXT 1. RPE clamped, 5 x 2 min SPXT 2. RPE clamped, 5 x 2 min SPXT 3. RPE clamped, 5 x 2 min GXT. Speed increased 1 km·h^{-1} every 2 min	66 ± 9 mL·kg^{1}·min^{-1} 65 ± 7 mL·kg^{-1}·min^{-1} 67 ± 8 mL·kg^{-1}·min^{-1} 64 ± 10 mL·kg^{-1}·min^{-1}
Scheadler and Devor (2015)	Thirteen well trained male endurance runners	Treadmill	SPXT. RPE clamped, 5 x 2 min. 8 % gradient Modified Astrand protocol	63 ± 7 mL·kg^{-1}·min^{-1} 65 ± 8 mL·kg^{-1}·min^{-1}*
Faulkner et al. (2015)	Thirteen recreationally active males	Treadmill	SPXT. RPE clamped, 5 x 2 min GXT. Speed increased 1 km·h^{-1} every 2 min	64 ± 3 mL·kg^{1}·min^{-1} 61 ± 5 mL·kg^{1}·min^{-1}
Astorino et al. (2015)	Thirty recreationally active males and females	Cycle ergometer	SPXT. RPE clamped, 5 x 2 min stages RAMP 1. Start 50-80 W, increased 25-40 W min^{-1} RAMP 2. Start 50-80 W, increased 25-40 W min^{-1}	50 ± 10 mL·kg^{-1}·min^{-1} * 47 ± 10 mL·kg^{-1}·min^{-1} 46 ± 10 mL·kg^{-1}·min^{-1}
Straub et al. (2014)	Sixteen trained male and female cyclists	Cycle ergometer	SPXT. RPE clamped, 5 x 2 min stages RAMP. Start at 80 W, increased by 30 W min^{-1} for men and	3.87 ± 0.72 L·min^{-1} 3.86 ± 0.73 L·min^{-1}

			20 W min^{-1} for women. Repeated twice.	
Mauger et al. (2013a)	Fourteen trained male runners	Treadmill	SPXT. RPE clamped, 5 x 2 min	64 ± 8 mL·kg^{-1}·min^{-1}*
			GXT. Speed increased by 1 km·h^{-1} every 2 min	61 ± **7** mL·kg^{-1}·min^{-1}
Chidnok et al. (2013)	Seven recreationally active males	Cycle ergometer	Modified SPXT. RPE clamped, 7 stages (duration individualised)	4.33 ± 0.60 L·min^{-1}
				4.31 ± 0.62 L·min^{-1}
			RAMP 1. 3 min unloaded, 30 W min^{-1}	4.36 ± 0.59 L·min^{-1}
			RAMP 2. 3 min unloaded, 30 W min^{-1}	
Mauger and Sculthorpe (2012)	Sixteen untrained, healthy males and females	Cycle ergometer	SPXT. RPE clamped, 5 x 2 min	40 ± 10 mL·kg^{-1}·min^{-1}*
			GXT. Started at 60 W, 30 W increase every 2 min	37 ± 8 mL·kg^{-1}·min^{-1}

* Denotes significant difference between SPXT and GXT ($P < 0.05$)

The findings of Mauger and Sculthorpe (2012) were criticised by Chidnok et al (2013) who argued that the high $\dot{V}O_{2max}$ in the SPXT could be explained by the longer GXT test duration (10 ± 0 vs. 13 ± 3 min, respectively). In response to the findings of Mauger and Sculthorpe (2012), Chidnok et al (2013) investigated whether the SPXT resulted in differences in $\dot{V}O_{2max}$ compared to a GXT. In their methodology, the SPXT protocol differed significantly from the original protocol and consisted of 7 stages in which stage duration equated to the duration of the initial RAMP test divided by 7. For the 7 stages RPE was clamped at 8, 10, 12, 14, 16, 18, and 20. They found that $\dot{V}O_{2max}$ did not significantly differ between the two RAMP protocols and the SPXT. Although the authors should be commended on their method of matching the test durations between the two protocols it is interesting that they decided to alter the SPXT duration to match that of the GXT. They argue that the longer duration of the GXT may have 'stifled' participants' ability to achieve a true $\dot{V}O_{2max}$ in that protocol, resulting in the SPXT producing a significantly higher $\dot{V}O_{2max}$. Whilst this argument is potentially valid, their decision to then alter and lengthen the SPXT undermines this argument. This is further supported by the authors citing Eston (2012) who clearly state that to truly evaluate whether the $\dot{V}O_{2max}$ values observed by Mauger and Sculthorpe (2012) were legitimate, a direct comparison where test duration is matched would be required. The most logical solution would be to alter the GXT, as their main argument is that the longer duration of the GXT may lead to an invalid $\dot{V}O_{2max}$ and it is the specific protocol of the SPXT that they were testing the validity of. Ultimately, it is difficult to directly compare their findings to the SPXT as described by Mauger and Sculthorpe (2012) as these protocols differ significantly.

The SPXT has since been applied to treadmill running (Mauger et al., 2013a; Faulkner et al., 2015; Scheadler & Devor, 2015; Hanson et al., 2016; Truong et al., 2017; Beltz et al.,

2018). Mauger et al (2013) reported significantly higher $\dot{V}O_{2max}$ values in the SPXT compared to the GXT. Their methodology consisted of a motorised treadmill for the GXT and a non-motorised treadmill for the SPXT, with thirteen of the fourteen participants achieving a higher $\dot{V}O_{2max}$ in the SPXT and all but two participants achieving a plateau in the GXT. Running speed was noted to be significantly higher during all stages of the GXT compared to the SPXT, including significantly higher peak speeds (16.3 ± 2.1 vs. 9.6 ± 1.2 $km^{.}h^{-1}$, in the GXT and SPXT respectively). This is due to the use of two different types of treadmill - which has been criticised (Eston et al., 2014; Poole, 2014). The much lower speeds achieved in the SPXT were most likely as a result of higher belt friction experienced on the non-motorised treadmill (Hopker et al., 2009). Finally, the specific model of non-motorised treadmill (Force 3.0, Woodway USA Inc., Wisconsin, USA) used in the study is traditionally intended for sprinting, making it inappropriate for longer durations and resulting in slower speeds and different biomechanics. For these reasons comparison of the two different modalities is inappropriate. This is to date the only treadmill-based study to find $\dot{V}O_{2max}$ to be higher in the SPXT, with studies utilising a motorised treadmill finding no differences between protocols (Faulkner et al., 2015; Hanson et al., 2016; Beltz et al., 2018). However, conducting a self-paced protocol on a motorised treadmills can also be challenging due to the requirement of the participant to manually alter their own work-rate, typically achieved using the buttons on the treadmill (Faulkner et al., 2015; Beltz et al., 2018). To date, the general consensus is that the SPXT provides equal or higher $\dot{V}O_{2max}$ in comparison to the GXT, with the exception of one study in which $\dot{V}O_{2max}$ was reported to be lower in the SPXT (discussed in 2.5.4).

Lim et al (2016) has investigated the use of the SPXT in the field. The primary aim of this study was to assess the concurrent validity and repeatability of a field-SPXT compared to a

GXT [as described by Faulkner et al (2015)]. In their study, the field-based SPXT utilised the same protocol as described by Mauger and Sculthorpe (2012) however rather than laboratory based, the trials were completed on an outdoor synthetic 400 m athletics track with physiological data collected via a portable K4-b-TX Cosmed gas analyser (Cosmed K4-b-TX, Rome, Italy). Global positioning system (GPS) was used to track changes in speed. $\dot{V}O_{2max}$ in the GXT was 63.5 ± 10.1 mL·kg^{-1}·min^{-1} and for the three SPXT trials was 65.5 ± 8.7, 65.4 ± 7.0, and 66.7 ± 7.7 mL·kg^{-1}·min^{-1} with no consequent familiarisation effect observed between the three field-SPXT trials (ICC = 0.80; SEM = 3.16 mL·kg^{-1}·min^{-1}) and a mean difference of 1.8 mL·kg^{-1}·min^{-1} between the three field-SPXT trials. Whilst the reported ICC was not as high as previously reported for the 20 m multi-stage shuttle run test (ICC = 0.95) (Lamb & Rogers, 2007; Aandstad et al., 2011), the findings for the 20 m multi-stage shuttle run test referred to predicted $\dot{V}O_{2max}$, and not measured, as per the findings of Lim et al (2016). Also, the small mean difference (1.8 mL·kg^{-1}·min^{-1}) for measured $\dot{V}O_{2max}$ reported by Lim et al (2016) suggests the field-based SPXT is a reliable method for direct $\dot{V}O_{2max}$ measurement, which may make it more appropriate and attractive to athletes and coaches than the laboratory based GXT, which does not currently provide a similar field-based protocol.

2.5.2. Pacing strategies in the SPXT

Whilst previously it has been stated that the RPE 20 stage is an 'all-out' effort (Jenkins et al., 2017a), precise instruction is rarely given to participants [or simply not reported]. Of the twelve SPXT studies [see table 2.1], five simply stated that participants were asked to match each RPE, with no further detail given, whilst another did not report any instruction. Of the studies that did give more detailed descriptions, these tended to differ. For instance, Mauger et al (2013a) clearly instructed the participants to vary their speed to match the

RPE for each given moment, as opposed to pacing themselves according to the projected end point of the test, and thus the final stage was instructed to be performed as a maximal effort with no regard to pacing for the 2 min duration. Faulkner et al (2015), and Straub et al (2014), instructed participants to modify their intensity on a 'moment-to-moment basis' but give no specific mention to the final stage, whilst Astorino et al (2015) simply stated that the final stage 'must elicit volitional exhaustion'. Alternatively, Chidnok et al (2013) stated that participants were instructed to 'pace them-selves within each stage in accordance to the prescribed RPE' and that they should 'reach volitional exhaustion at the end of the test'. It is arguable that participants could interpret this instruction to suggest that effort should be reserved until the end of the final stage as to ensure they are exhausted then, but not necessarily before (which an all-out effort may instead achieve). This is potentially reflected in the mean PO_{peak} participants' achieved in the RAMP and SPXT (385 ± 47 vs. 364 ± 46 W, respectively) by Chidnok et al (2013). It is conceivable that this lower PO – potentially brought on by confusion regarding the requirements of the protocol – may have had an impact on the ability of the participants to produce true a $\dot{V}O_{2max}$.

Hanson et al (2017) sought to provide some clarity regarding the differing pacing strategies during the final stage (RPE20) of the SPXT. They compared two SPXT protocols which were identical other than the final stage of each SPXT having a different prescribed pacing strategy. The order of these two trials were randomised and participants were verbally instructed to utilise either a 'conservative' or 'aggressive' pacing strategy. For the conservative strategy participants were asked at the onset of the final stage (from 8 min) to progressively increase their speed until approximately 09:30, in which they would switch to an all-out effort. Unfortunately, the authors do not elaborate on how the participants would know approximately 30 s remained. In the all-out trial participants were asked to

run aggressively from the offset of the final stage with the expectation that their speed would inevitably slow. $\dot{V}O_{2max}$ was not significantly different between aggressive and conservative strategies. Average velocity for the final 2 min did not significantly differ between aggressive and conservative strategies (12.3 ± 2.4 vs. 12.1 ± 1.9 $km \cdot h^{-1}$, respectively). This importantly suggests that a specific pacing strategy during the final stage of the SPXT may not be essential to ensure a similar outcome between participants for $\dot{V}O_{2max}$. This is also important if athletes and coaches want to use the velocity at RPE20 in training prescription, as they can be confident that how the final stage is paced will not ultimately affect the mean velocity.

2.5.3. Reliability of the SPXT

Along with the validity of the SPXT, the reliability of the protocol has also been investigated (Lim et al., 2016; Jenkins et al., 2017) in both cycling and outdoor running. Investigating the test-retest reliability of twenty-five healthy participants across three cycling-SPXT protocols, Jenkins et al (2017) reported that the coefficient of variation for $\dot{V}O_{2peak}$ was 4.7 %, which is similar to previous research for GXT protocols (Froelicher et al., 1974; Mauger et al., 2013a; Lim et al., 2016). Recently Lim et al (2016) concluded that a field-based SPXT was a reliable measure of $\dot{V}O_2$, with three repeated SPXT trials resulting in strong ICCs (<0.80). This is important as it not only shows that the SPXT is comparable to the GXT for $\dot{V}O_{2max}$ measurement, but that it is repeatable and also not subject to issues with familiarisation.

2.5.4. Mechanistic differences during the SPXT

Mauger and Sculthorpe (2012) speculated that the higher $\dot{V}O_2$ values attained in the SPXT could be due to a lower recruitment of type II muscle fibres until the latter stages of the

test, which they argue is supported by the drastic 70 W increase in PO witnessed during the initial parts of the final stage of the SPXT followed by a significant drop. Conversely, Scheadler and Devor (2015) argued that, in their study, the lower $\dot{V}O_{2max}$ reported during the SPXT may have been as a result of an increased recruitment of muscle fibres in the final stage due to too great an increase in intensity between stages 4 and 5. In their study, the final stage of the SPXT produced supramaximal running at ~106 % $_v\dot{V}O_{2max}$. Their argument that this caused a greater anaerobic contribution and thus a lower $\dot{V}O_{2max}$ seems unlikely as verification stages typically involve intensities in this range (as discussed in section 2.2.5). As an example, a participant may run the final stage at 16 $km\cdot h^{-1}$, meaning their verification stage would be set at 17 $km\cdot h^{-1}$. This would represent approximately 106 % $_v\dot{V}O_{2max}$, and as the verification stage is used as a tool to try and drive up $\dot{V}O_{2max}$ to ensure that the $\dot{V}O_{2peak}$ obtained in the main test is in fact a max, 106 % is not likely to be considered 'too anaerobic'. Additionally, they set the treadmill gradient of the SPXT at 8 %, to avoid participants 'maxing' out the speed of the treadmill. In their GXT, gradient increased by 2 % every 2 min, suggesting the earlier stages of the SPXT may have been performed at a higher work rate than the GXT, which could then have potentially altered the $\dot{V}O_2$ response in the latter stages. The utilisation of a greater gradient coupled with the low speeds associated with the early stages of the SPXT, may have resulted in a loss of efficiency and premature muscle fatigue (Kang et al., 2001).

A number of studies have reported lower HR_{max} values in the SPXT compared to the GXT (Mauger & Sculthorpe, 2012; Mauger et al., 2013a; Faulkner et al., 2015; Scheadler & Devor, 2015). Mauger et al (2013a) speculated that the lower HR_{max} recorded in the SPXT, coupled with no change in $\dot{V}_E$, may suggest that the higher $\dot{V}O_{2max}$ in the SPXT was more likely due to O_2 extraction than delivery, meaning some sort of muscular recruitment or

peripheral blood flow adaptation must have occurred, although this was not tested. Interestingly, multiple studies have found the SPXT to produce lower HR_{max} compared to the GXT, in the range of 2-4 bpm, but not to significance (Evans et al., 2014; Hanson et al., 2016; Truong et al., 2017; Beltz et al., 2018). To date, three studies have investigated the role of $\dot{Q}$ and SV during the SPXT (Astorino et al., 2015; Jenkins et al., 2017a; Beltz et al., 2018). $\dot{Q}$ was estimated using a non-invasive thoracic impedance device (PhysioFlow, Manatec Biomedical, France). In two of these studies (Astorino et al., 2015; Jenkins et al., 2017a) $\dot{Q}$ was significantly higher in the SPXT compared to the GXT, although no differences were observed by Beltz et al (2018). Jenkins et al (2017a) only reported differences in $\dot{V}O_{2max}$ in the group containing 18-30 year old participants and not in a group of 50-75 year old participants. Astorino et al (2015) suggested the higher $\dot{V}O_{2max}$ seen in their study may have been due to a greater O_2 delivery, as both HR_{max} and $\dot{Q}$ were higher in the SPXT but SV showed no difference between protocols. They concluded that the self-paced nature of the test may have played an important role in this as the average work-rate in the first three stages of the SPXT (RPE 11, 13 and 15) was lower compared to the equivalent stages of the GXT (176 ± 46 W vs. 190 ± 48 W, respectively). They highlighted that the higher $\dot{V}O_{2max}$ and $\dot{Q}$ seen in the younger population but not in the older population makes it easy [and perhaps attractive] to assume that the greater $\dot{Q}$ may be the main factor in the higher $\dot{V}O_{2max}$. They acknowledge, however, that the $\dot{V}O_{2max}$ and peak $\dot{Q}$ may not have occurred at the same time, which also applies to their finding of a higher SV during the SPXT, which is certainly a limitation. In addition to $\dot{Q}$ and SV, Jenkins et al (2017a) also measured the electromyography and muscle deoxyhaemoglobin of the vastus lateralis. They reported that oxygen extraction was not the likely cause of the higher $\dot{V}O_{2max}$ in their study due to the lack of differences in deoxyHB and muscle recruitment of the vastus lateralis between protocols. Whilst research [although it is

minimal] has shown thoracic impedance to be valid in estimating $\dot{Q}$ (Charloux et al., 2000; Tordi & Mourot, 2004; Welsman et al., 2005) it should be noted that there is a lack of standardisation in the testing (Suehiro et al., 2016). There is also a lack of research using such methods with healthy adults, as opposed to paediatric or clinical populations. With this in mind, it is necessary for invasive methods to determine $\dot{Q}$ to be adopted as to understand the role $\dot{Q}$ may play in the purported $\dot{V}O_{2max}$ differences between the SPXT and GXT.

Significantly higher maximal $\dot{V}_E$ ($\dot{V}_{Emax}$) have been recorded in the SPXT compared to the GXT (Astorino et al., 2015; Faulkner et al., 2015; Jenkins et al., 2017a). Norton et al (1995) previously demonstrated that supramaximal intensities (115 % $\dot{V}O_{2max}$) could increase ventilation beyond that achieved during $\dot{V}O_{2max}$. The authors suggested the exercise stimulus could be an important factor in increasing $\dot{V}_E$, with Faulkner et al (2015) postulating that the higher peak speeds reported in their own study could have driven up $\dot{V}_E$ as a result of elevated metabolic acidosis. Several authors have noted that an increased $\dot{V}_E$ may then require additional O_2 being needed for the respiratory musculature (Anholm et al., 1987; Aaron et al., 1992; Wilhite et al., 2013). Faulkner et al (2015) calculated the O_2 cost of ventilation between the two protocols and found no differences. Whilst both Astorino et al (2015) and Jenkins et al (2017a) found differences in both $\dot{V}O_{2max}$ and $\dot{V}_E$, they did not measure the O_2 cost of ventilation and so, due to the conflicting findings of these studies, the role of ventilation warrants further investigation.

2.6. Prescribing training via the GXT

2.6.1. Background

To improve $\dot{V}O_{2max}$, training at or near $\dot{V}O_{2max}$ is most likely required in a highly trained population, whilst moderately or recreationally individuals may even benefit from training at 65-80 % $\dot{V}O_{2max}$ (Smith et al., 1999; Smith et al., 2003; Denadai et al., 2006; Midgley et al., 2006a; Esfarjani & Laursen, 2007; Gormley et al., 2008; Manoel et al., 2017). Highly trained and recreationally trained runners will likely include both continuous runs and HIIT in their regime. Whilst continuous training, characterised by longer slower runs, has been shown to be effective (Overend et al., 1992; Burgomaster et al., 2008; McNicol et al., 2009), it is likely to be less beneficial for more highly trained athletes (Laursen & Jenkins, 2002) because the intensity required to elicit an improvement in $\dot{V}O_{2max}$ is largely dependent on the initial $\dot{V}O_{2max}$ of the individual, and so runners with high initial $\dot{V}O_{2max}$ will need to train at higher intensities (Swain & Franklin, 2002). For these individuals, training at or near $\dot{V}O_{2max}$ may be required to place maximal stress on the physiological processes and structures that limit $\dot{V}O_{2max}$ (Midgley et al., 2006a). When directly comparing continuous training protocols to prescribed HIIT, a vast majority of recent research have reported significantly greater improvements obtained via HIIT for physiological variables and performance (Esfarjani & Laursen, 2007; Helgerud et al., 2007; O'Brien et al., 2008; Ní Chéilleachair et al., 2017). Due to the popularity and effectiveness of using $_v\dot{V}O_{2max}$ and V_{max} in prescribing training intensities (see table 2.2), and the fact that these parameters can be easily obtained during the GXT, they are ideal for HIIT which is effective in improving cardiorespiratory fitness and performance in both highly and recreationally trained athletes. HIIT is typically characterised by repeated bouts of short to moderate duration exercise ($\leq$ 5 min) at an intensity greater than VT2 and

usually close to 100 % $\dot{V}O_{2max}$, with a recovery period that is usually either passive or at a low intensity (Laursen & Jenkins, 2002; García-Pinillos et al., 2017). HIIT sessions are made up of the following components: the 'work' component (high intensity part), and the 'recovery' component (low intensity part). For each of these components, the intensity and duration must be considered (Seiler & Sjursen, 2002).

Table 2.2 Summary of studies that have used running-based training protocols and HIIT as a key component. The studies are organised in descending order of publication date.

Study	Subjects	Study Duration (wk)	Starting $\dot{V}O_{2max}$ (mL·kg^1·min^{-1})	Interval sessions/wk	Reps/ session	Intensity	Work duration	Rest duration	Mean % improvement $\dot{V}O_{2max}$
Silva et al. (2017)	Eight male recreational runners	4	55 ± 8	2	5	$_v\dot{V}O_{2max}$	50 % T_{max}	1:1	5
Støren et al. (2017)	Twenty-six recreationally active participants	8	51 ± 8	3	4	90-95 % HR_{max}	4 min	3 min	11*
Manoel et al. (2017)	Eight moderately trained runners	4	50 ± 4	2 or 3	#	V_{max}	60 % T_{max}	1:1	0
Manoel et al. (2017)	Six moderately trained runners	4	49 ± 7	2 or 3	#	$_v\dot{V}O_{2max}$	60 % T_{max}	1:1	0
Esfarjani and Laursen (2007)	Six moderately trained runners	10	51 ± 2	2	8	$_v\dot{V}O_{2max}$	60 % T_{max}	1:1	9 *
Esfarjani	Six moderately	10	52 ± 3	2	12	130 %	30 s	4.5 min	6 *

and Laursen (2007)	trained runners					$_v\dot{V}O_{2max}$			
Helgerud et al. (2007)	Ten healthy students	8	56 ± 7	3	4	95 % HR_{max}	4 min	3 min	5 *
Denadai et al. (2006)	Eight well trained male runners	4	59 ± 6	2	4	95 % $_v\dot{V}O_{2max}$	60 % T_{max}	1:1	0
Denadai et al. (2006)	Eight well trained male runners	4	60 ± 6	2	5	$_v\dot{V}O_{2max}$	60 % T_{max}	1:1	-3
Smith et al. (2003)	Nine well trained athletes	4	61 ± 2	2	6	V_{max}	60 % T_{max}	1:2	6
Smith et al. (2003)	Nine well trained athletes	4	60 ± 1	2	5	V_{max}	70 % T_{max}	1:2	4
Smith et al. (1999)	Five male middle-distance runners	4	62 ± 6	2	5/6	$_v\dot{V}O_{2max}$	60-75 % T_{max}	undisclosed	5

* Denotes significant improvement from starting $\dot{V}O_{2max}$ ($P < 0.05$)

The number of intervals performed was adjusted so the total duration corresponded to 30 ± 2.5 min

42

2.6.2. Exercise intensity

Billat et al (1999) reported that 100 % $_v\dot{V}O_{2max}$ was the most effective intensity to maximise time spent at $\dot{V}O_{2max}$ compared to time-to-exhaustion runs at 90, 120 and 140 % (190, 16, 73, and 18 s, respectively). The time [that $\dot{V}O_{2max}$ could be maintained] was very low during the 90 % due to five out of six participants not reaching $\dot{V}O_{2max}$ during the run, suggesting 90 % would not be an ideal intensity. For this reason, prescribing training at $_v\dot{V}O_{2max}$, or similar intensities is preferred. Regarding frequency of training, 2-3 HIIT sessions a week at or above $_v\dot{V}O_{2max}$ would benefit recreational runners' athletic performance (García-Pinillos et al., 2017), although 1-2 interval sessions per week with at least 48 h recovery may be preferable to avoid sustaining injury from overuse (Midgley et al., 2006a).

2.6.3. Durations of work and rest intervals

Whilst the intensity of training is paramount, so is the duration, as durations that are too long may result in the individual not being able to complete the prescribed training, and durations which are too short may not allow time to elicit an appropriate physiological response, resulting in no physiological adaptation occurring. As such, it is important to consider that attaining and maintaining $\dot{V}O_{2max}$ are not mutually exclusive. Based on $\dot{V}O_2$ kinetics, $\dot{V}O_{2max}$ may be attained within $80 - 140$ s but a steady state $(\geq 95\ \dot{V}O_{2max})$ may not be achieved until up to approximately 4 min of exercise (Buchheit & Laursen, 2013). This distinction may be more critical for highly trained and elite athletes who may be reaching their trainable limit for $\dot{V}O_{2max}$, and as such, must train at intensities that attain and maintain $\dot{V}O_{2max}$ to elicit further improvement (Midgley et al., 2007). The current consensus for the intensity of the work-interval, based on a meta-analysis of 37 unique research studies and 334 participants, is 3-5 min [per work interval] (Bacon et al., 2013). In

line with the expected time it would take to attain $\dot{V}O_{2max}$, 1 min intervals have been found to be insufficient, eliciting a 85 % $\dot{V}O_{2peak}$ compared to 92-93 % in intervals lasting $2 - 6$ min when exercising at the same intensity (Seiler & Sjursen, 2002; O'Brien et al., 2008).

A more widely utilised method in prescribing interval duration is T_{max}, which offers an individualised approach, in comparison to fixed duration trials. Typically, intervals are set at 60 % T_{max} which would result in interval durations of 2-5 min (Smith et al., 2003; Denadai et al., 2006; Esfarjani & Laursen, 2007). Smith et al (2003) found that when prescribing training via 60 and 70 % T_{max} [at V_{max}] (two different groups), $\dot{V}O_{2max}$ improved by 6 and 3 % [respectively] and V_{max} improved by 5 and 2 %, however, for both groups these were insignificant improvements compared to pre-training. From a performance perspective, the group training at 60 % T_{max} significantly improved their 3000 m run performance by 3 %, which equated to 18 ± 4 s, whilst the 70 % T_{max} group improved by 6 ± 4 s, which was not significant. Whilst both groups trained at the same intensity, it's possible that the longer durations of the 70 % group meant that there was a greater anaerobic contribution towards the end of each rep. This is supported by the greater improvement in VT in the 60 % group (7 vs. 2 %, respectively) and the higher post-interval lactates of the 70 % group. Crucially, in the 60 % group, 96 % of the prescribed training was successfully completed whereas this was 86 % in the 70 % group, suggesting that 70 % T_{max} may be too long for interval training. Esfarjani and Laursen (2007) found that $\dot{V}O_{2max}$ improved by 9 % when training at 60% T_{max} however this was a 10 week programme, compared to the 4 weeks of Smith et al (2003). Other studies (Denadai et al., 2006; Manoel et al., 2017) have not found significant differences in $\dot{V}O_{2max}$ but this may be due to the relative short training duration of those studies (4 wk) which may not allow enough time for adaptations in trained athletes.

Most training studies that have utilised 60 % T_{max} typically used either 1:1 or 1:2 work:recovery ratio (Smith et al., 2003; Denadai et al., 2006; Esfarjani & Laursen, 2007; Manoel et al., 2017; Silva et al., 2017). Seiler and Hetlelid (2005) found that when trained runners could self-select the work rate for their interval work and recovery segments, 2 min recovery periods produced the highest work rate in relation to $\dot{V}O_{2max}$. This was in comparison to recovery durations of 1, 4, and 6 min. However, in less trained individuals, 1:1 ratio, or 2 min [which would likely be similar, or even less compared to their T_{max} work duration] may be too short to allow adequate recovery, suggesting longer recoveries such as those utilised by Smith et al (2003) may be ideal to increase the probability of participants successfully completing interval sessions at the required intensity.

2.7. Summary

The GXT is considered a gold standard protocol for $\dot{V}O_{2max}$, which is arguably the most widely tested parameter in the sport sciences. Despite its widespread use, the GXT is still criticised for not representing the real life challenges athletes encounter during sport and exercise (Noakes, 2008). The SPXT was introduced not to be better than the GXT, but to offer an alternative that perhaps answered some of the criticisms that the GXT could not address. The greater control over work-rate that the SPXT gives the participant, along with greater knowledge of the protocol duration, and the ability to provide an 'end-spurt' which is natural to endurance athletes (Tucker et al., 2006), arguably makes the SPXT more attractive to athletes and coaches. The SPXT has, to date, been investigated in both healthy and clinical populations in running and cycling. These have yielded mixed findings regarding the assessment of $\dot{V}O_{2max}$ via the SPXT, with the majority of studies finding the

SPXT to be comparable to the GXT (Straub et al., 2014; Faulkner et al., 2015; Hanson et al., 2016; Beltz et al., 2018), whilst some have reported higher (Mauger & Sculthorpe, 2012; Mauger et al., 2013a; Astorino et al., 2015; Jenkins et al., 2017a; Jenkins et al., 2017) and even lower (Scheadler & Devor, 2015) $\dot{V}O_{2max}$ in the SPXT. There has also been various modified versions of the SPXT (Chidnok et al., 2013; Evans et al., 2014; Truong et al., 2017) which have to date all produced similar $\dot{V}O_{2max}$ to the GXT. For these reasons, a noted criticism of the SPXT has been the various methodologies and protocols used (Hutchinson et al., 2017), rendering comparisons between studies problematic. Regardless of this, the general consensus is that the SPXT produces similar or higher $\dot{V}O_{2max}$ compared to the GXT. However, there are gaps in the research, because whilst the ability of the SPXT to assess $\dot{V}O_{2max}$ is fairly well investigated, limited research has been conducted on highly trained runners, which is of importance as all studies to date that have reported higher $\dot{V}O_{2max}$ in the SPXT have generally been carried out using lesser trained or clinical populations. In line with this, beyond $\dot{V}O_{2max}$, data regarding the actual usability of the SPXT for athletes and coaches is largely non-existent, whereas the GXT is well-established in this area and offers VT measurement and the attainment of useful performance parameters such as $_v\dot{V}O_{2max}$ and V_{max} which can be utilised for training prescription. Whilst the potential of the SPXT is well recognised, with it considered a 'paradigm shift' in exercise testing (Beltz et al., 2018) that has greater ecological validity than the GXT (Poole & Jones, 2017), large gaps in the research still exist, especially in regards to its application in trained runners.

2.8. Thesis aims and hypotheses

The overall aim of this thesis was to assess the suitability of the SPXT to calculate key aerobic parameters such as $\dot{V}O_{2max}$, to successfully prescribe training, and to be utilized as a field protocol, allowing for greater accessibility to athletes and coaches compared to previously established GXT protocols. Therefore, the following Chapters present a series of studies which contribute to the overall aim of the thesis. The aims and hypotheses of each experimental Chapter are as follows:

1. The majority of research surrounding the SPXT has focused on a cycling modality and used untrained participants, and so the first experimental Chapter aimed to assess the efficacy of the SPXT in assessing $\dot{V}O_{2max}$ in highly trained runners during motorised treadmill exercise.

- Aim: To assess the validity of two different SPXT protocols in assessing $\dot{V}O_{2max}$ compared to a GXT in treadmill running (see Chapter 4)

- $H1_0$: The speed-based SPXT will not be significantly different to the GXT in measuring $\dot{V}O_{2max}$.

- $H1_1$: The speed-based SPXT will be significantly different to the GXT in measuring $\dot{V}O_{2max}$.

- $H2_0$: The gradient-based SPXT will not be significantly different to the GXT in measuring $\dot{V}O_{2max}$.

- $H2_1$: The gradient-based SPXT will be significantly different to the GXT in measuring $\dot{V}O_{2max}$.

2. Prior research predominately focused on the validity of the SPXT as a $\dot{V}O_{2max}$ protocol

in different populations and modalities, however recent research has reported significant differences in $\dot{V}_{Emax}$ in the SPXT which may explain potential $\dot{V}O_{2max}$ differences between protocols due to differences in the oxygen cost of breathing.

- Aim: To assess the oxygen cost of breathing in the SPXT and GXT (see Chapter 5).

- $H3_0$: The oxygen cost of breathing will not be significantly different between protocols.

- $H3_1$: The oxygen cost of breathing will be significantly different between protocols.

3. The utility of the SPXT is currently limited to assessment of $\dot{V}O_{2max}$, yet there is significant potential to apply the protocol to a variety of other uses. The application of the SPXT in training prescription for athletes and coaches is yet to be investigated and this would provide a valuable additional use of the SPXT.

- Aim: To determine if the SPXT can successfully prescribe training and result in similar improvements in cardiorespiratory fitness compared to training prescribed via the GXT in recreationally trained runners (see Chapter 6).

- $H4_0$: The SPXT will not produce similar training improvements compared to training prescribed via the GXT

- $H4_1$: The SPXT will produce similar training improvements compared to training prescribed via the GXT

4. Research on the SPXT has not focused on the ability of the SPXT to validate other parameters of cardiorespiratory fitness such as VT1 and VT2.

- Aim: To determine if the SPXT can be used to accurately identify VT (see Chapter 7).

- $H5_0$: The SPXT will not be able to accurately identify VT.

- H5$_1$: The SPXT will be able to accurately identify VT.

Chapter 3. General Methods

3.1. Experimental Procedures

3.1.1. Equipment and calibration methods

All participants had their body mass and stature measured (Seca Beam scale and stadiometer, Birmingham, UK). Throughout the duration of the maximal exercise tests expired gases were measured with the use of an online breath-by-breath analysis system (Cortex Metalyzer 3BR2, Cortex, NL). Before every test the gas analyser was calibrated in accordance with the manufacturers guidelines, using a calibration gas and 3-litre syringe. A two-point gas calibration was completed using a measurement of ambient air and a measurement of standard compressed gas of 17 % O_2 and 5 % CO_2. The 3-litre syringe (Hans Rudolph Inc. Kansas, USA) was used to calibrate the flow sensor and turbine. Heart rate was measured using a Polar heart rate chest strap T31 (Polar Electro Inc, New York, USA). When capillary lactate sampling was required (Chapter 6), the blood lactate analyser (Biosen C-line, EKF diagnostic, Barleben, Germany) was calibrated using the manufacturers recommended 12 $mmol^.L^{-1}$ standard (EKF diagnostic, Barleben, Germany). This calibration process was then repeated automatically every 60 minutes.

3.1.2. Exercise tests (all studies)

Before each test, participants were instructed to maintain similar eating habits, abstain from alcohol (24 h) and caffeine (8 h), and to avoid exhaustive or vigorous exercise (48 h). These measures were verbally verified by the experimenter prior to testing.

3.1.3. Self-paced exercise test (Chapters 4, 5, & 6)

The test designed was replicated from Mauger and Sculthorpe (2012). The test was completed on a motorised H/P/Cosmos Saturn treadmill (H/P/Cosmos, Nussdorf-Traunstein, Germany). The test consisted of 5 x 2 min stages, resulting in a 10 min closed loop design. For each stage, the participants were asked to continuously vary their speed based on Borg's RPE 6-20 scale (Borg, 1982; Borg, 1990). Familiarisation of the RPE scale and how to vary their speed according to a fixed RPE was provided via verbal explanation prior to the warm-up with specific emphasis given to considering their RPE for each given moment, as opposed to viewing each stage as a 2 min effort at a particular RPE. This was to encourage free-flowing pace and avoid participants simply staying at the same speed for 2 minute blocks. Stage 1 (0-2 min) of the SPXT was fixed at an RPE of 11, stage 2 (2-4 min) fixed to an RPE of 13, stage 3 (4-6 min) fixed at an RPE of 15, stage 4 (6-8 min) fixed to an RPE of 17 and stage 5 (8-10 min) fixed to an RPE of 20. The RPE scale remained visible throughout the test and participants were consistently reminded to vary their intensity to suit the particular RPE for each given stage. Consequently, on the final stage (8-10 min), where RPE 20 'maximal effort' was required, participants were instructed to perform a maximal effort with no regard to pacing themselves for 2 min or saving energy for a final effort at the end of the stage. Verbal encouragement was given throughout the test. Treadmill gradient was set to 3 % in Chapters 4 and 5, and 1 % in Chapters 6.

To allow for continuous pacing throughout the protocol, and so participants did not have to manually adjust their speed, three 'zones' were marked out on the treadmill. The treadmill belt measured 2.5 m in length. The front section (0.9 m) of the treadmill represented an

increase in intensity, the middle section (0.7 m) represented no change in intensity and the back section (0.9 m) of the treadmill represented a reduction in intensity. By running in either the front or back zones, the experimenter adjusted the treadmill speed/gradient to ensure that the participant returned to the middle 'zone'. Changes in speed were recorded using a CMOS video camera (Samsung, Seoul, South Korea). Each recording was then replayed and changes were subsequently averaged over 30 s. Participants were informed about the self-pacing zones before the warm-up and then practiced utilising the zones after completing their individualised warm-up. The test did not start until the participants stated that they understood the zonal system.

3.1.4. GXT (Chapters 4, 5, & 6)

The test was completed on a motorised H/P/Cosmos Saturn treadmill (H/P/Cosmos, nussdorf-Traunstein, Germany). The GXT was the same as described by Mauger et al (2013a). The GXT commenced at a submaximal speed, gauged by the experimenter and subject, to help bring about volitional exhaustion within 8-12 min. Speed was increased by 1 $km^{.}h^{-1}$ every 2 min and the test was terminated when participants reached volitional exhaustion. Treadmill gradient was set to either 1 % (Chapter 6) or 3 % (Chapters 4 and 5). All previously described cardiorespiratory measures were recorded during this stage and participants continued until volitional exhaustion. 6-20 RPE was recorded 20 s before the end of each stage. Verbal encouragement was given throughout. V_{max} was defined as the highest speed that could been maintained for $\geq$ 30 s (Smith et al., 2003).

3.1.5. Verification Stage (Chapters 4, 5, & 6)

After completion of the GXT, participants received 20 min recovery (Nolan et al., 2014). In Chapter 4, this was 10 min recovery (Mauger et al., 2013a). This recovery consisted of walking around the laboratory and stretching. Participants would warm-up for 2 min at the same speed they initially completed for the warm-up before the GXT and the speed was gradually increased over 30 s up to a speed equivalent to one stage higher than the final stage achieved in the GXT. All previously described cardiorespiratory measures were recorded during this stage and participants continued until volitional exhaustion. Verbal encouragement was given throughout. In Chapters 4 and 5, when participants failed to meet the plateau criteria for $\dot{V}O_{2max}$, the verification stage was used to verify whether a true $\dot{V}O_{2max}$ was achieved and a maximal effort given, using two criteria: 1) $\dot{V}O_{2max}$ verification; 2) HR_{max} verification. $\dot{V}O_{2max}$ verification was achieved when the $\dot{V}O_{2max}$ from the verification stage was ≤ 2 % higher than the GXT. HR_{max} verification was achieved with a difference of ≤ 4 bpm between that achieved in the GXT and verification stage. In the absence of a $\dot{V}O_2$ plateau during the GXT, if the $\dot{V}O_{2max}$ verification was satisfied then this was accepted as evidence that a true $\dot{V}O_{2max}$ had been achieved. When the HR_{max} verification was satisfied, this was accepted as evidence that the participant provided a maximal effort and that $\dot{V}O_{2max}$ was probably elicited (Midgley et al., 2009).

3.1.6. Physiological measures

For each participant $\dot{V}O_{2max}$ ($mL^{.}kg^{-1.}min^{-1}$) was determined by the highest 30 s average during the entirety of the test. $\dot{V}O_{2max}$ was then verified by a plateau. A plateau in $\dot{V}O_2$ during the GXT was accepted if the change in $\dot{V}O_2$ during the highest 30 s average from each of the final two stages of the test were less than half of the normal stage-to-stage

difference in $\dot{V}O_2$ during the initial linear parts of the test for each subject. As an ancillary method to verify attainment of $\dot{V}O_{2max}$, secondary criteria were accepted when two of the following were attained: HR within 10 bpm of age-predicted maximum; RER ≥ 1.15 and RPE ≥ 17. $\dot{V}_{Emax}$ and maximal RER (RER_{max}) were all calculated as the highest 30 s average during the entirety of the test.

Chapter 4. Validity of the SPXT to assess $\dot{V}O_{2max}$ in highly trained runners

Aspects of the following chapter have been included within the following manuscript:

Hogg, J. S., Hopker, J. G., Mauger, A. R. (2015). The Self-paced VO_{2max} test to assess maximal oxygen uptake in highly trained runners. International Journal of Sport Performance and Physiology, 10(2): 172-177.

Available at: https://kar.kent.ac.uk/61030/

4.1. Abstract

The SPXT may be a more suitable alternative to traditional maximal tests for highly trained athletes due to the ability to self-regulate pace. This study aimed to examine whether the SPXT can be administered on a motorised treadmill. Fourteen highly trained male distance runners performed a standard GXT, a gradient-based SPXT (SPXTinc) and a speed-based SPXT (SPXTsp). Results demonstrated there was no significant difference (P = 0.32, ES = 0.21) in the $\dot{V}O_{2max}$ achieved in the SPXTsp (67.6 ± 3.6 mL·kg^{-1}·min^{-1}, 95%CI = 65.6 – 69.7 mL·kg^{-1}·min^{-1}) compared to that achieved in the GXT (68.6 ± 6.0 mL·kg^{-1}·min^{-1}, CI = 65.1 – 72.1 mL·kg^{-1}·min^{-1}). Participants achieved a significantly higher $\dot{V}O_{2max}$ in the SPXTinc (71 ± 4.3 mL·kg^{-1}·min^{-1}, 95%CI = 68.1 – 73.0 mL·kg^{-1}·min^{-1}) compared to both the GXT (P = .03, ES = .39) and SPXTsp (P < .01, ES = .76). The current study demonstrated that the speed based SPXT protocol produces similar $\dot{V}O_{2max}$ values to those obtained in the GXT and may represent a more appropriate and athlete-friendly test which is more orientated towards the variable speed found in competitive sport.

4.2. Introduction

To date, the SPXT has been shown to be comparable to the GXT in producing $\dot{V}O_{2max}$ (Straub et al., 2014; Faulkner et al., 2015; Scheadler & Devor, 2015; Hanson et al., 2016; Lim et al., 2016; Beltz et al., 2018) although several studies have also reported higher $\dot{V}O_{2max}$ values within the SPXT (Mauger & Sculthorpe, 2012; Mauger et al., 2013a; Astorino et al., 2015; Jenkins et al., 2017; Jenkins et al., 2017a). The majority of these studies have been completed using cycling ergometers. Of the treadmill based studies, most used either a non-motorised or semi-automated treadmill, and participants who were defined as either recreationally active or untrained. Therefore, the purpose of the current study was to investigate whether the SPXT could be successfully administered on a motorised treadmill in highly trained runners.

4.3. Method

4.3.1. Participants

Fourteen well-trained, male, middle-long distance runners (mean + SD: age = 28 ± 5 years, mass = 71 ± 7 kg, height = 175 ± 5cm), familiarised with treadmill running and $\dot{V}O_{2max}$ testing, volunteered to participate in this study. The study was conducted with the approval of the Ethics Committee of the School of Sport & Exercise Sciences at the University of Kent. All participants who volunteered read and provided written informed consent before participation.

4.3.2. Exercise Tests

All participants performed a standard GXT, self-paced gradient-based exercise test (SPXTinc) and self-paced speed-based exercise test (SPXTsp) in a randomised order, 2-7 days apart and at the same time of day (±2 h). At the onset of each testing session participants performed a self-paced warm-up on a motorised treadmill (Saturn, H/P/Cosmos, Nussdorf-Traunstein, Germany), which remained the same for all subsequent tests. Following the completion of the warm-up, participants' performed a GXT, SPXTinc or SPXTsp in which oxygen consumption (Cortex Metalyzer 3BR2; Cortex, Lepzig, Germany) and heart rate (Polar heart rate chest strap T31, Polar Electro Inc, New York, USA) were recorded for the duration of the test.

4.3.3. GXT

The GXT was completed as outlined in the general methods chapter (see Chapter 3).

4.3.4. SPXTinc Protocol

The SPXTinc utilised the same basic format of the SPXT as outlined in the general methods (see Chapter 3). However, instead of just speed, gradient could also be manipulated. The SPXTinc protocol commenced at a gradient of 3 % with speed varying for the first stage and incline remaining at 3 %. At the end of the first stage, gradient then became the variable instead of speed (which was fixed) for the middle 3 stages (3-8 min). At the end of the penultimate stage, incline would then be fixed at what it was at the end of the stage, with speed once again changing until the end of the stage and the test. The experimenter would adjust the speed and incline accordingly based on the participants'

positioning on the treadmill throughout the test with speed/incline able to increase or decrease depending on the individual's positioning.

4.3.5. SPXTsp Protocol

The SPXTsp was completed as outlined in the general methods chapter (see Chapter 3).

4.3.6. $\dot{V}O_{2max}$ determination

$\dot{V}O_2$ plateau and secondary criteria were calculated as outlined in the general methodology (see Chapter 3).

4.3.7. Statistical Analysis

All data are presented as means ± SD. Data were checked for normality of distribution using the Shapiro-Wilk statistic. Log transformation was used where the assumption of normality was violated. A one-way ANOVA with repeated measures was used to examine maximal value differences between protocols, with pairwise comparisons used to identify where statistical differences lay. Partial eta^2 (ηp^2) and *cohen's d* were used to report effect sizes and statistical significance was accepted when $P < 0.05$. A Bland and Altman 95% LoA analysis (Bland & Altman, 1986) quantified the agreement (bias ± random error [1.96 x SD]) between the measured $\dot{V}O_{2max}$ from each test. In accordance with recommendations for conducting LoA analysis, the data were checked for heteroscedastic error by conducting correlation analysis on the measurement error and the mean of the GXT and SPXT $\dot{V}O_{2max}$ scores. Oxygen cost of breathing for each protocol was calculated using $\Delta \dot{V}O_2 / \Delta \dot{V}_E$, as performed by Vella et al (2006). All statistical tests were completed using SPSS version 19.0 (Chicago, IL, USA).

4.4. Results

The mean stage-to-stage difference in $\dot{V}O_2$ for all participants was calculated as 215 ± 51 mL·min^{-1}, so that a mean plateau phenomenon was defined as a change in $\dot{V}O_2 \leq 108 \pm 25$ mL·min^{-1} (or an average of 1.5 mL·kg^{-1}·min^{-1}, considering the average body mass of the participants) between the two final stages of the protocol. A $\dot{V}O_2$ plateau was observed in 57 % of participants in the GXT. Of the participants who did not achieve a plateau, all achieved the $\dot{V}O_2$ verification criteria. In total, 86 % of participants achieved the $\dot{V}O_{2max}$ verification criteria and 93 % achieved the HR_{max} verification criteria.

There was a significant difference in $\dot{V}O_{2max}$ between the three protocols (Figure 4.1) ($F_{2,26} = 5.66$, $P = .01$, $\eta p^2 = .30$), a pairwise comparison revealed no significant difference in the $\dot{V}O_{2max}$ achieved between the SPXTsp (67.6 ± 3.6 mL·kg^{-1}·min^{-1}, 95%CI $= 65.6 - 69.7$ mL·kg^{-1}·min^{-1}) and the GXT (68.6 ± 6.0 mL·kg^{-1}·min^{-1}, 95%CI $= 65.1 - 72.1$ mL·kg^{-1}·min^{-1}). However, participants achieved a significantly higher $\dot{V}O_{2max}$ in the SPXTinc (71 ± 4.3 mL·kg^{-1}·min^{-1}, 95%CI $= 68.1 - 73.0$ mL·kg^{-1}·min^{-1}) compared to the GXT ($P = .03$, ES $= .47$) and SPXT$_{sp}$ ($P < .01$, ES $= .76$).

Figure 4.2 shows a representative subject's $\dot{V}O_{2max}$ and speed/power for all three protocols. No significant differences ($t_{13} = 1.22$, $P = .25$) were observed between $\dot{V}O_{2max}$ achieved in the GXT and the subsequent verification bout (68.6 ± 6.0 mL·kg^{-1}·min^{-1} vs. 67.9 ± 6.8 mL·kg^{-1}·min^{-1} respectively). LoA (Figure 4.3) values between the GXT and the SPXTsp, the GXT and the SPXTinc and the two SPXT protocols were 8 ± 4 mL·kg^{-1}·min^{-1}; 6 ± 3 mL·kg^{-1}·min^{-1}; and 5 ± 3 mL·kg^{-1}·min^{-1}, respectively. Nine participants achieved their highest $\dot{V}O_{2max}$ in the SPXTinc, with three achieving it in the GXT and two in the SPXTsp.

Peak speeds were significantly higher ($t_{13} = 4.33$, $P < .01$, ES = 1.17) in the SPXTsp compared to the GXT (19.3 ± 1.7 km·h^{-1} vs. 17.6 ± 1.2 km·h^{-1}). There was a significant difference in the oxygen cost of breathing calculated from the GXT (28.2 ± 2.8 mL·min^{-1}) compared to both the SPXTsp (26.4 ± 2.8 mL·min^{-1}) ($P = .02$) and SPXTinc (26.3 ± 3.3 mL·min^{-1}) ($P = .03$).
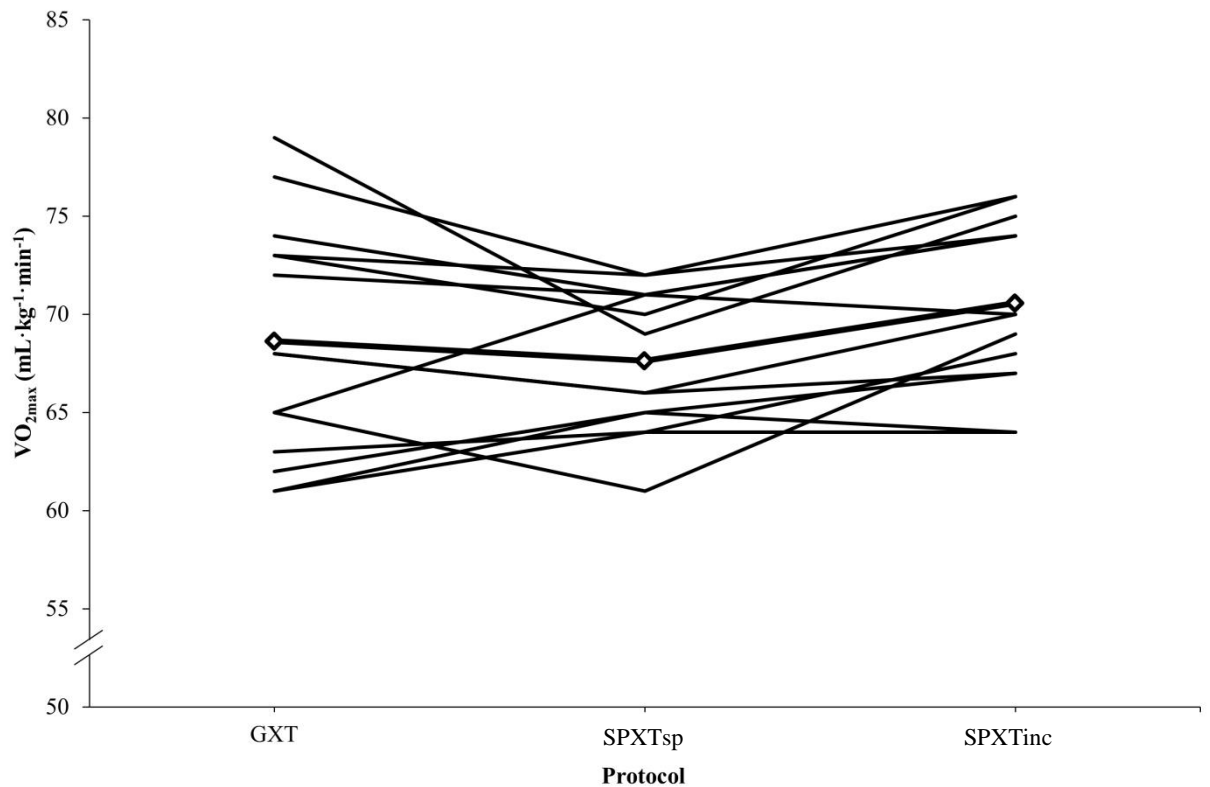
Figure 4.1 Differences in $\dot{V}O_{2max}$ between the GXT, SPXTsp and SPXTinc for all participants. The thick black line represents the mean difference for all participants. Out of the fourteen participants, nine achieved their highest $\dot{V}O_{2max}$ in the SPXTinc, three in the GXT and two in the SPXTsp.
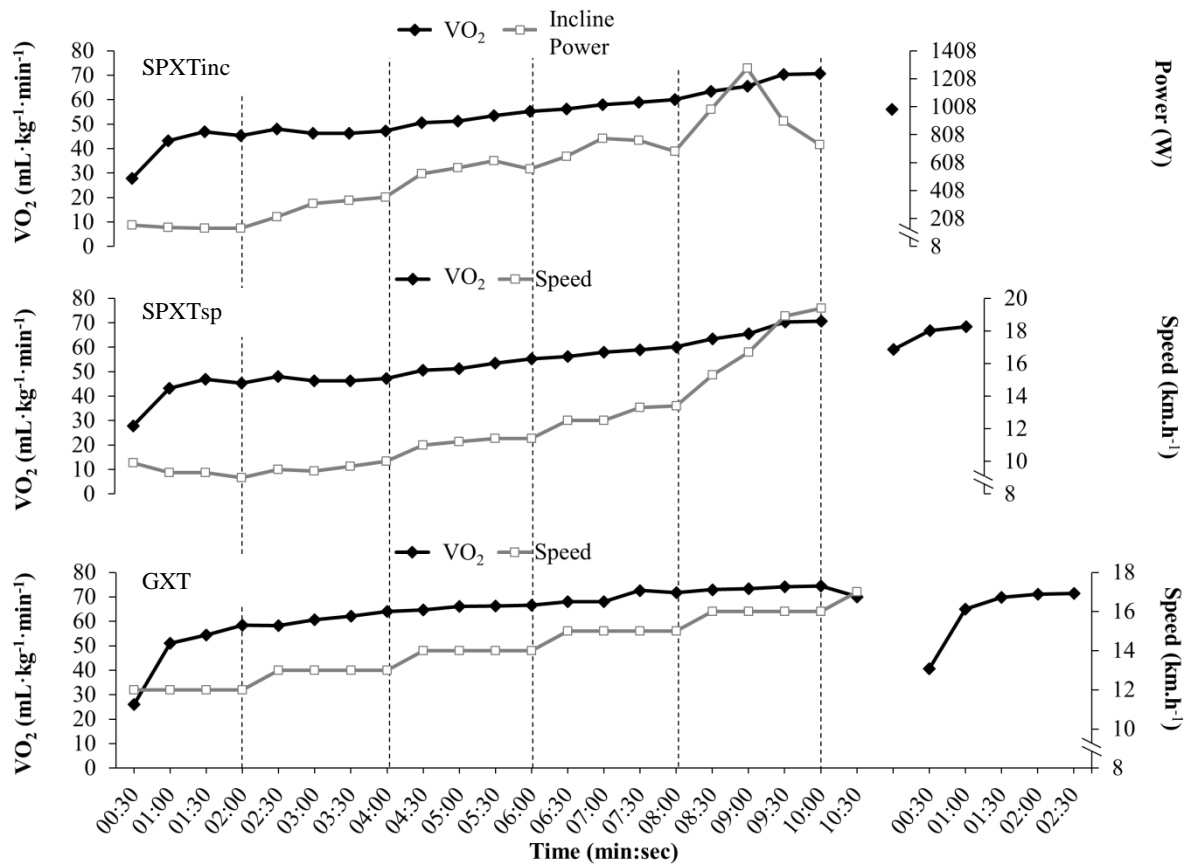
Figure 4.2 $\dot{V}O_2$ and speed (km·h^{-1}) or power (W) [for the SPXTinc] response for all three protocols [and verification stage] for a representative participant. Note that a $\dot{V}O_2$ plateau was achieved in all tests, yet the subject achieved a higher $\dot{V}O_{2max}$ in the SPXTinc (74 mL·kg^{-1}·min^{-1}) than in the GXT and SPXTsp.
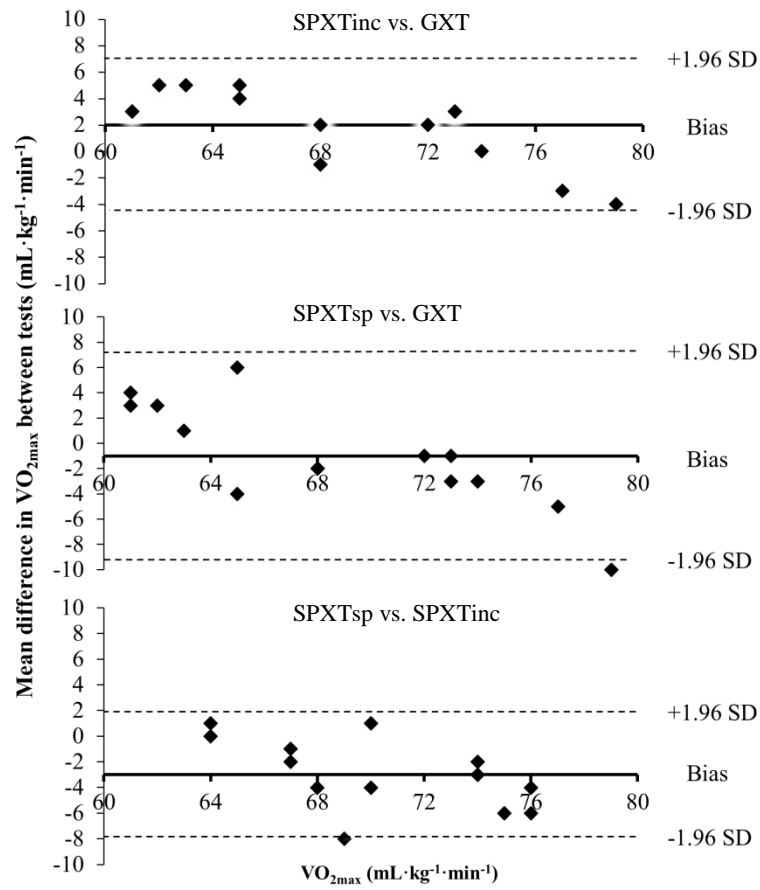
Figure 4.3 Limits of Agreement between $\dot{V}O_{2max}$ from each protocol for all three protocols. $SPXT_{inc}$ vs. GXT (top panel); SPXTsp vs. GXT (middle panel); SPXTsp vs. SPXTinc (bottom panel)

Table 4.1. Mean ± SD peak values for physiological and intensity variables recorded during all protocols

Variable	GXT	SPXTsp	SPXTinc
HR$_{max}$ (bpm)	183 ± 6	181 ± 9	183 ± 6
$\dot{V}_{Emax}$ (mL·min^{-1})	172.0 ± 23.5	176.9 ± 24.7	181.1 ± 22.4*
RER$_{max}$	1.14 ± 0.1	1.16 ± 0.1	1.16 ± 0.1
RPE$_{max}$	19 ± 1	20 ± 0*	20 ± 0*
Speed (km·h^{-1})	17.6 ± 1.2	19.0 ± 2.1*	15.1 ± 0.7
Incline (%)	3 ± 0	3 ± 0	11.0 ± 3.2*
TTE (min)	11 ± 1	10 ± 0	10 ± 0

*Denotes significant difference between either SPXTsp / SPXTinc and GXT ($P < 0.05$)

4.5. Discussion

The primary finding of this study was that the $\dot{V}O_{2max}$ values produced in the SPXTsp were not significantly different from those produced in the GXT, suggesting self-pacing, which better reflects real-world exercise, and sport (Noakes, 2008), can be simulated on a motorised treadmill in highly trained runners. This suggests that the SPXTsp is a suitable alternative to the GXT and may specifically suit those more accustomed to pacing.

Notably, the SPXTsp produced significantly higher peak speed values than in the GXT (19.0 ± 2.1 km·h^{-1} vs. 17.6 ± 1.2 km·h^{-1}, respectively). This finding is in contrast to Mauger et al (2013a) who found that peak speeds in the SPXT were significantly lower than in the GXT. However, this is likely a result of the non-motorised treadmill used in the study by Mauger et al (2013a) producing lower speeds due to higher belt friction (Hopker et al.,

2009). In the current study, the peak speeds observed in the SPXTsp may better reflect the finishing speeds these runners achieve in athletic performance where pacing is key (Bailey et al., 2011) and therefore makes this protocol more relevant for the competitive athlete. Future research should investigate the velocities achieved during the SPXT and how these may compare to well recognised parameters such as $_v\dot{V}O_{2max}$ or V_{max} during the GXT.

In the study by Mauger and Sculthorpe (2012), the higher $\dot{V}O_{2max}$ values achieved in the SPXT were attributed to a significant increase in PO in the final stage, followed by a significant drop by the end of the final stage. This observation was similar in the current findings (see Figure 4.2) where participants tended to achieve a 'spike' in intensity [in the SPXTinc] followed by a large drop during the second half of the final stage. However, during the SPXTsp, participants tended to maintain high speeds until the end of the test, perhaps suggesting they didn't fully exert themselves at the start of the final stage. It is possible that due to their trained status, it may be difficult to achieve the high speeds required to reach maximal exertion on a motorized treadmill. In the SPXTinc, the majority of the participants achieved their highest gradient early in the second-to-last stage (RPE 17) followed by a decline going into the final stage. This is supported by the finding from the LoA data that, in participants with consistently higher $\dot{V}O_{2max}$ values [compared to other participants], their highest recorded $\dot{V}O_{2max}$ tended to be achieved during the GXT. Conversely, this was reversed for the participants with lower $\dot{V}O_{2max}$ values, who tended to achieve their highest $\dot{V}O_{2max}$ in the SPXT protocols. It could be inferred that this may be due to the more seasoned athletes not reaching intensities high enough during the SPXT protocols to obtain a true $\dot{V}O_{2max}$. Alternatively, those with lower $\dot{V}O_{2max}$ may be less accustomed to GXT testing compared to the participants of a higher competitive standard,

and so found the self-paced nature of the SPXT less intimidating and strenuous than the GXT.

Chidnok et al (2013) suggested that the higher $\dot{V}O_{2max}$ found in the study by Mauger and Sculthorpe (2012) may be protocol dependent [as opposed to physiological limitations] due to the GXT test lasting significantly longer than the SPXT (13 vs. 10 min). However, in the current study [and Mauger et al (2013a)], there was no significant difference in the durations between the three protocols. Moreover, whilst protocols of longer durations have been suggested to underestimate $\dot{V}O_{2max}$ (Yoon et al., 2007), Midgley et al (2008) have suggested that the 8-12 min recommendation should not be considered absolute as longer protocols can still be valid, but shorter protocols may be preferred due to longer protocols not providing any additional information of real benefit.

Interestingly, the majority of participants anecdotally reported that they found the SPXTinc the most challenging and physically stressful. This is perhaps unsurprising considering the dual use of gradient and speed during this protocol. This is supported by the finding that RER [although not significant] was consistently higher during the SPXTinc, whilst $\dot{V}_E$ was significantly higher [compared to the SPXTsp and GXT], suggesting a potentially greater anaerobic cost during the SPXT in the final stage. While the exact oxygen cost of breathing cannot be accurately elucidated from the current study, it is still considered to be partly responsible for the rise in $\dot{V}O_2$ from VT to maximal intensities (Lucia et al., 2001), with it being reported to account for around 18-23 % of the $\dot{V}O_2$ slow component (Gaesser & Poole, 1996). However, using $\Delta\dot{V}O_2/\Delta\dot{V}_E$ data from Vella et al (2006), estimates for the breathing cost of $\dot{V}O_2$ from the three protocols can be accurately calculated - suggesting a significantly higher breathing cost developed from the GXT as opposed to the two SPXT

protocols. Therefore, the role of the oxygen cost of breathing in relation to the SPXT should be examined.

The SPXTinc produced significantly higher $\dot{V}O_{2max}$ values than both the SPXTsp and the GXT (~3 %). The minimal significant change in $\dot{V}O_2$ between trials has been suggested to be 2 %, whereas improvements in the region of 3 - 5 % and above have been accepted as an improvement in aerobic capacity. Previous research has found gradient based protocols to underestimate $\dot{V}O_{2max}$ (Buchfuhrer et al., 1983; Kang et al., 2001) due to a combination of a greater incline coupled with a low running speed, which may result in a loss of efficiency and premature muscle fatigue. Alternatively, especially as the SPXTsp produced no differences in $\dot{V}O_{2max}$ compared to the GXT, it is possible that $\dot{V}O_{2max}$ in the SPXTinc was higher *because* of the use of gradient. The uphill running could have triggered an increase in lower-extremity muscle-volume activation (Sloniger et al., 1997) and as a result, increased O_2 delivery to the working muscles, then driving up $\dot{V}O_{2max}$. As such, it seems how gradient is utilized may determine whether it increases or decreases $\dot{V}O_{2max}$. In the current study, during the SPXTinc, participants still reached, on average, peak speeds of 15.1 ± 0.7 km·h^{-1}. A 3 % gradient was utilised in the GXT to help counteract the effect gradient may have during the SPXTinc. In support of this, McCole et al (2001) found that $\dot{V}O_{2max}$ was not significantly different in two protocols where the participants reached gradients of 8 and 14 %. However, the gradient achieved in the SPXTinc was 11.0 ± 3.2 % compared to the 3 % during both the GXT and SPXTsp. It is therefore possible that the higher $\dot{V}O_{2max}$ in the SPXTinc was due to a combination of the significantly greater gradient paired with high velocities. For this reason, athletes and coaches looking for a self-paced test that is comparable to the GXT should use the speed-based SPXT over the gradient-based SPXT.

The ability to self-pace on a motorised treadmill was a key challenge of this Chapter. As previously discussed (see section 2.5), previous literature relied on participants using buttons on the treadmill to adjust their speed throughout the SPXT (Faulkner et al., 2015; Beltz et al., 2018) whilst other investigators have utilised sonar range finders to transform motorised treadmills into semi-automated treadmills (Scheadler et al., 2015; Truong et al., 2017). Due to sonar range finders not being commercially available, this was not achievable in the current chapter. Also, due to sonar range-finders still being considered novel and not wide-spread, how reactive they are to changes of pacing is questionable. Notably, further information was not given by authors who have utilised sonar range finders for self-pacing. A zonal system was selected over button pushing as the zonal system would likely require less interruption to the participants running pattern than manually pressing buttons on a panel. It is also speculated that a zonal system, which simply requires the participants to move between zones to signal to the tester that they want to change speed, may be more natural and fluid then buttons. It is accepted that this still does not constitute genuine self-pacing, which was always going to be difficult to achieve on motorized treadmill, however the comparable $\dot{V}O_{2max}$ between protocols (GXT and speed-based SPXT) and the fact that participants were still able to achieve higher speeds in the speed-based SPXT suggests the zonal system did not present a barrier to the participants' ability to self-pace.

4.6. Conclusion

This study demonstrates that a motorised self-paced speed-based running exercise test is a viable alternative to a GXT whilst also producing similar $\dot{V}O_{2max}$ values. The peak speeds achieved in the speed-based SPXT may better represent the finishing spurt achieved during a competitive race. The current findings show that self-paced exercise, to an extent, can be achieved on a motorised treadmill and may even be more effective than on a non-motorised treadmill where running mechanics are too dissimilar to normal running (Hopker et al., 2009). Future research should aim to investigate what measurements and parameters beyond $\dot{V}O_{2max}$ can be extracted from the SPXT and how these can be utilized by athletes and coaches both in the lab and in the field.

Chapter 5: The oxygen cost of breathing in the SPXT

5.1. Abstract

The SPXT may have a lower oxygen cost of breathing ($\dot{V}O_{2vent}$) compared to the GXT which may explain differences between protocols found in some previous research. This Chapter aimed to examine whether there are differences in the oxygen cost of breathing between the SPXT and GXT. Ten trained male runners performed a GXT, a speed-based SPXT, and two ventilation protocols based on either the GXT (G-VENT) or SPXT (S-VENT). Results demonstrated that there were no significant differences in the oxygen cost of breathing ($t_7 = -1.00$; $P = .34$,) between the GXT and SPXT (26.9 ± 4.2 mL·min^{-1} vs. 26.1 ± 5.3 mL·min^{-1}, respectively) and that $\dot{V}O_{2max}$ ($Z = -.43$, $P = .67$,) and $\dot{V}_{Emax}$ ($P = .15$) were not significantly different between the protocols. The mean velocity at RPE20 was also comparable to V_{max} calculated via the GXT ($t_8 = .74$, $P = .48$). The current study demonstrates that any differences in $\dot{V}O_{2max}$ are unlikely to be related to ventilation and that the finding of similar velocities between protocols suggests the SPXT may offer the potential for training prescription.

5.2. Introduction

In Chapter 4, two different SPXT protocols conducted on highly trained runners and completed on a motorised treadmill were validated against the GXT. The main finding was that the [speed-based] SPXT was a valid protocol for $\dot{V}O_{2max}$ measurement. Whilst most physiological variables were similar between protocols, $\dot{V}_{Emax}$ was significantly different from the GXT, which may indicate a different oxygen cost of breathing ($\dot{V}O_{2vent}$) between the two protocols. The purpose of this chapter was therefore to investigate this potential mechanistic difference.

Despite its relative infancy, the SPXT has been well researched in running (see Chapter 4; Mauger et al., 2013a; Faulkner et al., 2015; Scheadler & Devor, 2015; Hanson et al., 2016; Beltz et al., 2018) and cycling (Mauger & Sculthorpe, 2012; Chidnok et al., 2013; Straub et al., 2014; Astorino et al., 2015; Hanson et al., 2016; Jenkins et al., 2017a). However, much of the focus of this research has revolved around the validity of the protocol for $\dot{V}O_{2max}$ measurement. Nearly all of the aforementioned studies [except the work of Scheadler et al (2015)] have reported that the SPXT produces [at least] equal values to those achieved in the GXT. Additionally, some studies have even found the SPXT to produce significantly greater $\dot{V}O_{2max}$ compared to the GXT (Mauger & Sculthorpe, 2012; Mauger et al., 2013a; Astorino et al., 2015; Jenkins et al., 2017; Jenkins et al., 2017a).

Currently, research on the physiological mechanisms underpinning these potential differences in $\dot{V}O_{2max}$ have focused on the hemodynamic responses during the GXT and SPXT (Astorino et al., 2015; Jenkins et al., 2017a; Beltz et al., 2018). Mauger and

Sculthorpe (2012) speculated that the higher $\dot{V}O_{2max}$ observed during their SPXT may have been due to the self-paced nature of the test being less reliant on type II muscle fibres, thus restricting the more anaerobic component of the test until the latter stages and consequently increasing the recruitment of more oxygen-dependent type I fibres for the majority of the protocol. In their follow up study, Mauger et al (2013a) speculated that limb blood flow and O_2 extraction may have been improved – using the finding that HR_{max} was significantly lower in the SPXT as evidence, coupled with no differences in $\dot{V}_E$. Alternatively, a number of studies have reported significantly higher $\dot{V}_E$ during the SPXT (see Chapter 4; Astorino et al., 2015; Faulkner et al., 2015; Jenkins et al., 2017a; Jenkins et al., 2017). Faulkner et al (2015) speculated that the greater velocities achieved in the SPXT may drive up $\dot{V}_E$, which is in line with previous research regarding supramaximal intensities (Norton et al., 1995).

Several studies have reported that the oxygen cost of breathing was equal to ~10 % of $\dot{V}O_{2max}$ (Aaron et al., 1992; Vella et al., 2006; Turner et al., 2012) and this increased exponentially with increasing $\dot{V}_E$. It has been suggested that the respiratory muscles demand a significant amount of $\dot{Q}$ during exercise which may in turn limit blood flow to the working muscles (Harms et al., 1997; Harms et al., 1998). Multiple studies, both when higher $\dot{V}O_{2max}$ values have been achieved during the SPXT and when they have not, have shown a greater $\dot{V}_{Emax}$ during the SPXT. Chapter 4 found that $\dot{V}_{Emax}$ was significantly higher in one of the SPXT protocols compared to the GXT, and that, based on calculations by Vella et al (2006), there was a greater oxygen cost of breathing during the GXT. This suggests that the oxygen cost of breathing may be more efficient in the SPXT and that this could promote greater blood flow to limbs and thus improve O_2 delivery and extraction. As

such, this chapter aimed to investigate whether there was a difference in the oxygen cost of breathing between a treadmill SPXT and GXT.

5.3. Method

5.3.1. Participants

Ten trained male runners (mean ± SD: Age = 28 ± 5 years, mass = 72 ± 6 kg, height = 177 ± 7 cm) volunteered to participate in this study. The study was conducted with the approval of the Ethics Committee of the School of Sport & Exercise Sciences at the University of Kent. All participants who volunteered read and provided written informed consent before participation.

5.3.2. Exercise Tests

All participants visited the laboratory on five occasions. On separate occasions, participants completed a GXT and a speed-based SPXT; a ventilation protocol with ventilation trials calculated via the GXT (G-VENT); a ventilation protocol with ventilation trials calculated via the SPXT (S-VENT); and an initial eucapnic voluntary hyperpnoea (EVH) assessment. All participants completed the EVH assessment first, followed by the $\dot{V}O_{2max}$ protocols, and then the ventilation protocols in a randomised order. The EVH assessment required the participant to hyperventilate dry air containing 5% CO_2 as a method of diagnosing bronchoconstriction (Anderson et al., 2001). All participants completed a spirometry test before and after the EVH test. Participants who achieved a

post-EVH reduction in forced expiratory volume [in one second] compared to the pre-EVH spirometry test were excluded from further participation. Both the $\dot{V}O_{2max}$ and ventilation protocols were completed in a randomised order between the respective two trials. The ventilation protocols (G-VENT and S-VENT) were included to assess whether differences in ventilation between the SPXT and GXT existed.

5.3.3. $\dot{V}O_{2max}$ protocols

The GXT and SPXT were as described in the general methodology (see Chapter 3). $\dot{V}O_2$ (Metalyzer 3BR2, Cortex, Lepzig, Germany) and heart rate (T31, Polar Electro Inc, New York, USA) were recorded for the duration of the testing protocol. During the GXT, V_{max} was calculated as the highest velocity maintained for ≥ 30 s. In the SPXT, the mean velocity of the final stage ($_vRPE20$) was recorded.

5.3.4. Ventilation Protocols

Participants completed two ventilation protocols. Each ventilation protocol included ventilation trials that were either calculated via the GXT (G-VENT) or SPXT test (S-VENT). The protocols were randomized and the first ventilation trial took place at least 48 h after the second maximal exercise protocol. Each visit contained seven ventilation trials separated by 5 min of seated rest. Each trial lasted 3 min. The trials were completed at the following percentages of the participant's $\dot{V}_{Emax}$ taken from the relevant $\dot{V}O_{2max}$ protocol (GXT or SPXT) test: Rest, 100, 30, 75, 45, 60, 100 %. This order was chosen to avoid having back-to-back high intensity efforts which may cause respiratory muscle fatigue. An effort of 100 % was included twice to increase the participant's likelihood of achieving the required $\dot{V}_E$. The 100 % trial that they performed best (actual $\dot{V}_E$ closest to target $\dot{V}_E$) was

then selected for analysis. During each effort participants were asked to match the calculated $\dot{V}_E$ and real time feedback was given to the participant by the cortex metalyzer which showed their real-time breath-by-breath $\dot{V}_E$. Participants breathed into a 2-way breathing apparatus (Hans Rudolph Inc, Kansas, USA) that was connected to the Cortex metalyzer. The breathing apparatus was then connected to a gas canister with a gas concentration of 5%CO_2/21%O_2 (Anderson et al., 2001). CO_2 was included to avoid hypocapnoea (Aaron et al., 1992). To calculate $\dot{V}O_{2vent}$, resting $\dot{V}O_2$ was subtracted from those obtained from the mimicking trials (Turner et al., 2012). The O_2 cost per litre of $\dot{V}_E$ ($\Delta\dot{V}O_2/\Delta\dot{V}_E$) was calculated by dividing the change in $\dot{V}O_2$ by the change in $\dot{V}_E$ [from the resting value].

5.3.5. Statistical Analysis

All data are presented as means ± SD. Data were checked for normality of distribution using the Shapiro-Wilk statistic. Log transformation was used where the assumption of normality was violated. Differences in maximal variables between the GXT and SPXT were analysed using a paired samples t-test, or, where log transformation did not resolve the distribution of the data, a Wilcoxon signed rank test was used. In the G-VENT and S-VENT, to identify the differences in target and actual $\dot{V}_E$ (type) at different ventilation rates (trial), 2x5 ANOVA was used. Violation of the assumptions were assessed using the Mauchly's test of sphericity, if P was > 0.05 then sphericity was assumed but if $P < 0.05$ then Greenhouse-Geisser corrections were used. A paired samples t-test was used to assess individual differences in target and actual $\dot{V}_E$ for the individual ventilation trials. To identify differences in $\dot{V}O_{2vent}$ in the G-VENT and S-VENT (protocol) across the five different ventilation rates (trial), a 2x5 ANOVA was used. Partial eta-squared (η_p^2) was

used to report effect sizes, and statistical significance was accepted when $P < 0.05$. All statistical tests were completed using SPSS version 25 (Chicago, IL, USA).

5.4. Results

The average stage-to-stage difference in $\dot{V}O_2$ for all participants was calculated as 263 ± 67 mL·min^{-1}, so that a mean plateau phenomenon was defined as a change in $\dot{V}O_2 \leq 132 \pm 33$ mL·min^{-1} (or an average of 1.8 mL·kg^{-1}·min^{-1}, considering the average body mass of the participants) between the two highest 30 s averages during the final two stages of the test. A $\dot{V}O_2$ plateau was observed in 70 % of participants in the GXT. All participants satisfied the $\dot{V}O_{2max}$ verification criteria.

Differences in test protocols for key variables for all participants are presented in Table 5.1. There were no significant differences in $\dot{V}O_{2max}$ between the GXT and SPXT protocols ($Z = -.43$, $P = .67$). $\dot{V}_{Emax}$ was not significantly different between protocols ($t_9 = -1.59$; $P = .15$). RER_{max} was significantly greater in the SPXT ($t_9 = -3.81$, $P < .01$). Protocol duration was not significantly different between protocols ($t_9 = 1.63$, $P = .14$). RPE_{max} was significantly greater in the SPXT ($t_9 = -4.12$, $P < .01$). HR_{max} was not significantly different between protocols ($P = .83$, $t_9 = .22$). V_{max} and $_vRPE20$ were not significantly different ($t_8 = .74$, $P = .48$).

The O_2 cost per litre of ventilation at $\dot{V}_{Emax}$ during the breathing trials were not significantly different between the G-VENT and S-VENT protocols (2.79 ± 1.81 vs. 2.67 ± 1.73 mL/L, respectively) ($t_7 = -.19$, $P = .86$). There were no significant differences in the

oxygen cost of breathing calculated from the GXT (26.9 ± 4.2 mL·min^{-1}) compared to the SPXT (26.1 ± 5.3 mL·min^{-1}) ($t_7 = -1.00$, $P = .34$). Data for actual and target $\dot{V}_E$ are presented in table 5.2. There were no significant differences between target and actual $\dot{V}_E$ in both the G-VENT ($F_{1,9} = 3.71$, $P = .09$, $\eta_p^2 = .29$) and S-VENT ($F_{1,9} = 2.79$, $P = .13$, $\eta_p^2 = .24$). There was a significant interaction between ventilation trials and $\dot{V}_E$ type (target and actual) for both the G-VENT ($F_{2,14} = 6.48$, $P = .02$, $\eta_p^2 = .42$) and S-VENT ($F_{1,10} = 5.72$, $P = .04$, $\eta_p^2 = .39$). For actual $\dot{V}_E$, there was no difference between the two protocols ($F_{1,9} = 1.764$, $P = .22$, $\eta_p^2 = .16$) and no interaction effect between protocol and individual trials ($F_{2,15} = 1.03$, $P = .37$; $\eta_p^2 = .10$). Actual and target $\dot{V}_E$ were significantly different in the G-VENT for the trial at 100 % $\dot{V}_{Emax}$ ($t_9 = 2.47$ $P = .04$). For $\dot{V}O_{2vent}$ (Figure 5.1), there were no significant differences between protocols ($F_{1,9} = 2.36$, $P = .16$, $\eta_p^2 = .21$), and no interaction effect between protocol and ventilation trials $F_{4,36} = 1.66$, $P = .18$, $\eta_p^2 = .16$).

Table 5.1 Mean $\pm$ SD values for physiological and intensity variables for both protocols

Variable	GXT	SPXTsp
$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	68 ± 7.4	68 ± 7.2
HR_{max} (bpm)	185 ± 7	185 ± 9
$\dot{V}_{Emax}$ (L·min^{-1})	163.4 ± 19.4	168.5 ± 25.8
RER_{max}	1.15 ± 0.1	$1.20 \pm 0.0*$
RPE_{max}	19 ± 1	$20 \pm 0*$
V_{max} / $_vRPE20$ (km·h^{-1})	16.5 ± 2.0	16.3 ± 1.4
TTE (min)	10 ± 1	10 ± 0

* Denotes significant difference between protocols ($P < 0.05$)

Table 5.2 Mean $\pm$ SD values for actual and target $\dot{V}_E$ in the breathing trials in both ventilation protocols

Ventilation Trial (% $\dot{V}_{Emax}$)	G-VENT (L·min⁻¹)		S-VENT (L·min⁻¹)	
	Target	**Actual**	**Target**	**Actual**
30	49.0 ± 5.8	49.3 ± 5.3	50.6 ± 7.7	52.2 ± 7.2
45	73.5 ± 8.7	74.4 ± 7.5	75.8 ± 11.6	77.0 ± 9.8
60	98.0 ± 11.7	98.1 ± 10.8	101.1 ± 15.4	99.4 ± 14.4
75	122.5 ± 14.6	117.4 ± 10.4	126.4 ± 19.3	123.6 ± 16.6
100	163.4 ± 19.4	153.6 ± 16.7 *	168.5 ± 25.8	155.0 ± 20.0

* Denotes significant difference between target and actual $\dot{V}_E$ ($P < 0.05$)
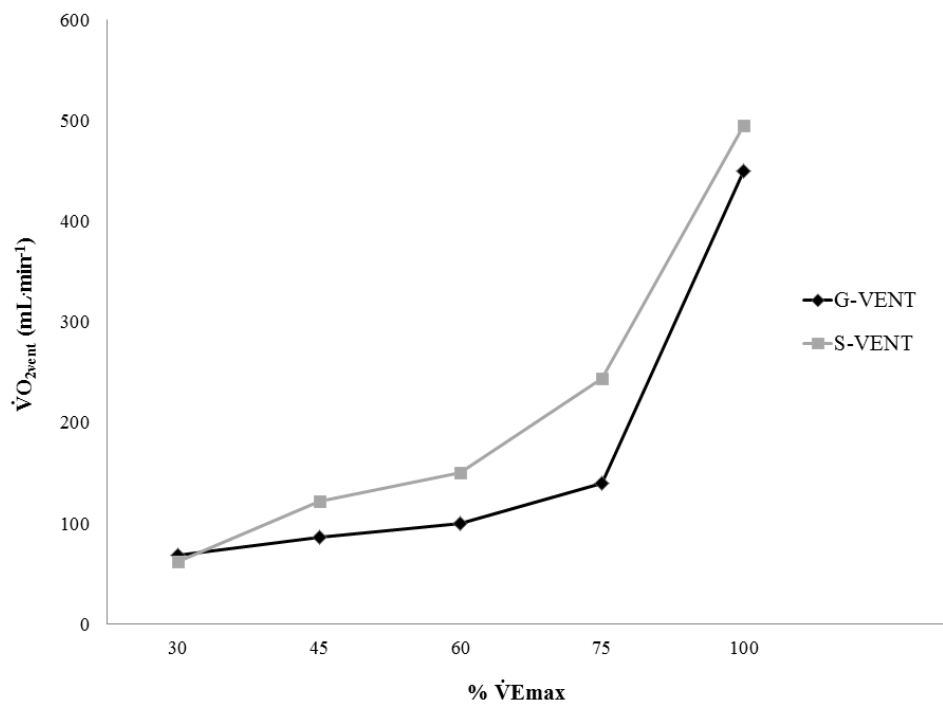
Figure 5.1 $\dot{V}O_{2vent}$ in the ventilation trials in both G-VENT and S-VENT for all participants

5.5. Discussion

Contrary to the first experimental chapter (see Chapter 4), $\dot{V}_{Emax}$ and the oxygen cost of breathing were not significantly different between the SPXT and GXT. As a result, there was no interaction between the various trials for $\dot{V}_E$ and $\dot{V}O_{2vent}$ and the G-VENT and S-VENT. A key decision of this chapter was to include the GXT and speed-based SPXT, but not the gradient-based SPXT. It is important to highlight than in Chapter 4, only the gradient-based SPXT provided significantly higher $\dot{V}_E$ compared to the GXT. However, the speed-based SPXT was selected for this Chapter due to it having greater 'real-world relevance' than the gradient-based SPXT, due to it being speed-based and thus easier to administer than also utilizing gradient. Whilst $\dot{V}_E$ was not significantly different in the speed-based SPXT in Chapter 4, estimated oxygen cost of breathing was still significantly different to the GXT which meant its selection was justified, however it cannot be known if the gradient based SPXT would have produced a significantly different outcome in this Chapter as it was not used and so this is a limitation of the current design.

A key challenge of this study was to simulate various breathing rates from an exercise test, in a passive rested state. Participants were asked to match the given $\dot{V}_E$ for each trial. As could be expected, this proved more problematic for the ventilation trials with a high $\dot{V}_E$ target compared to the trials with a lower $\dot{V}_E$ target. Matched breathing frequency was also originally included however this proved too problematic for the participants and so only $\dot{V}_E$ was matched for each trial. This is a limitation as breathing patterns may differ between protocols beyond just $\dot{V}_{E,}$ however as participants struggled to match breathing frequency coupled with high target $\dot{V}_{E,}$ these were not ultimately included. In the G-VENT trials, participants struggled to meet the $\dot{V}_E$ requirement during the 100 % trial. As these trials are

completed at such high $\dot{V}_E$, which may be unnatural in a non-exercise state, this is unsurprising. However, this was not the case during the S-VENT trials. Interestingly, the 30 % trial in the S-VENT trended towards being significantly different to the target, whereas this was not the case in the G-VENT. This suggests that whilst participants struggled to meet the 100 % target in the G-VENT and not the S-VENT, this may be more of a random occurrence, especially as the target values between the protocols were not significantly different. This may also emphasise the difficulty participants had in mimicking ventilation rates whilst at rest; although all trials had a duration of 3 min to allow participants to reach steady state. All trials [except the 100 % in the G-VENT) were similar to the target $\dot{V}_E$, however, the difficulty participants had in mimicking the ventilation rates is a significant limitation which questions the validity of the non-significant differences in oxygen cost of breathing between the two protocols.

In Chapter 4, the GXT produced significantly lower $\dot{V}_{Emax}$ values compared to a gradient-based SPXT and non-significantly lower $\dot{V}_{Emax}$ values compared to a speed-based SPXT. Using a calculation based on the data by Vella et al (2006), it was calculated that the GXT had a significantly greater oxygen cost of breathing compared to both the SPXT protocols. In the current Chapter, using data purely collected from the current cohort, there were no significant differences between the oxygen cost of breathing, which is to be expected considering the similar $\dot{V}_{Emax}$ values. Why the oxygen cost may have been different between the current study and Chapter 4 could potentially be explained by the differences in protocols. In the Chapter 4, whilst only the gradient based SPXT provided significantly greater $\dot{V}O_{2max}$ values, the speed-based SPXT produced significantly higher speeds compared to the GXT, and that, as noted in Chapter 4, participants anecdotally found the gradient based SPXT much more taxing than the other two protocols. As supramaximal

intensities have been found to drive up $\dot{V}_E$ (Norton et al., 1995) it is entirely possible these

differences in $\dot{V}_E$ may have been as a result of the greater intensities often achieved during

the SPXT. This would also be in agreement with previous findings in which $\dot{V}_E$ was higher

in the SPXT in which greater peak intensities were also achieved (Faulkner et al., 2015;

Jenkins et al., 2017a), although prior studies have found no differences in $\dot{V}_{Emax}$ despite

higher intensities achieved during the SPXT (Scheadler & Devor, 2015). Another finding

of the current study is that the $\dot{V}O_{2vent}$ reported during the 100 % $\dot{V}_E$ trial equates to ~9 %

of $\dot{V}O_{2max}$, which is in agreement with previous research (Vella et al., 2006; Turner et al.,

2012).

The finding that $\dot{V}O_{2max}$ was not significantly different between the GXT and SPXT (68 $\pm$

7.4 vs. 68 $\pm$ 7.1 mL$\cdot$kg$^{-1}\cdot$min^{-1}, respectively) contributes to the growing number of research

studies to find the SPXT to be a valid protocol for $\dot{V}O_{2max}$. RER_{max} was significantly

higher in the SPXT which has been reported previously (see Chapter 4; Mauger &

Sculthorpe, 2012; Jenkins et al., 2017a). In the study by Jenkins et al (2017a) both RER_{max}

and PO_{peak} in cycling were significantly higher in the SPXT across different populations.

This was also the case in the findings of Mauger and Sculthorpe (2012). Although not

significantly different, in Chapter 4, RER_{max} was consistently higher in both SPXT

protocols. Although mean velocities were not different, it's possible the final stage 'spurt'

associated with the SPXT may have added a greater anaerobic contribution to the SPXT,

thus driving up RER_{max}. This would also be supported by the finding that RPE_{max} was

significantly higher in the SPXT, suggesting participants found the SPXT more

challenging. However, it is worth noting that whilst 70 % of participants satisfied plateau

criteria in the GXT, all participants had $\dot{V}O_{2max}$ confirmed via the verification stage,

suggesting a maximal performance was still given in the GXT.

In Chapter 4, peak speeds were compared between SPXT protocols and GXT, finding that the SPXT produced significantly higher peak speeds compared to the GXT. A secondary finding of the current study is that the $_v$RPE20 is similar to the V_{max} calculated from the GXT. V_{max} has successfully been used as a training parameter (Smith et al., 2003; Manoel et al., 2017) and so if the SPXT could produce a comparable parameter, this would open up possibilities to prescribe training via the SPXT. This would then give the SPXT added utility. As such, it was found that the V_{max} calculated via the GXT and the $_v$RPE20 calculated via the SPXT were not significantly different. It is therefore recommended that future research investigate the use of $_v$RPE20 for training prescription in relation to the SPXT.

5.6. Conclusion

Whilst this study adds to the growing number of studies investigating $\dot{V}O_{2max}$ testing using the SPXT, any mechanistic differences in $\dot{V}O_{2max}$ found in the SPXT [although not in the current Chapter] are not likely due to ventilation, as no differences in this measure were found in the current study. However difficulties in mimicking ventilation rates mean this still requires further investigation. In line with the findings from Chapter 4, $\dot{V}O_{2max}$ was not significantly different between protocols, and as such, future research should develop beyond $\dot{V}O_{2max}$ validity during the SPXT. The utility of the SPXT in prescribing training should be investigated, and as an extension of this, the ability of the SPXT to provide

training parameters such as a velocity similar to V_{max}, and ventilatory thresholds would be

beneficial.

Chapter 6: Prescribing 6 weeks of running training using parameters from the SPXT

Aspects of the following chapter have been included within the following manuscript, Hogg, J. S., Hopker, J. G., Coakley, S. L., Mauger, A. R. (2018). Prescribing 6-wk of running training using parameters from a self-paced maximal oxygen uptake protocol. *European Journal of Applied Physiology*, *5*, 911-918.

Available at: https://kar.kent.ac.uk/65903/

6.1. Abstract

The SPXT may offer effective training prescription metrics for athletes. This study aimed to examine whether SPXT-derived data could be used for training prescription. Twenty-four recreationally active male and female runners were randomly assigned between two training groups: (1) Standardised (STND) and (2) Self-Paced (S-P). STND had training prescribed via GXT data, whereas S-P had training prescribed via SPXT data. $\dot{V}O_{2max}$, $_v\dot{V}O_{2max}$, T_{max}, $_vRPE20$, CS, and LT were determined before and after the 6 wk training. Results demonstrate that STND and S-P training significantly improved $\dot{V}O_{2max}$ by 4 ± 8 % and 6 ± 6 %, CS by 7 ± 7 % and 3 ± 3 %; LT by 5 ± 4 % and 7 ± 8 %, respectively (all $P < 0.05$), with no differences observed between groups. The current study demonstrates that novel metrics obtained from the SPXT can offer similar quality of training prescription and improvement in $\dot{V}O_{2max}$, CS and LT compared to training derived from a traditional GXT.

6.2. Introduction

In Chapter 5 the mechanistic differences regarding ventilation were investigated. $\dot{V}O_{2max}$ and key physiological variables were not different between protocols. As a secondary measure, the average velocity during the final stage of the SPXT was reported to not be significantly different to the V_{max} measured during the GXT. As the validity of the SPXT is now well founded, it is now important to assess the practical applications of the SPXT. Therefore, Chapter 6 will investigate the utility of the SPXT in training prescription.

The utility of the SPXT beyond simple $\dot{V}O_{2max}$ measurement has yet to be investigated in depth. Greater emphasis should be placed on the practical advantages the SPXT has over the GXT. The problems associated with the GXT are well documented (Noakes, 2008), whilst it has been put forward that the SPXT may represent a paradigm shift in $\dot{V}O_{2max}$ testing (Beltz et al., 2016). This is due to self-paced protocols offering greater ecological validity due to the self-paced and closed-loop nature, whilst also circumventing the issue of estimating the ramp-rate and starting work-rate for the researcher or practitioner (Poole & Jones, 2017).

The GXT offers additional metrics in addition to the measurement of $\dot{V}O_{2max,}$ such as $_v\dot{V}O_{2max}$, T_{max}, and V_{max}. However, the identification of T_{max} requires an additional test which adds to the impracticality of the GXT for prescribing training. Nevertheless, $\dot{V}O_{2max}$, $_v\dot{V}O_{2max}$, $T_{max,}$ and V_{max} have been shown to be useful and viable parameters in running training and performance (Billat & Koralsztein, 1996; Smith et al., 2003; Esfarjani & Laursen, 2007; Manoel et al., 2017) and can be used to prescribe training and assess

training adaptations. If similar metrics for training prescription could be acquired from the SPXT, in a singular test, it would demonstrate utility over and above traditional GXT assessment of $\dot{V}O_{2max}$, especially as the SPXT is an effective test for highly trained runners (see Chapter 4; Scheadler & Devor, 2015), and has good test-retest reliability (Lim et al., 2016; Jenkins et al., 2017a). As such, this study aimed to investigate whether training prescribed via novel metrics derived from the SPXT could result in comparable improvements in key aerobic parameters as training formulated from traditional GXT variables.

6.3. Method

6.3.1. Participants

Twenty-four recreationally active male (n = 16) and female runners (n = 8) (Mean ± SD: Age = 30 ± 9 years, body mass = 70 ± 13 kg, height = 172 ± 9 cm) volunteered to participate in this study. Sample size was estimated from power calculations (G-Power software, Franz Faul, Universitat Kiel, Germany) with mean and SD data from a similar training study (Esfarjani & Laursen, 2007). The study was conducted with the approval of the Ethics Committee of the School of Sport & Exercise Sciences at the University of Kent. All participants who volunteered read and provided written informed consent before participation.

6.3.2. Exercise Tests

Participants were randomly allocated into two groups: 'Standardised' (STND) and 'Self-paced' (S-P). All participants completed a GXT, an SPXT, and a sub-maximal lactate threshold (LT) test on a motorised treadmill (Saturn, H/P/Cosmos, Nussdorf-Traunstein, Germany), and a critical speed (CS) test as part of baseline testing on three separate occasions over a two week period. The $\dot{V}O_{2max}$ protocols were completed in a randomised order, 2-7 days apart and at the same time of day ($\pm$ 2 h). $\dot{V}O_2$ (Metalyzer 3BR2, Cortex, Lepzig, Germany) and heart rate (T31, Polar Electro Inc, New York, USA) were recorded for the duration of the testing protocol. Before each test, participants performed a warm-up of their choice on the motorised treadmill, which was kept the same for all subsequent tests. The CS test was completed on an all-weather synthetic 400 m running track using the method outlined by Galbraith (2011). Briefly, this involved three runs at distances of 3600 m, 2400 m, and 1200 m, each separated by 30 min recovery. For the LT protocol, participants completed 4 min stages on the treadmill with a capillary blood sample (Biosen C-Line, EKF Diagnostics, Barleben, Germany) taken at the end of each stage, with the velocity increasing by 1 $km \cdot h^{-1}$ at the beginning of each stage. Starting speed was estimated based on each participant's individual fitness level. The test was terminated once the first and second lactate thresholds (LT1 and LT2, respectively) had been obtained, defined as blood lactate readings of 2 and 4 $mmol.L^{-1}$, respectively. Following baseline testing all participants then undertook a 6 wk field-based training program, consisting of two high intensity interval training sessions, one recovery run, and a tempo run per week. Training sessions were either based on data from the SPXT or GXT [depending on group allocation]. Participants completed either a GXT, or SPXT mid-training [depending on group allocation] in the third week of the training programme. This test replaced one of the high intensity sessions for that week, with its sole purpose to recalibrate interval session

intensity in both groups. All baseline tests were then repeated in the immediate two-weeks that followed the 6 wk training intervention.

6.3.3. GXT

The GXT was conducted in accordance with the procedures previously outlined in the general methodology (see Chapter 3). V_{max} was determined as the highest velocity that could be maintained for at least 30 s.

6.3.4. Determination of T_{max}

For the GXT, T_{max} was measured in a separate bout of exercise (Smith et al., 2003). After a 20 min recovery (Nolan et al., 2014) following the GXT, participants warmed up on the treadmill at 60 % V_{max} for 5 min. Participants were then allowed to stretch before remounting the treadmill with the speed being ramped up over 30 s until V_{max} was reached. Participants were then asked to continue until volitional exhaustion. Heart rate and expired gas were recorded throughout this test.

6.3.5. Self-paced exercise test

The SPXT was conducted in accordance with the procedures previously outlined in the general methodology (see Chapter 3).

6.3.6. Determination of $\dot{V}O_{2max}$

$\dot{V}O_2$ plateau and secondary criteria were calculated as outlined in the general methodology (see Chapter 3).

6.3.7. Training programme

All participants completed two high-intensity interval sessions per week, along with a recovery run and a tempo run. This equated to four exercise sessions per week. Participants were free to schedule the sessions throughout each week but were encouraged to not complete interval sessions and tempo run on consecutive days. All sessions were completed using an assigned GPS watch (310XT, Garmin International Inc, KS, USA), and training was logged in a training diary

6.3.7.1. STND Group

For each interval session, participants completed 6 intervals at V_{max} with duration determined as 60 % of T_{max} (Smith et al., 2003). A 2:1 ratio was used to determine the recovery stage duration in-between each interval. Recovery run intensity was calculated as 60 % of their HR_{max} obtained from the GXT. Participants were required to run for 30 min. This session was included to help ensure participants would not be encouraged to supplement their program with additional training.

Tempo run intensity was determined from the submaximal LT test and participants were required to run at a velocity calculated as 50 % between LT1 and LT2 for 30 min.

6.3.7.2. S-P Group

For each interval session, participants completed 7 x 2 min intervals at $_v$RPE20. A 2:1 ratio was used to determine the recovery stage duration in-between each interval. The recovery run was the same as in the STND group, but intensity was calculated as 60 % of their HR_{max} obtained from the SPXT.

Tempo run intensity was determined by calculating the VT via the V-Slope method from the $\dot{V}O_2$ and $\dot{V}CO_2$ data collected during the SPXT (Beaver et al., 1986). The participants were then asked to run at an RPE that corresponded with the stage of the SPXT in which the VT was achieved. The participants were asked to freely adjust their pacing to match the required RPE.

6.3.8. Statistical Analysis

Data were checked for normality of distribution using the Shapiro-Wilk statistic. To assess maximal value differences between protocols, a paired samples t-test, or a Wilcoxon signed rank test for not normally distributed data, was performed. Based on the achieved effect size, a post hoc power analysis demonstrated that the statistical power of the pre-post $\dot{V}O_{2max}$ comparison was 0.93. To identify training responses for both training groups (group) and GXT and SPXT protocols (protocol) for before and after training (time-point) a mixed model ANOVA was used. Where no interaction effect was identified between a variable and protocol (GXT and SPXT), the protocol was omitted from further analysis of training responses for that variable. Participants' CS were calculated from the field test using a linear distance-time model. η_p^2 was used to report effect sizes, and statistical

significance was accepted when $P < 0.05$. All statistical tests were completed using SPSS version 24 (Chicago, IL, USA).

6.4. Results

6.4.1. SPXT vs. GXT Protocol Data

6.4.1.1. Incidence of $\dot{V}O_2$ plateau in GXT and secondary criteria achievement in SPXT

In pre-testing, the average stage-to-stage increase in $\dot{V}O_2$ for all participants was calculated as 268 ± 112 mL·min^{-1}, so that a mean plateau phenomenon for pre-testing was defined as a change in $\dot{V}O_2 \leq 134 \pm 56$ mL·min^{-1} (or relative $\dot{V}O_2$ 1.9 mL·kg^{-1}·min^{-1}), between the highest 30 s average obtained from each of the final two stages of the test for each participant. In the GXT, 50 % of participants achieved a plateau whilst the remaining participants all satisfied secondary criteria. In the SPXT, ninety-six percent of participants satisfied secondary criteria.

In post-testing, the average stage-to-stage increase in $\dot{V}O_2$ for all participants was calculated as 234 ± 66 mL·min^{-1}, so that a mean plateau phenomenon for post-testing was defined as a change in $\dot{V}O_2 \leq 117 \pm 33$ mL·min^{-1} (or relative $\dot{V}O_2$ 1.7 mL·kg^{-1}·min^{-1}), between the highest 30 s average obtained from each of the final two stages of the test for each participant. In the GXT, 63 % of participants achieved a plateau whilst the remaining participants all satisfied secondary criteria. In the SPXT, all participants satisfied secondary criteria.

6.4.1.2. Differences in test protocols

Differences in test protocols for key variables for all participants are presented in Table 6.1. Pre and post-training data were combined to compare the GXT and SPXT protocols. There were no significant differences in $\dot{V}O_{2max}$ between the GXT and SPXT protocols (t_{47} = .56, P = .58). RER_{max} was significantly greater in the SPXT compared to the GXT (t_{47} = -4.64, P < .01). There were no significant differences between test protocols for either HR_{max} (t_{47} = 1.27, P = .21) or $\dot{V}_{Emax}$ (t_{47} = -1.01, P = .32). Protocol duration was significantly longer in the GXT (t_{47} = 6.01, P < .01). RPE_{max} was significantly greater in the SPXT (Z = -5.15, P < .01). There were no significant differences between V_{max} and $_vRPE20$ (t_{45} = -1.54; P = .13).

Table 6.1 Mean ± SD values for physiological and intensity variables recorded during both GXT and SPXT protocols across both before and after training for all participants.

Variable	Protocol	
	GXT	**SPXT**
$\dot{V}O_{2max}$ **(mL·kg^{-1}·min^{-1})**	54 ± 5.8	54 ± 0.7
HR$_{max}$ (beats/min)	186 ± 12	184 ± 11
$\dot{V}_{Emax}$ **(mL·min^{-1})**	135.4 ± 29.4	137.2 ± 24.8
RER$_{max}$	1.15 ± 0.02	1.21 ± 0.00*
V$_{max}$ / $_v$RPE20 (km·h$^{-1)}$	14.8 ± 1.3	15 ± 1.5
Mean test time (min)	11 ± 1*	10 ± 0
RPE$_{max}$	19 ± 1	20 ± 0*

* Denotes significant difference between protocols (P < 0.05)

6.4.2. STND vs. S-P Training Data

6.4.2.1. Training prescription

Total prescribed training duration over the 6 wk period for both training groups was not significantly different ($t_{22} = -.46$, $P = .65$). The STND had a prescribed total duration of 804 ± 90 min whilst the S-P had a prescribed total duration of 816 ± 0 min. There was no significant difference between the mean interval session duration for both STND and S-P (37 ± 8 vs 38 ± 0 min, respectively) ($t_{22} = -.42$, $P = .68$).

Table 6.2 Training prescription for representative participants in both training groups.

Rep. participant	Interval session x 2		Tempo Run	Recovery Run
	Wk 1-3	**Wk 4-6**	**Wk 1-6**	**Wk 1-6**
STND	Work: 6 x 167 s @ 15 km$\cdot$h^{-1}	Work: 6 x 141 s @ 16 km$\cdot$h^{-1}	30 min @ 11.3 km$\cdot$h^{-1}	30 min @ 115 bpm
	Recovery: 5 x 334 s @ 8 km$\cdot$h^{-1}	Recovery: 5 x 282 s @ 8 km$\cdot$h^{-1}		
S-P	Work: 7 x 120 s @ 15.6 km$\cdot$h^{-1}	Work: 7 x 120 s @ 16.3 km$\cdot$h^{-1}	30 min @ RPE13	30 min @ 114 bpm
	Recovery: 6 x 240 s @ 8 km$\cdot$h^{-1}	Recovery: 6 x 240 s @ 8 km$\cdot$h^{-1}		

6.4.2.2. Responses to Training

Group data (pre- vs. post-training) are shown in Table 6.3. As outlined in the methods, participants were grouped into either S-P or STND, and conducted both an SPXT and GXT before and after the training intervention. There was no interaction effect for protocol duration between groups identified ($F_{1,22} = .56$, $P = .46$, $\eta_p^2 = .03$). As shown in Figure 6.1 and Table 6.3, there was a significant difference for $\dot{V}O_{2max}$ for pre and post training ($F_{1,22} = 7.461$, $P = .01$, $\eta_p^2 = .25$) but there was no interaction effect identified ($F_{1,22} < .01$, $P = .954$, $\eta_p^2 < .01$). Whilst there was a significant difference for $\dot{V}_{Emax}$ for pre and post training ($F_{1,22} = 12.59$, $P < .01$, $\eta_p^2 = .36$), there was no interaction effect identified ($F_{1,22} < .01$, $P = .98$, $\eta_p^2 < .01$). There was no interaction effect for HR_{max} ($F_{1,22} = 1.06$, $P = .31$, $\eta_p^2 = .05$). There was a significant difference for $_vRPE20$ and V_{max} for pre and post training ($F_{1,20} = 5.80$, $P = .03$, $\eta_p^2 = .23$). As shown in Figure 6.2, for both groups, there were no differences in V_{max} and $_vRPE20$ before training (14.3 ± 1.3 vs. 14.3 ± 1.7 km·h^{-1}, respectively), but $_vRPE20$ was greater than V_{max} after training (15.7 ± 1.3 vs. 15.2 ± 1.3 km·h^{-1}, respectively). CS significantly improved in both groups before and after training ($F_{1,21} = 26.12$, $P < .01$, $\eta_p^2 = .56$) however there was no interaction effect identified ($F_{1,21} = 3.01$, $P = .10$, $\eta_p^2 = .13$). Similarly, LT1 and LT2 significantly improved in both groups ($F_{1,21} = 14.64$, $P < .01$, $\eta_p^2 = .41$) however there was no interaction effect identified ($F_{1,21} = 1.23$, $P = .28$, $\eta_p^2 = .06$).

Table 6.3 Mean ± SD maximal values for physiological and threshold variables recorded before and after training for both training groups. In the STND all data is provided via the GXT and by the SPXT for the S-P.

	Training Group			
Variable	**Standardised (STND)**		**Self-Paced (S-P)**	
	Pre	Post	Pre	Post
$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	54 ± 5.0	56.3 ± 6.2*	51.7 ± 5.3	54.8 ± 5.7*
$\dot{V}_{Emax}$ (mL·min^{-1})	130.2 ± 22.6	134.7 ± 20.4*	134.3 ± 28.7	141.5 ± 29.0*
HR$_{max}$ (beats/min)	190 ± 13	188 ± 13	181 ± 13	182 ± 9
Critical speed (m.s^{-1})	3.47 ± .03	3.70 ± .03*	3.47 ± .04	3.59 ± .05*
LT1 (km·h^{-1})	10 ± 1.2	10.5 ± 1.2*	9.7 ± 1.5	10.5 ± 1.3*
LT2 (km·h^{-1})	11.7 ± 1.2	12.2 ± 0.8*	11.1 ± 1.8	12.1 ± 1.5*

* Denotes significant difference between the pre- and post-test ($P < 0.05$)

Table 6.4 Mean ± SD completion times for individual distance trials from the critical speed test for both groups before and after training

Distance trial	**Standardised (STND)**		**Self-Paced (S-P)**	
	Pre	Post	Pre	Post
3600 m (s)	1003 ± 87	940 ± 78	1021 ± 129	986 ± 121
2400 m (s)	667 ± 60	626 ± 54	681 ± 92	662 ± 91
1200 m (s)	306 ± 28	288 ± 22	320 ± 43	309 ± 40
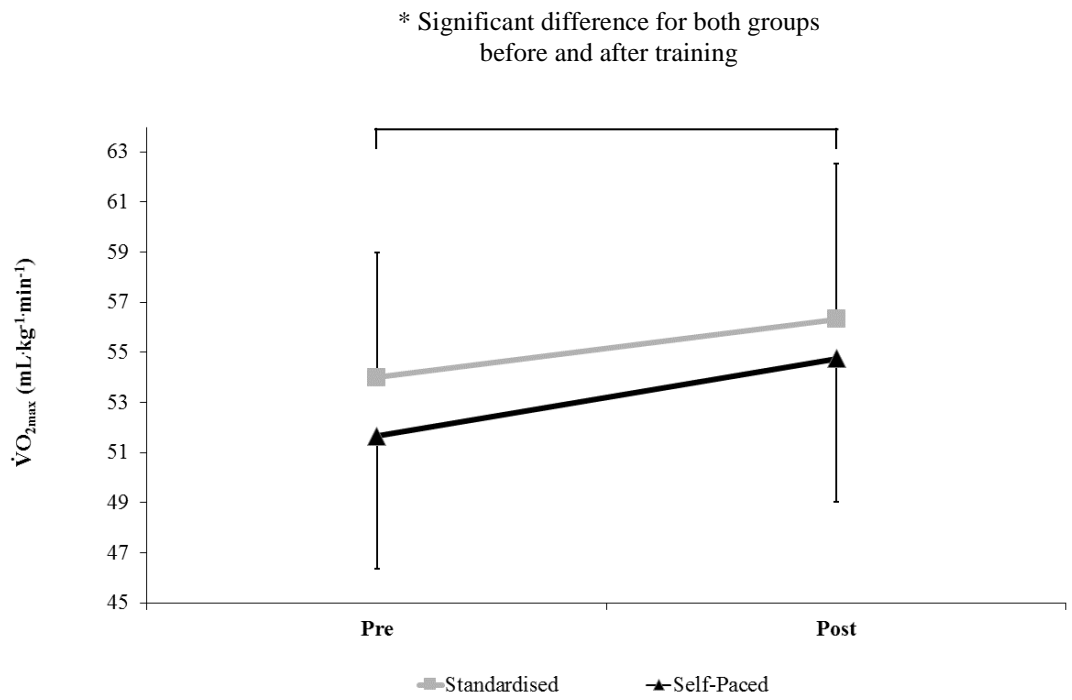
Figure 6.1 Mean ± SD differences in $\dot{V}O_{2max}$ between the STND and S-P training groups before and after training
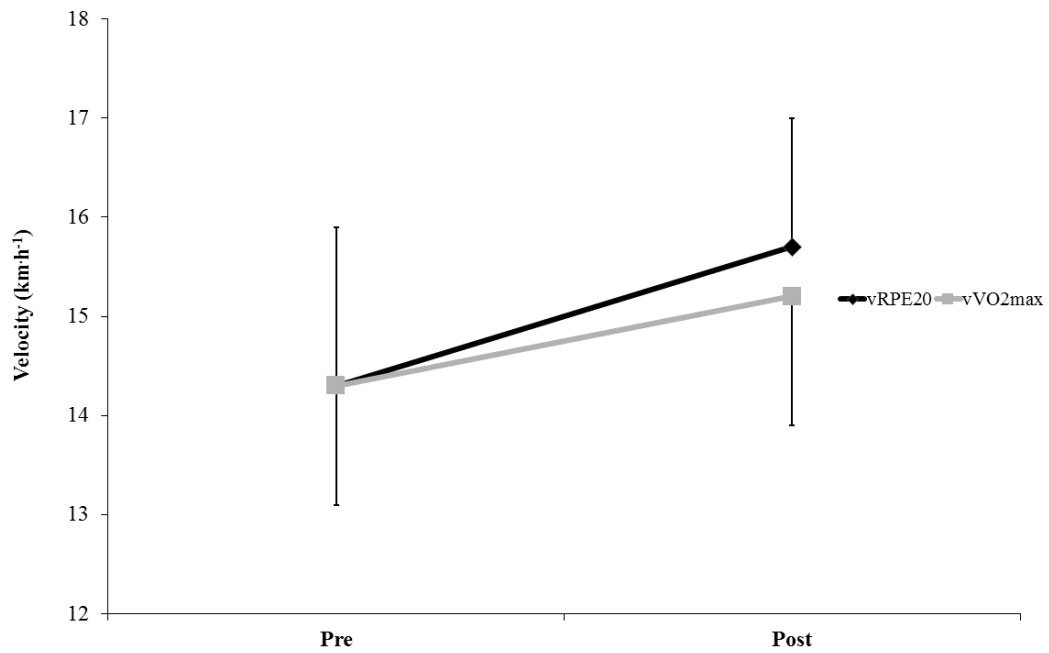
Figure 6.2 Mean ± SD Differences in the velocities V_{max} and $_vRPE20$ for all participants for before and after training

6.5. Discussion

The primary finding of this study was that following a 6 wk period of training, recreational runners' aerobic fitness and running performance was increased by a similar magnitude, regardless of whether SPXT or GXT data were used to prescribe training. Specifically, $\dot{V}O_{2max}$ in the STND group improved by 4 ± 8 %, and by 6 ± 6 % in the S-P group. An improvement in $\dot{V}O_{2max}$ in the region of ~3 % has previously been defined as a meaningful improvement in performance (Kirkeberg et al., 2011), as opposed to day-to-day variation. Previous literature has shown improvements in $\dot{V}O_{2max}$ by ~6 % when training at 106 % $_v\dot{V}O_{2max}$ (Franch et al., 1998) for similar training durations. However, in the

aforementioned study the starting $\dot{V}O_{2max}$ for the participants were significantly lower than those reported in the current study, which may suggest a greater level of trainability for $\dot{V}O_{2max}$ (Swain & Franklin, 2002) compared with the participants in the current study. Athletes of slightly higher training status' than those in the current study achieved little to no improvements in $\dot{V}O_{2max}$ over 4-6 wk of similar intensity training (Smith et al., 2003; Denadai et al., 2006; Manoel et al., 2017), but did show significant improvements in LT and 3-10 km running performance. Similar running programmes utilising interval training have also produced improvements in CS (Clark et al., 2013). This is supported by the findings of the current study that in both STND and S-P, CS improved by 7 ± 7 % and 3 ± 3 %, respectively (see Tables 6.3 and 6.4). For LT1 and LT2, STND improved by 5 ± 4 % and 3 % and S-P improved by 7 ± 8 % and 8 %.

An important finding of this study is that the novel training parameter extracted from the SPXT, $_vRPE20$, is effective at prescribing running intensity for interval training. The V_{max} for the STND before and after training was 14.3 ± 0.9 vs. 15.2 ± 1.0 $km\cdot h^{-1}$ compared to 14.2 ± 1.9 vs. 15.7 ± 1.9 $km\cdot h^{-1}$ for $_vRPE20$ in the S-P, respectively. V_{max} has recently been shown to be as beneficial as $_v\dot{V}O_{2max}$ for exercise prescription (Manoel et al., 2017), and like $_vRPE20$ is simple to calculate. Moreover, $_vRPE20$ has been shown to be repeatable regardless of the pacing strategy adopted during this final stage (Hanson et al., 2017). This should be reason to encourage further investigation to assess the potential of $_vRPE20$ in training prescription and its suitability as a performance parameter.

As the aim of the study was to investigate whether SPXT-derived training parameters could offer similar improvements in aerobic fitness compared to GXT prescribed training,

it was important that training prescription was similar between groups in both intensity and duration. To calculate interval duration for the STND, 60 % T_{max} was used. Setting interval duration at 60 % of an individual's T_{max} has been shown to produce significant improvements in aerobic parameters and 3-10 km running performance (Smith et al., 2003; Esfarjani & Laursen, 2007; Manoel et al., 2017). In the study by Smith et al (2003), 60 % T_{max} resulted in an average interval duration of 6 x 133 ± 4 s. This equated to ~13 min of high intensity effort per interval session. In the current study, 7 intervals at 120 s [which also matched the stage duration of the SPXT] resulted in ~14 min of high intensity effort, ensuring it was comparable to the STND group. Durations of 2 min have been shown to elicit responses closer to $\dot{V}O_{2max}$ compared to shorter intervals (O'Brien et al., 2008). Longer interval work periods may have resulted in a greater $\dot{V}O_{2max}$ improvement (Esfarjani & Laursen, 2007; O'Brien et al., 2008; Seiler & Sjursen, 2002) but also significantly increased the interval duration. As a consequence, the mean prescribed training duration for each interval session over the 6 wk training period was similar between groups (37 ± 8 vs. 38 ± 0 min for STND and S-P, respectively). Total training time over the 6 wk period was also similar (804 ± 90 vs. 816 ± 0 min, for STND and S-P respectively).

The similar $\dot{V}O_{2max}$ found between both protocols in this study is in line with previous research (see Chapter 4; Chidnok et al., 2013; Straub et al., 2014; Faulkner et al., 2015; Scheadler & Devor, 2015; Hanson et al., 2016; Lim et al., 2016). Even though test duration was significantly longer in the GXT, the test was still similar to the recommended duration of ~10 min (Yoon et al., 2007), and the $\dot{V}O_{2max}$ achieved was not significantly different between protocols. Interestingly, RER_{max} was significantly higher in the SPXT, which has been observed in some (see Chapter 4; Mauger & Sculthorpe, 2012; Jenkins et al., 2017a),

but not all previous SPXT literature (Straub et al., 2014; Astorino et al., 2015; Faulkner et al., 2015; Lim et al., 2016). Consequently, no consensus on whether the SPXT produces a higher RER_{max} can be currently drawn. However, it can be speculated that this potential difference in RER_{max} may be due to the higher peak velocities experienced in the SPXT compared to the GXT, indicative of a greater anaerobic contribution towards the end of the test. This is supported by the recent work of Hanson et al (2017) who found, when comparing two SPXT trials with different RPE20 pacing strategies, that RER_{max} was significantly greater in the SPXT that adopted the more aggressive pacing strategy.

A perceived limitation of this Chapter could be the lack of a control group, however as the main aim of the Chapter was to compare between the two methods of training this was not deemed essential. Comparing between the different methods; training via the SPXT-derived parameters, and the established method of prescribing training via GXT-derived parameters, was the central aim over investigating absolute improvements in cardiorespiratory fitness in individuals. This model has previously been utilized in the literature (Manoel et al., 2017).

6.6. Conclusion

The ability to prescribe training for recreationally active males and females via SPXT-derived parameters offers coaches and athletes valuable alternatives to traditional methods. Prescribing training via the SPXT is as effective but more time-efficient. Specifically, the

same level of improvement in key aerobic fitness parameters can be obtained when training is set via novel training parameters collected from a single 10 min SPXT test compared to that achieved using a GXT and a mandatory additional test to acquire T_{max} data. This alone may make the SPXT more attractive to athletes and coaches, however, recent research regarding a field based SPXT (Lim et al., 2016) may emphasise this further. Whilst a field-based SPXT has been shown to produce a valid directly measured $\dot{V}O_{2max}$, future research should investigate whether $\dot{V}O_{2max}$ can be accurately estimated from the field based SPXT. If so, athletes and coaches would then be able to utilise a single 10 min test on an athletics track, without expensive equipment, that would offer accurate $\dot{V}O_{2max}$ estimation and data for effective training prescription. Therefore, the current findings demonstrate that training parameters derived from the SPXT protocol can be used to prescribe effective running training that is similarly effective to training prescribed from GXT-derived parameters. Consequently, in the group that was prescribed training using SPXT-derived parameters, $\dot{V}O_{2max}$, LTs and CS showed similar improvements compared to runners who were prescribed training via the velocity at $\dot{V}O_{2max}$ and LT zones, with training durations and intensities suitably similar between groups throughout training.

Chapter 7: Comparison of the ventilatory thresholds obtained from the self-paced and graded exercise protocols

7.1. Abstract

The SPXT may offer the calculation of VT1 and VT2. This study aimed to examine whether VT1 and VT2 could be calculated via the SPXT. Data from twenty-one recreationally trained (RT) runners and twelve highly trained runners (HT) from the previous Chapters (4, 5, and 6) were analysed. VT1 was calculated using the V-Slope method and VT2 via plotting of $\dot{V}_E/\dot{V}CO_2$. Results demonstrated that in HT, VT1 and VT2 [as % $\dot{V}O_{2max}$] were similar between the SPXT (83 ± 6 and 91 ± 5 %, respectively) and GXT (85 ± 3 and 93 ± 3 %, respectively). In RT, VT2 was similar between SPXT and GXT (86 ± 5 vs. 88 ± 3 %, respectively) but VT1 was significantly lower in the SPXT compared to the GXT (73 ± 6 vs. 78 ± 3 %, respectively). The current study demonstrates that in highly trained runners, the SPXT offers similar ventilatory parameters compared to the GXT whereas in recreationally trained runners, there is some disparity in VT1, but VT2 is similar, suggesting that in general the SPXT calculates approximately the same ventilatory thresholds as via the GXT.

7.2. Introduction

In Chapter 6, the utility of the SPXT, and parameters derived from it in training prescription were explored. In recreationally trained runners the SPXT was able to offer similar training and performance benefits when compared to training set via the GXT. Whilst the primary training was intervals set using either $_v$RPE20, or V_{max} [in the SPXT and GXT, respectively], VT1 was also calculated in the SPXT to prescribe intensity for a tempo run and this was comparable to a tempo run set via LT for the GXT-set group. However, the wider validity of setting VT (both VT1 and VT2) via the SPXT was not explored and comprehensively compared to VT via the GXT and so Chapter 7 will focus on this concept.

The attainment of VT can be beneficial in prescribing exercise intensities and training zones for athletes (Esteve-Lanao et al., 2007; Seiler, 2010; Mora et al., 2016). Whilst no 'gold standard' for VT measurement exists, it is generally obtained during a GXT with either a RAMP or STEP design, and thus means the GXT is able to offer valuable information beyond $\dot{V}O_{2max}$ measurement (Black et al., 2014). This key factor means VT may be more beneficial than lactate thresholds, as the measurement of LT typically requires a protocol of much longer stages than those typically used in a GXT (Plato et al., 2008) and so additional testing is usually required.

Until recently, the SPXT has been used to predominantly assess $\dot{V}O_{2max}$, with it previously suggested that the disadvantage of the SPXT is that it cannot offer information on VT due to the irregular incremental work-rate design and that the measurement of VT requires

consistent increases in work-rate (Straub et al., 2014). This has been shown to not necessarily be the case as multiple studies have recently calculated VT via the SPXT and found it comparable to the GXT (Jenkins et al., 2017; Truong et al., 2017; Beltz et al., 2018). All of these studies have calculated VT1, with Truong et al (2017) unable to calculate VT2. This is perhaps due to the modified-SPXT that they used (which included 1 min stages instead of 2 min) resulting in an inconsistency in work-rate increase and thus made VT2 difficult to calculate. Of the two studies that have investigated VT in running-based SPXT, one has used a semi-automated treadmill and a modified SPXT whilst the other has used untrained participants. This Chapter will therefore investigate the use of the SPXT in identifying VT1 and VT2 in both recreationally and highly trained runners when using a motorised treadmill.

7.3. Method

7.3.1. Participants

This study utilised datasets from previous experimental Chapters (see Chapters 4, 5, and 6). Criteria for the inclusion of data was defined as participants who had completed both a GXT and a SPXT (hereon defined as a data set) within 7 days of one another under the same laboratory conditions. An SPXT could only be paired with the corresponding GXT which took place within the previously stated 7 day period, and vice-versa. Participant data were divided into two sub-sets: highly trained (HT) (data collected from Chapters 4 and 5) and recreationally trained (RT) (data collected from Chapter 6). In the RT subset, multiple data sets for a single participant could be included if they met the previously described

criteria. The HT subset included data for twelve highly trained male runners (mean ± SD: age = 27 ± 4 years, mass = 177 ± 7 cm, weight = 70 ± 7 kg). The RT subset included data for twenty-one recreationally trained male and female runners (mean + SD: age = 27 ± 7 years, mass = 172 ± 9 cm, weight = 68 ± 11 kg).

7.3.2. Protocols

The GXT and SPXT were as described in the general methodology (see Chapter 3). In the HT subset, the GXT and SPXT were completed using a 3 % gradient whilst the RT subset protocols utilised a 1 % gradient. $\dot{V}O_{2max}$, $\dot{V}O_2$ at VT1 ($\dot{V}O_{2VT1}$), $\dot{V}O_2$ at VT2 ($\dot{V}O_{2VT2}$), and HR were calculated as 30 s averages.

7.3.3. Determination of VT1 and VT2

VT1 was primarily defined using the V-Slope method (Beaver et al., 1986), described as the $\dot{V}O_2$ that corresponds with the first break-point ($\dot{V}O_{2VT1}$) in the $\dot{V}O_2$ vs. $\dot{V}CO_2$ relationship. This was then confirmed by at least one of the following criteria: an increase in $\dot{V}_E/\dot{V}O_2$ without a concurrent rise in $\dot{V}_E/\dot{V}CO_2$; first increase in $P_{ET}O_2$ with no concurrent fall in $P_{ET}CO_2$. VT2 was defined as the $\dot{V}O_2$ that corresponds with the break point ($\dot{V}O_{2VT2}$) in the $\dot{V}_E$ vs. $\dot{V}CO_2$ relationship (Beaver et al., 1986). This was then confirmed by at least one of the following secondary criteria: First non-linear increase in $\dot{V}_E/\dot{V}CO_2$ with a continued rise in $\dot{V}_E/\dot{V}O_2$; A fall in $P_{ET}CO_2$. Secondary criteria had to be within 3 % of V-Slope to be considered valid. For every data set, a trained researcher visually analysed the individual graphs to determine VT1 and VT2. A second trained researcher then confirmed VT1 and VT2 (Gaskill et al., 2001; Esteve-Lanao et al., 2007; Black et al., 2014). Where there was no agreement within 3 %, that data set was excluded

(Gaskill et al., 2001). Participants who did not meet all of the above criteria were excluded from that particular analysis. For these reasons, data for a particular participant could be present for VT1, but not VT2, and vice versa.

7.3.4. Statistical analysis

Due to differences in protocol gradient and fitness levels the HT and RT subsets were analysed separately and not compared. VT1 and VT2 variables were not compared as different participants were present in each. Data were checked for normality of distribution using the Shapiro-Wilk statistic. Log transformation was used where the assumption of normality was violated. To assess differences between protocols for each variable, a paired samples t-test, or a Wilcoxon signed rank test for not normally distributed data, was performed. Intra- and inter-rater reliability were assessed using ICC. C*ohen's d* were used to report effect sizes, and statistical significance was accepted when $P < 0.05$. All statistical tests were completed using SPSS version 25 (Chicago, IL, USA).

7.4. Results

7.4.1. Determination reliability of VT1 and VT2

Inter-rater reliability for the SPXT for VT1 and VT2 was 1.00 and 0.98. For the GXT for VT1 and VT2 it was 1.00 and 0.97. Intra-rater reliability for the SPXT for VT1 and VT2 was 0.97 and 1.00. For the GXT for VT1 and VT2 it was 0.99 and 1.00.

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7.4.2. Recreationally trained (RT) subset

7.4.2.1. VT1

Seventeen participants and twenty-four data sets were included for VT1 analysis. There were no significant differences in $\dot{V}O_{2max}$ between the GXT and SPXT protocols (t_{23} = -.65, P = .52, ES = .04). There were significant differences in the $\dot{V}O_{2VT1}$ (t_{23} = -4.51, $P <$ .01, ES = .42) and RPE associated with this threshold between protocols (Z = 2.15, P = .03, ES = .91). There were no significant differences in HR_{max} between protocols (t_{19} = -1.85, P = .08, ES = .40). HR at VT1 was not significantly different between protocols (t_{20} = -1.58, P = .16, ES = .30). There were no significant differences in the velocities associated with VT1 between protocols (Z = -1.91, P = .06, ES = .52) and $_{v}$RPE20 and V_{max} were not significantly different (t_{18} = 2.10, P = .05, ES = .30) although % V_{max} was significantly higher than % $_{v}$RPE20 (t_{18} = 2.10, P = .02, ES = .99)

7.4.2.2. VT2

Sixteen participants and twenty-two data sets were included for VT2 analysis. There were no significant differences in $\dot{V}O_{2max}$ (t_{21} = -.96, P = .35, ES = .06) and HR_{max} between the GXT and SPXT protocols (t_{18} = -1.74, P = .10, ES = .30). There was a significant difference in the $\dot{V}O_{2VT2}$ between protocols (t_{21} = -2.35, P = .03, ES = .20), although no differences when calculated as % $\dot{V}O_{2max}$ (t_{21} = -1.95, P = .06, ES = .60). HR at VT2 was significantly different between protocols (t_{16} = -2.85, P = .01, ES = .50). There were no significant differences in the velocities (t_{21} = -.20, P = .85, ES = .06) and RPE associated with VT2 between protocols (Z = -.15, P = .89, ES = .06). $_{v}$RPE20 and V_{max} were not significantly different (t_{20} = 2.00, P = .06, ES = .23).

Table 7.1 Mean ± SD values for variables corresponding to VT1 and VT2 recorded during both GXT and SPXT protocols for recreationally trained participants.

	VT1		VT2	
Variable	SPXT	GXT	SPXT	GXT
$\dot{V}O_2$ (L·min^{-1})	2.78 ± 0.5*	2.99 ± 0.5	3.10 ± 0.6*	3.22 ± 0.6
% $\dot{V}O_{2max}$	73 ± 6*	78 ± 3	86 ± 5	88 ± 3
HR (bpm)	158 ± 16	162 ± 12	169 ± 11*	174 ± 9
% HR_{max}	74 ± 6	78 ± 3	93 ± 3	94 ± 2
RPE	14 ± 1*	13 ± 1	16 ± 1	16 ± 2
Speed (km·h^{-1})	10.9 ± 1.3	11.5 ± 1.0	12.7 ± 1.8	12.8 ± 1.5
% $_vRPE20/V_{max}$	71 ± 7*	77 ± 5	85 ± 9	88 ± 7

* Denotes significant difference between protocols for VT1 or VT2 ($P < 0.05$)
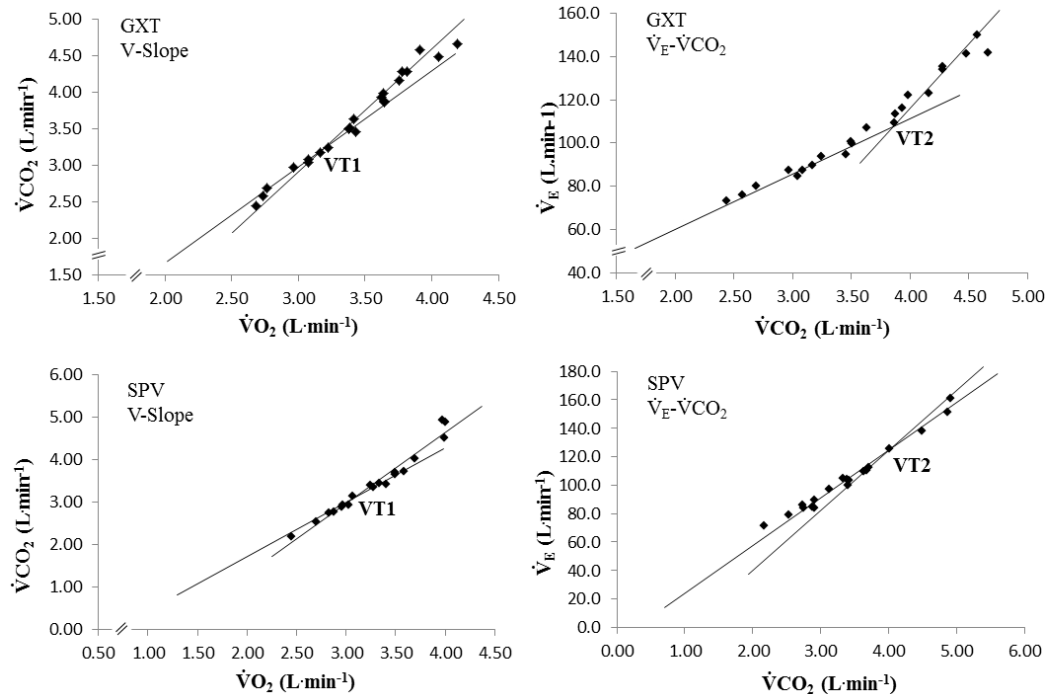
Figure 7.1 VT1 and VT2 calculated via the V-Slope and $\dot{V}_E$-$\dot{V}CO_2$ methods in both the GXT and SPXT for a representative participant in the recreationally trained subset.

7.4.3. Highly trained (HT) subset

7.4.3.1. VT1

Nine participants were included for VT1 analysis. There were no significant differences in $\dot{V}O_{2max}$ (t_8 = -.74, P = .48, ES = .16) and HR_{max} between the GXT and SPXT protocols (t_8 = -1.15, P = .29, ES = .21). There were no significant differences in the $\dot{V}O_{2VT1}$ (t_8 = -1.98, P = .10, ES = .34). There were no significant differences in the velocities (t_5 = -.73, P = .50, ES = .34), RPE (Z = -1.93, P = .09, ES = .91), and HR associated with VT1 (t_6 = -1.26, P = .26, ES = .43). $_v$RPE20 and V_{max} were not significantly different (Z = -.14, P = 1.00, ES = .07).

7.4.3.2. VT2

Eleven participants were included for VT2 analysis. There were no significant differences in $\dot{V}O_{2max}$ (t_{10} = -.43, P = .68, ES = .05) and HR_{max} between the GXT and SPXT protocols (t_9 = -.08, P = .94, ES = .10). There were no significant differences in the $\dot{V}O_{2VT2}$ (t_{10} = -1.75, P = .11, ES = .15). There were no significant differences in the velocities (t_5 = .35, P = .74, ES = .20), RPE (Z = -.67, P = .57, ES = .4) and HR associated with VT2 between protocols (t_7 = -1.99, P = .09, ES = .69). $_v$RPE20 and V_{max} were not significantly different (Z = -.67, P = .63, ES = .23).

Table 7.2 Mean ± SD values for variables corresponding to VT1 and VT2 recorded during both GXT and SPXT protocols for highly trained participants.

	VT1		VT2	
Variable	SPXT	GXT	SPXT	GXT
$\dot{V}O_2$ (L·min^{-1})	4.03 ± 0.5	4.18 ± 0.5	4.37 ± 0.6	4.54 ± 0.7
% $\dot{V}O_{2max}$	83 ± 5	85 ± 4	91 ± 5	93 ± 4
HR (bpm)	155 ± 11	159 ± 7	166 ± 12	173 ± 8
% HR$_{max}$	85 ± 3	86 ± 3	92 ± 4	94 ± 3
RPE	13 ± 1	12 ± 1	15 ± 1	15 ± 1
Speed (km·h^{-1})	13.7 ± 1.1	14 ± 0.6	15.5 ± 1.2	15.3 ± 0.8
% $_v$RPE20/V$_{max}$	79 ± 14	79 ± 2	89 ± 14	87 ± 3
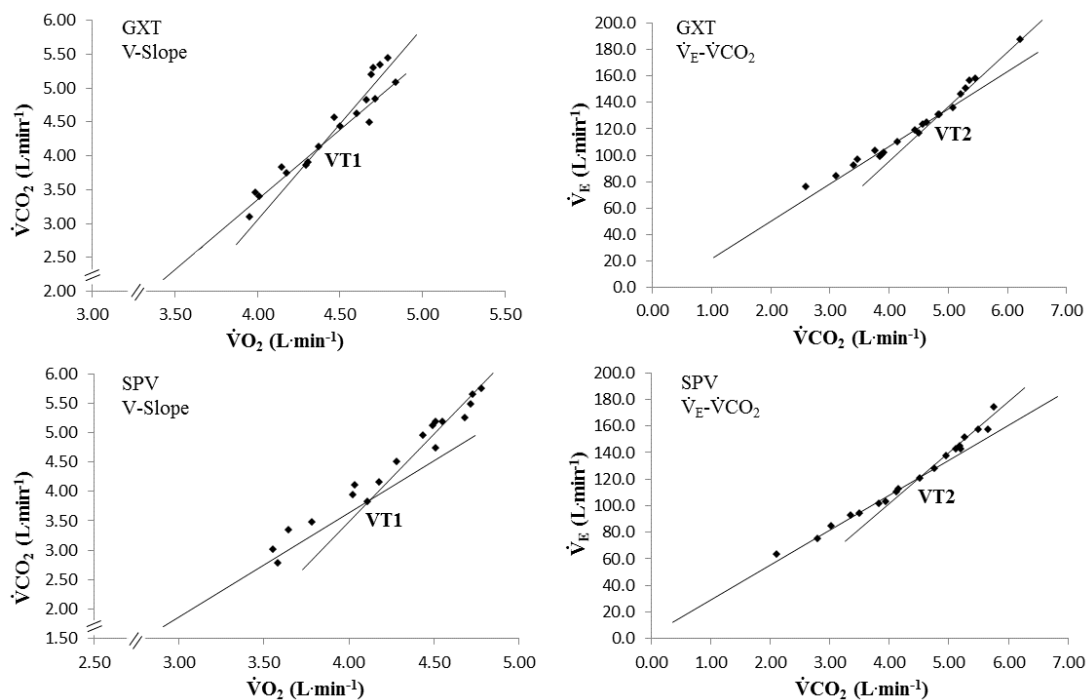
Figure 7.2 VT1 and VT2 calculated via the V-Slope and $\dot{V}_E$-$\dot{V}CO_2$ methods in both the GXT and SPXT for a representative participant in the highly trained subset.

7.5. Discussion

This is the first known study to investigate the use of the SPXT in identifying VT in both highly and recreationally trained runners. The main findings of this Chapter are that in highly trained runners, VT1 and VT2 calculated via the SPXT are similar to ventilatory thresholds calculated via the GXT. In recreationally trained runners, VT1 was lower in the SPXT compared to the GXT when calculated as either $\dot{V}O_2$ or RPE but was similar between protocols when calculated as a velocity or HR. In recreationally trained runners VT2 was lower in the SPXT when calculated as $\dot{V}O_2$ and HR, but similar as a velocity and RPE. These findings suggest the ventilatory thresholds calculated via the SPXT are comparable to the GXT.

In highly trained runners VT2 has been reported at ~88-90 % $\dot{V}O_{2max}$ (Esteve-Lanao et al. 2007; Rabadán et al., 2011) which is similar to the current findings (91 vs. 93 % in the SPXT and GXT, respectively). However, the finding that VT1 was between 83-85 % $\dot{V}O_{2max}$ is similar but higher than previous research where VT was observed at 77 % in highly trained runners (Rabadán et al., 2011), although it should be noted that athletes recruited by Rabadán et al (2011) were of a slightly lower fitness level [in relation to $\dot{V}O_{2max}$] compared to the current study. The observance of a higher VT1 may be linked to the specific training of the participants in the current study, however this was not investigated. Additionally, the use of 3 % gradient in the protocol for highly trained runners may have had an effect on VT as it has been shown that VT may be protocol dependent (Kang et al., 2001) although this warrants further investigation. In recreationally trained runners VT2 has been reported at 84 % $\dot{V}O_{2max}$ (Bergstrom et al., 2013) which is in

line with the current findings (86 vs. 88 % in the SPXT and GXT, respectively). VT1 in the recreationally trained runners was the only occasion where both the $\dot{V}O_{2VT1}$ and VT1 as a % $\dot{V}O_{2max}$ differed significantly between protocols. However, VT1 for both the SPXT and GXT were still similar to past research (McClave et al., 2011).

It has previously been suggested that a disadvantage of the SPXT is its inability to provide useful information on VT due to the requirement of a constant increase in work rate for its correct determination (Straub et al., 2014). However, there is no consensus [or gold standard] that protocols for VT determination must adhere to strict guidelines apart from the fact that most previous research has utilised STEP or RAMP protocols. Whilst Straub et al (2014) did not test their assumption, recently, multiple studies have demonstrated that the SPXT, in both cycling and running, can calculate VT (Jenkins et al., 2017a; Truong et al., 2017; Beltz et al., 2018). Whilst the two studies that have calculated VT via a running-based SPXT have used either a semi-automated treadmill, or untrained participants, the current study is the first to calculate VT via a SPXT in recreationally and highly trained runners using a motorised treadmill. Whilst the major concern of Straub et al was that the SPXT utilises variable speed [or work rate], it has previously been demonstrated in Chapter 4 (see Figure 4.2) that, although work-rate in the SPXT is not strictly linear, it still tends to form a step-like pattern as seen in a corresponding STEP-based GXT.

Interestingly, in recreationally trained runners, for VT1, despite most key variables being significantly higher in the GXT, RPE was instead significantly lower [compared to the SPXT]. Speculatively, it is possible that the higher reported RPE in the SPXT, despite the seemingly reduced physiological stress, may have been due to these recreationally trained

participants not being as accustomed with effort production trials and thus potentially over-estimated RPE in the initial stages. It should be noted that similar findings were reported in the HT group, although not of significance. These findings support the anecdotal findings of Straub et al (2014) who suggested that participants potentially perceived the SPXT as more physically demanding than the GXT, which may be linked to a 'need to think' in the SPXT compared to the GXT. In recent research by Hanson and Buckworth (2015), participants completed two running trials where one had a known end point and the other trial's end point was unknown to the participant. They reported that whilst the physiological variables between trials were the same, the known end point trial was completed significantly quicker than the unknown trial. The authors contributed this to teleoanticipation and suggested that during the unknown end-time trial, participants conserved their metabolic energy because they did not want to fatigue before the end of the trial. It is possible that this was similar for the recreational participants in the current study. Unlike Hanson and Buckworth (2015), end time in the SPXT [in this study] was known. However, because of the nature of the SPXT, it is possible that participants may have inadvertently constructed an exercise template with the known end point (10 min) in mind, and so ran more conservatively in the earlier stages to conserve energy for the final stage (which they were aware required an effort of RPE20) whilst still reporting a higher RPE.

A consistent finding of the current study was the differences in RPE associated with VT1 and VT2 between protocols in both the HT and RT groups. In RT, RPE at VT1 was lower in the GXT compared to the SPXT (13 vs. 14, respectively) and was the same (RPE 16) in both the GXT and SPXT for VT2. Similarly, in HT, RPE was again lower in the GXT compared to the SPXT (12 vs. 13) and the same for VT2 (RPE 15), however only RPE at VT1 in the RT was significantly different. The finding that the highly trained runners

found both VT1 and VT2 less perceptually challenging despite both VT occurring at higher intensities compared to the RT can be reasonably explained by their greater experience and training status. The finding that for both groups VT1 occurred at RPE 12-14 is in line with prior research (Hill et al., 1987).

A limitation of the current Chapter is the relatively small sample size of highly trained participants. Whilst VT data for a total of eleven highly trained runners were collected - which is comparable to past research (Black et al., 2014; Gordon et al., 2017; Truong et al., 2017) - issues with data collection meant the sample size of variables such as velocity at VT were relatively small. However, this relatively small sample size is predominately as a result of the strict criteria adhered to in regards to VT identification. Data from a total of forty-eight unique participants, and seventy-five data sets were initially analysed, with data from thirty-three participants meeting the criteria for VT1 and/or VT2. In line with prior literature (Gaskill et al., 2001; Cannon et al., 2009), data was rejected if it was deemed to have not met the criteria by either investigator. Interestingly however, in recent studies regarding the identification of VT in the SPXT (Jenkins et al., 2017a; Truong et al., 2017; Beltz et al., 2018), such criteria was not used, or specified, which raises questions regarding the validity of past findings and the robustness of methods used to identify VT. Whilst the sample size of highly trained participants was relatively small, due to the strict criteria used it can be reasoned that the findings regarding VT were representative and accurately judged.

7.6. Conclusion

Whilst the SPXT has previously been shown to be a valid protocol for $\dot{V}O_{2max}$ measurement and provides useful information for training prescription, this required further investigation so it could be determined to what extent the SPXT could offer valuable information that could already be provided via the GXT. This study demonstrated that the SPXT results in measurements of VT1 and VT2 in highly trained runners that are highly comparable to those derived from the GXT. These findings are also similar in recreationally trained runners, however there seems to be greater disparity in the calculation of VT1 in the SPXT for this population which may be due to inexperience of pacing on behalf of these runners, compared to their highly trained counterparts. These findings are important as they show the greater utility of the SPXT which is important for athletes and coaches who may want a more time economical alternative to the GXT whilst still obtaining the same outcome regarding data.

Chapter 8: General Discussion

8.1. General discussion

This thesis aimed to investigate the suitability of the SPXT as an alternative to the GXT in assessing cardiorespiratory fitness and prescribing endurance training and monitoring fitness parameters. Despite the long history of GXT, the issue of the practicality and real world application of these protocols was only seriously raised a decade ago by Noakes (2008) who highlighted the 'foreign' nature of the GXT in regards to how athletes actually exercise and compete. The SPXT, with its closed loop design and lack of a requirement of a set starting intensity, and the ability to self-regulate pace and intensity, may offer athletes and coaches an attractive alternative to traditional methods that simultaneously offers similar physiological data and parameters that can be used for training prescription.

The core underlying theme of SPXT-related research has been its validity in assessing $\dot{V}O_{2max}$ and how this has compared to 'gold standard' methods: the GXT. Whilst many research groups have investigated this, a criticism has been the perceived lack of consistency and uniformity between studies (Beltz et al., 2016; Hutchinson et al., 2017). This is predominately due to the methodologies used (Chidnok et al., 2013; Straub et al., 2014; Scheadler & Devor, 2015; Hanson et al., 2016; Truong et al., 2017) varying significantly from the original cycling and running protocols proposed (Mauger & Sculthorpe, 2012; Mauger et al., 2013a). Whereas the 'original' SPXT consisted of 5 x 2 min stage with RPE increments of 11, 13, 15, 17, and 20, various studies have altered this to include 1 min stages, customised stage durations and even the number of stages completed. This thesis aimed to standardise this and produce a collection of studies that consistently investigated the SPXT as it was originally defined. The major finding of this is

that in all the experimental Chapters there were no differences in $\dot{V}O_{2max}$ between the standard speed-based SPXT and the corresponding GXT. In Chapter 4, a gradient-based SPXT produced significantly higher $\dot{V}O_{2max}$ than both the GXT and the speed-based SPXT however it is likely those differences were due to a greater recruitment of muscle mass driving up $\dot{V}O_2$ (Sloniger et al., 1997), as a result of the combination of gradient and high speeds.

Excluding the Chapters in this thesis, thirteen original investigations on the SPXT have been published, with five of those finding higher $\dot{V}O_{2max}$ in the SPXT (Mauger & Sculthorpe 2012; Mauger et al., 2013a; Astorino et al., 2015; Jenkins et al., 2017; Jenkins et al., 2017a), and another study finding the SPXT to be lower than the GXT (Scheadler & Devor, 2015). The other seven have found no significant differences between the two protocols. It is worth clarifying that of those five, four were in cycling, and three of those four were in untrained or clinical populations. The remaining study was completed in untrained men (Mauger et al. 2013a), but included major methodological limitations that have been previously discussed both in this thesis and elsewhere (Chidnok et al., 2013; Eston et al., 2014; Poole, 2014). All of the Chapters in this thesis were completed using running based SPXT protocols, and either recreationally trained, or highly trained men and women. Whilst it is possible that physiological differences in lesser trained individuals, or how individuals of different training status' approach the SPXT, may contribute to the differences in $\dot{V}O_{2max}$ reported in those studies, the same cannot be said for participants of a higher training status as that has not been seen in this thesis or in other similar publications.

The finding of this thesis that no significant differences in $\dot{V}O_{2max}$ exist between the two protocols may be inferred as a lacklustre finding, but the opposite is actually true, and it is important to consider all research published on the SPXT to fully appreciate this. As previously discussed, only five studies have found the $\dot{V}O_2$ in the SPXT to produce higher $\dot{V}O_{2max}$, and all of these studies either specifically used lesser trained individuals, or had substantial methodological considerations. The same can be said for the one study that found the SPXT to produce significantly lower $\dot{V}O_{2max}$ (Scheadler & Devor, 2015). Whilst an incredibly novel study at the time, and an important one in the development of SPXT research, methodological issues regarding the differences in gradient between the GXT and SPXT (discussed further in section 2.5.4) potentially explain why $\dot{V}O_{2max}$ was lower in the SPXT. As discussed in the literature review (section 2.2), methodological decisions and considerations can impact the likelihood of an individual achieving a true $\dot{V}O_{2max}$, whether that is regarding the test duration (protocols that fall outside the recommended 8-12 min window), the use of speed or gradient, or the increments of work-rate chosen (Whipp et al., 1981; Davis et al., 1982; Astorino et al., 2004; Yoon et al., 2007; Midgley et al., 2008). This could arguably be applied to the comparison of the SPXT and GXT - whilst the SPXT rarely produces different $\dot{V}O_{2max}$ to the GXT, when the protocols are appropriately matched, a practitioner could be confident that the SPXT will almost always produce the same or higher $\dot{V}O_{2max}$.

To attempt to provide some clarity as to why the SPXT has sometimes produced higher $\dot{V}O_{2max}$ than the GXT, most studies have also looked at the differences in other key physiological variables [such as $\dot{V}_{Emax}$, HR_{max}, and RER_{max}] . Throughout this thesis, differences in these key physiological variables have been investigated. There have been no significant differences between the two protocols for HR_{max} or $\dot{V}_{Emax}$ in any of the

experimental Chapters, with only the gradient-based SPXT reporting a significantly higher $\dot{V}_{Emax}$ than both the GXT and SPXT in Chapter 4. Whilst these differences have been more commonly reported in cycling related SPXT studies (Astorino et al., 2015; Jenkins, Mauger & Hopker., 2017a) most literature related to similarly trained runners have found no differences (Hanson et al., 2016; Truong et al., 2017; Beltz et al., 2018). $\dot{V}_{Emax}$ has previously been reported to be significantly higher during the SPXT (Faulkner et al., 2015; Jenkins et al., 2017). Indeed, the differences in $\dot{V}_{Emax}$ in the gradient-based SPXT, the higher [but not significantly so] $\dot{V}_{Emax}$ during the speed based SPXT, and the finding of a significantly greater oxygen cost of breathing in the GXT in Chapter 4 led to the investigation of this mechanism in Chapter 5. However, no differences in $\dot{V}_{Emax}$ were then subsequently found in Chapter 5. Whilst several studies have investigated the mechanistic underpinnings of $\dot{V}O_{2max}$ in the SPXT, and differences in estimated $\dot{Q}$ have been found, even the authors of these findings concede that due to the estimative techniques used, the accuracy of the results are questionable. Importantly, the one study that has investigated the mechanistic underpinnings of the SPXT in treadmill running subsequently found no differences in $\dot{V}O_{2max}$ or any other key physiological variables (Beltz et al., 2018). Interestingly, in Chapters 5 and 6, RER_{max} was significantly higher during the SPXT compared to the GXT, which has been previously reported (Scheadler & Devor, 2015; Jenkins et al., 2017a). It is possible that this higher RER could be as a result of the higher peak work-rates achieved during the SPXT, thus resulting in a greater anaerobic contribution, thus driving up RER (Scheadler & Devor, 2015; Jenkins et al., 2017a). Across the four experimental Chapters in this thesis, no consistent findings of significantly different physiological variables were reported and so it can be reasonably suggested that, when completed in line with standard recommendation (fixing intensity to the required

RPE and producing a maximal effort at RPE20), there are not any consistently significant differences between the protocols for key variables such as $\dot{V}_{Emax}$, HR_{max}, and RER_{max}.

As discussed in the literature review (see section 2.2), there has been much debate regarding the ideal test duration when the primary goal is $\dot{V}O_{2max}$ achievement. As previously highlighted, differences in test duration are not necessarily an automatic sign of an invalid test, and in most cases this is not the case. The issue with slightly longer durations is more down to the lack of additional useful information they offer, as opposed to discrepancies in $\dot{V}O_{2max}$, which is only usually an issue when the duration is significantly longer than the upper suggested duration of the test (i.e. 12 min) (Buchfuhrer et al., 1983; Yoon et al., 2007). In this thesis, test duration was significantly longer in Chapter 6, but not in 4 and 5. It is important to note that [as previously stated] no differences in $\dot{V}O_{2max}$ between protocols in any of these Chapters exist. Issues about test duration have previously been highlighted regarding the findings of Mauger and Sculthorpe (2012). However in that study the protocol duration of the GXT was 13 ± 3 min [compared to 10 min in the SPXT] which is greater than the 11 ± 1 min reported in this thesis (Chapters 4 and 6). However, even then, the differences in $\dot{V}O_{2max}$ they reported are more likely related to the significant increase in PO achieved [in the SPXT]. One of the main complainants of this difference in protocol duration (Eston et al., 2014) then authored an SPXT study which also included significantly different test durations, but they conceded that this difference was not likely significant. What these differences in protocol duration do highlight though, is the difficulty in estimating the starting speed of the GXT, especially if the participant or athlete is not well-known to the tester. This has previously been highlighted as a key fault of the GXT and an advantage of the SPXT (Poole & Jones, 2017). Not only can incorrectly choosing the wrong starting speed potentially compromise

the data collected from the test, but it can also be inconvenient for laboratories that run on tight testing schedules.

A point that has been consistently stressed throughout this thesis is the necessity to move the conversation away from $\dot{V}O_{2max}$ assessment and more towards the practical implications and advantages of the SPXT compared to the GXT. A recurring theme of this thesis has been the running velocities obtained in the GXT and SPXT – V_{max} and $_vRPE20$, respectively. Whilst peak velocities were compared in Chapter 4, Chapter 5 introduced $_vRPE20$ and this was reported to be similar to the V_{max}, which is a well-researched and accepted parameter in both research and training prescription, obtained from the GXT. This was then similarly reported in Chapter 6. A key finding of this thesis was that $_vRPE20$ could be successfully used to prescribe interval training for recreational athletes in a similar way to V_{max} in the GXT. In the prescription of training using V_{max} and $_v\dot{V}O_{2max}$, a common method is to utilise T_{max}, which requires an additional test and therefore may be more inconvenient for the athlete. However, Chapter 6 showed that the same training benefits could be reached by prescribing training via $_vRPE20$ with set interval durations of 2 min. This means that not only is the SPXT 10 min long with no need to estimate starting speed, but no additional test is required afterwards to assign interval training duration. This makes the use of the SPXT valid for not only $\dot{V}O_{2max}$ assessment, but also makes training prescription potentially a much more streamlined time efficient process. This may be useful for athletes and coaches who want to assess fitness and prescribe training with minimal disruption to training.

8.2. General limitations

Prior to this thesis, only one study had investigated the use of the SPXT in treadmill running and in that study a non-motorised treadmill was used (Mauger et al., 2013a). This was criticised as it resulted in different treadmills being used for the SPXT and GXT (Eston et al., 2014; Poole, 2014). As such, it was important for this thesis to establish a method of self-pacing that could be carried out on a motorised treadmill. Whilst several studies have utilised sonar rang finders to transform motorised treadmills into 'sem-automatic' treadmills that may better allow for self-pacing (Scheadler et al., 2015; Truong et al., 2017), these are neither readily available or the technology currently sophisticated enough. Previous literature has relied on participants using buttons on the treadmill to adjust their speed throughout the SPXT (Faulkner et al., 2015; Beltz et al., 2018) however it was speculated this may rely too heavily on the participant making manual decisions which also required additional physical movements. This in turn may disrupt the participant's running pattern and rhythm. As such, a zonal system was selected which simply requires the participants to move between marked zones to signal to the tester that they want to change speed, which may be more natural and fluid then buttons. A cornerstone of the SPXT is that it is a self-pacing-centric and participant-driven protocol and it is this factor that makes it attractive over the GXT. The method used in this thesis then, to artificially create self-pacing may then be seen as a limitation and it is recognized that self-pacing can never be genuinely reproduced on a motorized treadmill. However, it is contended that the findings throughout the experimental Chapters of this thesis put forward a strong argument that self-pacing can be adequately achieved on a motorised treadmill. This is best reflected by the end-spurt, which is considered a key component of real-life exercise and competition, regularly being achieved during the SPXT.

Chapter 5 focused on the mechanistic underpinnings of the SPXT, specifically the oxygen cost of breathing during both the GXT and SPXT. This was based on the findings of Chapter 4, where $\dot{V}_E$ was significantly different between the gradient-based SPXT and the GXT. A limitation of this thesis was the decision to compare the oxygen cost of breathing of the speed-based SPXT with the GXT, and not the gradient-based SPXT. The speed-based SPXT was selected for Chapter 5 due to it having greater 'real-world relevance' than the gradient-based SPXT, due to it being speed-based and thus easier to administer than also utilising gradient. Whilst $\dot{V}_E$ was not significantly different in the speed-based SPXT in Chapter 4, estimated oxygen cost of breathing was still significantly different to the GXT which meant its selection was justified, however it cannot be known if the gradient based SPXT would have produced a significantly different outcome in Chapter 5 as it was not used and so this is a limitation of the current design. During the ventilation trials, participants were only asked to match a specific $\dot{V}_E$. Originally participants were also required to match specific breathing frequencies but this was deemed too difficult for participants to achieve, especially at higher $\dot{V}_E$ rates. Whilst participants did not have difficulties matching the required $\dot{V}_E$ at lower rates, the difficulties participants experienced at higher rates mean it is difficult to categorically say there were no differences in the oxygen cost of breathing.

Chapter 6 represented an important shift in the direction of SPXT-based research as this was the first investigation to focus more on the wider utility of the SPXT beyond $\dot{V}O_{2max}$ measurement. Whilst the Chapter is certainly novel, a perceived limitation of this Chapter could be the lack of a control group, however as the main aim of the Chapter was to compare between the two methods of training this was not deemed essential. Comparing between the different methods; training via the SPXT-derived parameters, and the

established method of prescribing training via GXT-derived parameters, was the central aim over investigating absolute improvements in cardiorespiratory fitness in individuals. This model has previously been utilized in the literature (Manoel et al., 2017). Furthermore, a control group, in addition to the two existing groups, would represent a significant challenge regarding participant recruitment, particularly due to the necessity for participants to commit to six weeks of training and a further 4 weeks of laboratory testing.

8.3. Future directions

Whilst the findings of this thesis add to the growing body of literature regarding the SPXT and its application, there are clearly areas that warrant further research and consideration. Currently, only one study has investigated the use of a field-based SPXT (Lim et al., 2016). The advantage of a field-based SPXT is that it may be more sport-specific for athletes compared to laboratory based protocols. A field-based SPXT would also allow for genuine self-pacing that, as discussed, is difficult to achieve in a laboratory on a treadmill. Lim et al (2016) reported that $\dot{V}O_{2max}$ directly measured in the field-based SPXT was comparable to a laboratory based SPXT. However, this still requires expensive portable gas analysers. As such, the progression of this would then be to investigate whether the field SPXT and its variables offer strong predictive qualities for $\dot{V}O_{2max}$, in a similar capacity to established protocols such as the University of Montreal track test and 20 m multi-stage shuttle run test. This would then allow coaches and athletes to conduct a running specific field protocol that potentially accurately predicts $\dot{V}O_{2max}$ and gives valuable data that can then be used to prescribe effective training for improvements in

$\dot{V}O_{2max}$, critical speed, and LT/VT thresholds [the training effects which have already been demonstrated (see Chapter 6)].

Throughout this thesis it was important to not only demonstrate that a 'true' $\dot{V}O_{2max}$ had been attained during the GXT, but that stringent criteria were in place to ensure this was the case and that it had been thoroughly considered. As previously discussed, much has been made of $\dot{V}O_{2max}$ criteria, ranging from a visible $\dot{V}O_2$ plateau, to verification stages and secondary criteria. However, similar widely recognised criteria are not considered for $\dot{V}O_{2max}$ assessment in the SPXT, especially the detection of a plateau, which is largely down to the variation of work-rate making this unachievable. If the SPXT is to be used more widely by both athletes and coaches, and researchers, then the use of criteria to confirm $\dot{V}O_{2max}$ in the SPXT is paramount and should be further investigated.

8.4. Conclusion

The overall aim of this thesis was to investigate the utility of the SPXT as an alternative to the GXT in highly trained and recreationally trained runners. Each of the experimental Chapters aimed to support this overall aim. The main findings of this thesis are that the SPXT is a valid protocol for assessing parameters of cardiorespiratory fitness, such as $\dot{V}O_{2max}$ and VT, in both highly and recreationally trained runners. Whilst it is not suggested that the SPXT is a superior protocol to the GXT, it can be concluded that it is an attractive alternative to the GXT, depending on the specific needs of the athletes and coaches.

Ultimately, the SPXT offers a more efficient design in regards to test duration whilst still offering largely the same information as the GXT, but also with the added benefit of a near-identical field variation of the protocol that may be more beneficial for athletes looking to replicate their actual sporting and exercise performance. Research related to the SPXT is still young and so further investigation is recommended to uncover the full potential of the protocol and its application for athletes, coaches, and practitioners.

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