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The distance-time relationship and its use in endurance training and performance

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Abstract

The aims of this thesis were to develop a time efficient field test of the distance-time relationship, assess its validity, reliability and sensitivity and utilise the test to monitor and prescribe endurance training in distance runners. Laboratory-based tests of the distance-time relationship often use lengthy recovery periods between trials, resulting in multiple visits and limiting their practical application. A field-based test, completed in a single visit, could improve the utility of the distance-time relationship.

A novel single visit field test comprising of 3 constant-distance trials, separated by a 30-minute recovery, was designed. This test estimates the highest sustainable rate of aerobic metabolism, or critical speed (CS), and the modelled maximum distance performed above CS (D′). When compared to a traditional multi-visit laboratory protocol, field test CS was highly correlated (r=0.89, P<0.01) and displayed a low typical error (3.4%). D′ was significantly lower in the field test protocol with a typical error of 44.8%. D′ was less reliable than CS with coefficients of variation of 14.1 and 1.7% respectively.

The single visit test was sensitive to small changes in CS during a yearlong training study. No change in D′ was detected during the study, however the variability of D′ may have reduced the ability to measure small performance changes.

The potential of the field test to model intermittent exercise was investigated. Using a linear model, actual and predicted time to exhaustion showed a weak correlation (r = -0.21 to -0.04, P>0.05) and high typical error (334-1709 s). Non-linear modelling of recovery did not improve the accuracy. A high variability in D′ may in part explain the low predictive ability of the models.

The conclusion from this thesis is that the single visit field test is a valid, reliable and sensitive test for CS, which provides a favourable alternative to multi-visit laboratory-based testing.

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Abbreviations

a	Intercept of the power-duration curve
ATP	Adenosine triphosphate
b	Critical power
°C	Degrees Centigrade
CL	Confidence limits
CO_2	Carbon Dioxide
CP	Critical Power
CS	Critical Speed
CV	Coefficient of variation
d	Distance run
D′	Maximum amount distance that can be completed above CS
D'_{bal}	Balance of D′ remaining
D_{CP}	Difference between the recovery power and the CP
D_{CS}	Difference between recovery speed and critical speed
DTE	Distance to exhaustion at a constant speed/velocity
EP	End Power
GD	Glycogen depleted
GET	Gas exchange threshold
GPS	Global Positioning System
H+	Hydrogen
hr	Hour
HR	Heart Rate
HR_{max}	Maximal heart rate
IAAF	International Association of Athletics Federations
1/time	Inverse of time (1 divided by time)
J	Joules
K+	Potassium
kJ	Kilojoule
km	Kilometers
km.h	Kilometers per hour
$L.min^{-1}$	Litters per minute
LOA	Limits of agreement

L.s	Litres per second
LT	Lactate threshold
LTPV	Lactate turnpoint velocity
MLSSV	Maximal lactate steady state velocity
m	Metres
min	Minutes
ml	Millilitres
$mL \cdot kg^{-1} \cdot km^{-1}$	Millilitres of O_2, per Kilogram of body weight, per kilometre
$mL \cdot kg^{-1} \cdot min^{-1}$	Millilitres of O_2, per Kilogram of body weight, per minute
mM	Millimolar
mmHg	Millimetres of mercury
$mmol \cdot L^{-1}$	Millimoles per Litre
$m.s^{-1}$	Metres per second
n	Number
N_2	Nitrogen
NG	Normal glycogen
N/kg	Newton's per Kilogram
O_2	Oxygen
OBLA	Onset of blood lactate accumulation
0f	Intercept of 1/time relationship
P	Power
P	Significance level
PCr	Phosphocreatine
Pi	Inorganic Phosphate
Pmax	Maximal instantaneous power
^{31}P-MRS	^{31}P Magnetic resonance spectroscopy
r	Correlation coefficient
R^2	Coefficient of determination
SD	Standard deviation
s	Seconds
SEE	Standard error of the estimate
S_r	Speed of recovery period
S_w	Speed of work period
t	Time

TD	Total distance (km)
$\tau_{D'}$	Time constant of D′ repletion
t_{lim}	Time limit
t_r	Time (duration) of recovery period
TTE	Time to exhaustion
$(t - u)$	Time between exercise segments resulting in depletion of W′
t_w	Time (duration) of work period
$\tau_{W'}$	Time constant for the reconstitution of W′
μL	Microliters
V	Percentage time above threshold velocity
$\dot{V}O_2$	Volume of Oxygen
$\dot{V}O_{2\,\mathrm{peak}}$	Peak oxygen uptake
$\dot{V}O_{2\,\mathrm{max}}$	Maximal oxygen uptake
v-$\dot{V}O_{2\,\mathrm{max}}$	Velocity at $\dot{V}O_{2\,\mathrm{max}}$
W	Watts
W′	The maximum amount of work that can be performed above CP
W'_{bal}	W′ at any given time during an intermittent exercise session
WEP	Work above end power
W'_{exp}	The amount of W′ expended
wk	Week
W_{lim}	Work limit
WR_6	Bout of exercise designed to induce exhaustion within 6-min
yrs	Years
*	Multiplied by
Δ	Difference

List of equations

$$d = (CS.t) + D' \qquad (1)$$

$$TTE = n(t_w+t_r) + \frac{D' - n[(S_w - CS)t_w - (CS - S_r)t_r]}{S_w - CS} \qquad (2)$$

$$W_{lim} = a + b.t_{lim} \qquad (3)$$

$$t_{lim} = \frac{a}{P - b} \qquad (4)$$

$$\text{Time} = W' / (\text{Power} - CP) \qquad (5)$$

$$\text{Power} = CP + (W' * 1/\text{time}) \qquad (6)$$

$$\text{Work} = W' + (CP * \text{time}) \qquad (7)$$

$$t = (D - D') / CS \qquad (8)$$

$$D = (CS*t) + D' \qquad (9)$$

$$0 \le S_r < CS < S_w < CS + D'/t_w \qquad (10)$$

$$D' - n[(S_w - CS)t_w - (CS - S_r)t_r] \qquad (11)$$

$$P = (W'/TTE) + CP \qquad (12)$$

$$W'_{bal} = W' - \int_0^t (W'_{exp}) (e^{-(t-u)/\tau}{}_{W'}) \qquad (13)$$

$$D'_{bal} = D' - \int_0^t (D'_{exp}) (e^{-(t-u)/}\tau_{D'}) \qquad (14)$$

Chapter 1 - Introduction

1.1 Background:

Utilisation of human performance testing is widespread in sports science research enabling scientists to evaluate the effects of nutrition, ergogenic aids, drugs, or training programs on endurance performance (Jeukendrup et al., 1996). Accordingly methods to evaluate human performance have been extensively investigated with an increasing demand for valid, reliable and convenient testing methods (Beaver, Wasserman and Whipp, 1986; Cheng et al., 1992; Billat, Hill, Pinoteau, Petit and Koralsztein, 1996; Jones and Doust 1998; Smith and Jones, 2001; Beneke, 2003; Dekerle, Baron, Dupont, Vanvelcenaher and Pelayo, 2003; Vanhatalo, Doust and Burnley, 2007; Pettitt, Jamnick & Clark, 2012; Mauger and Sculthorpe, 2012). Performance testing can be subdivided into either laboratory or field-based testing methods. Laboratory testing often involves the use of expensive highly accurate equipment and takes place in a controllable environment. This typically leads to high levels of reliability reported from such tests (Nummela et al., 2007). Field-testing protocols transport the athlete out of the laboratory often to an environment that closely replicates their sporting performance. In contrast to laboratory-based methods, field-testing may require less expensive equipment and takes place in an environment over which the researcher has less control. Therefore whilst the ecological validity of such tests is high, the reliability may be compromised (Nummela et al., 2007).

An important area within the field of endurance performance research involves assessing the relationship between distance and time. Methods used to assess the distance-time relationship can involve either laboratory or field based protocols. Research into the distance-time relationship first began in the early 20th century, where running world records were analysed to develop an approximate law of fatigue for humans (Kennelly, 1906; Hill, 1925). In the second half of the 20th century Monod and Scherrer (1965) investigated the relationship between power output and time to exhaustion for small muscle groups. The authors identified the parameter critical power (CP) from this relationship and suggested it represented the highest power output that could be maintained without exhaustion. Two decades later Moritani et al., (1981) expanded on the work of Monod and Scherrer (1965) and concluded that the relationship previously seen in small muscle groups was also demonstrable in whole body cycling exercise. The physiological significance of the parameters estimated from the power-time relationship has been the subject of much debate over the past half-century and as a consequence definitions of these parameters have varied. Critical power can be defined as the highest sustainable rate of aerobic metabolism (Hill, 1993), and W′ as the maximum amount of work that can be performed above CP (Jones et al., 2010). The power-time relationship was adapted for treadmill running by Hughson, Orok and Staudt (1984). The authors demonstrated that treadmill velocity and time to exhaustion conformed to a similar hyperbolic function as described previously for cycling. The running based parameters are termed critical speed (CS) and D′. The distance-time relationship can also be expressed by a linear model represented by the following equation where: d = distance run and t = running time:

$$d = (CS.t) + D' \qquad (1)$$

A runner's CS has been suggested to reflect the highest sustainable running speed that can be maintained without a continual rise in $\dot{V}O_2$ to $\dot{V}O_{2\,max}$, whilst D′ describes the maximum amount of work (distance) that can be performed above CS (Jones et al., 2010). It has been reported that the CS corresponds to an exercise intensity which lies between that associated with the lactate threshold and that eliciting $\dot{V}O_{2\,max}$ (Billat et al., 1998), thus demarcating the heavy and severe exercise intensity domains (Bull et al., 2008). The CS is also highly correlated with other indices of aerobic fitness such as the maximal lactate steady state and the $\dot{V}O_{2\,max}$, and is correlated with overall performance in long-duration events (Housh et al., 1991; Jenkins and Quigley, 1990). As such, assessment of the relationship between power or distance with time has become a useful tool available to sports scientists when assessing endurance athletes in both the laboratory and the field.

The overall aim of this thesis was to develop a valid, reliable and time efficient field test of the distance-time relationship that could be further utilised to investigate endurance training adaptations and the running performance of distance runners.

1.2 Rationale for a new distance-time protocol:

Following the work of Hughson et al., (1984) CS was commonly viewed as the treadmill analogue of CP, with early research in this area utilising laboratory-based treadmill tests to determine CS and D′ (Florence and Weir, 1997; Pepper et al., 1992). A distinct disadvantage with these laboratory-based protocols was the number of repeat running trials (typically 4-6) used in the calculation of the distance-time relationship (Smith and Jones, 2001; Kolbe et al., 1995) along with the length of recovery period required between trials (often >24 hours). A time efficient single-visit method would vastly improve the practical application of the distance-time relationship test. A further disadvantage with laboratory-based treadmill protocols is that the majority use time to exhaustion trials at a constant velocity (Florence and Weir, 1997; Pepper et al., 1992; Housh et al., 2001; Bull et al., 2008; Smith and Jones, 2001; Kolbe et al., 1995; Kranenburg and Smith, 1996; Bosquet et al., 2006). Constant velocity trials in running have shown poor reliability with coefficients of variation ranging from 15.1 to 25% (Laursen et al., 2007; Billat et al., 1994). The poor reliability of constant velocity running trials is also supported by similar research in both cycling and swimming (Jeukendrup et al., 1996; Alberty et al., 2006). In practical terms this level of reliability could result in variations in time to exhaustion ranging from 30-180 seconds during typical duration critical speed trials. An opposing view is that time to exhaustion trials are inherently reliable and the apparently poor reliability seen in some studies is an artefact of the relationship between exercise duration and power output (Hopkins, Schabort and Hawley, 2001). This relationship could mean that small (~1%) changes in a subject's ability to produce power from test to test result in much larger (~10–20%) random changes in time to exhaustion (Hinkson and Hopkins, 2005). However it is suggested that an intervention producing a substantial change in a subject's ability to produce power will also result in a large change in time to exhaustion, which will stand out against the large random changes (Hinkson and Hopkins, 2005). Notwithstanding this some research still suggests that fixed distance trials, where the athlete is required to cover a set distance in the fastest possible time, display greater reliability than constant velocity trials, with coefficients of variation ranging from 3.3% to 3.7% (Laursen et al., 2007; Nicholson and Sleivert, 2001). Fixed distance trials also mimic the demands of competitive races by allowing pace variation. Due to limitations with the manual speed control measures on standard motorised treadmills, fixed distance trials are arguably best performed in a field-based setting. Whilst fixed distance self-paced trials are possible in the laboratory on a treadmill, they are more complicated to administer and still do not allow the instantaneous and fluid changes of pace that an athlete can achieve on a running track. For certain sports, field tests may be preferable to laboratory tests, as they allow the athlete to perform in a simulated competitive setting (Nummela et al., 2007). Field tests are often viewed as less reliable than laboratory tests due to the lower level of control over external (environmental) factors. However, field tests could be viewed as more ecologically valid due to their greater specificity to the sport in question (Nummela et al., 2007). For a runner, a distance-time relationship test conducted in a field-based setting on an athletics track would arguably have greater ecological validity than the same test conducted in a laboratory on the treadmill.

A single-visit field test of the distance-time relationship would be more accessible and less time consuming for athletes and have greater ecological validity than a traditional laboratory treadmill based protocol. A single-visit fixed-distance field test *may* therefore have all of the necessary attributes to enhance the practical application of distance-time protocols by athletes, coaches and sports scientists alike. An initial aim of this thesis therefore was to develop a single-visit field test of the distance-time relationship and subsequently assess its reliability of CS and D′ estimates. A second aim was to assess the validity of the single-visit field test for estimating CS and D′ by comparing it with a traditional treadmill laboratory-based time to exhaustion protocol.

1.3 Changes in the distance-time relationship with training:

Joyner and Coyle (2008) propose a model of human performance focused around the concept of a ‘performance velocity’. Performance velocity is ultimately influenced by three main factors; firstly the level of aerobic metabolism that can be maintained during a race, known as performance $\dot{V}O_2$, which in turn is influenced by the $\dot{V}O_{2\,max}$ and the lactate threshold (LT). Secondly Joyner and Coyle suggest an athletes anaerobic capacity effects their performance velocity and finally the efficiency of converting the energy being used into movement (running economy) also plays an important role. Within Joyner and Coyle’s performance model $\dot{V}O_{2\,max}$, LT and running economy combine to influence to the critical performance velocity (speed) of an athlete.

$\dot{V}O_{2max}$, lactate threshold, exercise economy and CS have all been widely researched and identified as key parameters that contribute to endurance performance (Saltin and Astrand, 1967; Farrell et al., 1979; Conley and Krahenbuhl, 1980; Jones and Carter, 2000; Joyner and Coyle, 2008). Nevertheless there is limited research investigating the effects of prolonged endurance training on these fitness measures in highly trained distance runners.

A small number of studies have examined the effect of 4-8 weeks of training on the $\dot{V}O_{2max}$ of trained subjects. Results of such studies tend to be conflicting, with some studies reporting no change in $\dot{V}O_{2max}$ (Billat et al., 1999; Smith et al., 2003; Denadai et al., 2006), whilst others report increases of ~5% (Smith et al., 1999; Billat et al., 2002). Longer duration studies on trained runners are sparse. Tanaka et al., (1984) and Bragada et al., (2010) monitored groups of trained runners however the influence of training on the measured physiological variables was not examined. Svedenhag and Sjodin (1985) monitored elite runners over the course of a year and compared physiological adaptations in the laboratory with training diary records. In contrast to running several studies have examined the effects of a training period on the cycling power-time relationship. This research demonstrated that improvements ranging from 10-31% in critical power are possible following a period of training (Gaesser and Wilson 1988; Poole et al., 1990; Jenkins and Quigley 1992). However these studies featured either untrained or moderately trained subjects (mean $\dot{V}O_{2max}$ values ranging from 48.5 to 55.0 $mL.kg^{-1}.min^{-1}$), and utilized only a 6-8 week training period. There is a lack of information concerning the effect of prolonged endurance training on highly trained participants' CS and D′, where the training effects may be less pronounced.

The time efficiency and minimal equipment allow the potential for the single visit field test to be used at regular intervals to monitor the effects of prolonged endurance training on the distance-time relationship. Before the test can be utilised in such a way the sensitivity of the single visit field test in detecting changes in performance over a period of endurance training must be evaluated. Consequently a further aim of the thesis was to examine the ability of the single visit field test to detect training induced changes in the distance-time relationship in a group of highly trained distance runners. The sensitivity of the field test to detect such changes will be compared with that of the more traditional laboratory-based measures that underpin the performance velocity model. A subsequent aim was to assess the influence of training volume and intensity on the single visit field test alongside the laboratory-based measures.

1.4 The distance-time relationship and intermittent exercise:

In addition to monitoring changes in endurance performance a valid, reliable and sensitive single visit field test could also be used to provide training prescription. Interval training is a popular mode of training used in many sports, with high-intensity interval training being shown as an effective method of improving aerobic fitness (Gibala and McGee, 2008; Laursen and Jenkins, 2002). An interesting consideration therefore is the potential to model intermittent exercise using the distance-time relationship data from the single visit field test. Such modelling techniques could then be applied in training to prescribe intermittent interval-style work and recovery periods.

Interval training is a popular mode of conditioning in many sports and involves intermittent intervals of work and rest/relative rest (Morton and Billat, 2004). Beneke et al., (2003) report that intermittent exercise can induce lower blood lactate concentrations and allow greater exercise tolerance compared to a continuous protocol performed at a similar intensity. This gives interval training the advantage of enabling a greater amount of high intensity work to be conducted in a single session than would be possible with continuous training. Therefore the optimal design of an interval training session is one that is individualized to an athletes specific requirements.

It has been suggested that the distance-time relationship could be used to provide a scientific basis for intermittent exercise prescription (Clark, West, Reynolds, Murray, and Pettitt, 2013). CS demarcates the heavy and severe exercise intensity domains (Bull et al., 2008) therefore intermittent work and recovery speeds could be set above and below CS respectively to ensure athletes are working at the correct intensity.

Furthermore D′ represents the finite amount of work (distance) that can be conducted when speed surpasses CS. Consequently intermittent work and recovery durations could be set to achieve the desired number of repetitions in accordance with the depletion of D′.

Morton and Billat (2004) considered four independent variables when applying the distance-time relationship to model intermittent exercise performance. Speed during the work and recovery phases (S_w and S_r) along with the duration of the work and recovery phases (t_w and t_r) were studied. Therefore total endurance time, or time to exhaustion (TTE), during an interval session can be calculated from the following equation where n is equal to the number of complete work-recovery cycles (Morton and Billat, 2004):

$$TTE = n(t_w+t_r) + \frac{D' - n[(S_w - CS)t_w - (CS - S_r)t_r]}{S_w - CS} \qquad (2)$$

One potential criticism of the Morton and Billat model is that linear reconstitution of D′ during the recovery intervals is assumed. Recent data by Ferguson et al., (2010) cast doubt on this theory by suggesting that the recovery kinetics of W′ may in fact be curvilinear. Skiba et al., (2012) built on the work of Ferguson et al., (2010) and used an equation assuming exponential recovery of W′. Skiba et al. aimed to develop a continuous function that would account for the depletion and reconstitution kinetics of W′ during intermittent cycling exercise. Results revealed the model was able to describe the dynamic state of W′ during intermittent exercise. Skiba et al. suggest that W′ is reconstituted in a curvilinear fashion and therefore follows a predictable exponential time course during recovery. Skiba's work has advanced the knowledge of modelling intermittent exercise in cycling, however the application of this model in running exercise requires further research. Therefore it would be interesting to assess whether linear and exponential models could be accurately applied to the data from the single visit field-test to predict TTE during intermittent running exercise. This in turn would provide an insight into the ability of the single visit field-test to prescribe interval style training sessions.

1.5 Summary:

Laboratory-based protocols often require repeat visits to conduct the various running trials used in the calculation of the distance-time relationship. Furthermore there is still some debate concerning the reliability of TTE trials typically used in laboratory-based distance-time relationship testing. A valid, reliable and sensitive fixed-distance single visit field-test would be a valuable tool for sports scientists and coaches, enabling them to monitor adaptations to endurance training in highly trained athletes. Furthermore the single visit field test may provide a tool from which coaches can prescribe intermittent exercise based around the distance-time relationship. The overall aim of this thesis was to develop a valid, reliable and time efficient field test of the distance-time relationship that could be further utilised to investigate endurance training adaptations and the running performance of distance runners.

Chapter 2 – Literature review

2.1 Background:

An early investigation into the relationship between distance and time in running exercise was conducted by Kennelly (1906) who analysed running world records. Kennelly discovered a relationship between running speed and time and developed an approximate law of fatigue for athletes. The model predicted that doubling the race distance would lead to an increase in race time of 118%.

Following on from the work of Kennelly (1906), in his landmark paper, Hill (1925) plotted the average speed against the time taken for a range of male and female running world records. Hill noted very high speeds were only maintainable for a very short time, after which speed rapidly decreased as time increased until attaining a practically constant value after about 12 minutes. Hill posed two key questions, which still underpin the basis of research into the distance time relationship today: 1) What are the factors that determine the variation of speed with distance and 2) how far, knowing an athletes best times at two distances, is it possible to extrapolate the relationship to predict the finishing time for a greater or lesser distance.

Francis (1943) continued the investigations in this area by plotting speed against the logarithm of distance and fitting a hyperbolic curve to this relationship. Francis (1943) reported that this curve allowed satisfactory prediction of the time taken to cover a set distance, for distances ranging between 400 m and 19 km. Francis suggested that the asymptote of the hyperbolic relationship represented a speed that was sustainable without fatigue.

Two decades later it was the work of Monod and Scherrer (1965) that made the next breakthrough in this area of research. During their experiments Monod and Scherrer studied the work capacity of muscles during a series of tests at various power values. Throughout each test the power values chosen remained constant but were set sufficiently high enough to lead to local muscular exhaustion. Monod and Scherrer describe a *threshold of local exhaustion* as being reached when the muscle cannot sustain the originally imposed power. The total amount of work achieved during these tests at exhaustion was termed the *work limit*, whilst the duration of the test to exhaustion was termed the *time limit*. Monod and Scherrer (1965) studied the work limit and time limit of individual muscles and muscle groups across various dynamic tasks to exhaustion. They reported a linear relationship between the work limit and time limit for a series of tests to exhaustion performed with the same muscle group (Figure 2.1).

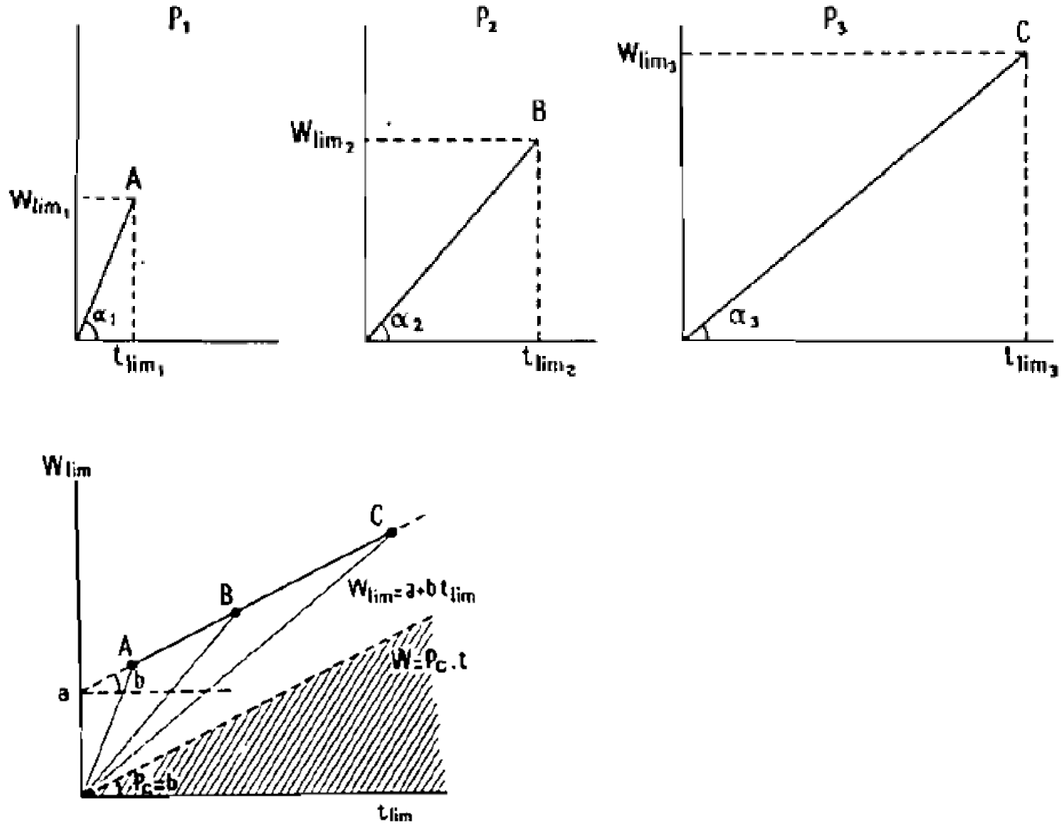

Figure 2.1. The relationship between work limit and time limit for three dynamic work tests of individual muscles to exhaustion. Monod and Scherrer (1965) *p.331*

Figure 2.1 shows an example of three dynamic work tests to exhaustion from the study of Monod and Scheerer (1965). Each *work limit* (W_{lim}) has been performed in a given *time limit* (t_{lim}) and a linear relationship exists between the three tests that can be explained by equation 3.

$$W_{\text{lim}} = \text{a} + \text{b}.t_{\text{lim}} \qquad (3)$$

Monod and Scherrer (1965) define the slope of this line (b) as the critical power (CP) and suggest this represents the maximum rate a muscle can sustain for a very long time without fatigue. The intercept of this line (a) is described as the muscles energy reserve.

Monod and Scherrer (1965) also propose an additional equation based around the power (P) that a muscle is working at

$$t_{\mathrm{lim}} = \frac{\mathrm{a}}{\mathrm{P} - b} \tag{4}$$

From equation 4 it can be seen that during dynamic exercise if the power of a muscle exceeds its CP, exhaustion can be predicted to occur in a time limit that depends on two factors; the extent above CP that the muscle is working and the energetic reserve of the muscle.

Further research by Moritani et al., (1981) investigated whether the relationship previously described for small muscle groups by Monod and Scherrer (1965) also applied to whole body exercise such as cycling. The authors studied the relationship between power (watts) and time to exhaustion (TTE) in eight male and eight female participants. Participants performed exercise tests to exhaustion on an electronically braked cycle ergometer at three different power outputs. Moritani et al. plotted the maximal work (W_{lim}) obtained from the three different power outputs against the t_{lim}. In agreement with the work of Monod and Scherrer (1965), Moritani et al. report the three plotted points were situated on a line defined by the relationship between W_{lim} and t_{lim} (equation 3). The R^2 values of individual plots ranged from 0.98-0.99 ($P<0.01$). Moritani et al., (1981) concluded that the relationship between power and TTE in cycling exercise conformed to a similar linear relationship to that demonstrated by Monod and Scherrer (1965) for individual muscle groups. Moritani et al. concur with the previous definition put forward by Monod (1972) that the intercept (a) of the W_{lim}-t_{lim} relationship reflects a reserve represented by energy contained in high-energy phosphorous components and that originating from the use of intramuscular glycogen. The slope of the W_{lim}-t_{lim} relationship (b or CP) was defined as a rate of energy supply with a magnitude determining the maximal power at which a muscle can work without fatigue.

Since the original research of Monod and Scherrer (1965) and Moritani et al., (1981) researchers describing the slope of the W_{lim}-t_{lim} relationship have tended to drop the use of '*b'* in favour of CP. The definition of CP has also evolved slightly to remove the use of terms such as ‘for a very long time’ and ‘without fatigue’. Currently it is generally accepted to define CP as the highest sustainable rate of aerobic metabolism (Hill, 1993). CP therefore represents the upper boundary of the heavy-intensity exercise domain, whereby a physiological steady state can be achieved whilst exercising within this domain (Chidnok et al., 2013a). Exercise above CP, however, is typified by the development of a $\dot{V}O_{2\,slow}$ component, pushing $\dot{V}O_2$ to its maximum and preventing a steady state. A similar evolution has occurred for the intercept of the W_{lim}-t_{lim} relationship, with current literature terming this parameter W′ in place of ‘*a*’. Historically W′ was postulated to represent a finite energy store (from stored O_2 and high-energy phosphates) which is expended during exercise above CP (Moritani et al., 1981; Monod and Scherrer, 1965). An alternative, more recent perspective, is that the W′ is related to the accumulation or depletion of one or more metabolites or substrates that are linked to the process of muscle fatigue until a critical concentration is attained, beyond which the same work rate cannot be tolerated (Coats et al., 2003; Jones et al., 2008). The premise of the CP model is that CP and W′ interact to determine the limit of tolerance during high-intensity exercise. Hence if an athlete exercises below CP, the demands of this exercise can be met predominantly by aerobic means resulting in continuation of exercise for an extended period of time. However when power output rises above CP, aerobic supply is insufficient to solely meet the exercise demands and the capacity-limited W′ makes up the shortfall (Chidnok et al., 2013).

2.2 The distance-time relationship in running exercise.

The first to look at the distance-time relationship in running exercise were Hughson, Orok and Staudt (1984). The authors explain that the calculation of power output during running is problematic; therefore the treadmill test uses speed in place of power and distance in place of work. Hughson et al., (1984) recruited six cross-country runners who ran to exhaustion on the treadmill at six different speeds between 19.2 and 22.4 $km.h^{-1}$. Each speed was presented in a random order and separated by at least 48 hours recovery. TTE at the different speeds ranged from 2-12 minutes in duration. A linear regression was fitted to the velocity versus 1/time data, with a good fit of the data reported (R^2 of individual plots ranging from 0.96-0.99). This confirmed that the hyperbolic model could be accurately applied to the velocity-time relationship. Hughson et al., (1984) concluded that treadmill speed and TTE conformed to a similar relationship to that previously described in individual muscle groups by Monod and Scherrer (1965) and in cycle ergometry by Moritani et al., (1981). The running based parameters derived from this relationship were termed 0f and W′. W′ was represented by the slope of the velocity vs. inverse of time relationship, whilst 0f was represented by the intercept. Hughson et al., (1984) describe W′ as an 'anaerobic capacity' reflecting an amount by which you could exceed a critical threshold. 0f was considered to be related to the aerobic energy supply and was suggested to reflect the aerobic power that could be utilised for long duration high-intensity exercise. This was reinforced by the fact that Hughson et al., (1984) report a high correlation between $\dot{V}O_{2\,max}$ and 0f (r = 0.84).

In the current literature we now know the parameters 0f and W′ as critical speed (CS) and D′ respectively. A runner's CS has been suggested to reflect the highest sustainable running speed that can be maintained without a continual rise in $\dot{V}O_2$ to $\dot{V}O_{2\,max}$, whilst D′ describes the maximum amount of work (distance) that can be performed above CS (Jones et al., 2010). In the summary of their findings Hughson et al., (1984) suggest CS and D′ might provide valuable indices of performance, which can be used to monitor training responses in competitive runners. However Hughson et al. suggest further research is needed to investigate the effect of training on CS and D′. Additionally Hughson et al. cite the need for repeat testing as a disadvantage of distance-time relationship testing.

2.3 Mathematical modelling.

Hill, Rose and Smith (1993) describes 3 mathematically equivalent models which can be used to describe the power-time or work-time relationship and calculate estimates of CP and W′. The three models are explained by the following equations (Hill, 1993):

1) The non-linear power-time model (hyperbolic model), where:

Time = W′ / (Power – CP) (5)

2) The linear power-1/time model (inverse of time model), where:

Power = CP + (W′ * 1/time) (6)

3) The linear work-time model, where:

Work = W’ + (CP * time) (7)

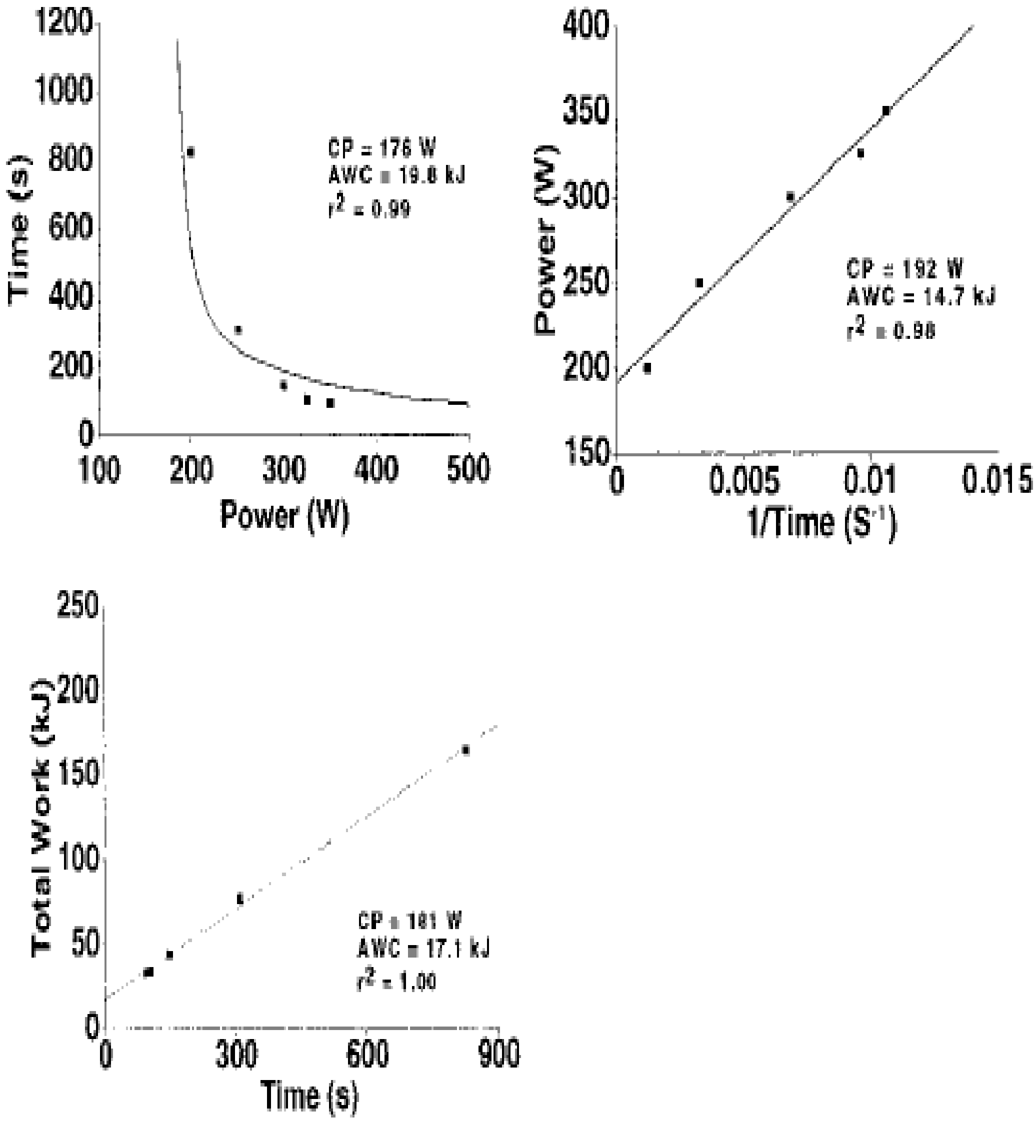

Figure 2.2. The three models presented graphically. (Bull et al., 2000, *p.527).*
Top left panel: The non-linear model. Top right panel: The 1/time model. Bottom left panel: The work-time model.

It has been postulated that the non-linear power-time model (hyperbolic model) is the only mathematical model appropriate for the calculation of the parameters from this relationship (Gaesser et al., 1990). However data from Smith and Hill (1992) dispute this suggestion. In a study of 47 participants, Smith and Hill (1992) reported no significant difference in the estimates generated from the power-time relationship using three different mathematical models. More recent investigations have aimed to continue the examination of this topic with a wider range of mathematical models.

Bull et al., (2000) examined the effect of mathematical modeling on the estimation of critical power. Bull et al., utilized 5 regression models to estimate CP from 5-6 constant power time to exhaustion cycling trials. Three of the five models were the same as those used by Hill (1993), whilst in addition Bull et al., included a 3-parameter non-linear model and an exponential model. The 3-parameter non-linear model was similar to the non-linear power-time model of Hill (1993) except it now included a third parameter of maximal instantaneous power (Pmax). The results indicated that the work-time model demonstrated the best fit of the data, with r^2 values ranging from 0.997–1.000 and standard error of the estimate (SEE) values of just 1–5W for CP. Significant mean differences were reported among the models used to estimate CP. From the five models examined, the nonlinear-3 model resulted in the lowest mean estimate of CP and also the lowest CP estimate for each subject. Morton (1996) suggested this might be a result of the nonlinear-3 model overcoming the physiological assumptions inherent in the nonlinear-2 model. These include the assumption that as time approaches zero, power is infinite, and the assumption that at exhaustion, all of the muscular energy reserves associated with W′ are exhausted.

Similar findings have been reported in running exercise where Housh et al., (2001) examined the effect that different mathematical models had on the estimation of CS. Ten male subjects performed 4 treadmill runs to exhaustion, subsequently five different mathematical models were used to estimate CS. The mathematical models chosen were identical to those used in the study by Bull et al., (2000) albeit with transposition of running related parameters. The results demonstrated that there were significant differences between the CS estimates from the 5 mathematical models. Gaesser et al., (1995) suggest this is a consequence of a number of factors, with the selection of the independent and dependent variables, the expression of the variables (i.e., time rather than 1/time), and the number of variables used in the model, all affecting the resulting r^2 values and the parameter estimates. Of the 5 models in the study by Bull et al., (2000) the linear distance-time model demonstrated the best fit of the data with r^2 values of 0.99-1.00 and SEE values ranging from 0.1-0.5 $km.h^{-1}$. Of the 5 models the non-linear models produced the lowest estimates of CS and the exponential model the highest. The linear distance-time model produced an estimation of CS that lay in the middle of the 5 models.

The linear distance-time model can be explained by the following equation where: d = distance run and t = running time

$$d = (CS.t\ ) + D' \quad (1)$$

The results of Bull et al., (2000) and Housh et al., (2001) are supported by the later work Hill, Alain and Kennedy (2003); Gamelin, Coquart, Ferrari, Vodougnon and Matran (2006) and Bull, Housh, Johnson and Rana (2008) who all demonstrated that linear distance(work)-time models result in high r^2 values and produce a low SEE.

Recent research by Bergstrom et al., (2014) extend the earlier analyses of Bull et al., (2000) to examine estimates of CP and W′ from five mathematical models and from a 3-minute all out test. Significant differences were observed between the mean CP estimated from the 6 methods ($P<0.01$). Results revealed that the exponential model and the 3-min test produced the highest estimates of CP, whilst the three parameter non-linear (non-linear-3) model produced the lowest estimate of CP. The non-linear-3 model is based on the hyperbolic relationship between power and time and includes a measure of maximal instantaneous power (P_{max}), which allows a non-zero time asymptote. The non-linear-3 model (along with the standard hyperbolic model) also produced the highest estimates of W′. Smith and Hill (1992) suggest that differences in the parameters derived from the different mathematical models may be an indication that the data points are outside of the range for which the power-time (distance-time) relationship is hyperbolic. However this is unlikely to be the case for the differences observed in the data from Bergstrom et al., (2014) where the duration of the 4 exhaustive rides used to estimate CP and W′ fell within what could be classed as an acceptable range (1.8 to 16.1 minutes).

A further mathematical model in addition to the five models described above was introduced by Peronnet and Thibault (1989). Hill (1993) explains that this model is a modification of the hyperbolic model that aims to improve upon some key flaws in the original model. The model of Peronnet and Thibault (1989) considers that:

(1) Energy from glycolysis is not available at its maximal rate at the onset of exercise – there is a delay in the response of the glycolytic processes.

(2) The total energy available from glycolysis declines in exercise bouts lasting over 15-minutes.

(3) Energy from aerobic metabolism is not available at the maximal rate at the onset of exercise – there is a delay in the response of the aerobic system.

(4) The percentage of $\dot{V}O_{2\,max}$ that can be sustained during exercise declines slightly as the duration of exercise increases.

Hill (1993) explains that the model of Peronnet and Thibault (1989) should demonstrate an improvement of the hyperbolic critical power model as it describes a relationship where speed continues to decline as time increases. This model should therefore be able to predict a finite time to exhaustion for any speed; even those below CS. This may therefore provide a better description of the distance-time relationship in long duration exercise (Hill, 1993). However a clear disadvantage of the model of Peronnet and Thibault are the complicated mathematical processes involved in the calculations, which limit the usage of this model. This has prevented the wide spread uptake of this model within the scientific literature, therefore data reporting the reliability and validity of this model are limited. Furthermore Alvarez-Ramirez (2002) present a number of criticisms of the Peronnet and Thibault model, suggesting that the introduction of exponential-type features for the reduction of energy available from aerobic and anaerobic metabolism would improve the original model.

2.4 Recommended duration of trials

In the original work of Monod and Scherrer (1965) the duration of the trials for some muscle groups ranged from 2-10 minutes whilst for other muscle groups the range was longer, lasting from 2-30 minutes. When Moritani et al., (1981) investigated the critical power concept using whole body exercise the longest trial was 10 minutes in duration. Poole (1986) suggests it is important that trials range from 1-10 minutes, whilst Hughson et al., (1984) suggest similar constraints recommending that predictive trials should range between 2 and 12 minutes. Hill (1993) suggest that there is a physical limit to the speed that can be maintained for even a very short time and equally a similar limit to the time that even the lowest speed can be sustained. In essence Hill (1993) suggests that the power-time (distance-time) relationship is not truly hyperbolic. However Hill (1993) proposes that the hyperbolic model (in any of its forms) describes the relationship between distance and time if speeds resulting in fatigue within approximately 1-40 minutes are chosen. In summary Hill (1993) concluded that the critical speed concept might be used whilst accepting that exercise trials are within the range of times for which the distance-time relationship is essentially hyperbolic. This has implications for the design of the single-visit protocol within this thesis, where distances will need to be carefully chosen in order to constrain the performance trial times within the above limits.

Vandewalle et al., (1997) extend the work of Hill (1993) by providing a rationale for constraining the t_{lim} of predictive trials within a set range. Vandewalle et al., (1997) concur with Hill (1993) that the relationship between work and time is not perfectly linear (Figure 2.3).

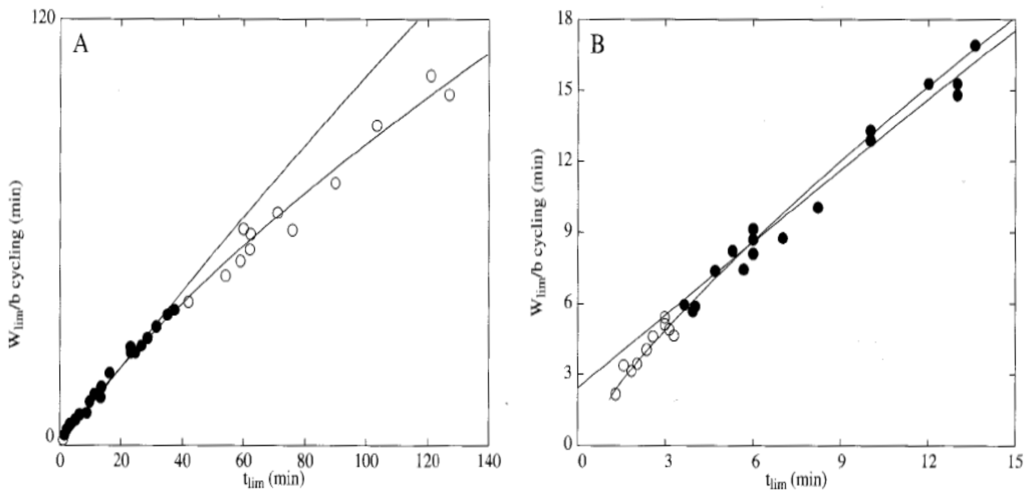

Figure 2.3. Relationship between exhaustion time and work performed at exhaustion for cycle ergometer exercise (Vandewalle et al., 1997, *p.92).*

In figure 2.3 Vandewalle et al., (1997) demonstrate that data from predictive trials longer than 35 min (Figure 2.3, part A, empty circles) and shorter than 3.5 min (Figure 2.3, part B, empty circles) fall under the regression line calculated from the data with t_{lim} between 3.5 and 35 min (black circles). Therefore the true relationship between work and time is not exactly linear and consequently the slope (CP) and the intercept (W′) of the relationship will depend on the range of exhaustion times chosen for the predictive trials. It can be seen from figure 2.3 that higher values of t_{lim} will result in a lower slope and a higher intercept (part A), whilst lower values of time limit will result in a greater slope and a lower intercept (part B). This suggestion is supported by the work of Clingeleffer, McNaughton and Davoren (1994) who estimated CP using the least squares method from 4 predictive trials of 90, 240, 600 and 1200 s in duration. They then repeated the CP estimation using the 240, 600 and 1200 s trials and finally with just the 600 and 1200 s trials. Results demonstrated that when the higher values of t_{lim} were used the regression line had a lower slope, resulting in a lower CP (CP = 164, 158, 149 W respectively).

An important factor governing the duration of predictive trials used in the distance-time relationship is the underlying assumption that mechanical efficiency or energy cost is independent of velocity (Vandewalle et al., 1997). In running exercise, energy cost is likely to be independent of velocity for velocities between 7 and 20 $km.h^{-1}$ (Margaria, Aghemo and Pinera Limas, 1975). Consequently in an average athlete this assumption is likely to be satisfied with the shortest trial in the distance-time relationship being around 2-3 minutes in duration. Maximal efforts for a shorter duration would likely be performed at velocities outside of this range, therefore invalidating the energy cost assumption.

Whilst previous research differs slightly in the suggested trial length used to estimate the distance-time relationship, trials falling within a time limit of 2-12 minutes appear appropriate based on the majority of research in this area.

2.5 The physiological significance of CS.

The physiological significance of the parameters estimated from the distance-time relationship has been the source of much debate in the scientific literature since the original suggestion by Monod and Scherrer (1965) that the CP provides an estimate of the power output that can be sustained for a very long time.

It could be argued that the distance-time relationship is a mathematical model of performance and as such has no physiology implied. Therefore comparisons of the CS and D′ with common physiological parameters should look only for correlation and not consider direct causation. A number of authors have attempted to rationalise the physiological significance of CP by comparing it to other recognised physiological thresholds and markers. Moritani et al., (1981) reported a high correlation (r = 0.93, P < 0.01), and no significant difference, between the $\dot{V}O_2$ at anaerobic threshold and the $\dot{V}O_2$ at CP. However subsequent research conflicts with the findings of Moritani et al., (1981) with CP reported as being 16-64% higher than the ventilatory anaerobic threshold (Poole et al., 1988; Talbert et al., 1991). Furthermore Housh et al., (1991) and McLellan and Cheung, (1992) compared the CP with the power associated with the lactate threshold. CP was shown to be significantly higher (28% and 13% respectively) than the lactate threshold (P<0.05).

Strong correlations have also been reported between the CS and $\dot{V}O_{2\,max}$. Housh et al., (1991a) conducted 4 all-out treadmill runs at a 0% gradient with velocities chosen to produce exhaustion within 2-12 minutes. Results from the 10 participants demonstrated that the calculated fatigue threshold (equivalent to CS) was correlated with $\dot{V}O_{2\,max}$. Furthermore, in a novel study, Hopkins et al., (1989) examined subjects over a variety of treadmill gradients at a constant velocity. Their results revealed a strong correlation (r = 0.81) between the treadmill gradient at which running (in theory) could be sustained for a very long time (akin to CS) and the $\dot{V}O_{2\,max}$. Finally results from the work of Pepper et al., (1992) and Housh et al., (1991a) demonstrate that CS was correlated with the velocity at $\dot{V}O_{2\,max}$ (r = 0.81-0.86) with no significant difference observed between the two measures.

It has been hypothesised that CS corresponds to an exercise intensity that lies between that associated with the lactate threshold and that eliciting $\dot{V}O_{2max}$ (Billat, Binsse, Petit and Koralsztein, 1998) and as such demarcates the heavy and severe exercise domains (Bull et al., 2008). CS, therefore, has been suggested to represent the highest running speed that can be maintained without a continued rise in $\dot{V}O_2$ to $\dot{V}O_{2max}$ (Jones et al., 2010; Poole et al., 1988). The boundary between the heavy and severe exercise domains separates work rates which can be conducted at a steady state from those which can not (Burnley, Doust and Vanhatalo (2006). The advantage of confirming whether CS represents the boundary between the heavy and severe intensity domains is important to athletes and researchers alike.

These suggestions set the scene for a variety of studies across a range of disciplines that directly compared the CS with other commonly used physiological demarcation points. An early study in this area by Smith and Jones (2001) investigated the relationship between the critical velocity, maximal lactate steady state velocity (MLSSV) and lactate turnpoint velocity (LTPV) during running exercise. The rationale for the study was that these physiological thresholds had been suggested to mark the transition between the heavy exercise domain (during which blood lactate is elevated above resting levels, however remains stable over time) and the severe exercise domain (during which blood lactate increases continuously during constant load exercise). Therefore Smith and Jones (2001) aimed to investigate the agreement between these three thresholds. Their results suggest that although no significant differences were observed between critical velocity, MLSSV and LTPV, the level of agreement between the parameters was not close enough to allow the accurate estimation of one parameter from the other. In a similar research study also using running as the mode of exercise, Denadai et al., (2005) compared the relationship between critical velocity, MLSSV and OBLA velocity (3.5 mM blood lactate). Whilst no significant difference was reported between CV and OBLA or between OBLA and MLSS, CV was shown to be significantly higher than MLSS. The authors therefore concluded that critical velocity does not represent a sustainable steady state exercise intensity.

Similar results have also been reported in cycling exercise where Pringle and Jones (2002) report that although a strong correlation was seen between CP and MLSS (r=0.95, P<0.01) there was a significant difference between the two measures, with CP being significantly higher than MLSS (242±25 and 222±23 W, P<0.05 respectively). Pringle and Jones (2002) suggest therefore that the MLSS represents the upper limit of the heavy exercise intensity domain. This is supported by the fact that during continuous exercise at ~6% above MLSS (a power-output close to CP), blood lactate concentration and $\dot{V}O_2$ both increased significantly with time. Further research in cycling by Dekerle et al., (2003) reports similar findings with CP shown to be significantly higher than MLSS work rate. Finally the same conclusions can be drawn from swimming based research where Dekerle et al., (2005) report that critical swimming speed was significantly higher than the speed at MLSS. In summary, although the CS is correlated with the ventilatory threshold, LT, MLSS and $\dot{V}O_{2\,max}$, it stands on its own as a distinct physiological marker. In terms of intensity, the CS sits at a higher intensity than the ventilatory and lactate thresholds, slightly higher than the MLSS, whilst below that associated with $\dot{V}O_{2\,max}$.

To gain an insight into the physiological significance of CS, a number of authors have directly assessed the duration for which exercise at CS can be maintained (Jenkins and Quigley, 1990; Housh et al., 1991a; McLellan and Cheung, 1992; Penteado et al., 2014). Jenkins and Quigley (1990) report that only 25% of participants in their study could sustain exercise at CP for 30 minutes without fatigue and that all participants had blood lactate levels elevated above baseline in the last 20-minutes of the exercise. The findings of Jenkins and Quigley (1990) are supported by the results from a similar study where only 1 out of the 14 participants studied could sustain exercise at the CP for 30 minutes (McLellan and Cheung, 1992). Furthermore similar results are apparent in running based research with Housh et al., (1991a) demonstrating that participants could sustain exercise at their CS for 10-17 minutes. More recent research by Penteado et al., (2014) supports the earlier work of Housh et al., (1991a) and reports that runners were only able to maintain exercise at critical speed for a mean duration of 19.3±6.4 minutes.

Rather than conducting continuous exercise at CP, as in the above studies, Burnley, Doust and Vanhatalo (2006) required participants to exercise just below and just above the CP, with the aim of gaining an insight into the intensity domains surrounding the CP. Subjects performed a ramp test, to determine $\dot{V}O_{2\,peak}$ and gas exchange threshold, along with a 3-minute all-out cycling test to determine end-test power. Subjects then performed 2 constant work rate tests for up to 30 minutes at a power output 15 W below and 15 W above the end-test power (~5% above and below respectively). During exercise just below CP, 9 of the 11 subjects were able to complete 30-minutes of exercise. Seven of these subjects met the criteria for achieving a lactate steady state (<1.0 mM increase between 10-30 minutes). In contrast, none of the subjects were able to complete a full 30-minutes of exercise at a work rate just above CP, with mean TTE being ~13 minutes. Furthermore the response of $\dot{V}O_2$ and blood lactate to exercise above CP was indicative of exercise in the severe intensity domain. $\dot{V}O_2$ rose to a level not significantly different to the $\dot{V}O_{2\,peak}$, whilst blood lactate rose continuously with time.

Other research has reported longer mean time to exhaustion at CP however these studies are notable for their considerable inter-individual variability in the TTE at CP (mean 33-minutes, range 18-60-minutes - Housh et al., 1989; mean 43-minutes, range 15-90-minutes - Scarborough et al., 1991). Taken together the results of these studies, along with the earlier research demonstrating that CP sits at an intensity above the MLSS (Pringle and Jones, 2002; Dekerle et al., 2003; Dekerle et al., 2005; Denadai et al., 2005), suggest the CP is not an exercise intensity that can be sustained forever.

Differences in the time to exhaustion at CP in the above studies may be partly due to differences in the mathematical model used to estimate CP (see section 2.3 for a detailed discussion of mathematical modelling). Bergstrom et al., (2014) have suggested that the linear, 2-parameter non-linear and exponential models may all overestimate the maximal rate of fatigue-less work. It has been suggested that the 3-parameter non-linear model produces estimates of CP that are lower than the other models (Bull et al., 2000; Housh et al., 2001; Bull et al., 2008; Bergstrom et al., 2014). Researchers have therefore also investigated the effects of continuous exercise at the CP estimated from the 3-parameter non-linear model. TTE in this instance was reported to more accurately reflect a sustainable exercise intensity, ranging from 43-60 minutes (Bull et al., 2000; Housh et al., 2001; Bull et al., 2008). Furthermore Bull et al., (2000) reported that, following exercise at the CV estimated from the non-linear-3 model, $\dot{V}O_2$ at exhaustion was significantly lower than $\dot{V}O_{2\,max}$, where as $\dot{V}O_2$ rose towards $\dot{V}O_{2\,max}$ when participants exercised at CV estimated from the other mathematical models. Therefore it is plausible that the 3-parameter non-linear model best represents the demarcation of the heavy and severe exercise intensity domains.

2.6 The physiological significance of D′.

A number of studies have also aimed to investigate the physiological significance of W′. The early work by Moritani et al., (1981) compared estimates of CP and W′ in normoxia (20.9% O_2) and hypoxia (9.0% O_2). By altering the availability of oxygen these environments provide a useful setting to investigate the suggested aerobic and anaerobic nature of CP and W′ respectively. Results revealed that lowering the inspired oxygen level reduced CP by ~50%, while seeming to have little effect on W′. This lead Moritani et al., to concur with the previous definition put forward by Monod (1972) that the W′ reflects a reserve represented by energy contained in high-energy phosphorous components and that originating from the use of intramuscular glycogen. The findings of Whipp et al., (1982) concur with Moritani et al., (1981). Whipp et al. assessed the effect of hypoxia (12% O_2) and hyperoxia (80% O_2) on CP and W′. Results revealed that CP was reduced by hypoxia and was increased by hyperoxia, however neither increasing nor decreasing the oxygen level significantly changed the W′. Whipp et al., (1982) suggest these results support the suggestion that only a fixed amount of work (W′) can be performed above CP. Recent research by Vanhatalo et al., (2010) support the findings of Whipp et al., (1982). Vanhatalo et al., (2010) investigated the effect of hyperoxia (70% O_2) on the power-duration relationship (during single leg knee extension exercise) and reported that CP was higher in hyperoxia compared with normoxia (18.0±2.3 vs 6.1±2.6W, $P<0.05$). However interestingly Vanhatalo et al.'s findings refute the suggestion of Whipp et al. that W′ remains unchanged despite increased inspired O_2 concentration. Vanhatalo et al., (2010) report a reduction of W′ in hyperoxia compared with normoxia (1.48±0.31 vs 1.92±0.70kj, $P<0.05$). These findings might suggest that the original definitions put forward by Moritani et al., (1981) and Monod (1972) were an oversimplification of the somewhat complicated physiology underpinning W′. However a further explanation for the findings of Vanhatalo et al., (2010), might be as a consequence, in part, of the reported inverse relationship between CP and W′ in the same study ($r=-0.88$, $P<0.05$). Vanhatalo et al., explain this relationship may be as a consequence of the changes induced by hyperoxia on the CP (the lower boundary of the severe intensity domain) and the $\dot{V}O_{2\ max}$ (the upper boundary of the severe domain). Vanhatalo et al., go on to explain that if the effect of the intervention causes a greater increase in CP than $\dot{V}O_{2\,max}$, the range of work rates encompassing the severe domain will be reduced and the W′ will decrease. Hyperoxia might be expected to have a greater effect on the lower end of the severe domain (CP) than it would on the upper limits of this domain ($\dot{V}O_{2\,max}$), thus perhaps explaining why CP was increased whilst W′ is reduced in hyperoxia.

A recent study by Broxterman et al., (2014) provides support for the suggestion that CP (but not W') is influenced by O_2 delivery and extraction (Moritani et al., 1981; Vanhatalo et al., 2010). Broxterman et al., (2014) aimed to manipulate the blood flow to the working muscles by altering the duty cycle of the muscle (i.e. the time the muscle is under tension). Broxterman et al., proposed that the duty cycle of a muscle (the time under tension) directly impacts the blood flow, in that high duty cycles limit the blood flow to skeletal muscle whilst low duty cycles do not present any compromise to blood flow. The methodology in the study by Broxterman et al., involved exercise on a handgrip ergometer at different duty cycles followed by 3 constant power tests on the same equipment to predict the power-duration relationship. Results revealed that CP was significantly reduced following the high duty cycle exercise compared with the low duty cycle exercise (3.9±0.9 W and 5.1±0.8 W respectively. $P<0.01$) as a result of the reduced blood flow. In contrast W′ was not significantly different in the 50% (high) duty cycle (452±141J) compared with the 20% (low) duty cycle (and 432±130J). CP has previously been shown to be dependent on O_2 delivery whereby research has reported lower CP in hypoxia (Moritani et al.,), whilst being elevated in hyperoxia (Vanhatalo et al., 2010). The findings of Broxterman et al., (2014) support the theory that CP is influenced by O_2 delivery and extraction where as W′ appears to be in part determined by mechanisms that are independent of O_2 delivery.

Glycogen depletion is known to result in reduced exercise tolerance; Miura et al., (2000) aimed to examine W′ during a condition where one of its suggested physiological determinants, muscle glycogen, was manipulated. Miura et al. aimed to establish the CP and W′ for subjects in normal glycogen (NG) and glycogen depleted (GD) states. There was no significant difference in CP between GD and NG state (NG:197.1±31.9 W, GD: 190.6±28.2 W, P=0.327). W′ in contrast was significantly reduced by the GD procedure (NG: 12.83±2.21 kJ, GD: 10.33± 2.41 kJ, P=0.01). Miura et al. suggest their findings indicate that the muscular glycogen store, the major anaerobic energy resource for such high intensity exercise, is a significant determinant of W′. However it should be noted that the authors did not directly measure the glycogen content of the working muscles via muscle biopsy. Furthermore Miura et al. point out a limitation with their work in that the muscle glycogen depletion anticipated from their protocol, is likely to occur alongside a range of other intracellular changes that could themselves influence exercise tolerance.

It has been reported that Creatine supplementation increases stores of PCr within the muscle (Harris et al., 1992). Increased levels of muscle PCr have been associated with an improvement in performance during high-intensity intermittent exercise (Birch et al., 1994). These findings may lead to the assumption that Creatine supplementation may affect the limit of tolerance during maximal exercise (Miura et al., 1999). In a double blind crossover design Miura et al., (1999) assessed the effect of 5 days of oral Creatine supplementation on the power-duration relationship. Results demonstrated no significant difference in CP between the Creatine and placebo conditions (PL 214.4 ±23.6, CR 207.0±19.8 W). In contrast, the Creatine supplementation significantly increased W′ (PL 10.9±2.7, CR 13.7±3.0 kJ, P<0.05). The results from Miura et al. suggest that Creatine and/or PCr content in the working muscle seem to be one of the important determinants of the W′. The findings of Miura et al., (1999) are supported by the later work of Eckerson et al., (2004) who also demonstrated improvements in W′ following a period of creatine supplementation. This lead the authors to suggest that W′ may be related to the amount of energy available from stored adenosine triphosphate (ATP) and PCr. Vanhatalo and Jones (2009) also explored the suggested link between PCr content and W′. Vanhatalo and Jones (2009) investigated the effect on W′ recovery of a 30 second all-out sprint followed by a 2 and 15 minute recovery period. Vanhatalo and Jones note that it has previously been shown from muscle biopsy experiments that PCr is resynthesized in an exponential fashion with a half time of approximately 56 s during recovery from a 30-s sprint (Bogdanis et al., 1995). Vanhatalo and Jones estimated therefore that approximately 80 and 100% of initial PCr content should have been restored after the 2 and 15-minute recovery periods respectively. Results revealed the estimates of PCr restoration closely parallel the restoration of W′ seen in their study, thereby supporting the notion that PCr content is a key determinant of W′. Furthermore CP was not affected by the prior sprint exercise adding weight to the earlier suggestion that CP is a parameter of strictly aerobic function. These findings are further supported by the recent work of Vanhatalo et al., (2010) who explored the mechanistic basis of exercise tolerance within the severe intensity domain via ^{31}P-MRS. Results suggested that the limit of tolerance during severe-intensity exercise (W′) might be linked to attaining critically low levels of muscle PCr concentration and/or pH.

A recent study by Johnson et al., (2014) aimed to explore the physiological significance of W′ by investigating the effect of prior upper body exercise on cycling work capacity and the power-duration relationship. The study design required subjects to conduct a severe-intensity intermittent arm-cranking exercise bout, then following a 4 minute recovery conduct one of four constant power leg cycling exercise bouts, from which the power-duration relationship was determined. Results revealed the tolerable duration of the constant power leg cycling bouts was 35±15% shorter in duration following the arm-cranking protocol. However interestingly CP was not significantly different following the arm-cranking bout compared to the leg only exercise protocol (control) – 264±20 W and 267±19 W respectively. W′ was significantly reduced following the arm-cranking protocol, amounting to a 32±6% reduction on average. The consistency of CP suggests the reduced exercise tolerance is attributable to the reduction in W′. These findings call into question the earlier work Moritani et al., (1981) and Monod (1972) as it could be suggested that if W′ was purely related to substrate depletion (energy contained in high-energy phosphorous components and that originating from the use of intramuscular glycogen) prior upper body exercise should produce a purely local effect. The main findings from the study by Johnson et al., (2014) however, report that prior severe-intensity upper body exercise reduces leg cycling W′ without a concomitant effect on CP. Johnson et al., (2014) suggest their study provides an insight into the physiological significance of W′ by providing empirical support for the suggestion that the magnitude of W′ is, in part, dependant on the accumulation of fatigue-inducing metabolites.

Murgatroyd et al., (2011) provide an interesting addition to the discussions surrounding the physiological significance of W′ by investigating oxygen uptake kinetics alongside W′. Results revealed a strong positive relationship (R^2 = 0.76, P< 0.05) between W′ and the magnitude of the $\dot{V}O_2$ slow component. Murgatroyd et al., (2011) suggest that this relationship is not surprising considering the evidence supporting a mechanistic relationship between the two parameters. For example endurance training has been shown to result in a decrease in both W′ and the magnitude of the $\dot{V}O_2$ slow component (Cleuziou et al., 2005; Demarle et al., 2001). Murgatroyd et al., (2011) state their data support the suggestion that the dynamics of the magnitude of the $\dot{V}O_2$ slow component contribute to determining exercise tolerance above CP.

Whilst accepting that the physiological nature of W′ is complex, the paper by Jones et al., (2010) summarizes this topic succinctly. Jones et al., (2010) explain that the original depiction of W′ as a fixed anaerobic energy reserve, primarily determined by the intramuscular PCr and glycogen stores, is now gradually becoming redefined. Jones et al. point to the work of Fitts (1994) acknowledging that the magnitude of the W′ may also be related to the accumulation of fatigue-related metabolites, such as H+, Pi and extracellular K+, which occur alongside the depletion of intramuscular PCr and glycogen. It has also been suggested that the W′ is linked to the development of the $\dot{V}O_2$ slow component (Murgatroyd et al., 2011), indicating that the power-time relationship may be linked to muscle metabolic and respiratory control processes within the severe intensity domain (Jones et al., 2010). This latest work suggests the earlier definition of W′ proposed by Monod (1972) and Moritani et al., (1981) based purely around substrate utilisation were an oversimplification of the somewhat complicated physiology underpinning W.

2.7 Prediction of performance from the distance time relationship

From knowing the relationship between distance and time it is possible to estimate the performance of an individual over a range of different distances and times. This process is outlined in figure 2.4 by Berthoin et al., (2006).

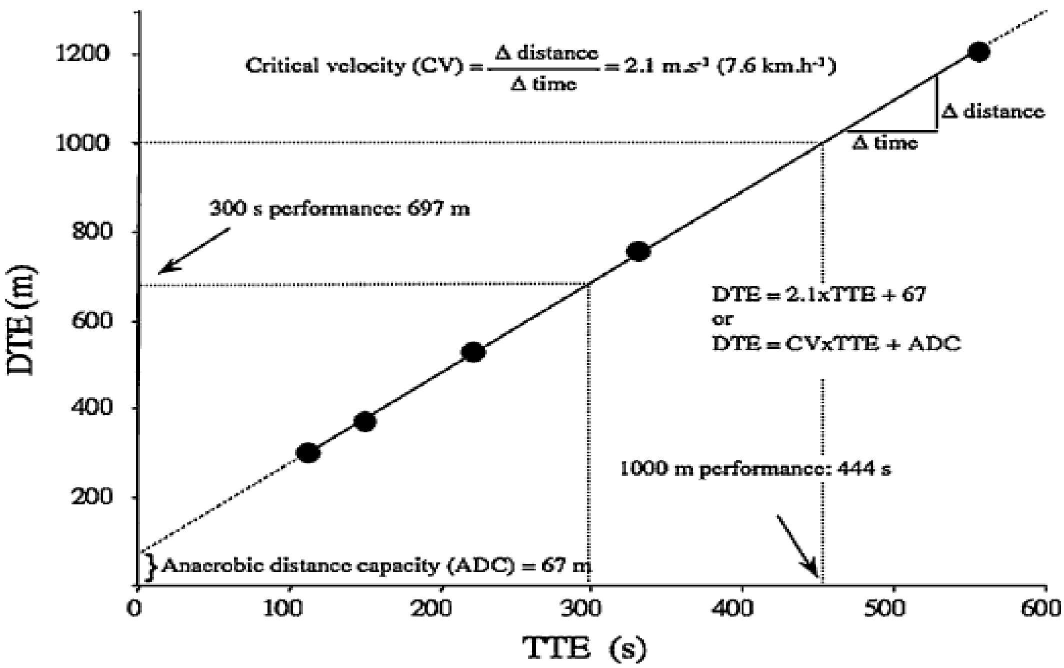

Figure 2.4. An example of the estimation of performance from the linear relationship between distance (DTE) and time (TTE). (Berthoin et al., 2006, *p.133).*

Figure 2.4 shows an example of the distance-time relationship calculated from five TTE running trials at 90, 95, 100, 105 and 110% of maximal aerobic velocity. The slope and intercept (CS and D′) of the linear relationship can be seen as 2.1 $m.s^{-1}$ and 67 m respectively. Once the CS and D′ are known the quickest time (*t*) that a set distance (D) can be covered in, and the maximum distance that can be covered in a set time can be estimated by the following equations:

$$t = (D - D') / CS \tag{8}$$

$$D = (CS*t) + D' \tag{9}$$

Using this relationship it can be seen that for the example athlete in figure 2.4, a 1000 m performance would be estimated to be completed in 444 s and that the best performance over 300 s would be estimated at 697 m.

Experimental evidence of the predictive ability of the CP test was provided by Housh, Housh & Bauge (1989). Housh et al. investigated the ability of the CP test to predict time to exhaustion in cycle ergometry. Fourteen participants completed a series of rides to exhaustion at constant power outputs in order to determine CP. Participants then completed rides to exhaustion at set percentages of their calculated CP in order to determine actual time to exhaustion. Actual time to exhaustion was then compared with predicted time to exhaustion, calculated from the CP relationship. Results revealed no significant (P>0.05) differences between the actual time to exhaustion and the predicted time to exhaustion for power loadings greater than CP.

Pepper et al., (1992) conducted a similar study in running based exercise. Four all-out treadmill runs were conducted and the velocity-time relationship was then used to predict times for a variety of treadmill velocities above and below the estimated critical velocity. Results revealed the velocity-time relationship allowed time-to-exhaustion to be accurately predicted for high-intensity exercise lasting less than 10 minutes. However predicted times for lower velocities were overestimations of the actual exhaustion time participants could achieve. The results of Pepper et al., (1992) support the suggestion by Housh et al., (1991a) that the velocity-time model did not hold true when applied to running at lower velocities.

Florence and Weir (1997) evaluated the ability of treadmill tests for CS to predict marathon-running performance. Twelve marathon runners performed a series of four randomly ordered treadmill runs to exhaustion. CS was determined from the slope of the distance-time relationship. Linear regression analyses revealed that marathon time was correlated with CS (r^2=0.76), however when marathon time was predicted using CS a SEE of 14.1 minutes was reported.

Ferguson et al., (2010) report that the linear model accurately predicted TTE during a bout of exercise designed to induce exhaustion within 6 minutes (WR_6). The mean actual TTE was 366±21 s, compared with predicted TTE of 360 s (6 min). This adds weight to previous reports that TTE during constant work rate exercise, within a constrained range of time limits, can be accurately predicted using the critical power model. Furthermore Chidnok et al., (2013) demonstrated that regardless of the protocol (constant work rate, self paced or ramp), exercise terminated predictably with complete depletion of W′. This adds further weight to the evidence suggesting that in continuous exercise, the linear model can accurately predict exercise performance.

However Hill (1993) adds a note of caution to the topic of performance prediction stating that as CS is an intensity that cannot be sustained forever, it should follow that any mathematical model will only describe distance-time data over a limited range of distances and times where the relationship remains linear (Hill, 1993). Consequently data from the distance-time relationship can be used to predict time to exhaustion over a set distance only when that distance is within the range for which the distance-time relationship is linear (Hill, 1993). Therefore the model cannot be applied to try and predict time-to-exhaustion at very high speeds (over short distances) or very low speeds (over very long distances).

2.8 Reliability and validity of CS and D′

Hopkins, Schabort and Hawley (2001) define reliability as the consistency or reproducibility of performance when someone performs a test repeatedly. Reliability, therefore, gives an indication of the ability of a physical performance test to provide the same result repeatedly. Hopkins et al., (2001) suggest their recommended measure of reliability is the typical percent error (the standard error of measurement expressed as a coefficient of variation [CV]). This measure is equivalent to the standard deviation of an individual's repeated measurements, expressed as a percent of the individual's mean test score. Hopkins et al., (2001) suggest the CV is appropriate for comparison of reliability between studies with participants of different age, sex and ability. Hopkins et al., (2001) also state a clear advantage of reporting reliability data expressed as a CV is that as a dimensionless measure, the CV allows the direct comparison of the reliability of performance measures between different tasks (cycling and running for example). Acceptable criteria for typical error have been put forward as a coefficient of variation of 10% or below (Stokes, 1985), whilst Hopkins (2000a) suggests a level of 5% or below. Atkinson and Nevill (2008) report that such criteria are in common use in the sport and exercise sciences, however they suggest that acceptable reliability would be better benchmarked as the amount of measurement error deemed acceptable for the effective practical use of the measurement tool. A test with poor reliability is unsuitable for tracking changes in performance between trials, and also lacks the precision for single trial assessment (Hopkins, 2000). It is surprising therefore that there is not a wealth of research into the reliability of the parameter estimates from the distance-time relationship.

Some short-term reliability studies over the course of ~1 week are available in the cycling literature. These studies were summarized by Hopkins, Schabort and Hawley (2001) and have been presented in a table (table 2.1) in this chapter to allow ease of comparison. Gaesser and Wilson (1988) assessed the reliability of CP and W′ calculated from 5 predictive trials performed on two occasions separated by a week. A high test-retest correlation (r=0.96) was reported for CP however the retest estimate was significantly higher (3%) than the first trial. A slightly lower test-retest correlation (r=0.79) was reported for W′, however there was no significant difference between the mean W′ from the first and second set of trials. This was despite 4 of the 11 retest estimates differing by over 15% from the first set. In their review paper Hopkins et al., (2001) report the CV for CP and W′ from the study by Gaesser and Wilson to be 3.0 and 9.8% respectively. In a similar study Nebelsick-Gullett et al., (1988) assessed the reliability of CP and W′ in 25 female participants. Three predictive trials were performed on the same day with 30 minutes recovery between trials. Trials were then repeated again within a 7-day time frame. A high test-retest correlation (r=0.94) was reported for CP whilst again a slightly lower test-retest correlation (r=0.87) was reported for W′. No significant differences were reported between the mean values for CP and W′ estimated from the first and second trials. Hopkins et al., (2001) report the CV for CP and W′ from the study by Nebelsick-Gullett et al. to be 5.6 and 11% respectively. Finally Smith and Hill (1993) assessed the reliability of CP and W′ in 13 male and 13 female participants. Subjects completed repeat tests of 5 predictive trials on separate days. Test-retest correlation coefficients of r=0.91 and r=0.72 were reported for CP and W′ respectively. Hopkins et al., (2001) report the CV for CP and W′ from the study by Smith and Hill to be around 6.0 and 10.5% respectively. Hill (1993) explains that the test-retest correlations for CP in the aforementioned research are similar to those reported in traditional testing of maximal aerobic power (Thoden 1990). In addition to the cycling based research Taylor and Batterham (2002) applied the power-duration relationship to high-intensity upper body exercise in order to assess the reliability of CP and W′.

Sixteen active male subjects performed two sets of 5 constant-power TTE trials on an arm-crank ergometer. Repeat trials were conducted 1-week apart. Results demonstrated no significant difference between the first and second trial parameter estimates for either CP or W′ (96 and 95 W; 7.5 and 7.6 kJ respectively). The 95% limits of agreement (LOA) for CP were reported as -15 to +17 W, whilst the ratio LOA for W′ suggest a repeat measurement may be between 0.57 and 1.67 times the original estimate.

More recent research in cycling has focused on the reliability of the parameter estimates from the 3-minute all-out test. These studies are summarised in table 2.1 to allow comparison with the relative reliability of traditional time to exhaustion protocols. The original work in this area by Burnley et al., (2006) and Vanhatalo (2008) report good reliability for CP (CV 3%) whilst a lower level of reliability was seen in the estimation of W′ (CV 9%). Johnson et al., (2011) reported no significant difference between test-retest measures of CP from a 3-minute test (CV 6.7%, typical error 15.3 W, intraclass correlation coefficient r=0.93). However significant differences between test-retest estimates and a lower level of reliability were reported for W′ (CV 20.7%, typical error 1.5 kJ, intraclass correlation coefficient r=0.87). It is important to note that Johnson et al., (2011) did not use a familiarisation trial in their study. Constantini et al., (2014) report a similar level of reliability to that of the original work by Burnley et al., (2006) and Vanhatalo (2008). Results revealed a CV of 3.5% for CP and 12% for W′.

Gaesser and Wilson (1988) and Smith and Hill (1993) both reported significantly higher CP values (~5%) from the second set of estimates, whilst mean W′ values remained unchanged between the test and retest trials. The higher test-retest correlation coefficient reported in the second set of predictive trials suggest that there may be a learning effect for time to exhaustion CP trials (Gaesser and Wilson, 1988; Smith and Hill, 1993), although this same learning effect did not seem to be present for W′. These findings suggest the need for at least one familiarisation trial in order to improve the reliability of the parameter estimates from the distance-time relationship. It has also been reported that pacing strategy can be optimised with additional familiarisation to the task (Mauger et al., 2009; Micklewright et al., 2010). This may also point to the need for a familiarisation trial in order to aid the reliability of the parameters estimates calculated from fixed distance self paced trials. The need for a familiarisation trial (repeat testing) detracts from the usability of the single visit protocol, however Hill (1993) suggested repeating just the longer trials may be an alternative approach, as it is these trials where the greatest learning effect is likely to be present.

Research into the reliability of the parameter estimates from running based research is sparse. Hinckson and Hopkins (2005) assessed the reliability of CS and D′ estimated from treadmill running trials. Eight male competitive runners conducted three constant-speed runs to exhaustion lasting approximately 2, 4, and 8 min, with a 30-min rest between runs. A pair of such tests 5-days apart was repeated 7 and 14 weeks later within a summer competitive season. Results demonstrated good reliability (expressed as CV) for CS (1.8%), but poor reliability for D′ (14%). Table 2.1 summarises this study and allows comparisons of the relative reliability between traditional time to exhaustion cycling trials, single visit cycling trails and time to exhaustion treadmill trials. The reliability data reported by Hinckson and Hopkins (2005) appear similar to that of the previous research for multiple visit TTE cycling and all out cycling performance. This suggests the reliability of the parameter estimates may be similar when calculated from the power-duration and distance-time relationship in cycling and running respectively. Hinckson and Hopkins (2005) investigated the reliability of CS and D′ via the use of constant-speed TTE runs on a treadmill, however there appears to be no research on the reliability of CS and D′ using constant distance trials in the field.

Table 2.1 A comparison of the relative reliability of the parameter estimates from different forms of power-time and distance-time test protocols.

Reference	Mode	Participants	Number of repeat trials	Number of tests to exhaustion	Duration of tests	Reliability of CP/CS	Reliability of W'/D'
Gaesser & Wilson (1988)	Cycle TTE	11 Male	2	5	1-10 min	3.0%	9.8%
Nebelsick-Gullet et al., (1988)	Cycle TTE	25 Female	2	3	≥1 min	5.6%	11%
Smith & Hill (1993)	Cycle TTE	13 Male & 13 Female	2	5	1-10 min	6.0%	10.5%
Burnley et al., (2006)	Cycle single-visit	9 Male & 2 Female	2	1	3 min	3%	9%
Johnson et al., (2011)	Cycle single-visit	6 Male & 5 Female	2	1	3 min	6.7%	20.7%
Constantini et al., (2014)	Cycle single-visit	6 Male and 6 Female	2	1	3 min	3.5%	12%
Hinckson and Hopkins (2005)	Treadmill TTE	8 Male	6	3	2-8 min	1.8%	14.0%

Reliability is reported as the typical error displayed as a coefficient of variation (CV) percentage. Table adapted from Hopkins et al., (2001).

A common theme in the above reliability studies in cycling and running is that the reliability of W′ or D′ appears to be lower than that of CP or CS (Table 2.1). Vandewalle et al., (1997) suggest that this maybe a consequence of the modelling technique in that that the y-intercept is more sensitive to variations in time than the slope. A large error in time limit could therefore have a small effect on the calculation of critical power, however in contrast the y-intercept is very sensitive to errors in time limit. Vandewalle et al., (1997) explain that because of fatigue and/or motivation the observed values of time limit and work limit (or distance limit) can be underestimations of the true values of exhaustion times and work or distance. To illustrate this point Vandewalle et al., present an example data set where the observed values of time limit differ (by 5%) from the true value of time limit. Vandewalle et al., reveal the error in the y-intercept in this instance is equal to 11% compared with 1.9% for the CP.

2.9 Advantage of field-based research within the distance-time domain.

CS has traditionally been viewed as the treadmill analogue of CP with the majority of early research using treadmill tests to determine the distance-time relationship. It is possible however to calculate the distance-time relationship in a field based setting without using a treadmill. For certain sports, field tests may be preferable to laboratory tests, as field tests are conducted while the athlete is performing in a simulated competitive setting (Nummela, Hamalainen and Rusko, 2007). Generally field tests are viewed as less reliable than laboratory tests, due to the lower level of control over external (environmental) factors available to the researcher. However field tests could be viewed as more ecologically valid due to their greater specificity to the sport in question (Nummela et al., 2007). For a runner, a distance-time relationship test conducted on an athletics track would arguably have greater ecological validity than the same test conducted on the treadmill. Furthermore Kachouri et al., (1996) suggest that the application of data collected during treadmill exercise to the design of an outdoor running training program may be questionable. This is due to the assumption that running biomechanics are the same in the field and on a treadmill. Kachouri et al., (1996) explains that even if the differences between treadmill and field running are small the effects of these slight differences are not negligible due to the hyperbolic nature of the distance-time relationship.

A further advantage of field-based distance-time protocols is that they can benefit from fixed distance performance trials that mimic the demands of competitive races by allowing pace variation. Whilst fixed distance self-paced trials are possible on a treadmill, they are more complicated to administer and arguably do not allow the instantaneous fluid changes of pace that an athlete can achieve on a running track. Treadmill distance-time protocols are therefore often limited to constant velocity time to exhaustion trials (Florence and Weir, 1997; Pepper et al., 1992; Housh et al., 2001; Bull et al., 2008; Smith and Jones, 2001; Kolbe et al., 1995; Kranenburg and Smith, 1996; Bosquet et al., 2006). Constant velocity time to exhaustion trials may be viewed as less ecologically valid as there may be a minimal number of real-life exercise performance scenarios where an athlete exercises at a constant intensity until voluntarily stopping (Laursen et al., 2007).

Furthermore, research into the reliability of constant velocity trials in running has shown them to display poor reliability. This is supported by similar findings in both cycling and swimming (Jeukendrup et al., 1996; Alberty et al., 2006). Laursen et al., (2007) conducted a comprehensive study comparing the reliability of constant velocity time to exhaustion trials with self-paced time trials over a set distance in trained runners. Participants completed two 5 km and two 1500 m time-trials, as well as four time to exhaustion trials; two at the equivalent mean 5-km running speed and two at the equivalent mean 1500 m running speed. All tests were conducted on a motorised treadmill. Laursen et al., (2007) reported a lower level of absolute reliability (higher variability) for the completion time of constant speed time-to-exhaustion running tests compared with time-trial tests at a variable self-selected speed. Mean typical error of the measurement reported as a coefficient of variation (CV) was 2.0% (range 1.3–4.0%) and 3.3% (range 2.1–6.8%) for the 5 km and 1500 m time trials, whilst for the time-to-exhaustion tests conducted at the same mean velocity, the CV was 15.1% (range 9.8–33.2%) and 13.2% (range 8.6–28.8%). The low variability of self-paced fixed distance trials in running is further supported by the research of Nicholson and Sleivert, (2001) who report a CV for repeated 10 km running trials of 3.7%.

The lower variability reported in time-trial tests may be a result of the more dramatic effect on performance of fatigue, boredom and lack of motivation during time-to-exhaustion protocols compared with time-trial tests (Laursen et al., 2007). During time-trial tests, athletes can increase or decrease their exercise intensity (pace) according to their motivation and their perception of fatigue (Hampson et al., 2001). In time-to-exhaustion tests exercise intensity is fixed, therefore as an athletes perception of fatigue increases they are only presented with the choice of continuing the trial at the same pace or stopping completely (Laursen et al., 2007). An alternative viewpoint is that the variations in pace permitted during constant distance time trial performances may actually serve as a disadvantage by adding ‘‘noise’’ to the measurement of physiological markers (Hinckson and Hopkins 2005). However Jeukendrup and Currell (2005) maintain that pacing strategy is an “inherent component of real performance” therefore not necessarily something that should be omitted from performance tests. Chidnok et al., (2013) add weight to this viewpoint by providing empirical evidence that the depletion of a reproducible capacity for work above critical power and ultimately the factors which lead to the termination of exercise during high-intensity exercise are not affected when subjects are allowed to self-pace.

An opposing view is that time to exhaustion trials are inherently reliable and the apparently poor reliability seen in some studies is an artefact of the relationship between exercise duration and power output (Hopkins, Schabort and Hawley, 2001). In fact when changes in time to exhaustion in reliability studies are converted to estimated changes in time-trial performance using the power-output-time relationship, measurement error seems comparable to that of actual time trials (Hinkson and Hopkins, 2005; Hopkins, Schabort and Hawley, 2001). The power-output-time relationship could mean that small (~1%) changes in a subject’s ability to produce power from test to test result in much larger (~10–20%) random changes in time to exhaustion (Hinkson and Hopkins, 2005). Therefore an intervention producing a substantial change in a subject’s ability to produce power will also result in a large change in time to exhaustion, which will stand out against the large random changes (Hinkson and Hopkins, 2005). Amann, Hopkins and Marcora (2008) support this view and draw on the example of priming exercise inducing a 30-60% improvement in performance when measured with a constant-power test, compared with just 2-3% when measured with a time trial (Jones, Wilkerson, Burnley and Koppo, 2003; Burnley, Doust and Jones, 2005). In their 2008 study Amann et al., further this point by demonstrating a similar level of sensitivity from constant-power and time trial tests, with both test protocols being able to detect statistically significant changes in endurance performance.

2.10 Application of the distance-time relationship to a field-testing environment.

McDermott, Forbes and Hill (1993) attempted to calculate the distance-time relationship from running trials in a field based setting, however the duration of the shortest trial fell outside of the ideal limits of the distance-time relationship. McDermott et al., (1993) tested twelve participants over all out runs of 400, 800 and 1600 meters on an outdoor running track; participants also completed a 5 km and a 10 km road race. All trials were completed on separate days. The distance-time relationship was calculated from the non-linear regression of speed and time for the three shortest distances, the four shortest distances and all five distances. The distance-time relationship from the three shortest trials was then used to predict the finish time over 10,000 m. The predicted 10,000 m time correlated with the actual 10 km race time (r=0.97, P <0.001) however the predicted time was on average 2-3 minutes faster than the actual times run by the participants. In their original work on the distance-time relationship Hughson et al., (1984) suggested runs of 2-12 minutes should be used to form the basis of the relationship. In the study by McDermott et al., (1993) the shortest trial used in the prediction was a 400-meter trial, where the average time of the participants was under 60 seconds. This may have contributed to the predicted 10,000 m time being on average 2-3 minutes quicker than the actual 10 km time. This is because a short distance trial may pull the bottom point in the linear relationship down, thus increasing the estimated CS. An inflated CS may have contributed to predicted race times being faster than participants could actually achieve.

The second limitation with the methodology of McDermott et al., (1993) is that whilst it may be considered to have greater ecological validity than treadmill testing, the feasibility of conducting 3 trials on separate days is just as time consuming for an athlete as the original treadmill protocols. A distinct disadvantage with the laboratory-based treadmill protocols was the number of repeat running trials (typically 4-6) used in the calculation of the distance-time relationship (Smith and Jones, 2001; Kolbe et al., 1995) along with the length of recovery period required between trials (often >24 hours).

Kranenburg and Smith (1996) expanded on the study of McDermott et al., (1993). They calculated the distance-time relationship on an indoor running track (measuring 454 m) in nine highly trained male runners. The track tests for the distance-time relationship involved all out runs over 2, 5 and 9 laps. Two of the trials were conducted on one day separated by 1 hour, with the final trial being conducted the following day. Participants also completed tests for the distance-time relationship on a treadmill at fixed velocities, with tests separated by the same time intervals as described for the track tests. The distance-time relationship for the treadmill and track tests was calculated from linear regression of the distance run versus time. The calculation of the goodness of fit for the track runs was r^2=0.99 and for the treadmill was r^2=0.90. The authors explain this difference by the fact that for the track runs, the participants knew the distance to be run and could pace their efforts accordingly. However for the treadmill runs the inability to change pace may have meant that motivation rather than fatigue contributed to the decision to cease running. The r^2 values for the treadmill tests suggest that the results may have been affected by such motivational issues and that potentially the efforts were not maximal. It should be noted however, that Galbraith and Dabinett (2009) report contrasting data where a similarly high data fit (r^2=0.99) was seen for treadmill and track runs.

Kranenburg and Smith (1996) state that the track-based field test for the distance-time relationship is a good method for coaches to assess the conditioning of their athletes and predict 10 km performance. The authors also state that it is easy to include the testing protocol in training workouts. However this would mean that athletes would have to alter two of their training sessions in order to accommodate the three runs. So whilst the methodology is again ecologically valid, the feasibility of the repeat testing makes the protocol difficult for athletes to implement.

2.11 Application of the distance-time relationship to a single visit protocol.

With the issue of repeat testing limiting the usability of many CS and CP testing protocols, researchers set out to develop single visit test protocols, first in cycling through the work of Dekerle et al., (2006) and Vanhatalo, Doust and Burnley (2007) and then in running through the work of Pettitt, Jamnick and Clark (2012).

Dekerle et al., (2006) compared the W′ estimated from three constant-load time to exhaustion tests on a cycle ergometer with the power output-time integral above CP during a single all-out 90-second cycle test (*W*90s’). Results revealed that W′ and *W*90s’ were not significantly different (*P*=0.96) and were significantly correlated (*r*=0.78). However the Bland and Altman plots revealed low limits of agreement between the two measures (2.3±7.2 kJ). Dekerle et al., also showed that power output was still considerably higher than the previously established critical power at the end of the 90-second all-out effort.

Morton (2006) suggests that during any exercise bout performed above CP, W′ is gradually expended and cannot be replenished until exercise is terminated or work rate falls below CP. The linear inverse of time model (equation 6) implies that at the time point where the W′ becomes wholly depleted, the highest achievable power output is CP [if W′=0, then P=CP] (Vanhatalo, Doust and Burnley, 2007). Vanhatalo et al. go on to suggest that it should therefore be possible to use the entire W′ in a sufficiently long all-out exercise bout, in which power output would decrease progressively until CP was attained. Therefore whilst the premise of using a single all-out exercise test to calculate CP and W′ is sound it would appear that the 90 second test used by Dekerle et al., (2006) is too short to achieve this aim. In their 2007 study Vanhatalo et al. set out to compare the parameters of the power–duration relationship derived from a 3-min all-out cycling test with those derived from a series of five exhaustive exercise bouts (the conventional method of CP determination). Specifically, they tested the hypotheses that the end power (EP) in a 3-min all-out cycling test was equivalent with CP and the work above end power (WEP) in the same test was equivalent to W′. Ten moderately trained participants (mean $\dot{V}O_{2\,max}$ 4.18±0.66 L.min^{-1}) took part in the study, each visiting the laboratory on eight occasions to complete the testing protocol. Results revealed that the EP from the 3-min test (287±55 W) was not significantly different from the CP calculated from the 5 constant power trials (287±56 W). Furthermore the WEP (15.0±4.7 kJ) was not significantly different from the W′ (16.0±3.8 kJ). EP and CP were highly correlated *r*=0.99 with a standard error of the estimate (SEE) of 6 W. WEP and W′ were also highly correlated *r*=0.84 with a SEE of 2.8 kJ. The results of this study by Vanhatalo et al., (2007) were the first to confirm that CP and W′ could be determined using a single bout of all-out exercise. It should be noted, however, that Bergstrom et al., (2014) have recently presented conflicting results, reporting that the CP (but not the W′) estimated from the 3-minute test was significantly greater than the CP estimated from four constant power TTE trials when modelled via the linear-work and linear-power models.

In terms of the time constraints of the protocol, the 3-min single visit test has a clear advantage over the traditional multiple trial repeat visit protocols. A further advantage of the 3-minute test, in addition to providing estimates of CP and W′, is its ability to provide an indication of $\dot{V}O_{2\,peak}$ and maximal lactate steady state from the single visit (Burnley, Doust and Vanhatalo et al., 2006). The estimation of MLSS typically requires repeated testing bouts, therefore the fact that a single visit cycling test can identify the boundary between the heavy and severe intensity domains is a clear advantage.

One downside of the 3-min test is the need to conduct a prior incremental exercise test to determine gas exchange threshold (GET) and $\dot{V}O_{2\,max}$ (Constantini et al., 2014). This incremental test is required in order to determine the linear resistance applied to the flywheel of the ergometer during the 3-min test. Typically this incremental test is performed on a separate day therefore slightly reducing the practical application of the 3-minute all-out test as a single-visit test for CP and W′. Constantini et al., (2014) assessed CP and W′ determined in a single session, whereby an incremental test and a 3-min test were conducted on the same day, separated by a 20-min recovery (combined test). This was compared with an incremental test and 3-min test performed on separate days (independent test). Results revealed no significant differences in CP or W′ estimated from the combined and independent tests.

Constantini et al., (2014) therefore suggest that the combined protocol allows the accurate and valid determination of CP and W′ in a single visit, thus further extending the practical application of the 3-minute protocol proposed by Vanhatalo et al., (2007).

Pettitt, Jamnick and Clark (2012) built on the work of Vanhatalo et al., (2007) and investigated the principle of applying a 3-min all out single-visit test to running based exercise. Pettitt et al. reported that CS values from the 3-minute running test (4.46±0.41 m.s) were not significantly different from the treadmill graded exercise test value for 50%Δ (4.55±0.24 m.s). In summary Pettitt et al. conclude that the 3-minute running test appears equally effective for running, in comparison to cycling. There are however still a number of limitations with the 3-minute all-out running test, which could prevent its widespread utilization by coaches and athletes. The 3-minute all-out running test relies on the use of GPS technology to track the displacement and speed of the participant during the test. This technology, although now reducing in price, may still be out of the reach of some athletes who as such would be precluded from implementing this test in their testing regime. A further disadvantage of the 3-minute all-out running test is that it lacks a high level of ecological validity, as all-out exercise performance for a set time period is not representative of traditional running competitions or race structures.

In summary, whilst protocols for running based single visit field-tests have previously been proposed, a fixed-distance single-visit field test of the distance-time relationship would be more accessible and have greater ecological validity. A single-visit fixed-distance field test *may* therefore have all of the necessary attributes to enhance the practical application of distance-time protocols by athletes, coaches and sports scientists alike.

In order to accurately assess the distance-time relationship from repeated trials within a single visit it is important that CS and D′ are fully recovered between bouts.

Ferguson et al., (2010) provided evidence for the recovery kinetics of CP and W′ following exhaustive exercise. Six participants performed a randomized series of four constant-load tests to exhaustion on separate days in order to determine the power-duration relationship. Participants then performed a conditioning bout to exhaustion at a constant-load designed to induce exhaustion in 6-minutes. The conditioning bout was followed by one of three recovery interventions of differing duration (2, 6, and 15 min) performed at 20 W. This was followed immediately by one of the constant-load tests to exhaustion in order to redefine the power-duration relationship after differing recovery durations. Following the conditioning bout the CP remained unchanged regardless of the recovery duration. However the W′ recovered to 37±5, 65±6 and 86±4% of the control value following 2, 6, and 15 min of recovery, respectively.

Based on the work of Ferguson et al., (2010) it would appear that a 15-minute recovery would not be sufficient to allow full reconstitution of W′ between exercise bouts in a single visit protocol. Skiba et al., (2012) built on the work of Ferguson et al. and produced a model describing the time course of W′ depletion as an exponential function yielding a time constant of ~377 seconds. Constantini et al., (2014) suggest the work of Skiba et al. implies a full recovery duration for W′ of approximately 25-min. The combined findings of Fergusion et al., (2010), Skiba et al., (2012) and Constantini et al., (2014) suggest that a recovery period of at least 25 minutes would be required between exercise bouts in a single visit protocol.

It is possible that having the exercise bouts which make up the distance-time relationship all in the same day, with a relatively short recovery between them, may induce an effect from one bout on the next, which could either limit (through fatigue) or aid (via priming oxygen uptake kinetics) the performance of the next trial. A limiting or aiding effect of a previous trial may have an impact on the estimated CS and D′ from the distance-time relationship. Burnley, Davison and Baker (2011) provide a brief review of the priming literature and report that priming exercise in the heavy and/or severe intensity domain followed by sufficient recovery (>9-10 min) has been shown to increase the limit of exercise tolerance by 10-60% (Bailey et al., 2009; Carter et al., 2005; Jones et al., 2003,) and increase mean power output during short term high-intensity performance by 2-5% (Burnley et al., 2005; Palmer et al., 2009).

Jones et al., (2003) demonstrated that the enhancement seen in exercise time to exhaustion is associated with a tendency for W′ to be increased following such priming bouts. Miura et al., (2009) reported that the tolerable duration of severe intensity exercise was increased following a 6 min bout at a heavy intensity (halfway between LT and $\dot{V}O_{2\,peak}$). However, in contrast to the work of Jones et al., (2003) the increase in TTE in the study by Miura et al., was attributed to a significant increase in CP (168.7±31.3 W, control; 176.5±34.3 W, heavy-intensity warm up) whilst W′ remained unchanged (11.0±3.1 kJ, control; 11.0±3.2 kJ, heavy-intensity warm up).

An important factor of whether priming exercise evokes an improvement for supra-CP exercise is likely to be the intensity of the priming bout (whether it is above CP) and the nature of the recovery period. These factors are of importance as they will influence the extent to which blood lactate levels remain elevated at the start of the post-priming bout (Ferguson et al., 2007). In line with this suggestion Burnley et al., (2005) propose that at the start of a post-priming bout, blood lactate levels <5 mM are associated with an increase in performance (Burnley, Jones and Doust, 2005; Jones et al., 2003), values modestly over 5 mM are associated with no change in performance (Burnley, Jones and Doust, 2005; Koppo and Bouckaert, 2002), whilst values substantially >5mM lead to reduced performance in the post priming bout (Karlsson et al., 1975; Ferguson et al., 2007). This has implications for a multi-trial single visit protocol, where it may be expected that, from trial two onwards, a priming effect of the previous trial would either aid or hinder the subsequent performance, thus altering the shape of the relationship between distance and time.

2.12 The effect of training on the distance-time relationship

Fry, Morton and Keast (1992) describe the process of training aimed at enhancing performance as a temporal adaptational process that involves a progressive and variable implementation of purposely-orientated physical loads. Training should mainly be considered a multifactorial process (Manzi et al., 2009) where adaptations leading to performance enhancements are achieved with proper manipulation of training loads via the interaction of volume and intensity (Mujika and Padilla, 2003).

Whilst research into the sensitivity of distance-time protocols to detect training induced changes in CS and D′ are lacking, several studies have investigated the effect of short duration training programmes on CP and W′. Table 2.2 provides a summary of these studies for ease of comparison. Gaesser and Wilson (1988) investigated the effect of a 6-week training intervention on the CP and W′ of 11 untrained men. Training was conducted 3 times per week on a cycle ergometer with participants performing either continuous training for 40 minutes at 50% $\dot{V}O_{2\,peak}$, or interval training comprising of 10 two-minute bouts at 100% $\dot{V}O_{2\,peak}$. CP increased in all individuals with a mean increase of 13% for the continuous group and 15% for the interval group. W′ was not statistically different after the training intervention in either group. In a similar study Poole et al., (1990) investigated the effects of 7 weeks of interval training on CP and W′, with participants performing 10 two-minute cycling bouts at 105% $\dot{V}O_{2\,peak}$ 3 times per week. CP responded in a similar fashion to the study by Gaesser and Wilson (1988), with increases in CP reported in all participants and a mean increase in CP of 10%. $\dot{V}O_{2\,max}$ increased by 15% as did the $\dot{V}O_2$ at CP, however interestingly the increases were not significantly correlated (r = 0.52). As in the study of Gaesser and Wilson (1988) the mean pre and post training intervention values for W′ remained unchanged, although considerable variation between participants was reported in the results, with increases in W′ of between 4 and 32% in four participants and decreases of between 5 and 19% in a further 3 participants. Kendall et al., (2009) compared the effects of four weeks of high intensity interval training (5x2 min bouts at ~80-120% $\dot{V}O_2$ at peak power output, 3 times per week) and creatine supplementation on CP and W′. However it is the results of their training-only (non supplementation) group that are of interest in this instance. The training-only group demonstrated no significant increases in either CP or W′ after the intervention. A possible explanation for the differences in CP findings between the studies was that both Gaesser and Wilson (1988) and Poole et al., (1990) used 10x2-min work bouts, compared with just 5 in the study by Kendall et al., (2009). The lower volume of work in the Kendall et al. study may have contributed to the lack of change in CP observed compared to the studies by Gaesser and Wilson and Poole et al.

Jenkins and Quigley (1992) investigated the effects of continuous endurance training on the CP of 12 participants. In this 8-week study participants trained for 30-40 minutes per day three times per week at an intensity corresponding to their CP. CP values were calculated on a cycle ergometer from 3 all-out predicting trials separated by 3-hour recovery periods. CP was shown to increase on average by 30% following the 8-week training period; this supports the original findings of Gaesser and Wilson (1988). Although it is interesting to note that the improvement in CP (30%) in the study by Jenkins and Quigley (1992) was far greater than the improvement (13%) reported in the study by Gaesser and Wilson (1988). The larger improvement in CP could be due to a combination of the longer intervention period (8 vs. 6 weeks) and the increased training intensity (~ CP vs. 50% $\dot{V}O_{2\,peak}$). In their later paper, Jenkins and Quigley (1993) investigated the effect of 8-weeks of high intensity interval training on the parameters of the power-time relationship. Eight male participants performed five all-out 1-minute cycling bouts at a high-intensity (0.736 N/kg), separated by 5-minute recovery periods, 3 days per week. As in their previous study (Jenkins and Quigley, 1992) parameters of the power-time relationship were calculated on a cycle ergometer from 3 all-out predicting trials separated by 3-hour recovery periods. Results revealed increases in W′ of 49% whilst no change was reported in CP. Conversely, Gaesser and Wilson (1988) reported no change in W′ following 6 weeks of training involving 10 two-minute bouts at 100% $\dot{V}O_{2\,peak}$ 3 times per week. Differences in the findings of the two studies might be due to a combination of the slightly longer training intervention (8 vs. 6 weeks) and the reduced duration and increased training intensity in Jenkins and Quigley’s study (1-min bouts at 0.736 N/kg [~480 W for the population group studied] vs. 2-min bouts at 100% $\dot{V}O_{2\,peak}$). The combined results of Gaesser and Wilson (1988); Poole et al., (1990); Kendall et al., (2009) and Jenkins and Quigley (1993) suggest that repeated bouts of training at high intensities for ~1-min duration may be necessary to produce significant increases in W′.

Table 2.2: A comparison of different training intervention studies and the relative effects on the power-duration relationship.

Reference	Mode	Participants	Training status of participants	Intervention	Frequency of intervention	Duration of interventi on	Change in CP	Change in W’
Gaesser & Wilson (1988)	Cycling	11 Male	Untrained	Continuous group: 40 minutes at 50% $\dot{V}O_{2\,peak}$	3 x per week	6-weeks	13% ↑	No change
				Interval group: 10 x 2-minute bouts at 100% $\dot{V}O_{2\,peak}$			15% ↑	No change
Jenkins and Quigley (1992)	Cycling	12 Male	Untrained	30-40 minutes at CP	3 x per week	8-weeks	30% ↑	No change
Poole et al., (1990)	Cycling	8 Male	Untrained	10 x 2-minute bouts at 105% $\dot{V}O_{2}$ peak	3 x per week	7-weeks	10% ↑	No change
Jenkins and Quigley (1993)	Cycling	8 Male	Untrained	5 x 1-minute high intensity cycling bouts at (0.736 N/kg)	3 x per week	8-weeks	No change	49% ↑
Kendall et al., (2009)	Cycling	42 Male	Recreationally active*	5 x 2-min bouts at ~80-120% $\dot{V}O_{2}$ at peak power output	3 x per week	4-weeks	No change	No change

↑ = increase; * = defined as 1–5 hr/wk aerobic exercise, resistance training, or recreational sports

It has been suggested that the CP and W′ may be correlated, in that an increase in one parameter may lead to a decrease in the other. Vanhatalo et al., (2010), for example, demonstrated an increase in CP and a decrease in W′ during a period exposed to hyperoxia, with an inverse correlation reported between the changes in CP and W (r =−0.88). Moreover Vandewalle et al., (1997) report the D′ of the distance-time relationship calculated from the 1500 m and 5000 m events progressively decreased from 219 to 188 m at the different Olympic games from 1972-1988, whilst the CS improved from 5.93-6.08 $m.s^{-1}$ during the same period. This suggests an interrelationship between the two parameters over a prolonged period. Furthermore in the study by Jenkins and Quigley (1992) W′ appeared to decline (-26%) after the 8 week training period whilst CP increased (31%) over the same period, however the decline observed in W′ did not attain statistical significance. Additionally, Vanhatalo, Doust and Burnley (2008) report that following a 4-week period of interval training at an intensity above CP, CP increased in all subjects, whilst W′ was reduced in eight out of the nine subjects (although again this decrease in W′ did not reach statistical significance). Additionally the change in CP was inversely related to the change in W′ (r = -0.75, P = 0.02). Bergstrom et al., (2014) point to the mathematical modelling of the power-duration relationship to provide further evidence of an interrelationship between CP and W′. Bergstrom et al. report from their data that the 3-parameter nonlinear model produced the lowest estimates of CP along with the highest estimates of W′ suggesting a certain level of interrelationship between the parameters. The results of Jenkins and Quigley (1992) and Vanhatalo, Doust and Burnley (2008) and Bergstrom et al., (2014) add further weight to the suggestion by Vandewalle et al., (1997) that an interrelationship exists between CP and W′.

Vanhatalo et al., (2010) suggest the interrelationship between CP and W′ may be explained by the relative changes induced by a given intervention on the CP and the $\dot{V}O_{2\,max}$ respectively. If the increase in CP is greater than the increase in $\dot{V}O_{2\,max}$ then the range of work rates encompassing the severe domain is reduced and the W′ must therefore decrease (Burnley & Jones, 2007). The fact that W′ has been shown to be reduced following interventions such as training and hyperoxia which are effective in altering both CP and $\dot{V}O_{2\,max}$ (Jenkins & Quigley, 1992; Vanhatalo et al., 2008;

Vanhatalo et al., 2010) might therefore reflect the fact that these interventions have a greater effect on ‘submaximal’ indices of aerobic fitness (such as the CP) than they do on the $\dot{V}O_{2\,max}$ (Vanhatalo et al., 2010). This suggestion by Vanhatalo et al., (2010) is not supported by the work of Jenkins and Quigley (1992) where no reduction in W′ was reported despite a 31% improvement in CP after training and only an 8.5% increase in $\dot{V}O_{2\,max}$ during the same period.

2.13 The distance time relationship and intermittent exercise

In athletic training the individualisation of exercise is a key factor in the development of fitness (Berthoin et al., 2006). For aerobic training, parameters such as $\dot{V}O_{2\,max}$, velocity at $\dot{V}O_{2\,max}$, lactate/ventilatory thresholds and maximal heart rate have all been used to prescribe individualised training intensities (Berthoin et al., 2006; Billat, 2001). Gas analysis and capillary blood sampling, however, are expensive techniques and heart rate is not immune from its own disadvantages. These include a small day-to-day variability in heart rate and a steady increase in heart rate during prolonged exercise (Achten and Jeukendrup 2003). Furthermore, factors such as dehydration and ambient temperature can have an effect on the heart rate-$\dot{V}O_2$ relationship (Achten and Jeukendrup, 2003). An additional consideration when defining training intensity as a percentage of HR_{max} or $\dot{V}O_{2\,max}$ is that CP does not occur at a fixed percentage of HR_{max} or $\dot{V}O_{2\,max}$ (Rossiter, 2010), furthermore between-subject differences in anaerobic capacity (Clark et al., 2013) result in the D′ not representing the same volume of supra-CS exercise in all individuals (Murgatroyd et al., 2011). The D′ is of considerable importance to sports performance because complete depletion of the D′ prevents an athlete performing at an intensity above CS (Skiba et al., 2012). The consequence of this is that the exercise intensity experienced during an interval training session will be variable between participants unless the distance-time relationship is accounted for. The distance-time relationship could therefore provide an alternative method for individualising exercise intensity in athletes training programs.

Interval training is a popular mode of conditioning used in exercise training programs in many sports, with high-intensity interval training being shown as an effective method of improving aerobic fitness (ÅStrand, ÅStrand, Christensen, and Hedman, 1960; Christensen, Hedman and Saltin, 1960; Gibala and McGee, 2008; Laursen and Jenkins, 2002). Intermittent exercise is defined by the intensity and duration of its work and recovery periods, along with the number of repetitions (Berthoin et al., 2006). In contrast to continuous exercise, intermittent exercise depends not only on $\dot{V}O_{2\,max}$ and running economy, but also on anaerobic capacity (Berthoin et al., 2006). Interval training has the advantage of enabling a greater amount of high intensity work to be conducted in a single session than would be possible with continuous training (Margaria et al., 1969). Therefore the optimal design of an interval training session is one that is individualized to athletes' specific requirements. The distance-time relationship could aid in the design of an interval training session by allowing interval intensity to be set as a percentage of an athletes CS and the number of interval repetitions to be set in accordance with the depletion of D′. Indeed Penteado et al., (2014) suggest it is important to understand how CS can be applied in the design (number and duration of repetitions and recovery) of interval training sessions.

An early study in this area by Kachouri et al., (1996) aimed to compare the CS from continuous and intermittent running exercise to gain an insight into how CS could be utilised in the design (number of repetitions and intensity) of interval type training sessions. Kachouri et al., (1996) recruited seven trained runners who each completed the Montreal track test (Leger and Boucher, 1980) on an outdoor 400 m athletics track. Participants then completed four further experimental trials on different days on the same outdoor running track. Trials 1 and 2 were used to calculate the continuous distance-time relationship and were performed in a random order. These trials involved TTE runs at 95 and 105% of the velocity at the end of the Montreal track test. Trials 3 and 4 were used to calculate the intermittent distance-time relationship and involved intermittent exercise with 'work' intervals at 95 and 105% of the velocity at the end of the Montreal track test, for a time equal to half the TTE of the continuous run at this intensity. Work intervals were interspersed with 'recovery' intervals at a slow jogging pace for a time equal to the running time. The continuous distance-time relationship was calculated from the distance covered and the TTE during the continuous runs at 95 and 105% by using the linear distance-time model (equation 1). In order to calculate the intermittent distance-time relationship the same mathematical model was used, however only the cumulated distance and time from the work intervals (and not the recovery intervals) were used.

Results demonstrated that exhaustion times for the continuous running at 95 and 105% were 715±152 s and 217±39 s respectively. These durations fall within the range of time limits suggested by Hughson et al., (1984) for trials in distance-time relationship. The continuous CS (4.60±0.42 $m.s^{-1}$) was not significantly different (*P*=0.58) from the intermittent CS (4.56±0.44 $m.s^{-1}$) and these values were significantly correlated (*r*=0.89, *P*=0.01). The continuous D′ (171±51 m) was however significantly lower (*P*=0.02) than the intermittent D′ (540±284 m) and these values were not correlated (*r*=-0.49, *P*=0.26). Kachouri et al., (1996) report that even though continuous and intermittent CS were not significantly different and were significantly correlated it was not possible to predict the maximal number of repetitions of an intermittent exercise session from continuous CS. A potential reason for this finding may be that the model used to calculate the intermittent distance-time relationship only considered the work intervals and not the recovery intervals.

Morton and Billat (2004) were the first to consider four independent variables when applying the distance-time relationship to model intermittent exercise performance. Morton and Billat (2004) considered the speed during the work and recovery phases (S_w and S_r), and the duration of the work and recovery phases (t_w and t_r). Morton and Billat (2004) explain there are a number of restrictions that need to be satisfied in order for their model to be meaningfully applied to intermittent exercise. These restrictions can be described by the following equation:

$$0 \leq S_r < CS < S_w < CS + D'/t_w \qquad (10)$$

These restrictions are in place to ensure that the S_r is greater than or equal to zero, but less than CS, otherwise no replenishment of D′ will occur during the recovery interval. Likewise S_w must be greater than CS in order for some of the D′ to be depleted during the work interval. Furthermore S_w must not be so high that exhaustion occurs in the first work interval (due to full depletion of the D′), otherwise intermittent exercise intervals will not be possible (Morton and Billat, 2004). An additional interpretation of these restrictions is that the average speed of the combined work and rest intervals must be greater than the CS otherwise exercise would, in theory, continue indefinitely.

Morton and Billat (2004) explain that the four key variables in the distance-time relationship for intermittent exercise can be combined into a single equation, which allows the total endurance time (TTE) of intermittent running exercise to be predicted. This equation assumes that during an intermittent exercise session, exhaustion will occur following a whole number (n) of complete work and rest cycles, each of duration $t_w + t_r$, plus a further partial work interval which ends at exhaustion. During these *n* complete cycles, the total drain on D′ will be $n(S_w - CS)t_w$, while the total refilling of D′ will be $n(CS - S_r)t_r$. The remaining D′ at the start of the final partial work interval is therefore calculated by:

$$D' - n[(S_w - CS)t_w - (CS - S_r)t_r] \qquad (11)$$

The remaining D′ drains at a rate of $S_w - CS$ (m.s^{-1}) during the final partial work interval. Therefore total endurance time during an intermittent exercise session can be calculated as:

$$t = n(t_w + t_r) + \frac{D' - n\,[(S_w - CS)t_w - (CS - S_r)t_r]}{Sw - CS} \qquad (2)$$

The idea that the W′ is expended during work bouts >CP and reconstituted during recovery intervals <CP is reinforced by the study of Jones et al., (2008). During their investigations Jones et al. used ^{31}P magnetic resonance spectroscopy (^{31}P-MRS); A technique offering a unique view of muscle metabolism in vivo whereby the changes in energy metabolites measured by ^{31}P-MRS closely reflect those measured biochemically from muscle biopsy samples (Bangsbo et al., 1993). Jones et al., (2008) demonstrated that when constant work rate exercise was performed slightly above CP, the intramuscular PCr concentration and pH continued to decrease whilst inorganic phosphate concentration (Pi) continued to increase until the limit of tolerance (TTE)

was reached. However during exercise performed just below the CP stable values for PCr concentration, PH and Pi were attained within 3 minutes of exercise. Jones et al., (2008) hypothesised that the recovery intervals during intermittent exercise allow some of the fatigue-related substrates to be resynthesized (e.g.: PCr) and allow clearance of some of the fatigue-related metabolites (e.g.: H^+) from the muscle, therefore delaying the arrival of a “limiting intramuscular environment” and increasing the TTE. A further study by Chidnok et al., (2013a) extends this theory. In their study Chidnok et al. used ^{31}P-MRS to determine the responses of PCr, Pi and ADP during intermittent high-intensity exercise. Intermittent exercise sessions involved 60-second work periods interspersed with 18, 30 or 48 s of passive recovery. Results revealed that PCr concentration displayed a “saw-tooth” response profile corresponding with the work and recovery intervals. Results also demonstrated that regardless of recovery-interval duration or total TTE of the exercise session, the values for the intramuscular high-energy phosphate compounds and metabolites were similar at the point of exhaustion. The authors suggest these findings support the suggestion that W′ and ultimately the limit of exercise tolerance are related to the depletion/accumulation of one or more substrates/metabolites which are linked to the process of muscle fatigue (for example low PCr concentration, low pH or high Pi concentration). This further supports the theory that, whilst W′ can be expended at different rates, the limit of tolerance for all constant-power exercise above CP will coincide with the complete depletion of W′. The earlier work of Chidnok et al., (2012) where the intensity of the recovery below CP was inversely related to the extent of the W′ restoration during the recovery intervals, provides further support.

There are a number of assumptions that underpin the distance-time relationship, which may not be valid in an intermittent exercise setting. It is assumed for example that the transitions from the work to recovery phase (and recovery to work phase), in terms of speed and also bioenergetics, are instantaneous and independent of the running speed (Morton and Billat, 2004). Furthermore during the recovery intervals of intermittent exercise it is assumed that an aerobic supply of energy is available at its maximal rate (critical speed) for the duration of the interval (Morton and Billat, 2004).

Morton and Billat (2004), therefore, aimed to test their intermittent critical power model and its inherent assumptions; they recruited six endurance-trained male athletes to help test their model. Upon entry to the study participants CS and D′ were calculated by fitting a linear distance-time model (equation 1) to their seasons best performances over 3, 5 and 10 km. The main study protocol involved three intermittent running tests performed on an outdoor 400 m athletics track. Tests were performed on separate days in a random order. Running speeds were based on the CS calculated from the ‘continuous’ running method described above (linear regression of seasons best times). The three interval sessions involved (1) 60 s fast running at 120% CS, followed by 60 s slower running at 50% CS; (2) 180 s at 100% CS, followed by 180 s 60% CS; and (3) 30 s at 135% CS, followed by 60 s at 65% CS. Participants followed a pacing cyclist traveling at the required speed and continued the intermittent fast and slow cycles until they could no longer maintain the required speed, at which point time TTE was recorded. Morton and Billat then calculated a second set of estimates for CS and D′, this time based on the intermittent model (equation 2).

Results revealed that D′ estimated from continuous running (219±53 m) was not significantly less (P=0.31) than when estimated from intermittent running (261±158 m). However CS from continuous running (4.00±0.26 $m.s^{-1}$) was significantly (P<0.01) higher than when estimated from intermittent exercise (3.28±0.27 $m.s^{-1}$). Morton and Billat (2004) state their results may suggest that the concepts characterized by CS and D′ are physiologically different in continuous versus intermittent running. However they suggest that this warrants further investigation with a larger participant group.

Tentative support for the model of Morton and Billat (2004) is provided by the work of Price and Moss (2007). Price and Moss investigated the effect on running performance of work:rest duration during prior intermittent exercise. Two intermittent treadmill exercise protocols were examined, which were matched in terms of duration (20 min), intensity (120% v-$\dot{V}O_{2\,max}$) and work:rest ratio (1:1.5). Protocols differed in the length of the work:rest interval, with the ‘short’ interval session consisting of 6:9 s work:passive rest, whilst the ‘long’ interval session consisted of 24:36 s work:passive rest intervals. Immediately after each interval session participants performed a TTE trial on the treadmill at 120% v-$\dot{V}O_{2\,max}$. According to the model of Morton and Billat (2004) an individual athlete would deplete the same amount of D′ in either the short or the long interval session (due to the sessions being matched in duration and intensity). Therefore in theory an athlete would enter the TTE trial with the same D′ regardless of which interval session they had completed, suggesting a similar TTE would be seen after the short and long interval sessions. In support of this Price and Moss (2007) report no significant difference in TTE following the short and long interval protocols.

Chidnok et al., (2013a) investigated the CP and W′ calculated from 4 severe intensity constant power trials of knee-extension exercise on a custom designed ergometer (TTE ~2-12 min). The CP and W were calculated from these trials using a linear inverse-time model. CP and W′ were then applied to the intermittent model of Morton and Billat (2004) to predict TTE during 3 different intermittent sessions, involving 60 s work periods interspersed with either 18, 30 or 48 s of passive recovery. Chidnok et al., (2013a) report that the actual TTE values from the 3 intermittent exercise sessions were not significantly different from the TTE values predicted using the intermittent model of Morton and Billat. Specifically, predicted and actual TTE values for the three protocols were 312 vs 302±68 s, 540 vs 516±142 s and 864 vs 847±240 s for the shortest, intermediate and longest recoveries respectively. Chidnok et al., (2013a) therefore suggest that the intermittent CP model might be a valuable tool for applied sports scientists to allow the individualised prescription of interval training sessions, which may optimize gains in fitness and performance in the longer term.

The intermittent model of Morton and Billat (2004) assumes D′ is reconstituted in a linear fashion, however this has recently been questioned by Ferguson et al., (2010). Ferguson et al. set out to determine the kinetics of W′ recovery from exhausting supra-CP constant load cycle ergometry. They also aimed to compare the recovery of W′ with that of $\dot{V}O_2$ and lactic acid to give an insight into the composition of W′. Ferguson et al., (2010) recruited six recreationally active participants who completed four constant load tests to exhaustion on a cycle ergometer on separate days. Each test was performed at a different work rate, chosen to achieve TTE within a range of 3-12 minutes. CP and W’ were determined from a linear regression of power vs. time. A work rate predicted to induce exhaustion in a time of 6 minutes (WR_6) was derived via interpolation using the following equation:

$$P = (W'/TTE) + CP \tag{12}$$

The power-time relationship was then redefined with a conditioning bout at WR_6 and a 20 W recovery (of either 2, 6 or 15 minutes) immediately preceding each of the three constant load tests used to predict CP and W’.

The model of Morton and Billat (2004) assumes that W’ is reconstituted in linear fashion via the following equation

$$(CS - S_r)t_r \tag{11}$$

Applying the mean data from the participants in the Ferguson et al., (2010) study (CP 212 W, W’ 21.60 kJ, WR_6 269 W, power of recovery 20 W, time of work 366 s, time of recovery 120 s) to this equation predicts that W’ would be fully reconstituted after the 2min recovery period. The same is true for the data in an earlier study by the same group where again the linear model predicts W’ will be fully reconstituted after a 2-min recovery (Ferguson et al., 2007). Ferguson et al., (2010) reported that following the exhaustive priming bout at WR_6 CP remained unchanged, from the original power-time test value, regardless of the recovery duration. This is supported by an earlier study that demonstrated no change in CP following a 2-min recovery (Ferguson et al., 2007). W’, however, was significantly reduced following each of the WR_6 bouts, with the magnitude of the reduction in W’ being related to the duration of the intervening 20 W recovery. Following the 2-min recovery W’ had on average recovered to 37±5% of its original values. After the 6 and 15-min recoveries this had increased to 65±6 and 86±4% recovery respectively. This is further supported by the earlier work of Ferguson et al., (2007), where (if slight methodological differences are accounted for **see footnote*) a similar recovery profile of W’ was shown following a 2-min recovery. These findings are also supported by the earlier work of Vanhatalo and Jones (2009) who investigated the effect of a 30 second all-out sprint, followed by a 2 min and a 15 minute recovery on the parameters of the power-duration relationship estimated from the 3-minute all-out test. Results revealed that prior sprint exercise had no significant effect on the CP regardless of recovery duration (control 235±44, 2-min 223±46, 15-min 232±50 W respectively). In contrast the W′ was significantly reduced when the recovery was limited to just 2-min compared with the control and 15-min recovery conditions (control 20.8±3.9, 2-min 16.5±3.3, 15-min 21.2±4,5 kJ respectively).

Ferguson et al., (2010) report an interpolated half time for W′ of 234±32 s. After the 15-min recovery $\dot{V}O_2$ and lactic acid were still elevated above baseline, however the recovery of $\dot{V}O_2$ was significantly faster and the recovery of lactic acid significantly slower than that of W′ (interpolated half time for $\dot{V}O_2$ and lactic acid of 74±2 and 1366±799 s respectively). The differing recovery profiles of W′, $\dot{V}O_2$ and lactic acid can be seen in Figure 2.5.

Footnote:

** These differences concern the exhausting work bout used in the two studies. In the Ferguson et al., (2010) study WR_6 was calculated, however in the 2007 study WR_8 was calculated but participants only performed 6 min of exercise at this intensity so would not have fully depleted W′. After 2 minutes W′ was reported to be 66% reconstituted. At first sight this seems to conflict with the 2010 data, however if you account for the differences in methodology and assume that 6 min at an intensity predicted to fully exhaust in 8 min, would in fact deplete 75% of W′, then if the remaining 25% W′ not fully exhausted is taken from the 66% reconstituted figure you are left with 41% reconstituted in the 2 min recovery – which closely matches the 37% reported in the 2010 study.*

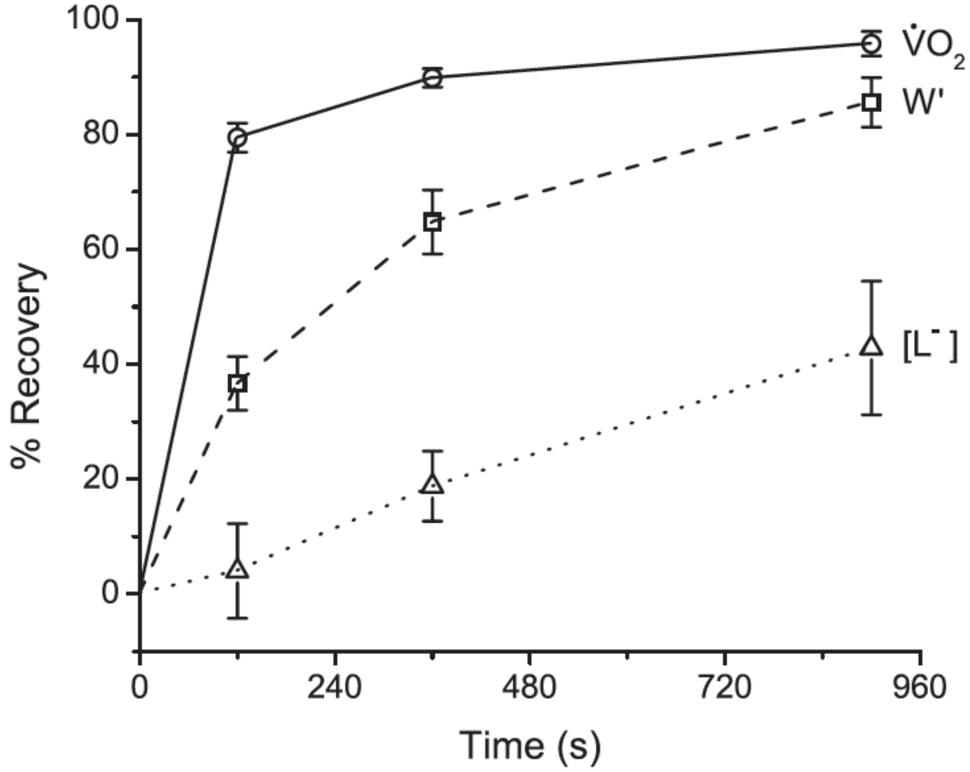

Figure 2.5. Recovery profiles for W′, $\dot{V}O_2$ and lactic acid ($[L^-]$). Error bars represent SD (Ferguson et al., 2010, *p.870).*

Therefore in contrast to its depletion, W′ recovery did not fit well with the linear model, leading Ferguson et al., (2010) to conclude that the recovery of W′ is not linear and in fact follows a curvilinear pattern of reconstitution following supra-CP exercise. Ferguson et al., (2010) suggest that the unchanged CP seen in their study following exhaustive maximal exercise, supports the claim that W′ depletion alone shapes the tolerance to exercise performed in the severe intensity domain. This is supported by the later work of Ferguson et al., (2013) where high intensity interval training was investigated and it was again concluded that the distance-time relationship determined performance in such tasks, with the profile of D′ depletion and recovery shaping the tolerance to exercise above CS.

Based on the findings of Ferguson et al., (2010), Skiba et al., (2012) assumed that the reconstitution of W′ followed a predictable exponential time course. Skiba et al. were able to develop a continuous equation describing the remaining W′ at any given time during an intermittent exercise session (W'_{bal}).

$$W'_{bal} = W' - \int_{0}^{t} (W'_{exp}) \left(e^{-(t-u)/\tau_{W'}}\right) \quad (13)$$

In this equation W′ is estimated from a traditional two-parameter model; W'_{exp} is equal to the expended W′; $(t – u)$ is the time in seconds between the segments of the exercise session that resulted in a depletion of W′; and $\tau_{W'}$ is the time constant for the reconstitution of W′. This equation describes the amount of W′ remaining at time (t) as being equal to the difference between the known W′ and the total amount of W′ expended before time t in the exercise session, where each joule of W′ is being reconstituted in an exponential fashion during recovery at an intensity <CP (Skiba et al., 2012).

In their study Skiba et al., (2012) assessed seven athletes performing intermittent cycle exercise, with 60 s work intervals above CP and 30 s recovery intervals in either the low, moderate, heavy or severe intensity domains. The data from the four intermittent exercise bouts were fit to equation 13 by inputting the number of joules of W′ expended above CP each second. The time constant for the reconstitution of W′ ($\tau_{W'}$) was varied in a repetitive process until the W'_{bal} equalled zero at exhaustion. The $\tau_{W'}$ was then plotted against the difference between the recovery power and the CP (D_{CP}) i.e. indicating how far below CP the recovery power was.

Skiba et al., (2012) report that $\tau_{W'}$ was inversely correlated with CP in the low, moderate and heavy recoveries. This suggests that participants with a higher CP recovered more quickly than those with a lower CP. Skiba et al. also demonstrated that the $\tau_{W'}$ was inversely correlated with D_{CP} in the low, moderate and heavy recoveries. This suggests that the higher the D_{CP} (i.e. the lower the intensity of the recovery), the lower the $\tau_{W'}$ and therefore the quicker the recovery. This demonstrates that equation 13 produces sound data in keeping with expected physiological outcomes. The mean $\tau_{W'}$ becomes higher as the recovery intensity goes from the low – moderate - heavy intensity domain. In the severe domain (above CP) the $\tau_{W'}$ increased to non-physiological values indicating no recovery of W′, merely a lower rate of depletion during the recovery interval.

Skiba et al., (2012) suggest a possible explanation for the inverse correlation between $\tau_{W'}$ and D_{CP} is that a smaller "oxidative reserve" would be available with increasing recovery intensity. In simple terms this means that the smaller the difference between the $\dot{V}O_2$ required to maintain recovery power and the $\dot{V}O_2$ at CP, the smaller the capacity to reconstitute the W′. Finally Skiba et al. suggest that the greater variation in the $\tau_{W'}$ seen in the moderate and heavy recovery sessions might indicate that the process of W′ reconstitution becomes more complex as the recovery intensity increases.

Results of previous research investigating the modelling of intermittent exercise using CS and D′ have produced conflicting results. The recent work of Skiba et al., (2012), using an exponential recovery model of W′ in cycling exercise, has the potential to further advance research in this area. However the application of this model to intermittent running exercise warrants further investigation. An accurate method of modeling D′ reconstitution would allow the distance-time relationship to be used in the design of interval training sessions. Thereby allowing interval intensity to be set as a percentage of an athletes CS and the number of interval repetitions to be set in accordance with the depletion of D′.

Interval training modelled around the CS and D′ was used in the study by Clark et al., (2013) to investigate the effect of different high intensity interval training sessions on CS and D′. The study by Clark et al. was the first study to apply the distance-time model to prescribe and evaluate a running training program. However the study was not specifically designed to model the reconstitution of D′ and as such only depleted D′ to a maximum of 80% during each work interval and did not provide details of the time or intensity of the recovery intervals. Further research investigating the feasibility of prescribing an interval running session based around CS and D′ is required.

2.14 Thesis aims and hypotheses

The overall aim of this thesis was to develop a time efficient field test of the distance-time relationship, assess its validity and reliability and then utilise the test to investigate the endurance training and performance of distance runners. A further underpinning theme of the thesis is the comparison between the single visit field test and traditional laboratory-based measures of endurance performance.

The experimental chapters have individual sub-aims, which together contributed to the overall thesis aims. These were constructed as follows:

A single-visit field test of the distance-time relationship would be more accessible, and less time consuming than a traditional laboratory-based treadmill protocol.

1. The aim of the first experimental chapter was to assess the reliability of CS and D′ determined from a single-visit field test (chapter 4).

$H1_0$: The single visit field test will not produce reliable values of CS in comparison to laboratory-based methods.
$H1_1$: The single visit field test will produce reliable values of CS in comparison to laboratory-based methods.

$H2_0$: The single visit field test will not produce reliable values of D' in comparison to laboratory-based methods.
$H2_1$: The single visit field test will produce reliable values of D' in comparison to laboratory-based methods.

2. The aim of the second experimental chapter was to assess the validity of the single-visit field test by comparing it with a traditional laboratory-based treadmill time to exhaustion protocol (chapter 5).

$H3_0$: The single visit field test will not produce valid values of CS in comparison to laboratory-based methods.
$H3_1$: The single visit field test will produce valid values of CS in comparison to laboratory-based methods.

$H4_0$: The single visit field test will not produce valid values of D' in comparison to laboratory-based methods.

$H4_1$: The single visit field test will produce valid values of D' in comparison to laboratory-based methods.

The time efficiency and the need for minimal equipment allow the single visit field test to be regularly used to monitor the effects of prolonged endurance training on the distance-time relationship. Before the test can be utilised in such a way the sensitivity of the single visit field test in detecting changes in performance over a period of endurance training must be evaluated.

3. The aim of the third experimental chapter was to examine the ability of the single visit field test to detect training induced changes in the distance-time relationship in a group of highly trained distance runners. The sensitivity of the field test to detect such changes will be compared with that of the more traditional laboratory-based measures (chapter 6).

$H5_0$: CS will not increase significantly during the training year.
$H5_1$: CS will increase significantly during the training year.

$H6_0$: D' will not increase significantly during the training year.
$H6_1$: D' will increase significantly during the training year.

In addition to monitoring changes in endurance performance a valid, reliable and sensitive single visit field test could also be used to provide training prescription. A broader practical application of the single visit field test is the potential to model intermittent exercise. Such modelling techniques could then be applied in training to prescribe intermittent interval-style work and recovery periods.

4. The aim of the fourth experimental chapter was to assess whether linear and exponential models could be accurately applied to the data from the single visit field-test to predict TTE during intermittent running exercise (chapter 7). This in turn would provide an insight into the ability of the single visit field-test to prescribe interval style training sessions.

$H7_0$: An exponential model applied to the CS and D′ from the single visit field test does not accurately predict TTE during intermittent running.

$H7_1$: An exponential model applied to the CS and D′ from the single visit field test accurately predicts TTE during intermittent running.

Chapter 3 – General Methods

The purpose of the general methods chapter is twofold; to describe the methodological approaches repeated throughout this thesis and explain the calibration methods conducted before and during the experimental studies.

3.1 Preliminary laboratory visit protocol

On arrival at the laboratory participants' body mass and stature were measured to the nearest 0.1 kg/cm respectively. (Seca Beam Scale and Stadiometer, Birmingham, UK). Prior to testing, subjects completed a 5-min self-paced warm-up (Smith and Jones, 2001), on an H/P/Cosmos Pulsar 3P treadmill (H/P/Cosmos Sports and Medical, Nussdorf-Traunstein, Germany) set to a 1% gradient, as recommended by Jones and Doust (1996). This was followed by a 5-min self-selected stretching routine. Immediately preceding the warm-up, a 10 µL fingertip capillary blood sample was collected to determine resting blood lactate concentration (Biosen C-line, EKF diagnostic, Barleben, Germany).

The laboratory test was conducted in two parts; the first part was a submaximal treadmill test (Jones, 2008). The initial treadmill belt speed was decided individually for each athlete to ensure that 5-9 stages were completed during the submaximal phase of the test (Jones, 2008). Each stage of the test was 4 minutes in duration at which point the treadmill belt speed was increased by 1.0 $km{\cdot}h^{-1}$ (Spurway and Jones, 2008). Throughout the test, participants' expired gases were measured on a breath-by-breath basis (MetaLyzer, Cortex Biophysik, Leipzig, Germany). In the last 30 seconds of each stage average heart rate (310XT, Garmin International Inc. Kansas, USA), and rating of perceived exertion (RPE) using the Borg 6-20 scale (Borg, 1998) were recorded. At the end of each 4-minute stage a 10 µL fingertip capillary blood sample was collected to determine blood lactate concentration, prior to the treadmill belt speed being increased by 1.0 $km{\cdot}h^{-1}$. Part 1 of the protocol was terminated when the subject reached a lactate concentration >4.0 $mmol{\cdot}L^{-1}$. This part of the test was used to determine LT, running economy and the energy cost of running. The definitions accepted for these parameters during all experimental work are defined below. The LT was identified as the exercise intensity that produced a 1 mmol·L increase in blood lactate concentration above baseline (Hagberg and Coyle, 1983). Running economy was calculated over the range of submaximal velocities by recording the average $\dot{V}O_2$ (mL·kg^{-1}·min^{-1}) for the last minute of each stage. The speed of each stage along with the average $\dot{V}O_2$ were used to calculate the oxygen cost (mL·kg^{-1}·km^{-1}) of running (Jones, 2008), where: $\dot{V}O_2$ (mL·kg^{-1}·km^{-1}) = $\dot{V}O_2$ (mL·kg^{-1}·min^{-1}) / (speed/60). The energy cost of running (kcal·kg^{-1}·km^{-1}) was calculated at the highest individual speed with an RER <1.0. Updated nonprotein respiratory quotient equations (Peronnet and Massicotte 1991) were used to estimate substrate utilisation (g.min^{-1}) during this period. The oxygen cost (mL·kg^{-1}·km^{-1}) and the energy equivalent of oxygen (kcal.L^{-1}) were used to calculate the energy cost (kcal·kg^{-1}·km^{-1}) of running (Shaw et al., 2014), where: energy cost (kcal·kg^{-1}·km^{-1}) = (oxygen cost /1000) * energy equivalent of oxygen.

Following a 15-minute recovery, the second part of the test was initiated at a speed 2.0 km·h^{-1} below the completion speed of part 1. Whilst the treadmill speed remained constant throughout part 2 of the protocol, treadmill gradient was increased by 1% every minute until volitional exhaustion. Pulmonary gas exchange was measured on a breath-by-breath basis (MetaLyzer, Cortex Biophysik, Leipzig, Germany). The second phase of the test was used to determine $\dot{V}O_{2\,max}$ and the velocity at $\dot{V}O_{2\,max}$ (v-$\dot{V}O_{2\,max,}$). $\dot{V}O_{2\,max}$ was calculated as the highest $\dot{V}O_2$ achieved during the test, using a rolling 30 second average. The v-$\dot{V}O_{2\,max}$ was calculated by solving the regression equation describing the relationship between $\dot{V}O_2$ at sub-maximal intensity and $\dot{V}O_{2\,max}$ (Jones, 1998).

3.2 Field test protocol

The distance-time relationship was calculated from three constant distance runs over 9 laps, 6 laps and 3 laps (3600, 2400, 1200 m) of a competition standard 400m outdoor running track. These distances were estimated to yield finishing times between 2 and 12 min (Hughson et al., 1984). Testing was not conducted if wind speed > 2.0 m·s^{-1} was measured (Jones and Doust, 1996). Prior to testing subjects completed a 5-min self-paced warm-up followed by a 5-min self-selected stretching routine (Smith and Jones, 2001). Participants were instructed to cover the set distance in the fastest time possible, with runs hand-timed to the nearest second. Participants were not provided with feedback on the elapsed time during the track runs. Chidnok et al., (2013) recently reported that exhaustion during high-intensity exercise was unaffected when pacing strategy is self-selected. All three runs were conducted on the same day with a 30-min rest between each trial. Runs were conducted in the order of longest to shortest distance (lowest to highest mean speed), matching the methodology used in the cycling based research by Jenkins and Quigley (1992).

3.3 Calibration methods

3.3.1 Gas analyser

The gas analyser was calibrated according to the manufacturer's guidelines, using a calibration gas of known composition and a 3-litre syringe. Calibrations took place prior to each test and within the 15-min break between part 1 and 2 of the preliminary laboratory visit protocol. A two-point gas calibration was conducted using ambient air and a certified alpha standard compressed gas mix of 17% O_2 and 5% CO_2 with a balance of N_2 (BOC Gases, Guildford, Surrey, UK). The flow sensor and turbine were calibrated using a 3-litre syringe (Hans Rudolph Inc. Kansas, USA) moved in time with a set flow rate. A further calibration check was then conducted at flow rates of 0.5, 1.0 and 3.0 $L.s^{-1}$. Reliability data from these calibration checks demonstrate 95% LOAs of 41 ml, 29 ml and 50 ml for inspiration, and 121 ml, 62 ml and 91 ml for expiration across the three flow rates.

3.3.2 Treadmill

The treadmill speed was checked prior to each study by following the manufactures recommended guidelines concerning the timing of belt revolutions. The treadmill was set to the required speed and allowed to run for 1 minute, the time taken for ten belt revolutions was then hand timed to the nearest 0.01 of a second. Speed during the ten revolutions was calculated by dividing the distance the belt had travelled (calculated by multiplying the belt length by 10) by the recorded time. This procedure was conducted at three representative speeds (13, 14 and 15 $km.h^{-1}$). Data from the speed checks revealed treadmill speed was always within 0.02 $m \cdot s^{-1}$ of the desired speed across all experimental work.

3.3.3 Blood lactate analyser

Prior to each test 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. Reliability data from this device in our laboratory reveal a within-sample coefficient of variation of 2.5% (95% CL: 1.9-3.5%) for repeat tests on the same blood sample. The typical error for duplicate samples taken consecutively was 0.07 $mmol.L^{-1}$ (95% CL: 0.05-0.13 $mmol.L^{-1}$).

3.3.4 Garmin GPS watch

A small calibration study was performed to assess the reliability and validity of the GPS watch (Garmin Forerunner 310XT, Garmin International, Kansas, USA). This study took the form of eleven experimental visits during which a single subject completed repeated tests over a prescribed distance.

Visit one involved 30 separate running trials in lane one of an outdoor 400 m athletics track. All running trials consisted of one lap of the athletics track, with the running path set on the outside line of lane one. During all trials two identical GPS watches (Garmin Forerunner 310XT, Garmin International, Kansas, USA) recorded distance covered every second. Ten runs were completed at an approximate speed of 5 $km.h^{-1}$, followed by a further ten runs at 10 $km.h^{-1}$ and finally ten runs at 15 $km.h^{-1}$. Running pace was set using a pushbike (Muddyfox Turbulent 26 inch Mountain Bike, Muddyfox, Essex, UK) fitted with a speedometer (Atech F13 Wireless Cycle Computer, Atech Scientific Measurement Limited, Hong Kong). All 30 runs were conducted on the same day, with a 3-min rest between runs and a 30-min rest between speeds. Actual track distance was calculated using a Trumeter 5500 measuring wheel (Trumeter Company Inc, Florida, USA), by recording 3 measurements on the outside line of lane one and taking the average.

Temperature, humidity, pressure, visibility and wind speed were recorded before each different set of trials at an individual speed, along with the number of GPS satellites that the watch had detected. Mean (± SD) environmental conditions across the 30 runs were: Temperature, 21.8±5.1 °C; Humidity, 58.7±11.4%; Pressure, 760±1 mmHg; Wind speed, 0.5±0.5 $m.s^{-1}$. Visibility was very good across the 30 runs, with full sun and only slight cloud cover. The number of satellites detected by the watches across the 30 runs ranged from 8-10.

During visit two 3 separate running trials in lane one of an outdoor 400 m athletics track were completed. One run was conducted at an approximate speed of 5 km.h^{-1}, followed by a further 1 run at 10 km.h^{-1} and a final 1 run at 15 km.h^{-1}. All 3 runs were conducted on the same day, with a 3-min rest between runs. This process was then repeated on separate days during visits 3-11 (a total of 10 different days). The runs during visits 2-11 were all conducted at the same time of day (± 2 hours) and were conducted within a 3-week period.

Temperature, humidity, pressure, visibility and wind speed were recorded before each run, along with the number of GPS satellites that the watch had detected. Mean (± SD) environmental conditions across the 10 days were: Temperature, 24.4±5.9 °C; Humidity, 49.7±9.4%; Pressure, 752±6 mmHg; Wind speed, 1.4±1.0 m.s^{-1}. Visibility ranged from excellent to moderate across the 10 days; with weather conditions ranging from complete cloud cover and heavy rain to clear sky and full sun. The number of satellites detected by the watches across the 30 runs ranged from 7-11.

The results of the calibration study reveal that the mean (2 watches and 3 speeds – a total of 60 trials) distance recorded on the Garmin watch was 1.5% greater than the actual distance. The difference between the actual distance and Garmin recorded distance was significant (P<0.01), however the agreement was good, with a typical error of 2.96 m (95% CL: 2.51-3.61 m). No significant differences were seen between the two watches at any of the speeds, or between the three speeds in an individual watch (P = 0.20). The within-day reliability was calculated using the combined data from the two watches across the three speeds during visit 1 (a total of 60 trials). The within-day reliability expressed in the form of typical error (as a CV %) ranged from 0.1-1.0%. The 95% limits of agreement method was used to assess the level of agreement between the actual distance and the Garmin recorded distance between repeated trials. The 95% limits of agreement between repeated trials within the same day was 7.8 m (figure 3.1). The between-day reliability was calculated using the combined data from the two watches across the three speeds during visits 2-11 (a total of 60 trials). The between-day reliability ranged from: 0.5-1.5%. The 95% limits of agreement between repeated trials across different days was 12.5 m (figure 3.2).

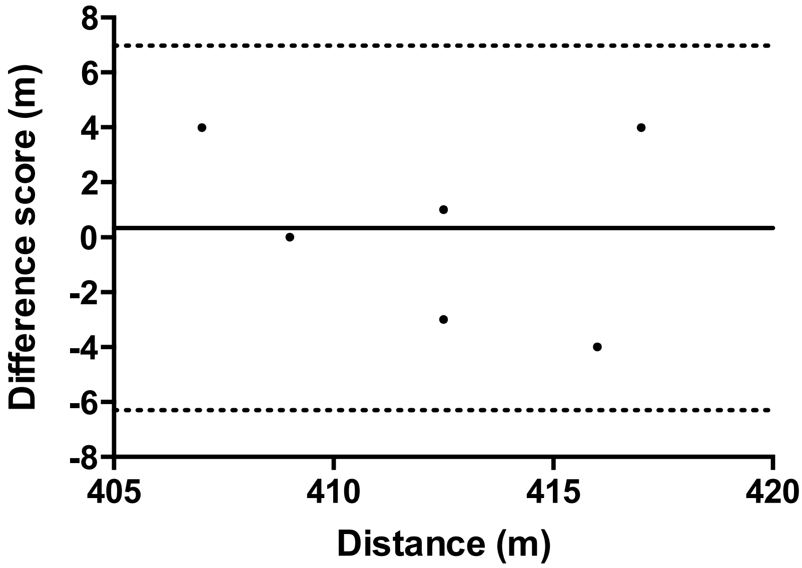

Figure 3.1: Bland-Altman plot of the agreement between actual distance and Garmin recorded distance between repeated trials within the same day. The solid horizontal line represents the mean bias, whilst the dashed lines represent the 95% limits of agreement. Data are from trials 2-1.

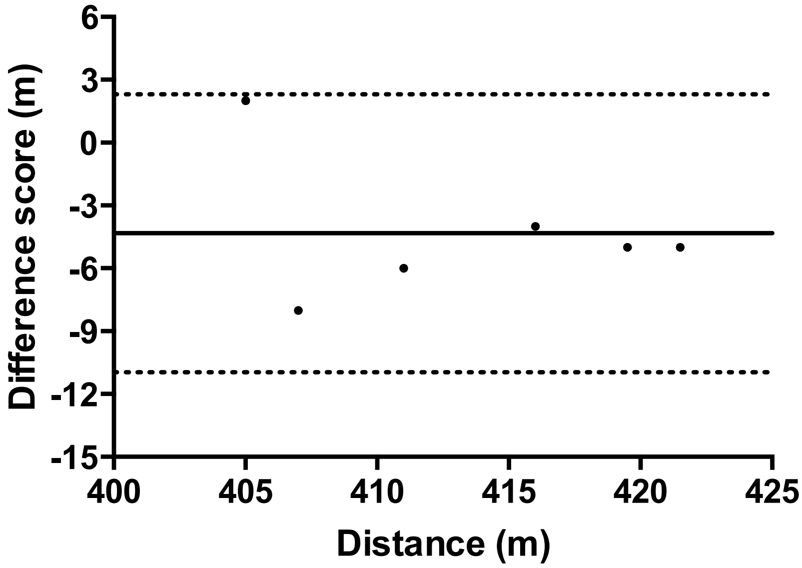

Figure 3.2: Bland-Altman plot of the agreement between actual distance and Garmin recorded distance between repeated trials across different days. The solid horizontal line represents the mean bias, whilst the dashed lines represent the 95% limits of agreement. Data are from day 2-1.

Chapter 4 – The reliability of a novel field test of the distance-time relationship

Aspects of the following chapter have been published in the following manuscript: Galbraith A., Hopker J. G., Jobson S. A., & Passfield L. (2011) A novel field test to determine critical speed. *Journal of Sports Medicine and Doping Studies,* 1(01):1-4.

4.1 Introduction

It has been suggested that the critical power demarcates the heavy and severe exercise domains (Bull et al., 2008) and as such corresponds to an exercise intensity which lies between that associated with the lactate threshold and that eliciting $\dot{V}O_{2\,max}$ (Billat et al., 1998). Consequently, CP has been associated with overall athletic performance in long-duration events (Housh et al., 1991; Jenkins and Quigley, 1990). The concept of CP has been applied to treadmill running (Hughson, Orok and Staudt, 1984), where the relation between treadmill running velocity and time to exhaustion conforms to a hyperbolic function similar to that seen in cycling. This relationship has traditionally been termed critical velocity, however as the present study utilised a field test where subjects were required to run a set number of laps of an athletics track, critical speed is a more appropriate term. Therefore, to allow standardisation of terminology CS will be used for the remainder of the chapter, regardless of whether the reference is to treadmill or field-testing.

Early research in this area utilised the work-time model and estimated CP and W′ by plotting the total work done against the time taken to complete that work. For running exercise this relationship has been transformed into a distance-time model, where the total distance covered is plotted against the time taken to cover that distance (Kranenburg and Smith, 1996). The distance-time model can be described by a linear relationship (equation 1) where the slope of the regression line represents CS and the *y*-intercept represents D′.

The traditional method of testing CS in a laboratory involves athletes completing a set number of time-to-exhaustion (TTE) trials at a constant speed on the treadmill. Constant speed trials have been shown to have poor reliability with coefficients of variation ranging from 15.1% to 25% (Laursen et al., 2007; Billat et al., 1994). This is supported by similar research in both cycling and swimming, which also demonstrates the poor reliability of constant power/speed trials (Jeukendrup et al., 1996; Alberty et al., 2006). Research into the reliability of CS and D′ parameters is limited; Hinckson and Hopkins (2005) investigated the reliability of CS and D′ measured on a treadmill. They demonstrated good reliability of CS data (CV 1.8%), but poor reliability of D′ data (CV 14%). Hinckson and Hopkins used constant speed trials where participants were required to run to exhaustion at three pre-set constant speeds that resulted in exhaustion times of approximately 1–2, 3–4 and 7–10 minutes.

Constant distance trials, where the athlete is required to cover a set distance in the fastest possible time, have been shown to have a far better reliability, with coefficients of variation ranging from 3.3% to 3.7% (Laursen et al., 2007; Nicholson and Sleivert, 2001). Due to the limitations of the manual speed control measures on standard motorised treadmills, such trials are arguably best performed in a field-based setting. However, there appears to be no research on the reliability of CS and D′ using constant distance trials in the field. The aim of this first experimental chapter therefore, was to assess the reliability of CS and D′ determined from a fixed-distance single-visit field test. This chapter contributes to the overall thesis aim of developing a reliable and time efficient field test of the distance-time relationship that can then be utilised in the subsequent chapters to investigate the endurance training and performance of distance runners.

4.2 Method

Participants: Following institutional ethical approval, ten trained male middle-distance runners (mean (±SD) age: 22±4 yrs; $\dot{V}O_{2\,max}$ 69.1±4.2 mL•kg^{-1}•min^{-1}; 1500 m personal best time: 250.4±15.0 s) were recruited for the study. All athletes were competitive club standard runners who had been competing for a minimum of 2 years. Subjects refrained from heavy exercise in the 24 hours prior to all tests and reported for testing 3 hours postprandial. Tests for individual subjects were completed at the same time of day to eliminate a possible effect of circadian rhythms (Drust, Waterhouse, Atkinson, Edwards and Reilly, 2005).

Experimental design: This investigation followed a repeated trial design, allowing the reliability of the distance time relationship to be assessed across three visits. In total each subject completed five experimental visits. At visit 1, subjects completed an incremental exercise test to determine $\dot{V}O_{2\,max.}$ During visit 2 subjects completed a familiarisation of the field test protocol. During visits 3, 4 and 5 subjects completed repeated tests of the field test protocol in order to determine the reliability of CS and D′.

Preliminary laboratory visit protocol: The preliminary laboratory visit protocol is outlined in the general methods (Chapter 3).

Field test protocol: The field test protocol is outlined in the general methods (Chapter 3).

Data analysis: Linear regression of distance and time was used to calculate CS and D′ from the results of each set of three running trials. The 2-parameter linear distance-time model (equation 1) was utilised; where: d = distance run (m) and t = running time (s).

$$d = (CS.t)+D' \tag{1}$$

In addition a further mathematically equivalent model was used to produce a second set of estimates for CS and D′. The linear inverse of time model can be explained as:

$$\text{Speed} = CS + (D' * 1/\text{time}) \tag{6}$$

The two models were compared for their coefficient of determination (R^2) and standard error of the estimate (SEE) in order to determine which model was the most appropriate to apply in the main analysis.

Data were assessed for normality of distribution using the Shapiro–Wilk test. To assess the reliability of CS and D′, the within-subject variation, expressed as a coefficient of variation (CV), was derived from log-transformed data (Hopkins, 2000a). Confidence limits (95% CL) of the CV and 95% limits of agreement were calculated to assess the variability of the repeated tests (Hopkins, 2000a). Comparisons of CS and D′ across days were assessed using repeated measures ANOVA. Statistical significance was set at 95% confidence ($P < 0.05$). Results are reported as mean ± SD unless otherwise stated.

4.3 Results

Laboratory and field-test data

Table 4.1 shows the mean values for the parameters measured during the initial laboratory treadmill test. Table 4.2 displays the mean values for the parameters estimated from the three repeat field tests.

Table 4.1: The physiological variables measured at the preliminary visit test.

	Mass (kg)	$\dot{V}O_{2\,max}$ (mL.kg^{-1}·min^{-1})	v$\dot{V}O_{2\,max}$ (km.h^{-1})	LT (km.h^{-1})	Running economy (mL.kg^{-1}km^{-1})	Energy cost (kcal·kg^{1}·km^{-1})
Mean	67.2±6.4	69.1±4.2	20.7±1.7	15.3±1.4	202.8±17.2	1.08±0.06

Data are presented as mean ± SD.

Table 4.2: The field-test parameters estimated from the three tests.

	Linear distance-time model		Linear inverse-time model	
	CS (m.s^{-1})	D′ (m)	CS (m.s^{-1})	D′ (m)
Mean	4.75±0.30	169±39	4.74±0.30	171±38

Data are presented as mean ± SD; Mean values are taken across trials 1-3

Goodness of fit

Table 4.3 displays the R^2 and the SEE for CS and D′ from the different mathematical models. The goodness of fit of the data, for a representative subject, for the two models is also shown in figure 4.1.

Table 4.3: Goodness of fit of the data to the mathematical models

	Linear distance-time model			Linear inverse-time model		
	R^2	SEE CS (%)	SEE D′ (%)	R^2	SEE CS (%)	SEE D′ (%)
Mean	1.00±0.00	0.86±0.55	7.91±4.83	0.992±0.01	0.91±0.59	13.44±8.44

Data are presented as mean ± SD; Mean values are taken across trials 1-3; SEE = Standard error of the estimate

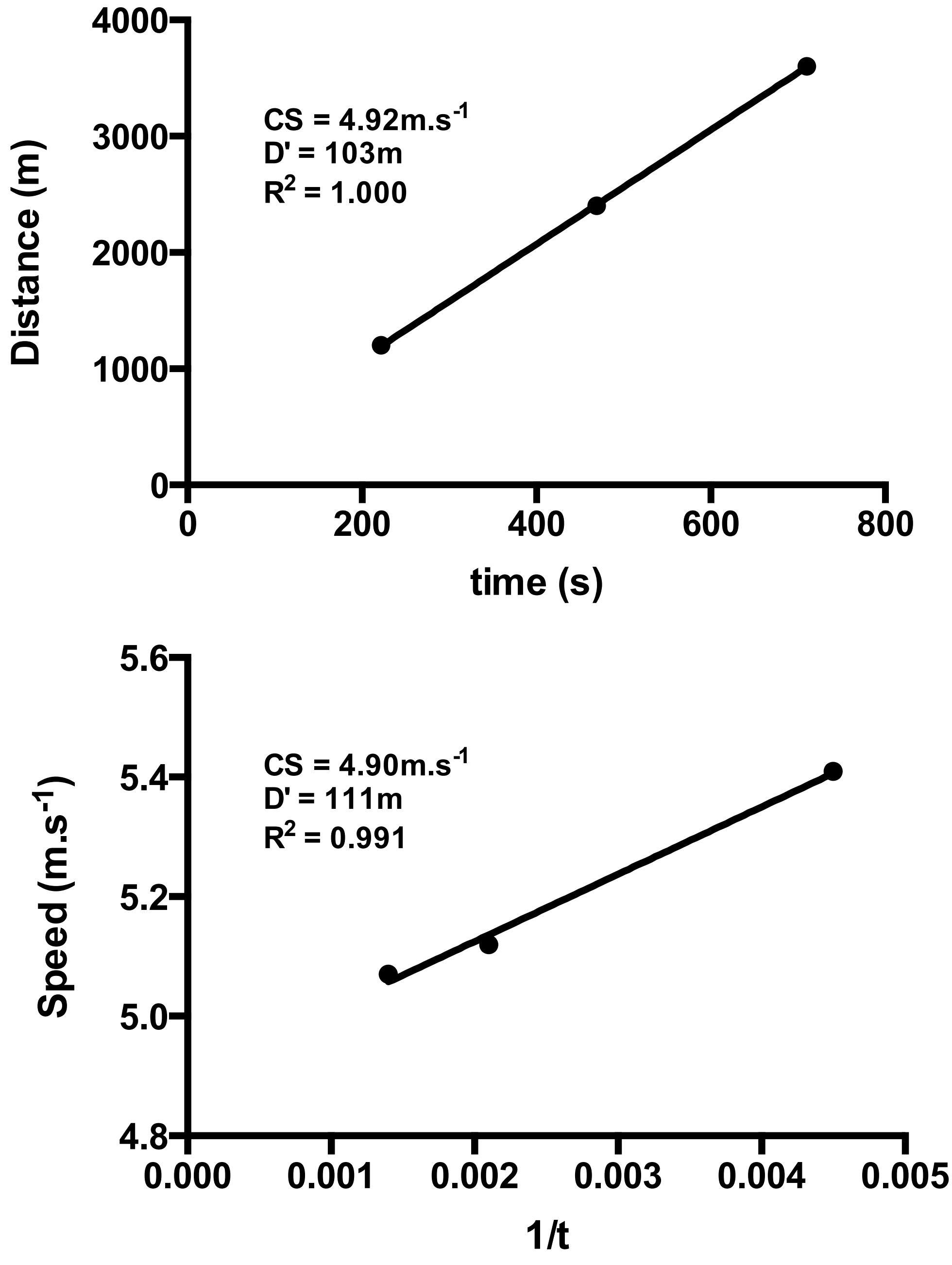

Figure 4.1: Data plots from a representative subject showing the CS, D′ and R^2 calculated from the linear distance-time model (top) and inverse of time model (bottom). Data are modelled using the values from subject 1, trial 1.

From table 4.3 it can be seen that the R^2 was consistently high for both models and the SEE for CS consistently low for both models. A 3x2 (trial x model) repeated measures ANOVA revealed no significant effect of trial on the SEE for CS and D′ (P=0.52 and P=0.55 respectively). There was a strong trend towards a significant effect of model on the SEE for CS (P=0.06). The SEE for D′ was higher than that of CS across all trials and was also higher when modelled using the 1/t model compared with the linear distance-time model (P<0.01). Data in the remaining analysis below is modelled using the linear distance-time model.

Reliability of CS and D′

The mean group typical error for CS (expressed as a CV) was 2.0% (95% CL: 1.4-3.8%) for trials 2-1 and 1.3% (95% CL: 0.9-2.4%) for trials 3-2. There was no significant difference in CS across trials (P=0.43). Repeated measures ANOVA also confirmed the absence of an order effect in the data. The test-retest correlations for CS were r=0.96 and r=0.95 (P<0.01) for trials 2-1 and 3-1 respectively. The limits of agreement for CS were ±0.27 $m \cdot s^{-1}$ of the measure for trials 2–1 and ±0.18 $m \cdot s^{-1}$ for trials 3–2 (Figure 4.2). Applying the sample size calculations outlined by Hopkins (2000a) to the reliability data reveals a sample size of 18 participants would be needed to detect a change in CS in subsequent research studies.

D′ proved to be less reliable with a group CV of 18.4% (95% CL: 13.5–39.9%) for trials 2–1 and 9.8% (95% CL: 7.0–19.6%) for trials 3–2 (Figure 4.3), although this variability did not result in significant differences between trials (P=0.66). The test-retest correlations for D′ were r=0.52 (P=0.12) and r=0.85 (P<0.01) for trials 2-1 and 3-1 respectively. The limits of agreement for D′ were ±82 m for trials 2–1 and ±40 m for trials 3–2 (Figure 4.3).

A nonparametric Spearman's rho correlation revealed a significant inverse relationship between CS and D′ across the three repeat trials (r = -0.61, P<0.01).

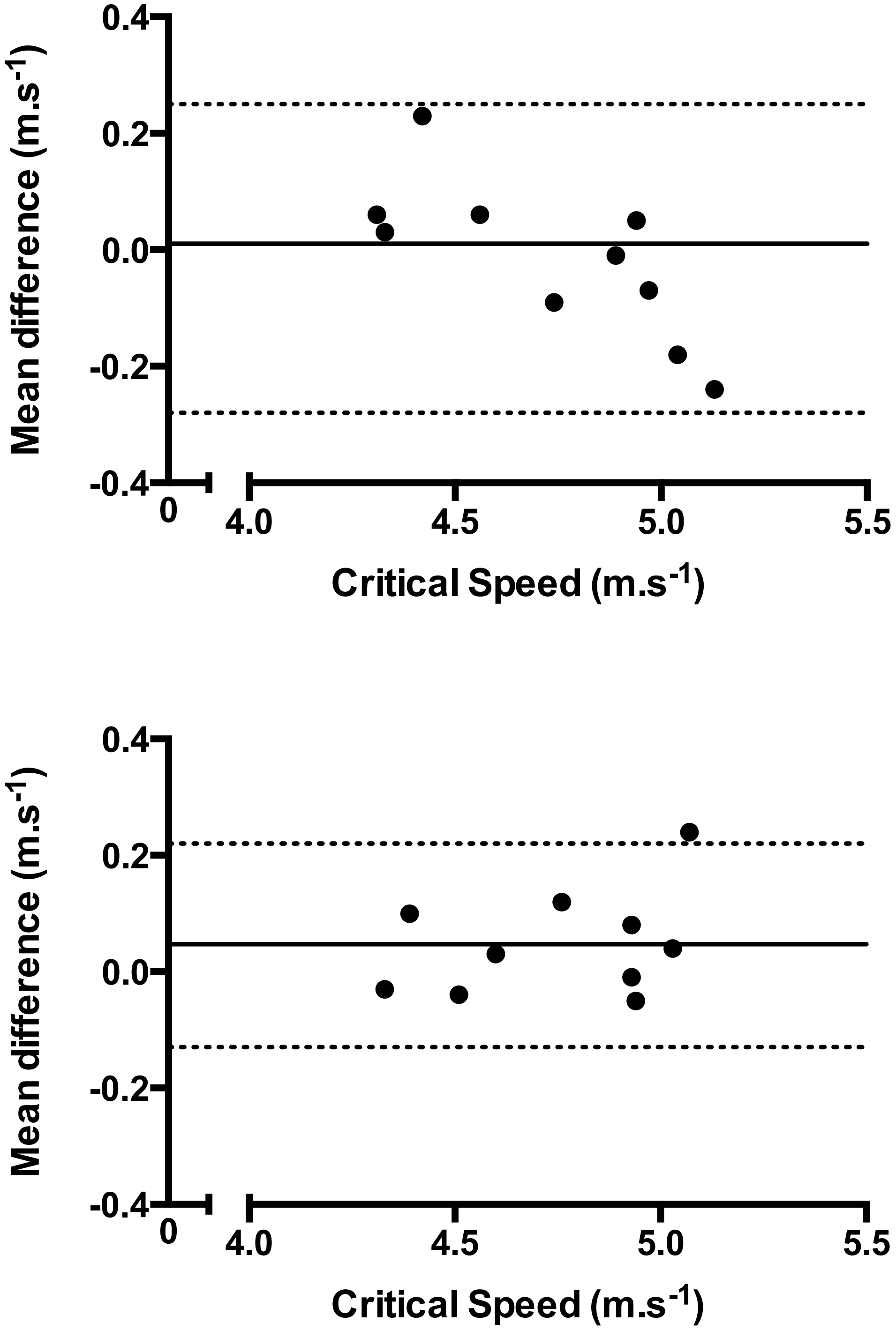

Figure 4.2: Bland-Altman plots of the test–re-test differences in CS between trials 1 and 2 [top] and trials 2 and 3 [bottom]. The solid horizontal lines represent mean bias, whilst the dashed lines represent the 95% limits of agreement.

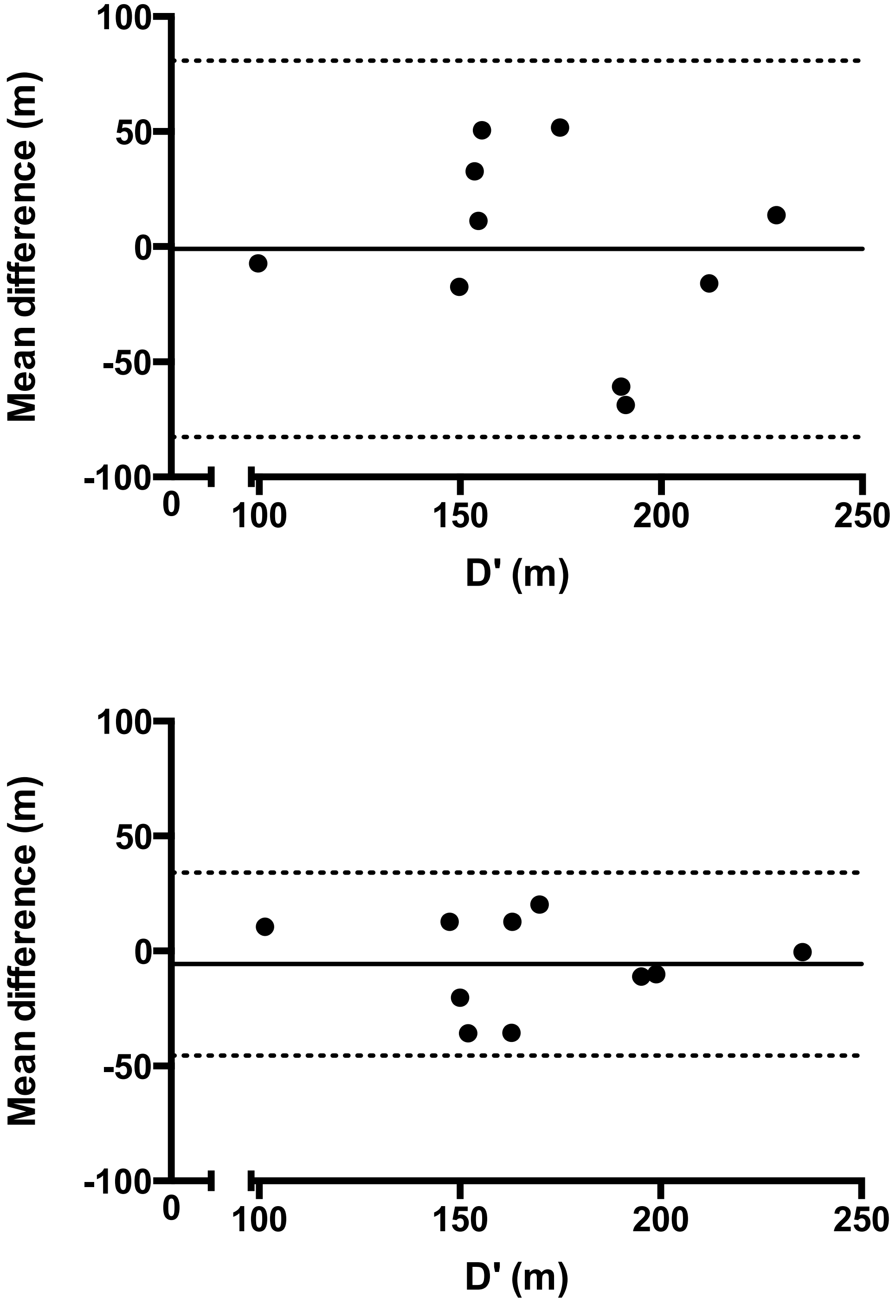

Figure 4.3: Bland-Altman plots of the test–re-test differences in D′ between trials 1 and 2 [top] and trials 2 and 3 [bottom]. The solid horizontal lines represent mean bias, whilst the dashed lines represent the 95% limits of agreement.

Reliability of individual performance trials

Table 4.4 shows the reliability of the individual constant-distance performance trials used in the field test. From table 4.4 it can be seen that a low group mean typical error (expressed as a CV) was reported for the individual performance trials. The test-retest correlation coefficients ranged from r=0.95-0.96 for the 9 lap, r=0.92-0.93 for the 6 lap and r=0.82-0.91 for the 3 lap runs respectively.

Table 4.4: Reliability of individual constant-distance trial performance's

	9 lap	6 lap	3 lap
Performance time (s)	725 ± 41	472 ± 26	218 ± 10
CV trial 2-1 (%)	1.8 (1.2-3.3)	1.6 (1.1-3.0)	2.2 (1.5-4.1)
CV trial 3-2 (%)	1.2 (0.8-2.2)	1.6 (1.1-2.9)	1.4 (1.0-2.5)

Performance times are presented as mean ± SD. Mean values are taken across trials 1-3. CV = coefficient of variation. CV data are presented with 95% confidence limits in parentheses.

Table 4.5: Relationship between individual performance trials and the distance-time relationship

	9 lap	6 lap	3 lap
CS	-0.99**	-0.94**	-0.74*
D′	0.31	0.13	-0.25

Data are presented as Pearson product-moment correlation coefficients (r). Data are taken from trial 1 using the linear distance-time model **P=<0.01; *P<0.05

Table 4.5 shows the Pearson product moment correlations between the individual constant-distance performance trials and the CS and D′. Significant inverse correlations were seen between CS and the 9, 6 and 3 lap trials. No significant relationships were seen between D′ and the individual performance trials.

Table 4.7: Atmospheric conditions across the four tests

	Field test 1	Field test 2	Field test 3	Laboratory test
Wind Speed ($m.s^{-1}$)	0.6 ± 0.6	0.6 ± 0.7	1.1 ± 0.6	N/A
Temperature (°C)	18.1 ± 3.5	17.7 ± 3.5	14.7***** ± 2.6	18.3 ± 0.4
Pressure (mmHg)	762 ± 5	758 ± 3	756 ± 18	764 ± 5
Humidity (%)	59 ± 12	65 ± 14	69 ± 8	55 ± 13

Data are presented as mean ± SD. ***** = Temperature was significantly lower than tests 1, 2 and laboratory test (P=0.01, P=0.02, P<0.01).

Table 4.7 shows the atmospheric conditions across the four tests. No significant differences were observed in environmental conditions between the tests, except for field-test 3, where the air temperature was significantly lower then the other three tests (P<0.05).

4.4 Discussion

The results of the current study demonstrate that critical speed can be reliably tested using a novel same day field test. The mean coefficient of variation of 1.7% is similar to the values of 1.8 and 3% previously reported during laboratory based testing of CS and single-visit all-out testing for CP (Hinckson and Hopkins, 2005; Burnley, Doust and Vanhatalo, 2006). Furthermore the intraclass correlation coefficient for CS (r=0.91 and r=0.95, P<0.01) from the present study compares with the data reported between two repeated 3-min all out tests for CP (r=0.99, P<0.01) in the study by Burnley et al., (2006). Previous research has reported a lower level of reliability for the intercept of the distance-time and power-time relationships, with Hinckson and Hopkins (2005) reporting a CV of 14% for D′ and Constantini et al., (2014) 12% for W′. In agreement with previous literature, D′ in the present study proved to be less reliable than CS, with a CV of 14.1%. The CS and D′ reliability results of the current study are similar to those reported previously during laboratory-based testing, however the variation in D′ is unlikely to be acceptable when evaluating the relatively small training-induced changes seen in well-trained athletes (Hopkins, 2000a). Such a conclusion is supported by limits of agreement analyses which suggest that, with 95%

probability, the differences between the test and retest measures of D′ in an individual, from the well-trained running population, will at best lie between ±40 m. Assuming that the bias is negligible, ratio limits of agreement suggest that, between any two tests, CS may typically differ by 4.6% and D′ by 36.4%, in a positive or negative direction. The Bland-Altman plot of the test–re-test differences in CS between trials 1 and 2 (figure 4.2) showed evidence of heteroscedastic errors, therefore ratio limits of agreement were calculated (Nevil and Atkinson, 1997). The ratio limits of agreement were 0.94 and 1.06. Therefore, if a subject's CS in trial 1 was 4.73 $m.s^{-1}$, it is possible the CS from trial 2 (worst case scenario) could be as low as 4.46 $m.s^{-1}$ or as high as 4.99 $m.s^{-1}$.

Smith and Hill (1993) state that a familiarisation trial serves to reduce the practice effect associated with multiple tests involving maximal effort. A familiarisation visit was included in the current study prior to the three main trials. There were no significant differences in CS or D′ across trials (P=0.43 and P=0.66 respectively), however the coefficient of variation and 95% LOA for both CS and D′ decreased from trials 2–1 to trials 3–2. The test re-test correlation for D′ also improved from trials 2-1 to trials 3-2. Taken together, this supports the presence of a learning effect for CS and D′, suggesting the need for several familiarisation trials before using the novel constant-distance field test to monitor performance. The results of the present research conflict with earlier reports whose results suggest a learning effect was present for CP but not W′ (Gaesser and Wilson, 1988; Smith and Hill, 1993).

Most of the previous literature investigating CS has required a subject to run at a set speed until exhaustion. These types of test have traditionally been shown to have poor reliability with coefficients of variation ranging from 15.1 to 25% (Laursen et al., 2007; Billat et al., 1994). Similar findings have also been reported in both cycling (Jeukendrup et al., 1996) and swimming (Alberty et al., 2006). Hinckson and Hopkins (2005) used a variety of approaches to produce estimates of test-retest error of measurement calculated from time to exhaustion. In contrast to previous research all reliability estimates were <3%, and some were ~1%, resulting in the authors stating that their findings should lay to rest any concerns that time to exhaustion is inherently an unreliable measure of endurance performance.

Regardless of their reliability it has traditionally been argued that constant speed trials performed on a treadmill are not ecologically valid, and do not mimic any training or race situation for a competitive athlete. In training and racing athletes are required to cover a set distance in the fastest time possible, and are rarely (if ever), required to run at a constant speed until exhaustion. Recent research by Hanley (2014) disputes this suggestion and provides evidence of a constant speed approach during competitive long distance running events. Hanley (2014) examined the pacing profiles during the senior men's IAAF world cross-country championships. The analysis of race splits indicated that only the very best athletes were able to keep up with or dictate a lead pace that other athletes tried to follow but eventually dropped off. The slowest finishers became detached from the lead pace by the end of the first lap with those in the top 15 not losing contact until halfway through the race, while the eventual medal positions were decided at the very end. The analysis by Hanley suggests a TTE element is present in competitive race events, with the most successful athletes being the ones who can maintain a speed close to that of the leading group for as long as possible until the medal positions are decided in the later part of the race.

In the current study constant distance trials were chosen to form the basis of the distance-time relationship. Although this approach resulted in reliable estimates for CS and D′ further research is needed to compare parameter estimates from the traditional laboratory-based constant-speed approach with the field-based constant-distance trial approach. One disadvantage of the constant-distance trial approach is the potential influence of pacing. The impact of poor pacing strategy was decreased in the current study by the selection of trained distance runners as participants, however alterations in pacing might indicate why the coefficient of variation decreased over the time course of the repeated experimental trials.

A novel aspect of the constant distance field trial used in the present study was that each of the individual runs used to model CS and D′ were completed with a 30-min recovery period between them. This allowed the whole testing session to be completed within a 90-minute time frame. Traditionally when CS and D′ are tested in a laboratory on a treadmill, recovery periods in excess of 24 hours are used (Smith and Jones, 2001; Hill and Ferguson, 1999), making this a protracted approach. The results of the current study demonstrate that the constant distance field trial is a reliable method of assessing CS and D′ that may present a more attractive option to sports scientists, athletes and coaches wishing to monitor physical fitness and prescribe endurance training.

Reliability of individual constant-distance performance trials

The repeat trials in this study allow the evaluation of not only the reliability of the distance-time relationship parameter estimates but also the assessment of the relative reliability of the individual performance trials. This study utilised 3 constant distance trials, where the athlete was required to cover a set distance in the fastest possible time. Such trials have previously been shown to have a greater level of reliability than constant speed TTE trials, with coefficients of variation ranging from 3.3% to 3.7% (Laursen et al., 2007; Nicholson and Sleivert, 2001). Whilst the present study cannot provide corresponding reliability for TTE trials and cannot therefore provided a direct comparison, its results do support the earlier work of Laursen et al., (2007) and Nicholson and Sleivert (2001) suggesting a high level of reliability from constant distance trials. Table 4.4 reveals a low group mean typical error (CV range 0.8-4.1%) across all of the individual performance trials. Mean CV for the 9, 6 and 3-lap runs was 1.5, 1.6 and 1.8% respectively. The test-retest correlation coefficients ranged from r=0.95-0.96 for the 9 lap, r=0.92-0.93 for the 6 lap and r=0.82-0.91 for the 3 lap runs respectively. Although only small differences in reliability (evidenced by differing CV and test-retest correlations) were seen between the 9, 6 and 3-lap runs (3600, 2400, 1200 m) the data does point to a greater level of reliability in longer duration efforts than shorter duration efforts. This supports the earlier work of Laursen et al., (2007) who reported CV's of 2.0% (range 1.3–4.0%) and 3.3% (range 2.1–6.8%) for their 5000 and 1500 m time trials. However the CV for repeated 10'000 m running trials of 3.7% reported by Nicholson and Sleivert (2001) does not appear to fit this pattern. Hopkins and Hewson (2001) suggest the variability of running performance can be affected by age, ability and competitive experience. Differences in these factors between the participants in the above studies may account for some of the differences in reliability reported.

The greater variability seen in the 3-lap trials may have contributed to the greater variability in D′. Dekerle et al., (2002) explains that relatively small changes in performance time during the shortest trial in the distance-time relationship have been suggested to result in large changes in the resulting D′. This is further supported by Vandewalle et al., (1997) who suggest the y-intercept (seen here as D′) is more sensitive to variations in time than the slope (CS).

Relationship between CS and D′

The results of the present study revealed a significant inverse relationship between CS and D′ across the three repeat trials (r = -0.61, P<0.01). This relationship suggests that runners with a higher CS tend to have a lower D′ whilst runners with a lower CS tend to have a higher D′. These results support earlier work which has also suggested an interrelationship exists between CP and W′ (Vandewalle et al., 1997; Jenkins and Quigley, 1992; Vanhatalo, Doust and Burnley, 2008; Bergstrom et al., 2014). The findings of Vanhatalo, Doust and Burnley (2008) suggest the type of training an athlete undertakes will influence their CP and W′. They report that a 4-week period of interval training at an intensity above CP, increased CP in all subjects, whilst W′ was reduced in eight out of the nine subjects. Therefore the training background of the participants may contribute to the relationship between CS and D′ seen in the present study. Although the participants in the present study were all middle distance runners, some were 800 m specialists whilst others were 5000 m specialists. The relatively low participant numbers meant there were not enough athletes from each specialism to make a full comparison, however it is interesting to note that the runner with the fastest 800 m time had the highest D′ and the lowest CS, whilst the runner with the fastest 5000 m time had the highest CS and a D′ lower than 60% of the group. Therefore it may be that differences in training also influenced the CS and D′ values in the present study and contributed to the inverse relationship between CS and D′.

Jenkins and Quigley (1992) suggest a relationship between CP and W′ with the TTE of the individual performance trials used in the power-duration relationship. Jenkins and Quigley report CP was significantly correlated with endurance time in the longest of the 3 trials used to establish CP in their study (r=0.65, P<0.01), whilst correlations between CP and endurance time in the medium trial and the shortest length trial were successively lower (r=0.44 and r=0.32 respectively). The data from the present study provide support for this suggestion (table 4.5) revealing that, whilst CS was significantly correlated with all 3 of the individual performance trials, this relationship was strongest for the longest (9 lap trial) and decreased for the 6 and 3 lap trials. Jenkins and Quigley (1992) report a contrasting relationship between W′ and the individual performance trials, with the strongest correlation for the shortest trial (r=0.72, P<0.01) and lower correlations for the medium and longest length trials (r=0.58 and r=0.28 respectively). The data from the present study fail to support the relationship between trial length and W′ reported by Jenkins and Quigley. Table 4.5 reveals no significant relationships were seen between D′ and the individual performance trials. Further research that assesses the potential relationship between CS and D′, with the finishing time of the individual performance trials used in the distance-time relationship, may help clarify the conflicting reports in this area.

Goodness of fit of the data and choice of model

There was no significant difference in CS or D′ calculated from the linear distance-time model or the linear inverse of time model (table 4.2). The R^2 and SEE were calculated to assess the fit of the data points to the two different models (table 4.3). There was a significant effect of model on the SEE of D′, with the SEE being significantly lower in the linear distance-time model. Furthermore, there was a strong trend towards the same effect in the SEE of CS. These results support the earlier work of Bull et al., (2000) in cycling and Housh et al., (2001) in running who report that, of the 5 mathematical models studied, the work-time model in cycling and the distance-time model in running resulted in the lowest SEE.

Ferguson et al., (2013) suggest acceptable limits for the SEE are <2% for CS and <10% for D′. In all of the tests (n=30; 10 participants with 3 repeat field test trials) the SEE for CS using the linear distance-time model fell within these limits (ranging from 0.0-1.9%). This is in agreement with the data from Murgatroyd et al., (2011) who report the SEE of their CP estimations ranged from 0.2–1.4%. The SEE for D′ was higher than that of CS across all tests. In 4 out of the 30 tests the SEE was greater than the 10% limit recommended by Ferguson et al., (ranging from 0.1-16.2%), however this lower accuracy in prediction did not result in a significantly different group mean D′ between models (table 4.2). Nevertheless repeating those tests may have improved the overall quality of the D′ data.

It is acknowledged that the accuracy of the parameter estimates is improved by administering additional predictive trials (Vanhatalo et al., 2008), however in an effort to keep the single-visit protocol within a feasible timeframe, the number of trials was limited to three. The good linear fit of the data in the present study, evidenced by the high R^2 (table 4.3) and the agreement in parameter estimates between the different models (table 4.2), justify this approach. Furthermore both CS and D′ were highly correlated between models (r=0.996 and r=0.950 P<0.01, respectively). This supports the earlier work of Vanhatalo et al., (2008), who also report strong correlations between the linear distance-time and linear 1/t models for CP (r=0.999) and W′ (r =0.991). Vanhatalo et al., (2008) state good correlation of the parameter estimates between the models indicates that there is no systematic error in the predicting trial data.

The results of the present study suggest a good level of agreement between the parameter estimates from the linear distance-time and the inverse of time models, however due to the greater accuracy of its predictions (inferred from a lower SEE), the linear distance-time model was used during the subsequent experimental chapters.

Order of placement and recovery between performance trials

Clarke and Skiba (2013) state the individual trials used to calculate CP and W′ should be performed in random order to promote statistical independence between the data points and to eliminate possible confounds introduced by the order of the tests. In the current study the three individual performance trials that made up the distance-time relationship were performed on the same day in descending order of distance (ascending order of mean speed). This conflicts with the suggestion of Clarke and Skiba (2013), however matches the methodology of Jenkins and Quigley (1992), who performed three trials at set work rates in ascending order of power. The methodological design in the present study was also supported by unpublished pilot work (in a small sample, n=3) from our laboratory. This work indicated that the elevated blood lactate seen following the individual runs returned to a significantly lower value (P=0.01), post recovery, when trials were performed in descending, rather than ascending, order of distance. The results of the present study suggest a field-test with 3 constant-distance performance trials, performed in descending order, produces reliable values for CS and D′.

In contrast to the present study, Jenkins and Quigley (1992) separated the trials in their study with a recovery period of at least 3 hours. In an attempt to constrain the single-visit field test to a realistic time frame, a recovery period of 30-minutes was used between trials in the present study. This decision was supported by unpublished pilot work (in a small sample, n=3) from our laboratory indicating that although blood lactate remained elevated above baseline following a 30-minute recovery (mean difference 2.1 $mmol.l^{-1}$), compared to a 60-minute recovery (no significant difference to baseline, P=0.91), performance time in the constant distance trials was not significantly different between the 30 and 60-minute recovery periods (P=0.39).

Further research to investigate the validity of CS and D′, estimated from a single visit field-test (with a 30-minute recovery period between trials), is needed before the test can be applied in a practical setting.

4.5 Conclusion

The results of the current study demonstrate that a novel constant distance field trial reliably assesses CS, producing reliability data comparable to that previously reported for laboratory-based measures of CS and CP. Although the assessment of D′ is less reliable, coefficients of variation are also similar to those reported previously during laboratory-based testing. It may therefore be suggested that the novel constant distance field trial could be used as a reliable alternative to treadmill-based constant speed trials. Further research is needed to compare parameter estimates from the traditional laboratory-based constant-speed approach with the field-based constant-distance trial approach. Additional examination into the validity of a 30-minute recovery period between trials is also needed.

Chapter 5 – The validity of a field test of the distance-time relationship

Aspects of the following chapter have been published in the following manuscript: Galbraith A., Hopker J., Lelliott S., Diddams L., Passfield L. (2014) A Single-Visit Field Test of Critical Speed. *International Journal of Sports Physiology and Performance*, *9(6)*, 931-935.

5.1 Introduction

A track based field test of the distance-time relationship has been suggested as a useful method to assess endurance runners' fitness (Kranenburg and Smith, 1996). Kranenburg and Smith conducted a direct comparison of CS determined on the treadmill and in the field. They found a strong correlation between CS for both tests (r=0.94, P<0.01). Athletes would, however, need to make major adjustments to their training schedule in order to accommodate the protocol for this field test (a minimum of three track tests across two consecutive days). Therefore, whilst the ecological validity of distance-time relationship field tests may be appealing for athletes and coaches, the feasibility of the repeated days of testing prevents their wide-scale adoption.

In chapter 4 a novel field test of the distance-time relationship was presented, where all measurements are taken on the same day in a single visit. The novel protocol could enable the measurement of CS and D′ to be more accessible and less time consuming for athletes and coaches to adopt. This is important, as for certain sports, field tests may be preferable to laboratory tests (Nummela et al., 2007). Often field tests are viewed as less reliable than laboratory tests, due to the lower level of control over environmental factors, however chapter 4 demonstrates comparable reliability between the new field test protocol and more traditional laboratory-based measures of CS and D′. Furthermore, field tests may provide greater ecological validity due to their greater specificity to a given sports performance (Nummela et al., 2007). For example, a runner may see greater relevance for a test conducted on an athletics track rather than on the treadmill. Moreover, treadmill protocols tend to use time to exhaustion trials at a set speed (Florence and Weir, 1997; Pepper, Housh and Johnson, 1992; Housh et al., 2001), whereas field-based protocols can benefit from fixed distance trials that closely mimic the demands of competitive races. Whilst fixed distance self-paced trials are possible on a treadmill, they are complicated to conduct and tend not to allow the typical changes of pace encountered when running on an athletics track.

A central aim when developing the single-visit field test in chapter 4 was to produce a protocol that could be conducted in a single visit within a feasible time frame. The number of visits and the total duration of the visit were considered important for the future uptake of the protocol by athletes and coaches and as such impact the overall practical application of the protocol. Although chapter 4 reports a high level of reliability within the parameter estimates, further research is needed to compare CS and D′ from the traditional laboratory-based multi-visit approach with the single visit field-based approach. Additional examination into the effect of the recovery duration between trials in the single-visit protocol is also needed in order to determine the validity of a single-visit field test with a 30-minute recovery between trials.

The aim of this study was to assess the validity of CS and D′, determined from a single-visit field test, by comparing parameter estimates with that of a traditional multi-visit treadmill time to exhaustion protocol. The study also aimed to investigate the effect of different recovery durations between field-test trials, on the parameter estimates.

5.2 Method

Participants: Ten male middle-distance runners (mean (±SD): age: 39±7 yrs; Stature: 181±7 cm; Mass: 75.2±5.0 kg and 5 km personal best time: 1136±61 s) were recruited for the study. All participants were competitive club standard runners who had been competing for a minimum of 2 years. All participants provided written informed consent for this study that had been approved by the University's ethics committee.

Experimental design: The protocol involved a total of 7 exercise testing sessions for each participant. Visit 1 included a maximal incremental treadmill test to determine $\dot{V}O_{2\,max}$, and a familiarisation for the treadmill based CS test. During visit 2 participants were familiarized with the CS field test using a 30-min recovery between each of the 3 runs. After these initial testing and familiarisation visits, a further 3 'experimental' laboratory visits were undertaken to determine CS on the treadmill. These visits involved constant speed runs to exhaustion. Two further 'experimental' field-testing sessions took place. On each field testing visit participants completed 3 fixed distance timed runs, on one occasion with a 30-min recovery between runs and on a separate day with a 60-min recovery.

All testing sessions were completed in a random order and all tests were completed at the same time of day (±2 hrs). Participants were instructed to arrive for testing in a rested and fully hydrated state, at least 3 hours post-prandial and having avoided strenuous exercise in the preceding 24 hours. Prior to each test session participants completed a standardized warm-up consisting of 5-min self-paced jogging, followed by 5-min of their usual stretching exercises (Smith and Jones, 2001). All 7 testing sessions for each participant were completed within a period of 3-weeks.

Preliminary laboratory visit protocol: The preliminary laboratory visit protocol is outlined in the general methods (Chapter 3). Environmental conditions during the preliminary visit session were within a temperature, pressure and relative humidity range of 18.0-19.5 ˚C, 745-756 mmHg and 34-55%. Table 5.1 shows the mean values for the parameters measured during the preliminary laboratory visit test.

Table 5.1: The physiological variables measured at the preliminary visit test.

	$\dot{V}O_{2\,max}$ ($mL.kg^{-1}.min^{-1}$)	v-$\dot{V}O_{2\,max}$ ($km.h^{-1}$)	Running economy ($mL.kg^{-1}.km^{-1}$)	Energy cost ($kcal \cdot kg^{1} \cdot km^{-1}$)
Mean	60.7 ± 2.8	15.4 ± 0.6	199.3 ± 16.1	1.02 ± 0.08

Data are presented as mean ± SD

A 30-min recovery period followed the preliminary visit protocol, after which participants completed a familiarisation trial of the treadmill based CS test protocol (detailed below).

Treadmill test protocol: Three constant speed time-to-exhaustion runs following a similar protocol to Smith and Jones (2001) were conducted. The velocities for each participant were set at 100, 105 and 110% of their v-$\dot{V}O_{2\,max}$. Runs were conducted on separate days with a minimum of 24-hours recovery (Smith and Jones, 2001; Hugshon et al., 1984). Runs were hand timed to the nearest second and the distance run was subsequently calculated. During the test elapsed time, distance covered and velocity were masked from the participant’s view. Throughout testing environmental conditions were within a temperature, pressure and relative humidity range of 18.2-19.6 ^{o}C, 749-761 mmHg and 33-54%.

Field test protocol: The field test protocol is outlined in the general methods (Chapter 3). In addition to completing the standard field test protocol with a 30-min rest period, an additional field test was conducted on a separate day with a 60-min rest between runs. Mean environmental conditions during the field tests were: temperature 11.5 °C (range 8.6-13.4 ˚C), humidity 72% (range 56-83%.), barometric pressure 758 mmHg (range 739-776 mmHg) and wind speed 1.4 $m \cdot s^{-1}$ (range 0.2-1.8 $m \cdot s^{-1}$).

Data analysis: Participants' CS and D′ were calculated from the treadmill and field test runs using a linear distance-time model. Data were checked for normality of distribution using the Shapiro-Wilk statistic. Repeated-measures ANOVA were used to identify differences in CS and D′ between the treadmill and field tests. The Pearson product moment correlation coefficient was used to assess the relationship between the treadmill and field tests. The 95% limits of agreement and Bland Altman plots (Bland and Altman, 1986), along with the typical error of the estimate were calculated to assess agreement between methods. The reliability of the distance-time relationship over repeated tests was assessed by comparing CS and D′ from the field familiarisation trial and the 30-min field-test. The within-participant variation was expressed as a coefficient of variation (CV) derived from log-transformed data (Hopkins, 2000). The 95% confidence intervals were calculated for each CV. The 95% limits of agreement were calculated to assess the variability of the repeated tests. Analysis was conducted using the SPSS statistical software package (IBM SPSS statistics, Rel. 20.0, 2011. SPSS Inc. Chicago, USA). Statistical significance was accepted at $P < 0.05$ for all tests.

5.3 Results

Table 5.2 displays the mean values for participants' CS and D′ estimated from the treadmill and field tests.

Table 5.2: Participants CS and D′ estimated from the treadmill and field tests.

	Treadmill	Field-30	Field-60
CS ($m \cdot s^{-1}$)	4.05 ± 0.22	4.07 ± 0.28	4.07 ± 0.26
D′ (m)	250 ± 84	106* ± 57	102* ± 36

Data are presented as mean ±SD. Field-30 = 30-min recovery between runs ; Field-60 = 60-min recovery between runs. ***** Significantly different to Treadmill, $P < 0.01$

It can be seen from table 5.2 that there was no significant difference in the mean CS (P=0.80) between the 3 tests (treadmill, 30-min field and 60-min field). D′ differed between the 3 tests, being significantly higher in the treadmill test than in the 30 and 60-min field tests ($P < 0.01$).

A strong relationship was seen between treadmill CS and CS from the 30-min (r = 0.89, P<0.01) and 60-min (r = 0.82, P<0.01) field tests. Strong relationships were also evident between the CS (r = 0.96, P<0.01) and the D′ (r = 0.77, P=0.01) from the 30 and 60-min field tests. However, there was no significant relationship between the D′ from the treadmill test and D′ from the 30 (r = 0.13, P = 0.72) and 60-min (r = 0.33, P = 0.36) field tests.

The 95% limits of agreement method was used to assess the level of agreement between the CS from the treadmill test and the CS from the 30 and 60-min field tests. Results revealed close agreement between methods (95% limits of agreement = 0.25 $m \cdot s^{-1}$ and 0.30 $m \cdot s^{-1}$ respectively). The 95% limits of agreement for D′ between the treadmill test and the 30-min and 60-min field tests were 187 and 157 m respectively. The Bland-Altman plots for CS and D′ can be seen in Figure 5.1.

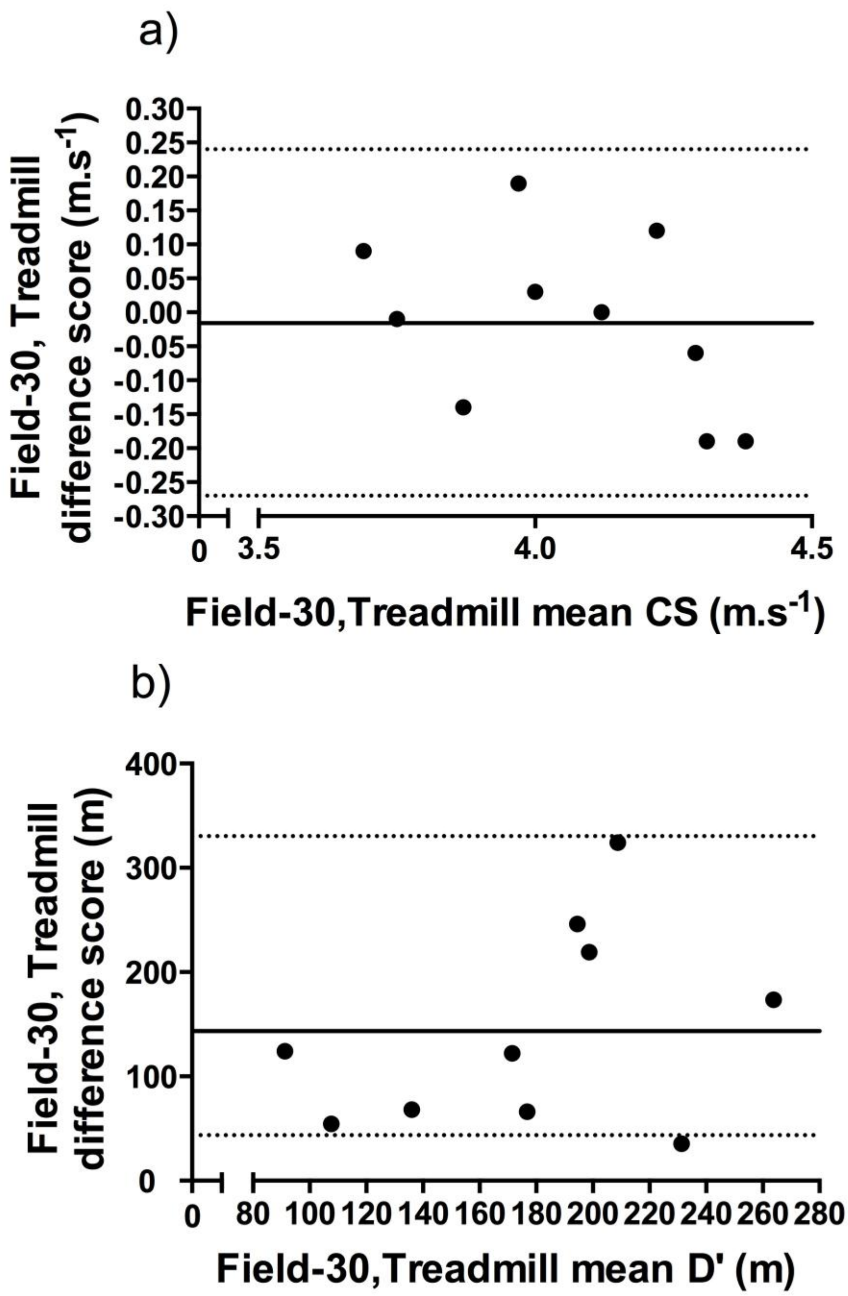

Figure 5.1: Bland-Altman plot of differences in CS (a) and D′ (b) between the treadmill and the 30-min field tests. The solid horizontal lines represent mean bias, whilst the dashed lines represent the 95% limits of agreement.

The typical error of the estimate was calculated by using the field test as the practical variable and the treadmill test as the criterion variable (Hopkins, 2000). The typical error of the estimate for CS was 0.14 $m \cdot s^{-1}$ (95% confidence limits: 0.09-0.26 $m \cdot s^{-1}$) for the 30-min field test and 0.16 $m \cdot s^{-1}$ (95% confidence limits: 0.11-0.31 $m \cdot s^{-1}$) for the 60-min field-test. The typical error of the estimate for D′ was 88 m (95%

confidence limits: 60-169 m) for the 30-min field test and 84 m (95% confidence limits: 57-161 m) for the 60-min field test.

The R^2 for the linear regression of distance and time was greater than 0.999 for all three tests. The SEE (±SD) for CS ($m.s^{-1}$) and D′ (m) from the three tests was 0.04 $m.s^{-1}$ (0.03 $m.s^{-1}$) and 17 m (11 m); 0.04 $m.s^{-1}$ (0.03 $m.s^{-1}$) and 16 m (14 m); 0.14 $m.s^{-1}$ (0.06 $m.s^{-1}$) and 59 m (30 m) respectively for the 30-minute field test, 60-minute field test and treadmill test.

The reliability of the distance-time relationship over repeated 30-minute field tests (expressed as a coefficient of variation) was 0.4% (95% confidence limits: 0.3-0.8%) for CS. D′ proved less reliable with a coefficient of variation of 13% (95% confidence limits: 10-27%). There was no significant difference in CS or D′ across the two trials for the 30-minute field test (P=0.34 ; P=0.67). The 95% limits of agreement were ±0.05 $m \cdot s^{-1}$ of the measure for CS and ±20 m of the measure for D′.

5.4 Discussion

The main finding of this study was that the single-visit field test of CS using a 30-min rest period agrees well with CS determined over multiple visits using a treadmill. The typical error of the estimate for CS was 0.14 $m \cdot s^{-1}$, which Hopkins (2000) suggests can be interpreted as small. The typical error for CS from the 30 and 60-minute field test protocols (~3.4-3.9%) is comparable with the values of 4.3-4.6% reported by Vanhatalo, Doust and Burnley (2008) between the end test power from a single-visit 3-minute test and the CP from a multi-visit laboratory test. There was no significant difference between CS on the track (4.07 $m \cdot s^{-1}$) compared to the treadmill (4.05 $m \cdot s^{-1}$). Furthermore the strong correlations between CS from the field and treadmill tests in the present study (r = 0.89, P <0.01) are similar to those previously reported (r = 0.94, P < 0.01) by Kranenburg and Smith (1996).

The agreement between D′ from the field test and D′ from the laboratory test was not as good, with a typical error of the estimate of 88 m. This level of agreement is interpreted by Hopkins (2000) as moderate. Differences in D′ were also evident between test methods (Table 9). The D′ was higher with the treadmill protocol (249

m) compared to the 30-min (106 m) and 60-min (102 m) field protocols. The CS and D′ were measured with fixed distance runs in the field and time to exhaustion runs on a treadmill. Laursen et al., (2007) previously compared these approaches on a treadmill and reported lower levels of reliability for constant speed time-to-exhaustion tests compared with time-trial running tests. The differing reliability of these approaches may have influenced the variables computed from the treadmill and field tests. Additionally, due to the comparison of fixed distance and time to exhaustion runs, it was not possible to exactly match the performance time between comparable runs. During the 3 treadmill runs participants ran at percentages of their v-$\dot{V}O_{2\,max}$ estimated to produce an exhaustion time similar to that of the field runs. It has been suggested that CS and D′ are dependent on the range of exhaustion times (t_{lim}) achieved and that higher values of t_{lim} result in a higher calculated D′ (Vandewalle et al., 1997). A longer t_{lim} during the treadmill runs might contribute to the higher D′ observed. However this was not found to be the case as there was no difference (P = 0.87) between the combined t_{lim} for the 3 treadmill (1667 ± 309) and 30-min field test (1698 ± 92) runs. Therefore, it is unlikely that differences in t_{lim} are responsible for the difference in D′ between the treadmill and field tests.

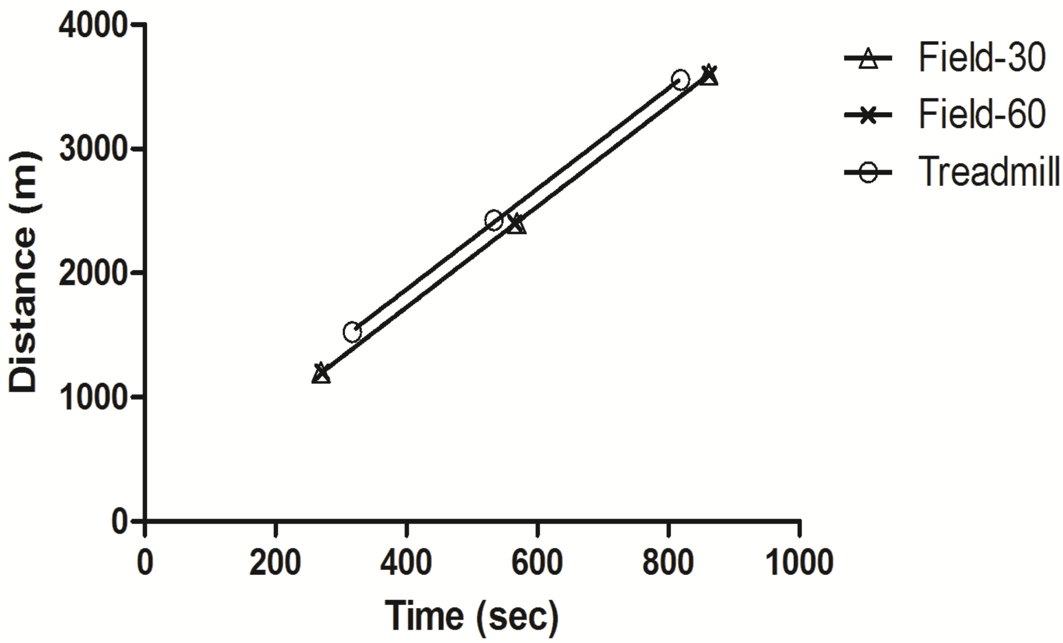

Figure 5.2: The distance-time relationship for the three test methods. Data are calculated from the mean distance and time (n=10) for each test method.

Figure 5.2 shows that participants covered any given distance at a faster speed on the treadmill than in the field. The reasons for this remain unclear but are unlikely to be related to accumulated fatigue as a consequence of the 30 or 60-min recovery time during the single-visit field test protocol. If fatigue were a factor, then the 3600 m run (i.e. the first distance run in the field protocol) would yield similar times (as fatigue should not be a factor). It can be seen from Table 5.3 that this is not apparent, as participants' mean speed over 3600 m is ~ 4% higher on the treadmill than in the field.

Table 5.3: Predicted mean speed ($m \cdot s^{-1}$) over three set distances.

	Mean Speed ($m \cdot s^{-1}$)			
Distance (m)	**Treadmill**	**Field-30**	**Field-60**	**Difference (%)**
3600	4.35	4.18	4.18	4.2
2400	4.52	4.24	4.24	6.7
1200	5.12	4.44	4.44	15.2

Data are calculated from the linear distance-time relationships in Figure 5.2. Field-30 = 30-min recovery between runs ; Field-60 = 60-min recovery between runs.

Furthermore, if residual fatigue were a factor it would be logical to expect the difference between laboratory and field tests to be smaller when the 60-min recovery was utilized. Again, it can be seen from Table 5.3 that this is not the case, and thus it would appear that the lower D′ in the field tests was not a consequence of residual fatigue during the single-visit field-test protocol.

The exact reason for the differences observed in D′ during this study remain unclear, although inherent differences in the mechanics of indoor (treadmill) and outdoor (track) running might be responsible. Jones and Doust (1996) suggest that a 1% treadmill gradient best replicates the demands of outdoor running for speeds between 2.9 and 5.0 $m \cdot s^{-1}$. The current findings suggest that a 1 percent gradient for treadmill running is less challenging than track running, and as a consequence, predicted time to cover a set distance on the treadmill was quicker than in the field (Table 5.3). The difference was greater for 2400 m and 1200 m distances where the mean speed approached and then exceeded 5.0 $m \cdot s^{-1}$. It seems possible that a treadmill grade of greater than 1% may be necessary for the speeds used in the current study. These changes to the treadmill protocol may then bring the treadmill D′ measurement more in line with that of the field protocol. However, it is unlikely that the fairly large differences between treadmill and field running reported in Table 5.3 can be solely attributed to treadmill grade. Furthermore it could be argued that differences between indoor and outdoor running would presumably effect the CS as well as the D′. However it has been suggested that the y-intercept is more sensitive to variations in time than the slope (Vandewalle et al., 1997), justifying how differences between indoor and outdoor running may effect D′ whilst the CS remains unchanged.

A further suggestion for the differences observed in D′ between the treadmill and the field protocols may be the effect of self-pacing in the field trial protocols. Chidnok et al., (2013) reported that work above end power (akin to D′) was not significantly different between self-paced, constant work rate and ramp-based exercise protocols, therefore this suggestion seems unlikely.

It is possible that having the exercise bouts which make up the distance-time relationship all in the same day, with a relatively short recovery between them, may induce a priming effect from one bout on the next, which could either limit or aid the performance of the next trial. A limiting or aiding effect from a previous trial may have an impact on the estimated D′ from the distance-time relationship. The trials in the single-visit protocol are always presented in a fixed order (9 lap, 6 lap, 3 lap runs), therefore any effect of priming would only influence the 6 and 3 lap trials, rather than the 9 lap trial. This may therefore induce a greater impact on D′ than CS (Jenkins and Quigley, 1992). If the priming bout (the 9 lap trial) had a detrimental effect on performance in the 6 lap trial and subsequently the priming bout (the 6 lap trial) had a detrimental effect on performance in the 3 lap trial, the combined effect may have contributed to a lower D′ in the single-visit field test protocol compared with the multi-visit treadmill protocol.

An important factor determining whether priming exercise evokes a performance advantage or disadvantage during supra-CP exercise is the extent to which blood lactate levels remain elevated at the start of the post-priming bout (Ferguson et al., 2007). Burnley et al., (2005) propose that at the start of a post-priming bout, blood lactate levels <5 mM are associated with an increase in performance (Burnley, Jones and Doust, 2005; Jones et al., 2003). The small pilot study (discussed in chapter 4) reveals post priming blood lactate levels of <5 mM immediately preceding the 6-lap and 3-lap runs. Based on the findings of Burnley et al., (2005) this may have been expected to induce a performance advantage in the 6 and 3 lap runs, which in turn would have improved performance times in the fixed distance trials, consequently raising the estimated D′. This was however not seen in the D′ results of the field-test trials in the present study, where a lower D′ was reported compared to the traditional multi-visit treadmill protocol. In summary, the conflicting results from the priming literature fail to provide sufficient supporting evidence to explain the differences in D′ between the field and treadmill tests observed in the present study.

Although differences in D′ between single-visit field and multi-visit treadmill testing were reported in the present study, this result does not stand in isolation. Differences in parameter estimates have previously been reported when single-visit cycle testing was compared with multi-visit cycle testing (Bergstrom et al., 2014). Bergstrom et al., demonstrated the single-visit 3-min test resulted in a higher estimated CP than that from the linear-work, linear-power and hyperbolic models using 4 constant power TTE trials. However W′ from the 3-min test was not significantly different from that estimated from the linear-work and linear-power models.

There was no significant difference in CS calculated from the 30-min or the 60-min field tests (Table 5.2). This is in keeping with previous research which reported no significant difference in CS compared to a control value, following either a 2, 6 or 15-min recovery (Ferguson et al., 2010). There was also no significant difference in D′ between the 30 and 60-min field tests (Table 5.2). In contrast to the current study, the longest recovery duration in previous research was 15-min (Ferguson et al., 2010), by which point 86% repletion of D′ was reported. Based on the result of the present study, a recovery of longer than 30 minutes between runs seems unnecessary for the calculation of CS and D′ during a single-visit field test. When using the 30-min rest period the field test can be accommodated into a single session of around 90-min duration.

5.5 Conclusions

The single-visit field test of CS using a 30-min rest period agrees well with CS determined over multiple visits using a treadmill (typical error of the estimate 0.14 $m \cdot s^{-1}$). Therefore, when assessing CS the single visit field test protocol may provide a suitable alternative to treadmill based testing over multiple days. The agreement between D′ from the field test and D′ from the laboratory test was not as good, with a typical error of the estimate of 88 m. The single visit field test is an accessible test for the majority of athletes and can be completed within 90 minutes, making it an attractive option for athletes and coaches who want to monitor CS.

Chapter 6 – Monitoring the distance-time relationship during a competitive athletics season

Aspects of the following chapter have been published in the following manuscript: Galbraith A., Hopker J., Cardinale, M., Cunniffe, B., Passfield L. (2014) A 1-Year Study of Endurance Runners: Training, Laboratory Tests and Field Tests. *International Journal of Sports Physiology and Performance*, *9(6)*,1019-25.

6.1 Introduction

Endurance runners may complete high volumes of training over many years to produce elite performance (Jones, 1998). However, surprisingly little has been documented about the training completed or the corresponding changes elicited in laboratory and field performance tests of highly trained runners, especially in longitudinal studies. A small number of studies have examined the acute effect of 4-8 weeks of training on the $\dot{V}O_{2\,max}$ of trained runners. Results of these studies are contradictory, with some reporting no change in $\dot{V}O_{2\,max}$ (Billat et al., 1998; Smith et al., 2003; Denadai et al., 2006), whilst others report increases of up to ~5% (Smith et al., 1999; Billat et al., 2002). The extent to which seasonal changes in fitness occur in highly trained runners is unknown. Accordingly, the contradictory findings may be a consequence of variation in the seasonal timing of these relatively short-term studies. An increase in running performance without concomitant increases in $\dot{V}O_{2\,max}$ was highlighted in a 5-year case study of an elite female runner (Jones, 1998). Longitudinal cohort studies of trained runners are sparse. Two studies involving groups of trained runners have previously been published where performance changes were reported, however runners' training was not examined (Tanaka et al., 1984; Bragada et al., 2010). Svedenhag and Sjodin (1985) monitored elite runners over the course of a year and compared increases in $\dot{V}O_{2\,max}$ and economy with training. Training was not recorded directly however, but with diary records. The determination of the distance-time relationship is based on actual performances times (either to exhaustion, or to complete a set distance). Accordingly Jones et al., (2010) suggest that measuring changes in this relationship could be more valuable to athletes and coaches than laboratory measures of $\dot{V}O_{2\,max}$ and lactate threshold (LT). A distance-time relationship test, therefore, may be an ideal way to assess training induced changes in performance during a longitudinal cohort study.

In contrast to running, several studies have examined the effects of a training period on the cycling power output-time relationship. This research has demonstrated that improvements ranging from 10-31% in critical power are possible following a period of training (Gaesser and Wilson, 1988; Poole et al., 1990; Jenkins and Quigley, 1992). These studies, however, featured either untrained or moderately trained subjects (mean $\dot{V}O_{2\,max}$ values ranging from 48.5 to 55.0 mL·kg^{-1}·min^{-1}), and utilized only a 6-8 week training period. To our knowledge previous studies have not examined the effect of prolonged endurance training on highly trained participants' CS and D′.

Chapters 4 and 5 describe a single-visit field test of the distance-time relationship, with a 30-minute recovery between trials. This test is presented as a valid, reliable and more attractive option for assessing the distance-time relationship than traditional multi-visit testing. The time efficiency and minimal equipment increase the practical application of the single-visit field test, allowing the potential for the test to be used at regular intervals to monitor the effects of prolonged endurance training on CS and D′.

The primary aim of this study was to examine the ability of the single-visit field test to detect training induced changes in the distance-time relationship in a group of highly trained distance runners. A second aim was to examine and compare the effects of endurance training on laboratory and field performance tests.

6.2 Method

Participants: Fourteen male middle and long distance runners (n=6 middle-distance; n=8 long-distance) were recruited from local athletics clubs. Participants were competitive club and national-level runners, with at least an 8-year history of running training and competition (average 11 years). At the start of the study participants displayed the following characteristics (mean ± SD): Age 28±8 yr, weight 67.0±6.3 kg, $\dot{V}O_{2\,max}$ 69.8±6.3 mL·kg^{-1}·min^{-1}. Mean (± SD) performance times over a range of distances during the study duration are shown in table 6.1. Participants were categorised into either the middle-distance or long-distance performance discipline according to the distance of their main target race of the season. All participants provided written informed consent for this study that had been approved by the University's ethics committee.

Table 6.1: An overview of the participants' performance level during the season

	Seasons best performance time			
	(min:s)		(hr.min)	
	800 m	1500 m	½ Marathon	Marathon
Middle-distance runners (n=6)	1:56.2±3.0 s	3:58.2±4.9 s		
Long-distance runners (n=8)			1:10:02±3:48	2:28:50±12:27

Data are presented as mean ± SD

Experimental design: This was a 1-year observational study of highly trained runners, examining their training and corresponding changes in both field and laboratory fitness tests. The participants' training was set by their coach and was not manipulated or directly influenced as part of this study. Participants completed five laboratory tests and nine field tests over the course of 1-year (Figure 6.1).

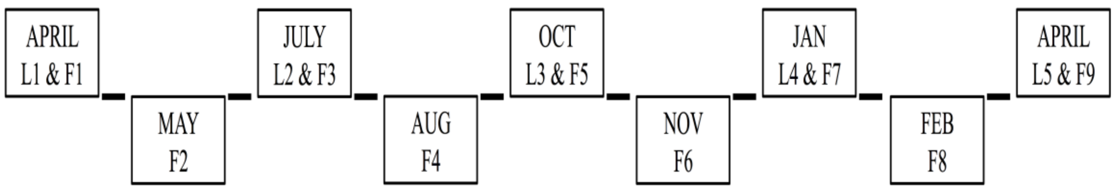

Figure 6.1: Schematic diagram illustrating the testing schedule.

Key: L = Laboratory test; F = Field test; — = 42-day training period (8 in total)

All participants completed a familiarisation session for each test prior to commencing the study. During the study participants were asked to maintain their normal diet, but no dietary analysis or data collection was performed. Throughout the study all test sessions were conducted at the same time of day (±2 hr), to reduce any possible effect of circadian rhythms (Drust et al., 2005). Participants were instructed to arrive for testing in a rested and fully hydrated state, at least 3 hours post-prandial and having avoided strenuous exercise in the preceding 24 hours.

Laboratory-test protocol: The laboratory-test involved a submaximal section to assess LT and running economy followed by a maximal section to assess $\dot{V}O_{2\,max}$ and the v-$\dot{V}O_{2\,max}$. Full details of the laboratory test protocol are outlined in the general methods (Chapter 3) under the heading 'preliminary laboratory visit protocol'. Throughout these testing sessions laboratory conditions were maintained within a temperature range of 17.5-19.5 °C and 35-65% relative humidity.

Field-test protocol: The field test protocol was a single visit fixed distance test for CS and D′. Full details of the field test protocol are outlined in the general methods (Chapter 3). Mean environmental conditions during the field tests across the study were: Temperature 13.8 °C (range 0-24 °C), Humidity 64% (range 38-94%), Pressure 766 mmHg (range 756-772 mmHg) and Wind Speed 1.8 $m \cdot s^{-1}$ (range 0.0-2.0 $m \cdot s^{-1}$).

Training data collection: Throughout the study participants recorded every training session and race with a wrist worn GPS and heart rate monitor (310XT, Garmin International Inc. Kansas, USA). Data were recorded using the watches smart-recording function.

Data analysis: CS and D′ were calculated from the field test trials using a linear distance-time model (equation 1). Data were checked for normality of distribution using the Shapiro-Wilk statistic, log transformation was used where the assumption of normality was violated. Repeated-measures ANOVA were used to identify differences in the laboratory and field-test variables across the season. Participants' training data was analysed for the 42-day period immediately preceding each testing session giving a total of 8 separate periods of training data analysis (Figure 6.1). Training files were stored on the GPS watch of each participant, with an individual file created for each training session within a training period. Training files were then processed with a macro to produce metrics such as total distance covered, total training time and time spent above and below threshold velocity during a training period. A multiple linear regression was conducted to assess the amount of variance in CS that could be explained by the training. A hierarchical (block-wise) variable entry method was used for the multiple linear regression, where predictors were entered into the model in order of their expected importance in predicting the outcome. The expected importance was based on the correlation between predictors and the outcome variable (CS). Pearson correlation coefficients were used to assess the relationship between the pooled laboratory and field-test variables, and between the pooled training and laboratory-test variables. Analysis was conducted using SPSS statistics software (IBM SPSS statistics, Rel.20.0, 2011. SPSS Inc. Chicago, USA). Statistical significance was accepted at P<0.05.

6.3 Results

Changes in the field-test variables during the season: Differences in CS and D′ across the testing sessions are shown in Figure 6.2. The overall group CS changed significantly during the season (P=0.02) being at its lowest during August and reaching a peak in February. In contrast, D′ did not change throughout the study (P=0.11). On average across the study the long-distance runners displayed a significantly higher CS and a significantly lower D′ than the middle-distance runners (5.07 ± 0.31 m.s^{-1} and 94 ± 49 m vs. 4.76 ± 0.22 m.s^{-1} and 162 ± 44 m, P<0.01).

The R^2 for the linear regression of distance and time ranged from 0.99-1.00 across all tests. The SEE for CS and D′ across the field tests ranged from 0.00-0.11 m.s^{-1} for CS and 0-64 m for D′.

Changes in laboratory-test variables during the season: The physiological variables measured during the five laboratory-testing sessions are shown in Table 6.2. Absolute $\dot{V}O_{2\,max}$ (L·min^{-1}) changed significantly during the season (P<0.01), and was higher in October (P<0.01) and January (P=0.01), than in the April baseline test. A similar response (P<0.01) was apparent for relative $\dot{V}O_{2\,max}$ (mL·kg^{-1}·min^{-1}). There were no changes in the other laboratory measures during the study. When the group was split by running discipline the middle-distance runners displayed a significantly higher $\dot{V}O_{2\,max}$ and a significantly lower LT, on average across the study, than the long-distance runners (5.03 ± 0.46 L·min^{-1}and 14.9 ± 0.99 km.h^{-1} vs. 4.72 ± 0.49 L·min^{-1} and 16.2 ± 1.07 km.h^{-1}, P=0.01).

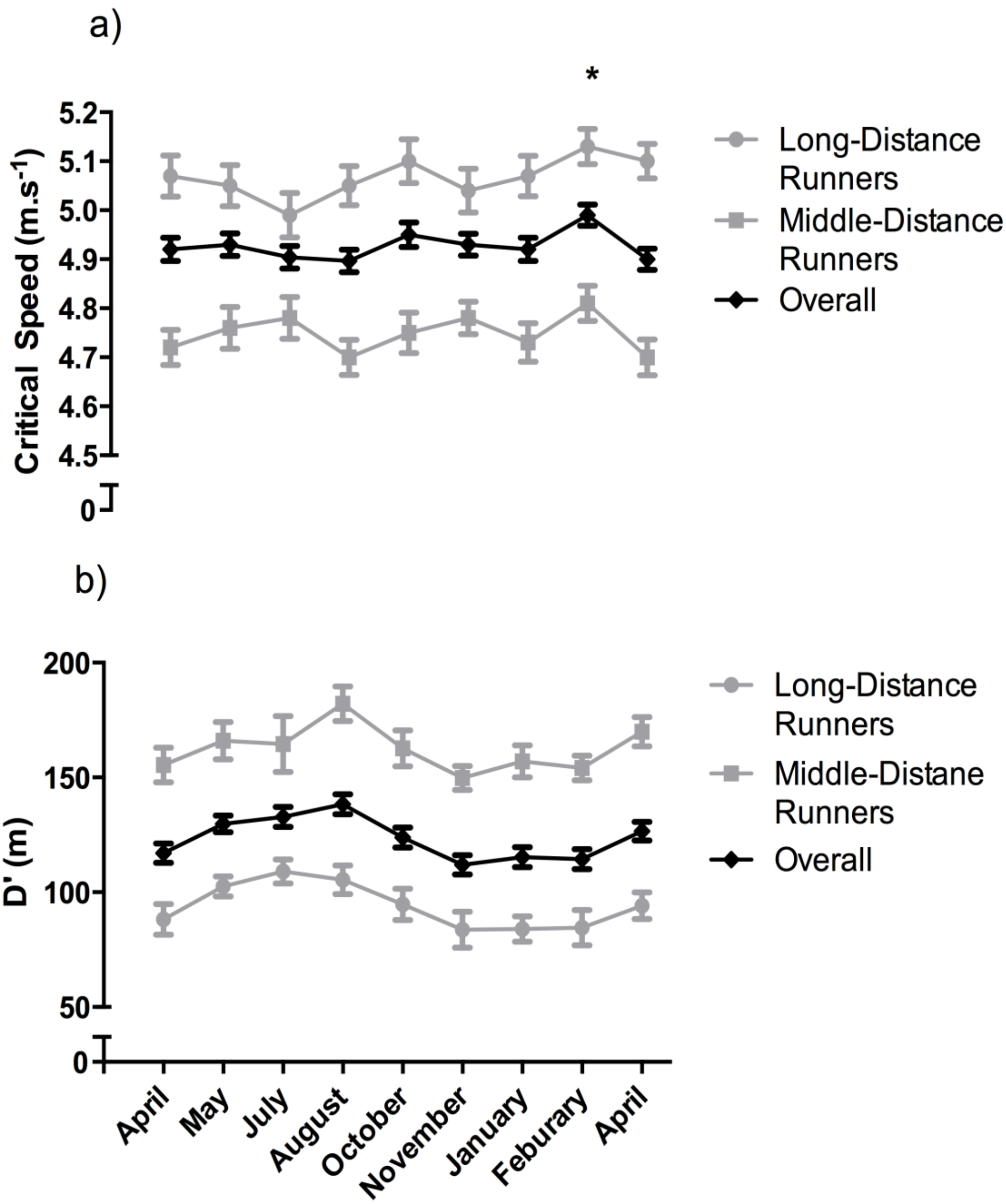

Figure 6.2: Changes in CS (a) and D′ (b) across the 9 field-testing sessions.

Data are presented as mean ± SEM. The field-test points are representative of the points in Figure 6.1 and span across a whole training year. ***** Significantly higher than August, *P* = 0.01

Table 6.2: The physiological variables measured across the 5 laboratory-testing sessions.

	April	July	October	January	April
Mass (kg)	67.0 ± 6.3	67.3 ± 6.4	67.3 ± 6.9	67.0 ± 6.4	67.0 ± 6.7
LT ($km \cdot h^{-1}$)	15.7 ± 1.2	15.5 ± 1.3	15.8 ± 1.4	15.7 ± 1.1	15.6 ± 1.2
RE at $16 km \cdot h^{-1}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	222.6 ± 14.5	228.0 ± 12.2	224.5 ± 13.4	229.6 ± 12.6	223.2 ± 12.0
Energy cost of running ($kcal \cdot kg^{-1} \cdot km^{-1}$)	1.13 ± 0.07	1.16 ± 0.06	1.16 ± 0.07	1.17 ± 0.06	1.14 ± 0.07
$\dot{V}O_{2\,max}$ ($L \cdot min^{-1}$)	4.7 ± 0.4	4.8 ± 0.5	5.0* ± 0.4	5.0* ± 0.4	4.9 ± 0.5
$\dot{V}O_{2\,max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	69.8 ± 6.3	71.0 ± 6.7	74.0* ± 4.4	74.2* ± 5.5	73.5 ± 6.2
v-$\dot{V}O_{2\,max}$ ($km \cdot h^{-1}$)	19.1 ± 1.7	19.2 ± 1.6	20.0 ± 1.4	19.7 ± 1.3	20.1 ± 1.4

Data are presented as mean ±SD ; ***** Significantly higher than April baseline test, $P \leq 0.01$; RE = Running economy

Relationships between laboratory and field-test variables: The relationships between the pooled laboratory and field-test variables throughout the study were assessed. The strongest relationship was between CS and speed at LT (r=0.89, P<0.01). This relationship was slightly stronger in the long-distance runners compared with the middle-distance runners (r=0.90 and r=0.77, P<0.01 respectively). Relationships were also seen between CS and $\dot{V}O_{2\ max}$ and CS and v-$\dot{V}O_{2\ max}$ (r=0.40, P<0.01 and r=0.48, P<0.01 respectively). There was no significant relationship between CS and running economy throughout the study (r=-0.06, P=0.62).

Changes in training patterns during the season: The total distance run changed across the study periods (P=0.01). Between January-February (Figure 6.3) total distance run by the overall group was significantly further than between May-July (P=0.01) and July-August (P=0.02).

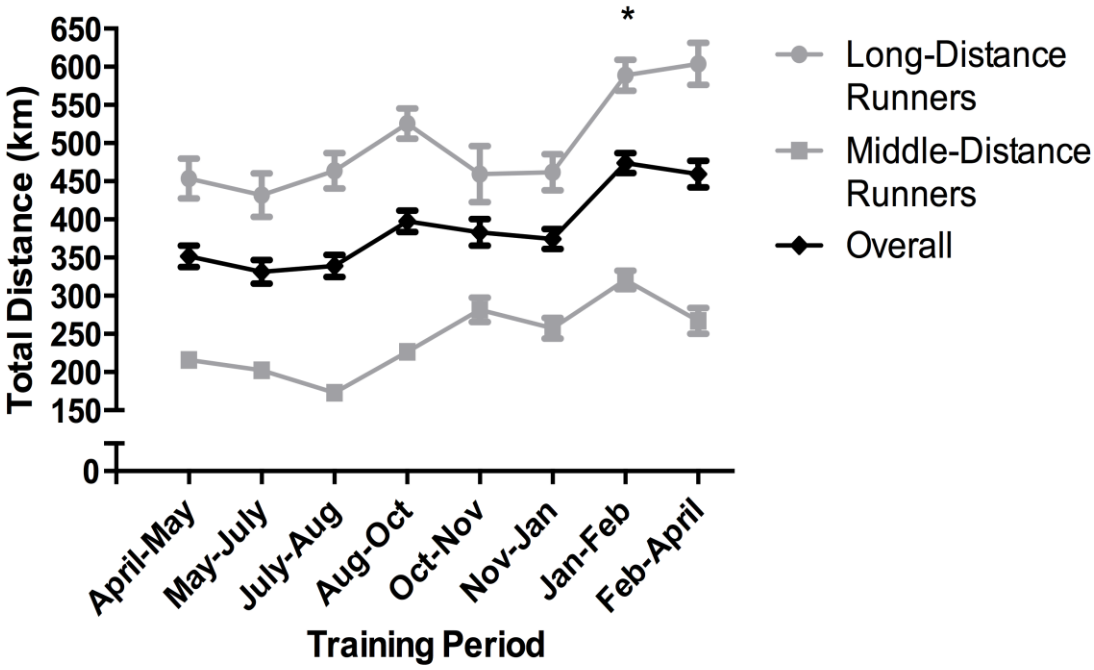

Figure 6.3: Distance run in different periods across the training year.

Data are presented as mean ± SEM. The x-axis markers are representative of the 42-day training periods shown in Figure 6.1. ***** Significantly higher than May-July and July-August, P < 0.05

The total time athletes trained also changed during the season (P=0.01). Total training time during January-February (2183 min) was greater than during May-July and July-August (1559 and 1548 min) (P=0.01). The percentage of total time athletes spent above threshold velocity did not change during the study (P=0.11). Participants spent 31 ± 19% of their total training time above threshold velocity (Figure 6.4). The long-distance runners trained for a significantly longer time (P<0.01) than the middle-distance runners (~2200 vs. ~1200 min per period respectively), however the percentage of training time spent in the different intensity zones was not significantly different between the groups.

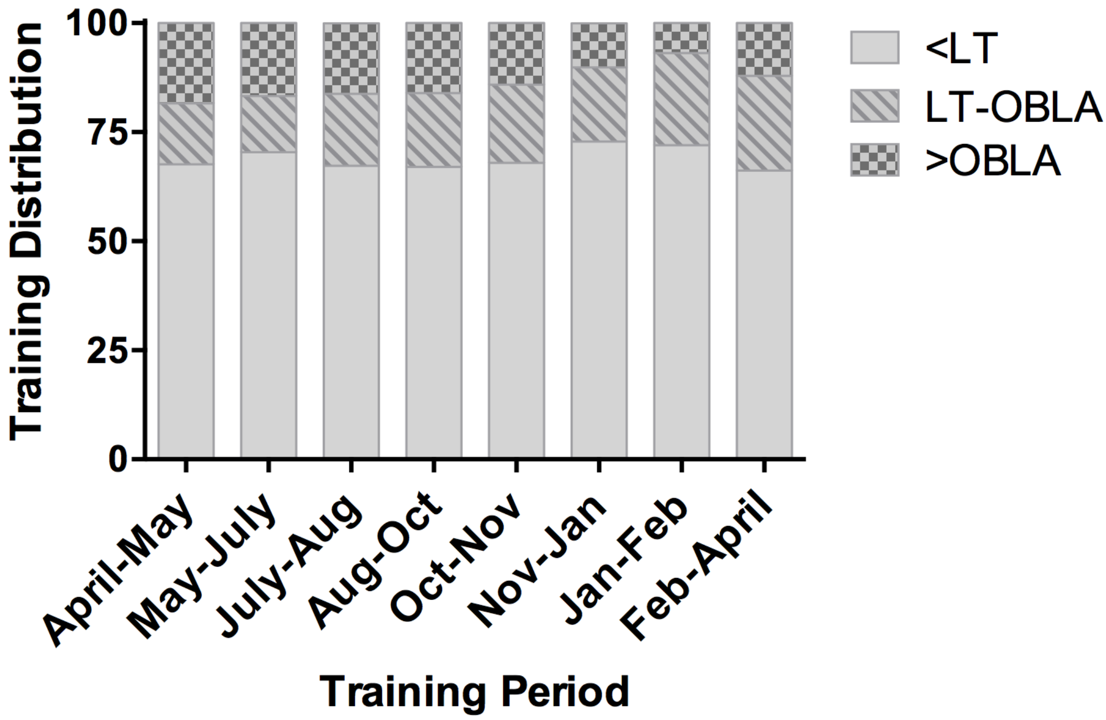

Figure 6.4: Training intensity distribution as a percentage of total training time.
Data are presented as mean values. The x-axis markers are representative of the 42-day training periods shown in Figure 6.1. OBLA = 4 mmol·L blood lactate point

Relationship between training and field-test variables: Multiple linear regression was used to model the relationship between training and CS. Total distance covered in training was the strongest single predictor and was entered into the model first. Examination of the variance inflation factor (VIF) and the tolerance statistic lead to the predictor 'total training time' being excluded from the model, due to multicollinearity with total training distance. A similar rationale prevented time above threshold velocity and time below threshold velocity being entered into the model together. In the final model; distance covered (km) in the 42-day period prior to the field test for CS and time spent above threshold velocity during the same period were found to determine changes in CS (explaining 33% of the variation in CS). Total distance was the strongest single predictor ($R^2=0.282$, $P<0.01$) of CS, although by including the time spent above threshold velocity the strength of the regression was increased ($R^2_{Change}=0.043$, $P=0.01$), with beta coefficients of 0.532, $P<0.01$ and 0.206, $P=0.01$ respectively. The final model was:

CS = 4.52 + (0.001*TD) + (0.004*V)

Where CS=critical speed ($m \cdot s^{-1}$); TD=total distance (km) and V=percentage time above threshold velocity.

Relationship between training and laboratory-test variables: The total distance and total time athletes completed in a training period correlated with the subsequent LT, running economy and v-$\dot{V}O_{2\,max}$ ($r=0.55$, $r=-0.33$, $r=0.37$; $P\leq0.01$ respectively for total distance and $r=0.46$, $r=-0.32$, $r=0.27$; $P<0.05$ respectively for total time). Training volume and $\dot{V}O_{2\,max}$ were not correlated ($r=0.02$). The percentage of total time that athletes spent training above threshold velocity in a training period was significantly correlated with the subsequent relative $\dot{V}O_{2\,max}$ ($r=0.31$, $P=0.02$).

6.4 Discussion

The main findings of this longitudinal study of endurance runners training demonstrate that CS changes during the course of a season. Changes in CS were related to the total training distance and the time spent training above LT.

A link between CS, training volume and intensity has not previously been reported in the literature. In the current study, participants' CS was lowest during August (4.90 $m \cdot s^{-1}$), and peaked in February (4.99 $m \cdot s^{-1}$), equating to a 1.9% improvement in CS. This change in CS was greater than the coefficient of variation previously reported for repeat testing with this protocol (chapter 4). The increase in critical speed was related to an increase in training volume. Training time and distance were both significantly higher in January-February than in July-August. In July-August participants trained on average for 1549 (±803) minutes and covered a total distance of 339 (±206) km, where as in January-February this increased on average to 2184 (±883) minutes and 474 (±188) km. It might be expected that CS would be higher in August when training and race distances are typically shorter, and completed at a high average velocity. However, the results of the current study demonstrate the opposite. This seems counterintuitive, although the training and CS data provide some explanations as to why this might occur. The current study did not find a significant change in training intensity across the season. Additionally, total training distance was significantly lower in July-August. Therefore, it seems that a decrease in training volume with no corresponding increase in training intensity results in a drop in CS.

The 1.9% increase in CS from the lowest to highest values of the season appears to be a small change given the volume of training the athletes were completing. Although, it is important to remember that the athletes involved in this study were already highly trained endurance athletes (mean $\dot{V}O_{2\,max}$ of ~70 $mL \cdot kg^{-1} \cdot min^{-1}$) who had been training for an average of 5 days per week in the 8 years prior to the study. Nevertheless it seems apparent that the CS of well-trained runners shows only a small change during the course of a training year. In contrast untrained subjects have achieved far larger increases in critical power (10-31%) following a 6-8 week period of continuous and/or interval cycle training (Gaesser and Wilson, 1988; Poole et al., 1990; Jenkins and Quigley, 1992).

Although relatively small, the 1.9% (0.09 m·s) change in CS found during the season still implies a meaningful change in performance for a well-trained distance runner. Using the distance-time relationship, the shortest time an athlete could complete a race distance can be predicted (Jones et al., 2010). Thus, an increase in CS from 4.90 m·s to 4.99 m·s corresponds to a 36 second improvement in 10’000 m race time (based on a stable D′ of 130 m). Using the methods of Hopkins (2000a) the likelihood of this being a true change in CS is 73%.

Unlike CS, D′ did not change during the season. Research examining longitudinal changes in D′ in highly trained distance runners is lacking. In untrained cyclists a 49% increase in W′ (the power-time equivalent of D′) following 8 weeks of high-intensity all-out cycling interval training has been shown (Jenkins and Quigley, 1993). The use of untrained participants and their focus on very short-term high-intensity all-out training might explain their different findings. Specifically, the trained participants in the present study predominantly performed continuous training or longer interval type training (interval duration >1min) which has previously been shown to produce no significant changes in W′ (Gaesser and Wilson, 1988; Poole et al., 1990; Jenkins and Quigley, 1992). The reliability of D′ has been shown to be lower than that of CS (chapters 4 and 5), which may have reduced the ability to measure changes in D′ in the present study.

During the study $\dot{V}O_{2\,max}$ was ~6% higher in October and January compared with the April baseline test. This is in contrast to Svedenhag and Sjodin (1985) who found a significantly higher $\dot{V}O_{2\,max}$ in trained runners during July-September compared with January. The magnitude of the increase in $\dot{V}O_{2\,max}$ in the current study is similar to that reported by Tanaka et al., (1984) who found a 5.8% increase following 9 months of training. Significant correlations between total training volume (miles per week) and $\dot{V}O_{2\,max}$ have previously been shown in a study of 78 well-trained runners (r=0.55 for 1-mile specialists to r=0.76 for marathon runners) (Foster, 1983), however a similar relationship was not apparent in the present study. This may be due to differences in group homogeneity (47-81 $mL \cdot kg^{-1} \cdot min^{-1}$ in the study by Foster, vs. 61-82 $mL \cdot kg^{-1} \cdot min^{-1}$ for the present study).

No changes in running economy, LT running speed or the velocity at $\dot{V}O_{2\,max}$ were found during the study. These results contrast with Svedenhag and Sjodin (1985) who report a 3.4% improvement in running economy in a group of highly trained runners following one year's training. Short-term training studies have reported improvements in running economy of ~6% in trained runners after 4 weeks of training at or around the v-$\dot{V}O_{2\,max}$ (Billat et al., 1999; Denadai et al., 2006). The reason for these divergent findings may relate to the intensity of the participants training. Compared to an intensity set at v-$\dot{V}O_{2\,max}$ (Billat et al., 1999; Denadai et al., 2006) the training intensity in the current study was lower. Only ~14% of the training time was spent at intensities exceeding OBLA (Figure 6.4). This may also explain why no change in LT was observed. The lower training intensities seen in the present study are supported by the values reported in a group of highly trained endurance runners by Robinson et al., (1991), where only 4% of the recorded heart rates during their 6-week training study equalled or exceeded the anaerobic threshold heart rate. Londeree (1997) suggests that athletes need to train at intensities above OBLA to bring about changes in lactate metabolism. Notably, the time athletes spent above and below LT velocity did not change during the course of the season and was not different between the middle and long-distance runners. Previous studies have also suggested that the intensity distribution of endurance athletes' training remains similar throughout the course of a year (Kohrt et al., 1989; Seiler, 2010). These observations may indicate that higher intensity training is important to gain improvements in LT and running economy.

The conclusions of the present study may be limited by the absence of a control group. This was a deliberate decision because the purpose was not to test the efficacy of the training, but rather to use the training to stimulate physiological change, which could then be tracked by the laboratory and field tests across the course of the season.

It is interesting to consider whether CS and D′ are correlated with any more 'traditional' laboratory measures of physiological fitness. CS and the speed at LT were significantly correlated (r=0.89, P<0.01). Similarly strong correlations between track-based CS and the speed at ventilatory threshold (r=0.96, P<0.01) have previously been reported (Kranenburg and Smith, 1996). Weak relationships were seen in the current study between CS and $\dot{V}O_{2\,max}$ and CS and v-$\dot{V}O_{2\,max}$ (r=0.40, P<0.01 and r=0.48, P<0.01 respectively). These correlations are weaker than previously reported correlations between field-tests of CS with $\dot{V}O_{2\,max}$ and v-$\dot{V}O_{2\,max}$ (r=0.88 and r=0.89 respectively, Kranenburg and Smith, 1996; r = 0.73 and r = 0.80 respectively, Clarke et al., 2014). In contrast to the current study, Kranenburg and Smith and Clarke et al., only compared CS at one particular point in the training year.

The results of the current study may question how indicative laboratory tests are of performance in the field.

Comparisons of highly trained endurance athletes from different running disciplines across a training year are sparse in the literature. Although only a small sample this data suggests that middle-distance runners have a higher $\dot{V}O_{2\,max}$ and D′, whilst long-distance runners have a higher CS and LT. In terms of training differences between these groups, the long-distance runners typically trained for longer durations and covered greater distance in training than the middle-distance runners, although no differences were observed in the percentage of time spent above threshold velocity.

Vandewalle et al., (1997) report the D′ of the distance-time relationship calculated from the 1500 m and 5000 m events progressively decreased from 219 to 188 m at the different Olympic games from 1972-1988, whilst the CS improved from 5.93-6.08 $m.s^{-1}$ during the same period. This suggests an interrelationship between the two parameters over a prolonged period. The present findings, demonstrating an inverse relationship between CS and D′ across the study (r = -0.71, P<0.01), support this suggestion.

6.5 Conclusion

The conclusion from this study is that $\dot{V}O_{2\,max}$ and CS change over the course of a training year in a group of highly trained runners. The improvements in CS were related to an increase in training distance and the percentage of total training time at a velocity above threshold-velocity. Results demonstrate the single-visit field test is sensitive to the relatively small training induced changes in fitness that occur in highly trained distance-runners over the course of a year. The single-visit test could provide a useful tool for athletes, coaches and sports scientists looking to monitor the effects of endurance training and performance on the distance-time relationship in the field.

Chapter 7 – Using the distance-time relationship to model intermittent running performance

Aspects of the following chapter have been accepted for publication and are currently in press in the following manuscript: Galbraith A., Hopker J., Passfield L. (2015) Modeling intermittent running from a single-visit field test. *International Journal of Sports Medicine*.

7.1 Introduction

In addition to monitoring changes in endurance performance (chapter 6), the single visit field test could also be used to provide training prescription. An interesting consideration is the potential to model intermittent exercise using the distance-time relationship data from the single visit field test. Such modelling techniques could be applied in training to prescribe intermittent interval-style work and recovery periods.

Interval training is a popular mode of conditioning in many sports and involves intermittent periods of work and relative recovery (Morton and Billat, 2004). Interval training has the advantage of enabling a greater amount of high intensity work to be conducted in a single session than would be possible with continuous training (Margaria et al., 1969*)*. High intensity running training, in terms of time spent above lactate threshold velocity, has previously been shown to be a contributing factor to longitudinal increases in performance (Galbraith et al., 2014 [Chapter 6]). Therefore designing interval-training sessions that are individualized to athletes' specific needs is important. For aerobic training, parameters such as $\dot{V}O_{2\,max}$, velocity at $\dot{V}O_{2\,max}$, lactate/ventilatory thresholds and maximal heart rate have all been used to prescribe individualised training intensities (Berthoin et al., 2006).

The distance-time relationship can be used to calculate a two parameter model of critical speed (CS) and D′. A runner's CS has been suggested to reflect the highest sustainable running speed that can be maintained without a continual rise in $\dot{V}O_2$ to $\dot{V}O_{2\,max}$, whilst D′ is notionally the maximum amount of work (recorded as distance) that can be performed above CS (Jones et al., 2010). Ferguson et al., (2013) explain that an additional consideration when defining exercise intensity is that CS does not occur at a fixed percentage of maximal heart rate or $\dot{V}O_{2\,max}$ (Rossiter, 2010). Furthermore between-subject differences in anaerobic capacity (Clark et al., 2013) result in the D′ not representing the same volume of supra-CS exercise in all individuals (Murgatroyd et al., 2011). The consequence of this is that the exercise intensity experienced during an interval training session will be variable between participants unless the distance-time relationship is accounted for (Ferguson et al., 2013). The distance-time relationship is of considerable importance to sports performance because complete depletion of the D′ prevents an athlete performing at an intensity above CS (Skiba et al., 2012). Chapters 4 and 5 present a running-based single-visit field test of the distance-time relationship which can be completed in ~90 minutes. This raises the possibility that the single-visit field test could be used to design interval training; setting interval intensity at a percentage of CS and the number of interval repetitions in accordance with the depletion of D′. Thereby inducing the desired training load through the interplay between CS, D′ and time to exhaustion (TTE).

Morton and Billat (2004) applied the distance-time relationship to intermittent exercise, studying the speed and duration during the work and recovery phases (S_w, t_w, S_r, t_r). Morton and Billat suggest that the time to exhaustion (TTE) of an athlete during an interval session can be calculated from the following equation, where n is equal to the number of complete work-recovery cycles:

$$TTE = n(t_w+t_r) + \frac{D' - n[(S_w - CS)t_w - (CS - S_r)t_r]}{S_w - CS} \qquad (2)$$

Chidnok et al., (2012) utilised this linear model to investigate the effect of different recovery intensities during cycling exercise, whilst Skiba et al., (2012) suggest a non-linear recovery model may be more appropriate. The application of these models to intermittent running exercise warrants further investigation. A model that can account for the depletion and restoration of D′ during intermittent exercise, by accurately predicting the end point of exercise, could aid the design of interval training sessions. Furthermore such modelling may have a performance application, allowing real-time monitoring of D′ during competitions, thereby informing race tactics.

The aim of this chapter was to assess whether the distance-time relationship data from a single-visit field test could be accurately applied to linear and non-linear models to predict TTE during intermittent running exercise. This in turn would provide an insight into the ability of the single visit field-test to prescribe interval style training sessions.

7.2 Method

Participants: Thirteen male middle/long-distance runners (mean (±SD) age: 33 ± 14 yrs; 5000 m time: 1090 ± 86 s) were recruited for the study. All participants were competitive club standard runners who had been competing for a minimum of 3 years. All participants provided written informed consent for this study that had been approved by the University of Kent School of Sport and Exercise Sciences Research Ethics Committee.

Experimental design: The study involved two types of test; a single visit field test of the distance-time relationship, and an interval test, both completed on a standard outdoor 400 m athletics track. A familiarisation session for each type of test was undertaken prior to commencing data collection.

Participants completed the same warm up and cool down routine, consisting of 5-10 minutes jogging at a self-selected pace, followed by the athlete's normal stretching routine (Smith and Jones, 2001). Tests for each participant were completed at the same time of day (± 2 hrs), with at least 48 hours recovery between test sessions. Participants were asked to arrive for testing in a well-hydrated and rested state, having avoided strenuous exercise in the preceding 24 hours.

Field-test protocol: The field test protocol is outlined in the general methods (Chapter 3). Mean (±SD) environmental conditions during the field tests were: temperature 5.7 °C (2.4 °C), humidity 74% (11%), barometric pressure 761 mmHg (2 mmHg) and wind speed 1.3 $m \cdot s^{-1}$ (0.3 $m \cdot s^{-1}$).

Interval test protocol: Three typical interval sessions were conducted, modelled using the CS from the field test. The interval sessions consisted of:

a) 1000 m 'work intervals' at 107% of CS with 200 m 'recovery intervals' at 95% CS.
b) 600 m 'work intervals' at 110% of CS with 200 m 'recovery intervals' at 90% CS.
c) 200 m 'work intervals' at 150% of CS with 200 m 'recovery intervals' at 80% CS.

Participants ran on the inside line of lane 1 of the running track and were provided with split times every 100 m to ensure they maintained the required speed during the work and recovery intervals. A whistle was used to signal to participants if an increase or decrease of pace was required. Similar pace control methods have recently been used by La Torre et al., (2012) and Penteado et al., (2014). Participants were instructed to continue the alternate work/recovery periods for as long as possible. The interval session was terminated if the participant was unable to continue, or if the participant was 0.5 s slower than the designated split time for 3 consecutive 100 m splits. Runs were hand timed with TTE recorded to the nearest second.

The three interval sessions were conducted on separate days with a minimum of 24 hours recovery between tests. Tests were only conducted if the wind speed was lower than 2.0 $m \cdot s^{-1}$. Mean (±SD) environmental conditions during the interval tests were: temperature 7.3 °C (4.2 ˚C), humidity 78% (12%), barometric pressure 760 mmHg (3 mmHg) and wind speed 1.2 $m \cdot s^{-1}$ (0.6 $m \cdot s^{-1}$).

Data analysis: To calculate CS and D′ a linear distance-time model was applied to the three runs from the single visit field test. The linear distance-time model is represented by equation 1.

For the linear recovery model the depletion of D′ during the work (w) intervals and the restoration of D′ during the recovery (r) intervals was estimated as follows: where S = speed and t = time in seconds (Morton and Billat, 2004).

$$\text{Depletion of D}' \text{ during work interval} = (S_w - CS)t_w \qquad (11)$$

$$\text{Restoration of D}' \text{ during recovery interval} = (CS - S_r)t_r \qquad (11)$$

Actual TTE (total running time of combined work and rest intervals) and predicted TTE (total estimated running time calculated from equation 2 using CS and D′ from the field test protocol and S_w, S_r, t_w and t_r from the interval session) were calculated.

To assess the effect of non-linear recovery of D′, equation 13 (Skiba et al., 2012) was re-written for D’ (equation 14) and then used to estimate the balance of D′ (D'_{bal}) remaining at the point the interval session was terminated. The time constant of D′ repletion ($\tau_{D'}$) was set at 578 s. This was based on the mean $\tau_{W'}$ reported by Skiba et al., (2012) for recovery in the heavy exercise intensity domain (the same intensity domain used for recovery in the current study)

$$D'_{bal} = D' - \int_{0}^{t} (D'_{exp}) \left(e^{-(t-u)/\tau_{D'}}\right) \tag{14}$$

To investigate $\tau_{D'}$, the time constant for each participant for each trial was varied iteratively until modelled D'_{bal} equalled zero at the point of interval session termination (Skiba et al., 2012). The intensity of the recovery interval for each participant across each trial was also recorded by calculating the difference between recovery speed and critical speed (D_{CS}).

Data were checked for normality of distribution using the Shapiro-Wilk statistic. Paired samples t-tests were used to identify differences in actual and predicted TTE. Pearson correlation coefficients were used to assess the relationship between these parameters. The 95% limits of agreement and Bland Altman plots (Bland and Altman, 1986) along with the typical error were calculated to assess agreement between methods. A Repeated measures ANVOA was used to identify differences between linear and non-linear models across the interval sessions. Analysis was conducted using the SPSS statistical software package (IBM SPSS statistics, Rel. 20.0, 2011. SPSS Inc. Chicago, USA). Statistical significance was accepted at $P < 0.05$ for all tests.

7.3 Results

Participants' mean (±SD) CS and D′ calculated from the field-test protocol were 4.41 ± 0.48 $m.s^{-1}$ and 121 ± 52 m respectively. The R^2 for the linear regression of distance and time ranged from 0.997-1.000. The mean (±SD) SEE for CS ($m.s^{-1}$) and D′ (m) from the field test was 0.03 ± 0.02 $m.s^{-1}$ and 18 ± 11 m.

Linear model:

Table 7.1: Comparison of actual and predicted TTE

	Actual TTE (s)	**Predicted TTE (s)**
1000m trial	806 ± 246	734 ± 355
600m trial	745 ± 242	1003 ± 422
200m trial	310 ± 191 *****	2364 ± 2399

TTE = time to exhaustion. Data are presented as mean ±SD. Predicted TTE is estimated from the linear model. ***** Significantly lower than predicted TTE (P = 0.01)

Table 7.1 shows the actual and predicted TTE, which were not significantly different in the 1000 m (P = 0.59) and 600 m (P = 0.09) trials. The actual TTE was significantly lower (P = 0.01) than predicted TTE in the 200 m trial.

There were no significant relationships between actual and predicted TTE across the different interval trials (Figure 7.1). The typical error between actual and predicted TTE was 334 s, 350 s and 1709 s for the 1000, 600 and 200 m trials, respectively.

Figure 7.2 shows the closest agreement between actual and predicted TTE was in the 1000 m and 600 m trials (95% limits of agreement = 926 and 969 s respectively). Agreement between actual and predicted TTE became considerably worse in the 200 m trial (95% limits of agreement = 4734 s). The plots in Figure 7.2 showed evidence of heteroscedastic errors, this was most evident in the 200 m trial (c), therefore ratio limits of agreement were calculated (Nevill and Atkinson, 1997). The ratio limits of agreement were 0.17 and 115.51. Therefore, if a subject's actual TTE in the 200 m trial was 310 s, it is possible the predicted TTE (worst case scenario) could be as low as 54 s (310 x 0.17) or as high as 35808 s (310 x 115.51).

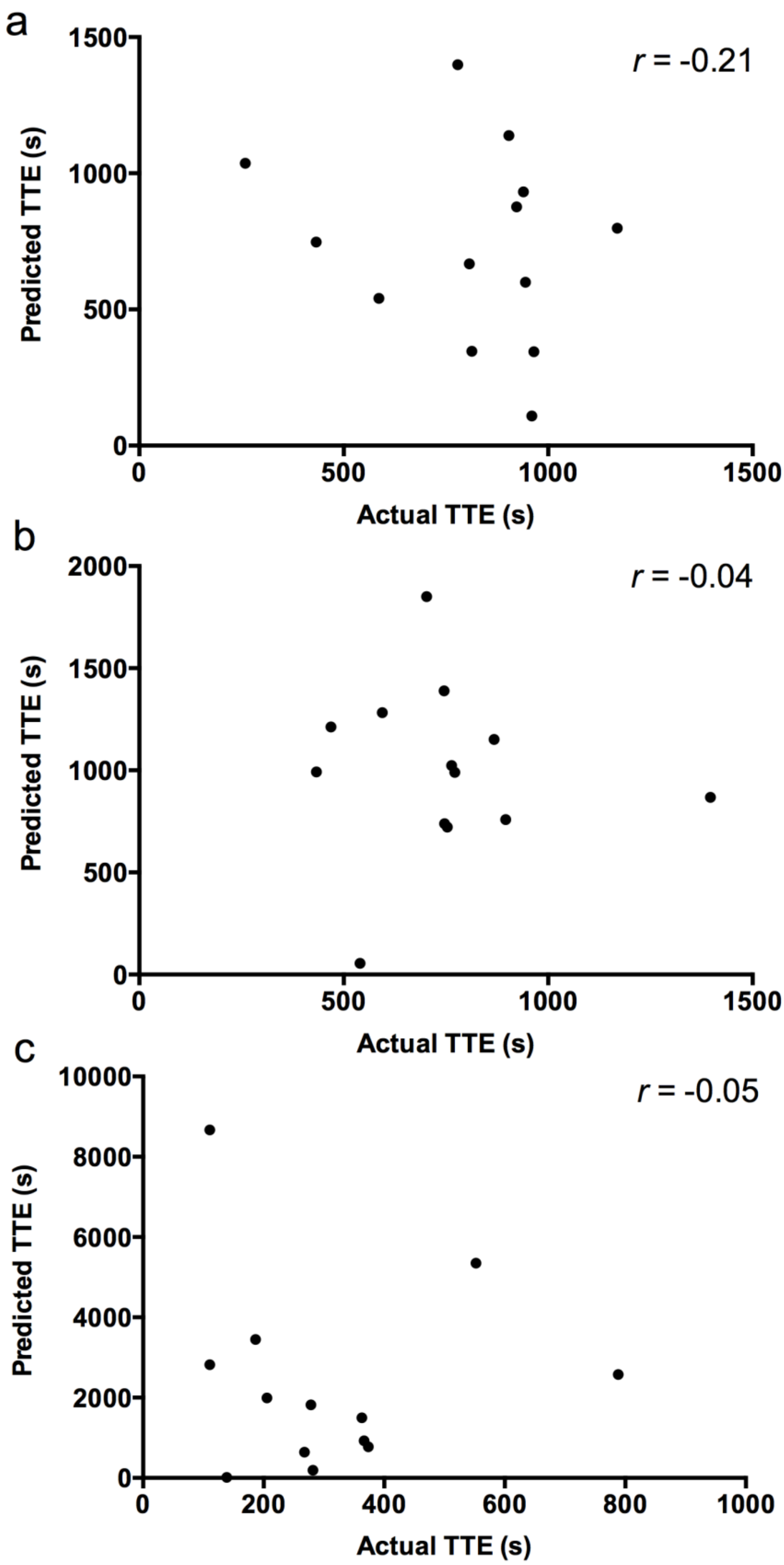

Figure 7.1: Relationship between the actual and predicted time to exhaustion (TTE) for the 1000 m trial (a), the 600 m trial (b) and the 200 m trial (c). Predicted TTE is estimated from the linear model.

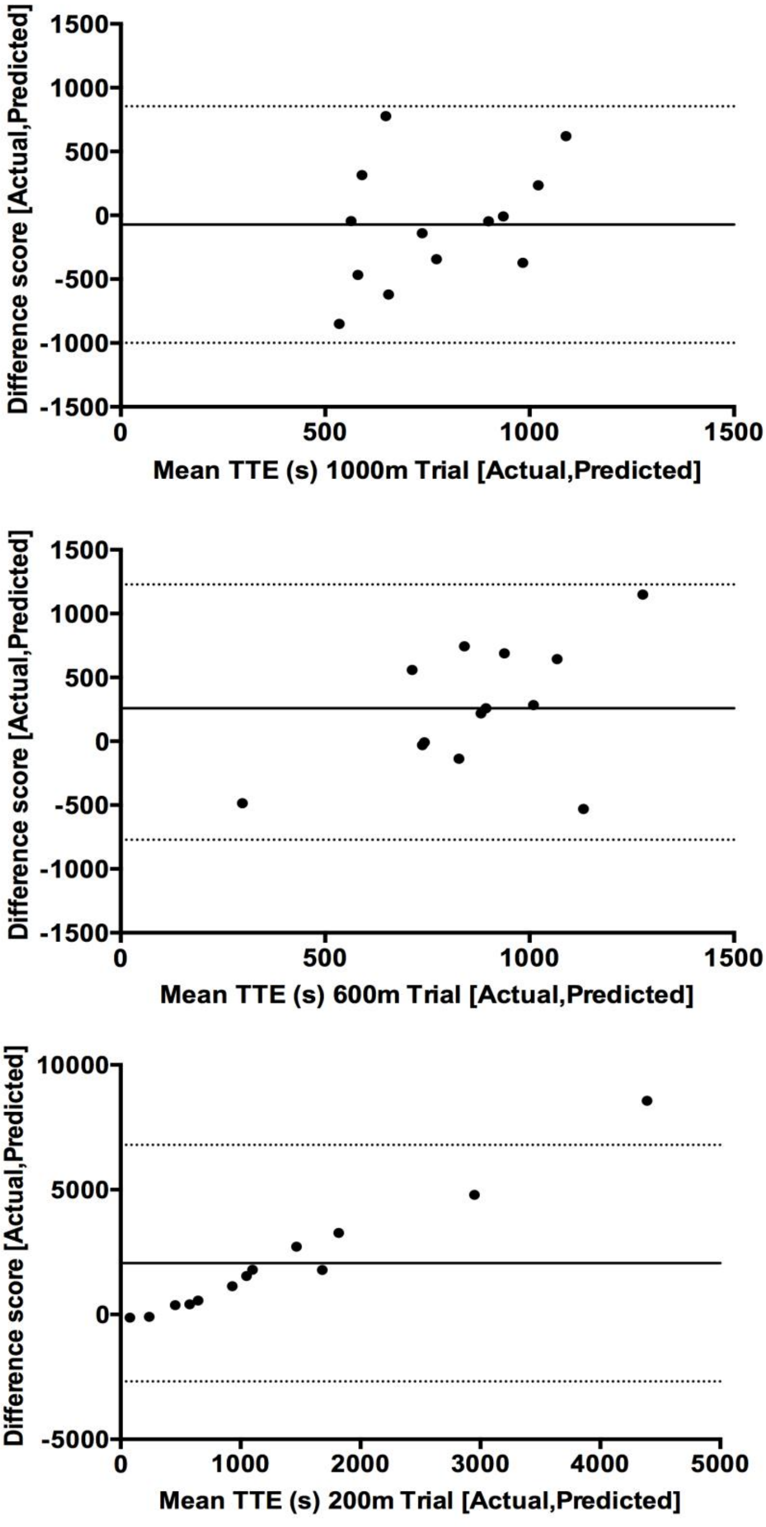

Figure 7.2: Bland-Altman plots of differences in time to exhaustion (TTE) between the actual and predicted methods for the 1000 m trial (top), the 600 m trial (middle) and the 200 m trial (bottom). The solid horizontal lines show the mean bias, whilst the dashed lines represent the 95% limits of agreement. Predicted TTE is estimated from the linear model.

Linear vs. non-linear model:

Table 7.2: D'_{bal} (m) at interval session termination estimated from linear and non-linear models

1000m Trial		**600 m Trial**		**200 m Trial ***	
Linear	**Non-linear**	**Linear**	**Non-linear**	**Linear**	**Non-linear ****
-16.9 ± 46.7	-19.8 ± 34.4	10.2 ± 37.4	-19.5 ± 26.3	47.0 ± 39.2	-24.4 ±33.3

D'_{bal} = balance of D′ remaining. Values are displayed as mean ± SD. Non-linear model $\tau_{D'}$ = 578 s. ***** 200 m trial D'_{bal} significantly higher than 1000 m trial (*P*=0.03). ****** Non-linear 200 m trial D'_{bal} significantly lower than linear 200 m trial D'_{bal} (*P*<0.01).

Table 7.2 shows the D'_{bal} at interval session termination estimated from the linear model of Morton and Billat (2004) and the non-linear model of Skiba et al., (2012). A 3x2 (trial x model) repeated measures ANOVA showed a significant effect for 'model' (P<0.01). The mean D'_{bal} at interval session termination was significantly lower when estimated from the non-linear model (-21.2 and 13.4 m, respectively). There was a significant effect of 'trial' on D'_{bal} at interval session termination, with differences observed between the 1000 and 200 m trials (P=0.03). There was a significant interaction effect (trial x model) for D'_{bal} at interval session termination (P<0.01). This effect was seen between the linear and non-linear models in the 200 m trial. The non-linear modelled D'_{bal} at interval session termination was significantly lower than that of the linear model (-24.4 and 47.0 m, respectively) in the 200 m trial.

Non-linear model $\tau_{D'}$:

Table 7.3: Calculated $\tau_{D'}$ (s) and D_{CS} (m.s^{-1}) for each trial

1000 m Trial		**600 m Trial**		**200 m Trial**	
$\boldsymbol{\tau_{D'}}$	$\mathbf{D_{CS}}$ *****	$\boldsymbol{\tau_{D'}}$	$\mathbf{D_{CS}}$	$\boldsymbol{\tau_{D'}}$	$\mathbf{D_{CS}}$ ◆
353 ± 118	0.35 ± 0.09	378 ± 100	0.51 ± 0.08	397 ± 167	0.82 ± 0.16

$\tau_{D'}$ = time constant of D′ repletion; D_{CS} = difference between recovery speed and critical speed. Values are displayed as mean ± SD. ***** Significantly lower than 600 m and 200 m trial D_{CS} (P<0.01). ◆ Significantly higher than 1000 m and 600 m trial D_{CS} (P<0.01).

Table 7.3 shows the Mean $\tau_{D'}$ and D_{CS} for each trial using the non-linear model. There was no significant difference in $\tau_{D'}$ across trials (P>0.05). D_{CS} was significantly different across trials (P<0.01), with all trials being significantly different from each other.

7.4 Discussion

The main finding of this study is that the Morton and Billat (2004) model of intermittent running based upon CS and D′ does not closely predict TTE. No significant differences in actual and predicted TTE were seen in the 1000 m and 600 m trials. However, there was a trend (P = 0.09) for actual TTE to be lower than predicted TTE in the 600 m trial. A progressive statistics approach (Hopkins et al., 2009) was used to provide inferences about the magnitude of this trend. Using this method the standardised mean difference between actual TTE and predicted TTE for the 600 m trial produced a small effect. This supports the reported finding of no significant difference in actual and predicted TTE in the 600 m trial. Actual TTE was significantly lower (P = 0.01) than predicted TTE in the 200 m trial. Furthermore, the lack of correlation (range r = -0.21 to -0.04, P>0.05) and the relatively high typical error (range 334-1709 s) across the trials, support the conclusion that the intermittent critical speed model cannot be used to accurately predict TTE in intermittent running exercise. When modelled in this way, the CS and D′ from the field test tend to predict a greater TTE than could be achieved. This could result in an interval session with an unrealistic number of work and recovery intervals. The findings of the current study support the earlier work of Kachouri et al., (1996), who report that it is not possible to predict the maximum number of repetitions of an intermittent exercise session from the continuous distance-time relationship.

The agreement between actual and predicted TTE in the 200 m interval trial was considerably worse than in the other two trials. Vandewalle at al (1997) suggest that the distance-time relationship should not be extrapolated for time durations that are very short or very long. The 200 m trial was the shortest bout with a mean work interval ~27-40 s. Therefore, this trial may have fallen outside of the *'window'* for which predictions from the distance-time relationship are valid (Vandewalle at al., 1997). This is further supported by Chidnok et al., (2013a), who report that the ability to predict TTE may be less accurate at higher, compared to lower, severe-intensity work-rates. This suggests that the ability to model intermittent exercise may be specific to the percentages of CS used during the work and recovery intervals, with percentages set closer to CS allowing a more accurate prediction.

The variability in D′ has been reported to be high (Hinckson and Hopkins, 2005; Galbraith et al., 2011 [Chapter 4]; Galbraith et al., 2014a [Chapter 5]). This variability may explain the inability of the model to predict TTE. Consequently, the actual and predicted D′ were considered in the current study. The predicted D′ was calculated from the linear distance-time relationship of three runs in the field test. The actual D′ was calculated post-hoc as the starting D′ that would allow full depletion at interval session termination. Although actual and predicted TTE from the combined trials were significantly different (P = 0.01), there were no significant mean group differences between actual (111 ± 67 m) and predicted (120 ± 52 m) D′ (P = 0.23; typical error = 33 m). Therefore, it seems plausible to attribute some of the differences seen in actual and predicted TTE to relatively small errors in the estimation of D′ for each participant. These errors could be due to the relatively high variability in D′ between repeat trials.

CS and D′ are assumed to be synonymous with their cycling equivalents (CP and W′), therefore, for clarity, during the next section CS and D′ alone will be used. It has been suggested that D′ is depleted in a linear fashion during exercise above CS, resulting in a predictable TTE (Chidnok et al., 2012; Chidnok et al., 2013; Ferguson et al., 2010). What is less clear is whether the reconstitution of D′ (once exercise drops below CS) also occurs in a linear fashion, or if recovery kinetics are different. Morton and Billat (2004) and Chidnok et al., (2012) assumed a linear reconstitution of D′ during the recovery intervals. Ferguson et al., (2010) cast doubt on this theory and suggest that the recovery kinetics of D′ may in fact be curvilinear. Skiba et al., (2012) more recently modelled recovery of D′ using an exponential model. Results of their work demonstrated the model provided a better 'fit' than the traditional linear approach in describing the dynamic state of D′ during intermittent cycling exercise. If the recovery of D′ is curvilinear, athletes in the current study may be expected to replenish less of their D′ during the recovery intervals than a linear model would predict. Therefore, with a slower replenishment of D′ during the recovery intervals, athletes would be predicted to fatigue quicker and have a shorter TTE in the overall interval session. Consequently, TTE predicted from a curvilinear model may be brought closer to the actual TTE.

To assess the effect of the recovery model, the linear model of Morton and Billat (2004) and the non-linear model of Skiba et al., (2012) were compared (Table 7.2). Although there was a significant effect for model on the D'_{bal} at interval session termination, the non-linear model only resulted in a D'_{bal} closer to zero at interval session termination in the 200 m trial. Overall (regardless of trial), the non-linear model did not produce a D'_{bal} at interval session termination that was closer to zero than the linear model (-21.2 and 13.4 m, respectively).

The results of the present investigation suggest that the linear model of Morton and Billat (2004) and the model developed for cycling by Skiba et al., (2012) cannot accurately model intermittent running exercise. These models, therefore, appear to have limited application in the design of interval training sessions, where the number of work:recovery periods an athlete can perform at given intensity cannot be accurately predicted. It could be argued, however, that predicting the exact number of repetitions is not important; as long as the athlete performs enough repetitions to cause fatigue (and therefore send a signal for adaptation), the purpose of the workout has been met. However the inability to accurately model intermittent exercise within a controlled interval session reduces the likelihood that the models, in their present form, have any further real-time performance monitoring application during competition.

When comparing the linear model of Morton and Billat (2004) and the non-linear model of Skiba et al., (2012), it should be noted that the model of Skiba et al. (equation 13) was derived for cycling exercise and suggests a time constant of W′ repletion ($\tau_{W'}$) of 578 s. It is possible that recovery of W′ and D′ may differ and therefore a specific time constant of D′ repletion ($\tau_{D'}$) may be required for running research. To further investigate $\tau_{D'}$, the time constant for each participant for each trial was varied by an iterative process until modelled D'_{bal} equalled zero at the point of interval session termination (Skiba et al., 2012). The intensity of the recovery interval for each participant across each trial was also recorded by calculating the difference between recovery speed and critical speed (D_{CS}). Mean $\tau_{D'}$ and D_{CS} for each trial are shown in table 7.3.

D_{CS} was significantly different across trials ($P<0.01$), with all trials being significantly different from each other. However, it can be estimated that the recovery speed during all trials fell within the heavy exercise domain (between gas exchange threshold and CS), as recovery speed during trials was 95, 90 and 80% of CS for the 1000 m, 600 m and 200 m trials, respectively. There was no significant difference in $\tau_{D'}$ across trials ($P>0.05$). Skiba et al., (2012) reported differences in $\tau_{W'}$ across all trials in their study, however trials in the Skiba et al. study spanned the exercise intensity domains, suggesting that $\tau_{W'}$ may vary depending on the intensity of the exercise. Recovery intensity in the present study fell in the heavy domain for all trials, therefore based on the findings of Skiba et al. differences in $\tau_{D'}$ within this domain were not expected. Furthermore, there was no significant correlation between $\tau_{D'}$ and CS across any of the trials (r = -0.20, P=0.23; combined trial data). Using the magnitude scale proposed by Hopkins et al., (2009) this level of correlation would be described as small. This is in contrast to the findings of Skiba et al., (2012), who report a trend (P=0.08) for an inverse relationship between $\tau_{D'}$ and CS within the heavy intensity domain. There was a small non-significant correlation between $\tau_{D'}$ and

D_{CS} across the trials (r = -0.04, P=0.81; combined trial data). This is also in contrast to the findings of Skiba et al., (2012) who report a large inverse relationship between $\tau_{D'}$ and D_{CS} (r = -0.67, P < 0.01). Mean $\tau_{D'}$ across the three trials was 377 ± 129 s. This is in contrast to the reported $\tau_{W'}$ of 578 ± 105 s during the heavy intensity recovery condition of Skiba et al., (2012). It would appear from the above results that there might be differences in the time constants between W′ in cycling and D′ in running. Further research to develop a running specific D'_{bal} model and $\tau_{D'}$ is needed before the true potential of the non-linear model during intermittent running exercise can be assessed.

Whilst the ability to perform continuous and intermittent exercise are somewhat different abilities, the underpinning rationale governing the distance-time relationship suggests it may be possible to predict intermittent exercise performance from the results of a continuous-running field test. The results of the present investigation suggest that CS and D′ estimated from a continuous-running field test cannot accurately quantify TTE during intermittent running. This may be due to the variability in the measurement of D′ (Galbraith et al., 2011 [Chapter 4]; Galbraith et al., 2014a [Chapter 5]) and differing recovery kinetics between running and cycling exercise.

7.5 Conclusion

The current study set out to model intermittent exercise using the single visit field test, thus providing an insight into the ability of the distance-time relationship to prescribe interval style training sessions. The results of this study demonstrate that neither the linear nor nonlinear recovery models accurately predict TTE in intermittent exercise. This suggests that models based upon CS and D′ do not presently appear applicable to intermittent running exercise. Coaches therefore need to be wary of prescribing intervals based on these methods. This has implications for the practical application of the distance-time relationship to prescribe intermittent exercise and monitor real-time performance. Future research should determine whether a distance-time model is appropriate for intermittent exercise and what recovery kinetics should be assumed.

Chapter 8 – General discussion

8.1 General discussion

The overall aim of this thesis was to develop a time efficient field test of the distance-time relationship that could be utilised to investigate the endurance training and performance of distance runners. The rationale for this new protocol was twofold; firstly, laboratory based tests of the distance-time relationship have traditionally used lengthy recovery periods between trials, resulting in multiple laboratory visits and limiting the practical application of such tests (Smith and Jones, 2001; Hill and Ferguson, 1999). Secondly the ecological validity of treadmill based constant-speed time to exhaustion protocols has been questioned, in that such protocols do not represent the methods used in training or competition by endurance runners. However more recent research disputes this view (Hanley, 2014). A field-based test using constant-distance trials, which can be completed in a single visit, presents a superior test on both levels. Such a test has the potential to improve the usability of the distance-time relationship by sports scientists and coaches, thereby allowing regular assessment of CS and D′ along with exercise prescription based on this data. The first two experimental chapters (chapters 4 and 5) assessed the reliability and validity of the new single-visit field test. The test was then applied at regular intervals to assess the distance-time relationship (chapter 6). Finally the ability to model exhaustion during an intermittent exercise session gave an insight into the utility of the test to design training (chapter 7).

Chapter 4 presents a novel single-visit field test comprising of 3 constant-distance trials separated by a 30-minute recovery period. The results of chapter 4 demonstrate that critical speed can be reliably tested using this single-visit protocol. The mean coefficient of variation of 1.7% between repeated trials is similar to the value of 1.8% reported during laboratory based testing of CS (Hinckson and Hopkins, 2005) and compares favourably with the value of 3% reported for single-visit all-out testing of CP (Burnley, Doust and Vanhatalo, 2006). Furthermore the intraclass correlation coefficient for CS (r=0.95, P<0.01) reported in chapter 4 compares with the data reported between two repeated 3-min all-out tests for CP (r=0.99, P<0.01) in the study by Burnley et al., (2006). Hopkins (2000a) suggests a 5% coefficient of variation as an acceptable upper limit in sports science reliability studies. Given that the CV values observed in chapter 4 were below this boundary, the estimation of CS from the single-visit field test could be considered as reliable. It could be argued, however, that accepting a test as reliable based purely on an arbitrary coefficient of variation value has little relevance to the competitive sporting environment. In such instances assessing the level of performance change a test can detect and considering the smallest worthwhile change may give a greater insight into the true value of the test. Based on a CS of 4.72 $m.s^{-1}$ and the coefficient of variation for CS of 1.7%, an athlete would have to improve their CS by 0.08 $m.s^{-1}$ (Confidence limits 0.06-0.15 $m.s^{-1}$) in order to detect a meaningful change in performance. Theoretically this could be achieved with just a 1% improvement during the constant distance trials. In performance terms this level of change in CS could lead to a 17 second improvement over 5000 m (estimated using equation 8 and based on a CS of 4.72 $m.s^{-1}$ (increasing to 4.80 $m.s^{-1}$) with a stable D' of 169 m). This level of change would certainly be worthwhile in performance terms, even at an elite level. For example in the 2013 men's 5000 m World Championship final the whole field of 15 finishers spanned a time frame of ~37 seconds. A performance improvement of ~17 seconds would have moved the athlete in 14th place up to finish in 8th place. The time efficient nature and comparable level of reliability with that of laboratory protocols make the single-visit field test an attractive option in comparison to other currently available methods of assessing the distance-time relationship. It should be noted, however, that in the same World Championship race in 2013, a time frame of less than 1 second separated the first 4 finishers. It is doubtful that any performance test can boast a level of reliability good enough to allow it to detect such performance changes with any level certainty.

In agreement with previous literature, chapter 4 reports D′ to be less reliable than CS, with a CV of 14.1%. Based on a D′ of 170 m and the coefficient of variation for D′ of 14.1%, an athlete would have to improve their CS by over 24 m in order to detect a meaningful change in performance. This level of variation in D′ is unlikely to be acceptable when evaluating the relatively small training-induced changes seen in well-trained athletes (Hopkins, 2000). Although the assessment of D′ was less reliable than CS, the coefficients of variation reported in chapter 4 were similar to that reported previously during laboratory-based testing (Hinckson and Hopkins, 2005; Constantini et al., 2014). The findings reported in chapter 4 suggest that the single-visit field test can be used as an equally reliable, time efficient alternative to treadmill-based tests of the distance-time relationship.

Chapter 4 demonstrated the single-visit field test produced reliability values similar to that of laboratory based testing, however the validity of conducting trials in a single-visit warranted further comparison with a traditional multi-visit approach. Chapter 5 demonstrates that CS estimated from a single-visit (4.07 $m \cdot s^{-1}$) was not different to that measured over several visits in the laboratory (4.05 $m \cdot s^{-1}$). The typical error for CS reported in chapter 5 (~3.4-3.9%) is comparable with the values (4.3-4.6%) reported by Vanhatalo, Doust and Burnley (2008) between end test power from a single-visit 3-minute test and CP from a multi-visit laboratory test. Furthermore the strong correlations between CS from the field and treadmill tests in chapter 5 (r = 0.89, P <0.01) are similar to those previously reported (r = 0.94, P < 0.01) by Kranenburg and Smith (1996) between fixed-distance field test and TTE laboratory based trials. The D′ was higher with the multi-visit treadmill protocol (249 m) compared to the single-visit field test protocol (106 m). The typical error of the estimate for D′ (from the 30-minute recovery protocol) of 88 m is interpreted by Hopkins (2000) as moderate. It is possible, in part, that the difference in D′ seen between protocols can be attributed to underlying differences between treadmill and track running, that are a function of the treadmill test rather than the field test. Chapter 5 reports that the 1 percent gradient used for treadmill running may present less of a challenge than exercising outside on a running track. This may have contributed to the time predicted to cover a set distance on the treadmill being quicker than in the field (Table 5.3). The difference between treadmill and track running was greatest for the 1200 m distance, the consequence of which may have been an elevated D′ in the treadmill trials.

There was no significant difference in CS calculated from the 30-min or the 60-min field tests in chapter 5. This is in keeping with previous research which reported no significant difference in CS compared to a control value, following either a 2, 6 or 15-min recovery (Ferguson et al., 2010). There was also no significant difference in D′ between the 30 and 60-min field tests, however given the variability in D′ chapter 5 may lack sufficient statistical power to conclude this with any certainty. The mean difference of just 4 m between D′ from the 30-min and 60-min field-tests does however suggest the two tests produce similar values for D′. In contrast to the recoveries used in chapter 5, the longest recovery duration in previous research was 15-min (Ferguson et al., 2010), by which point 86% repletion of D′ was reported. Based on the result of the present study, a recovery of longer than 30 minutes between runs seems unnecessary for the calculation of CS and D′ during a single-visit field test. When using the 30-min rest period the field test can be accommodated into a single session of around 90-min duration.

At the start of this thesis it was hypothesised that the single visit field test would produce valid and reliable values of CS and D′ in comparison to laboratory based methods (hypotheses 1-4, page 64). Taken together, the results from chapters 4 and 5 suggest hypotheses $H1_1$ and $H3_1$, in respect of CS, can be accepted. The single-visit field test, with a 30-minute recovery between trials, can be put forward as valid, reliable and more attractive option for assessing CS from the distance-time relationship, than traditional multi-visit testing. The time efficiency and minimal equipment increase the practical application of the single-visit field test, allowing the potential for the test to be used at regular intervals to monitor the effects of prolonged endurance training on the distance-time relationship. The alternative hypothesis $H2_1$ can also be accepted, as D′ from the single visit field test demonstrated a similar level of reliability to that previously reported during laboratory-based tests. However the limited level of agreement with laboratory based tests, lead to the null hypothesis $H4_0$ being accepted.

Chapter 6 set out to measure the training of endurance runners for one year and apply the single-visit field test at regular intervals to monitor the effects of training on CS and D′. Chapter 6 aimed to examine the ability of the single-visit field test to detect training induced changes in the distance-time relationship in a group of highly trained distance runners. It was hypothesised that CS and D’ would change significantly during the training year (hypotheses $H5_1$ and $H6_1$ respectively - page 65) in highly trained distance runners. The results of chapter 6 reveal CS was lowest during August (4.90 $m \cdot s^{-1}$), and peaked in February (4.99 $m \cdot s^{-1}$), equating to a 1.9% change in CS. The change in CS is also greater than the coefficient of variation previously reported for repeat testing with this single-visit protocol (chapter 4), suggesting a true change in CS was observed. Using the methods of Hopkins (2000a) the likelihood of this being a true change in CS is 73%. The modest 1.9% (0.09 $m \cdot s^{-1}$) change in CS reported in chapter 6 still implies a meaningful change in performance for a distance runner. Using the distance-time relationship, it is possible to predict the shortest time an athlete could complete a given race distance (Jones et al., 2010). Thus, an increase in CS from 4.90 m·s to 4.99 m·s corresponds to a 36 second improvement in 10’000 m race time (based on a stable D′ of 130 m). The results of chapter 6 support the alternative hypothesis ($H5_1$), demonstrating that CS changed significantly during the training year and that the single visit field test is sensitive to the small changes in CS seen in highly trained distance runners. Unlike CS, D′ did not change significantly during the season. Research examining longitudinal changes in D′ in highly trained distance runners is lacking. In untrained cyclists, large increases (49%) in W′ have been reported following 8 weeks of high-intensity training (Jenkins and Quigley, 1993). However, the use of untrained participants and the high-intensity all-out training might explain the different findings. Specifically, the trained participants in the present study predominantly performed continuous training or longer interval type training (interval duration >1 min), which has previously been shown to produce no significant changes in W′ (Gaesser and Wilson, 1988; Poole et al., 1990; Jenkins and Quigley, 1992). Notwithstanding this, chapter 4 reports D′ to have a lower level of reliability than CS. This may have reduced the ability to measure the small performance changes expected in highly trained athletes and ultimately leads to null hypothesis $H6_0$ being accepted. The sample size in chapter 6 (14 participants) is comparable with other studies assessing changes in the distance-time/power-time relationship (Gaesser and Wilson, 1988; Poole et al., 1990; Jenkins and Quigley, 1992). Due to the variability associated with the measurement of D’ (CV of 14.1%, reported in chapter 4), a larger sample size may have been necessary in order to detect potential changes in D’ with any level of certainty. Based on the similar reliability between D’ and W’ it could also be suggested that previous studies, where no change in W’ was reported, could also be classed as slightly underpowered (Gaesser and Wilson, 1988; Poole et al., 1990; Jenkins and Quigley, 1992). Applying the sample size calculations outlined by Hopkins (2000a) to the D’ reliability data from chapter 4 reveals a sample size in the region of 42 participants would be needed to detect a possible change in D’ in subsequent research studies.

Having developed a reliable and valid single-visit field test of the distance-time relationship (chapters 4 and 5), a principle aim of the chapter 6 was to capitalise on the time efficiency of this test and use it to monitor the effects of prolonged endurance training on the distance-time relationship. The combined results of chapters 4, 5 and 6 suggest the single-visit field test is a reliable and valid test that is sensitive enough to detect small changes in CS. The single-visit test can be put forward as a useful tool for athletes, coaches and sports scientists looking to monitor the effects of endurance training and performance on CS in the field.

In addition to monitoring changes in endurance performance a valid, reliable and sensitive single visit field test may have a use in training prescription. The potential of the single visit field test to model intermittent exercise could allow the prescription of intermittent interval-style work and recovery periods based around the CS and D′. The relatively high variability in D′ reported in chapter 4 may however reduce the ability of the single-visit field test to prescribe training. Chapter 7, therefore, aimed to investigate whether the distance-time relationship estimated from the single-visit field test could be accurately applied to linear and non-linear models to predict time to exhaustion during intermittent running exercise. This in turn would provide an insight into the ability of the single visit field-test to prescribe interval style training sessions. It was hypothesized that an exponential model could be applied to the CS and D′ from the single visit field test to accurately predict TTE during intermittent running (hypothesis $H7_1$, page 66).

The main findings of chapter 7 were that the linear model of intermittent running based upon CS and D′ (Morton and Billat, 2004) does not closely predict TTE. Although no significant differences in actual and predicted TTE were seen in the 1000 m trial, actual TTE was significantly lower (P = 0.01) than predicted TTE in the 200 m trial and there was a trend for a similar effect (P = 0.09) in the 600 m trial. Furthermore, the lack of correlation (range r = -0.21 to -0.04, P>0.05) and the relatively high typical error (range 334-1709 s) across trials, support the conclusion that the intermittent critical speed model cannot be used to accurately predict TTE in intermittent running exercise. When modelled in this way, CS and D′ from the single-visit field test tend to predict a greater TTE than could be achieved, resulting in an interval session with an unrealistic number of work and recovery intervals. The results of chapter 7 support the earlier work of Kachouri et al., (1996), who report that it is not possible to predict the maximum number of repetitions of an intermittent exercise session from the continuous distance-time relationship. To assess the effect of the recovery model, chapter 7 compared the linear model of Morton and Billat (2004) and the non-linear model of Skiba et al., (2012). Overall (regardless of trial), the non-linear model did not produce a D'_{bal} at interval session termination that was closer to zero than the linear model (-21.2 and 13.4 m, respectively).

The variability in D′ has been reported to be high (chapter 4); this variability may explain the inability of the models to predict TTE. Consequently, the actual and predicted D′ were considered in the chapter 7. Although actual and predicted TTE from the combined trials were significantly different (P = 0.01), there were no significant mean group differences between actual (111 ± 67 m) and predicted (120 ± 52 m) D′ (P = 0.23; typical error = 33 m). Therefore, it seems plausible to attribute some of the differences seen in actual and predicted TTE to relatively small errors in the estimation of D′ for each participant. These errors could be due to the relatively high variability in D′ between repeat trials. In the non-linear model mean $\tau_{D'}$ across the three trials was 377 ± 129 s. This is in contrast to the reported $\tau_{W'}$ of 578 ± 105 s during the heavy intensity recovery condition of Skiba et al., (2012). The results of chapter 7 suggest there might be differences in the time constant for W′ and D′ repletion. Future research should determine whether a distance-time model is appropriate for intermittent exercise and what recovery kinetics should be assumed.

Chapters 4, 5 and 6 describe a valid, reliable and sensitive single-visit field test that can be used to monitor changes in CS. Chapter 7 set out to model intermittent exercise using the single visit field test, thereby providing an insight into the ability of the distance-time relationship to prescribe interval style training sessions. The results of chapter 7 demonstrate that neither the linear nor nonlinear recovery models accurately predict TTE in intermittent exercise. This leads to the null hypothesis $H7_0$ being accepted, suggesting these models presently appear to have limited application in the design of interval training sessions, where the number of work:recovery periods an athlete can perform at given intensity cannot be accurately predicted. Coaches therefore need to be wary of prescribing intervals based on these methods using the current models. Furthermore the inability to accurately model intermittent exercise within a controlled interval session reduces the likelihood that the models, in their present form, have any further real-time performance monitoring application during competition.

8.2 Practical applications

The main practical application of the single-visit field test is as a time efficient test which can be used to monitor the effects of prolonged endurance training on the CS. This new protocol is more accessible and less time disruptive of training for athletes, thereby providing a useful tool for athletes, coaches and sports scientists looking to monitor the effects of endurance training and performance in the field.

A further practical application of the single-visit field test may lie in the area of performance prediction (Jones et al., 2010). It has been suggested that, using the following equation, the distance-time relationship can be used to calculate the quickest time in which an athlete could complete a set distance (Gaesser et al., 1995). Where t = predicted time taken to complete a set distance and D = the chosen set distance:

$$t = (D-D')/CS \qquad (8)$$

This prediction of performance could provide a runner with a realistic target to aim for in competitive races. Predicted performance from the distance-time relationship has shown good correlation with actual performance over distances ranging from 10,000 m (Kranenburg and Smith, 1996) to the Marathon (Florence and Weir, 1997). The variability of D′ seen in chapter 4, however, questions the usability of the distance-time relationship within this area.

It has also been suggested that an athlete and their coach could use information obtained from the distance-time relationship to formulate pacing and tactical strategies aimed at maximizing competitive performance (Jones et al., 2010). For example, in a competitive race situation the best tactical pacing strategy for an athlete with a relatively low CS but a high D′, might be to slow the pace and use their high D′ to full effect in a sprint finish (Jones et al., 2010).

8.3 Future directions

Consolidation of the findings from this thesis point to the potential for future research investigations in a number of key areas. Firstly, a low level of reliability in the D′ estimated from the single-visit field test has been reported in chapter 4. This level of variability is similar to that previously reported in the literature for D’ and also similar to the reliability reported for W’ in cycling based research. These findings suggest that D’/W’ has a greater level of variability associated with its estimation than CS/CP. The single-visit field test used fixed-distance trials, which were shown to have a relatively high level of reliability (CV 1.2-2.2%, Table 4.4). Nevertheless, it appears when these trials are modelled to form the distance-time relationship, CS retains a similar level of reliability to the modelled data (CV 1.7%), however the reliability of D’ is considerably worse than that of CS and that of the constant-distance trial data inputted into the model (CV 14.1%). This variability in D′ may have reduced the sensitivity of the single-visit field test, preventing the test from detecting potential changes in D′ in a group of highly trained athletes in chapter 6. Furthermore the variability in D′ may have also contributed to the differences in actual and predicted time to exhaustion seen in chapter 7, thereby limiting the ability of the single-visit field test to prescribe interval training. Future research examining novel methods of modelling the distance-time relationship from the single-visit field test in an attempt to improve the reliability of D′ are recommended. It could however be suggested that the greater variability associated with D’ may be attributed to natural biological variation associated with this parameter, rather than variability associated with the modelling process. Parallel research into the physiological underpinnings of D’ may help develop future knowledge in this area.

Secondly, chapter 7 suggests the time constant for D′ repletion may differ from values previously proposed for the modelling of intermittent cycling exercise. Future research to develop a new model for assessing the depletion of D′ during intermittent exercise is required. In their recent paper Skiba et al (2014) present some modifications to the model of Skiba et al (2012). One interesting suggestion is that the $\tau_{W'}$ can be calculated as the starting W' divided by the D_{CP}. Future research investigating the application of such modifications to the intermittent exercise model within a running setting would further develop research in this area. Additionally, in their 2012 paper, Skiba (2012) varied the time constant iteratively until modelled W'_{bal} was zero at the point of interval session termination. A similar method was used in chapter 7 to estimate the time constant for D' repletion. Recent research by Chidnok et al (2013b) questions the notion that W'_{bal}/D'_{bal} will be zero at the point of termination of an interval training session. Chidnok et al (2013b) required participants to conduct single-leg knee extension exercise to exhaustion at an intensity predicted to exhaust W' in 180 seconds. Following exhaustion, exercise intensity was immediately dropped to a lower work rate, however an intensity still above CP. Results revealed that participants maintained exercise at this new intensity for on average 39±31 seconds beyond the point of initial exhaustion. This questions the notion of the power-duration relationship when applied to intermittent exercise, where in theory at the point of exhaustion W'_{bal} should be zero and therefore intensity would need to drop below CP in order for exercise to continue. Further research to extend the findings of Chidnok et al (2013b) into running based exercise would help improve understanding of W'_{bal} in relation to intermittent exercise.

Finally, further analysis of the longitudinal data set collected in chapter 6 presents a number of opportunities for future research. Initially training intensity could be benchmarked in relation to time spent above and below CS and the relationship between times spent in each zone and changes in the distance-time relationship investigated. This may provide an insight into the practical application of prescribing training zones based around CS and inform coaches of the practicality of such prescription in altering the parameters of the distance-time relationship.

In addition to future research directly following on from the experimental chapters in this thesis, a number of additional research themes in relation to the distance-time relationship provide useful avenues for further research. One such area involves further investigation into the physiological underpinnings of CS and D'. A novel consideration in this area may be the use of Near Infrared Spectroscopy (NIRS) to monitor muscle oxygenation during intermittent exercise. Initial pilot work with this device during a sample interval session suggested that muscle oxygenation might display a "saw-tooth" response during intermittent exercise. Muscle oxygenation decreased during exercise above CS and increased when intensity dropped below CS. The pattern of the NIRS response closely matched the predicated depletion and reconstitution of D' estimated form the intermittent distance-time model. Further research to expand this pilot work may provide evidence to further develop understanding of the physiological significance of CS and D'.

Another research theme is the utilisation of distance-time relationship data to inform applied practice in the field. Chapter 7 suggests that predicting and prescribing specific intermittent exercise sessions based on the distance-time relationship may not be a useful coaching tool using the present modelling techniques. It is possible that the distance-time relationship could still have a place in prescribing more general training intensities rather than specific interval repetitions and durations. Murgatroyd et al., (2011) suggest that because CP does not occur at a fixed percentage of $\dot{V}O_{2\,max}$, the exercise intensity experienced during an interval training session will be variable between participants unless the distance-time relationship is accounted for. The distance-time relationship could therefore provide an alternative method for individualising exercise intensity in athletes training programs. A relatively simple way of assessing this suggestion in running based research might be to investigate the variability in time-to-exhaustion at differing percentages of CS and vVO_{2max}. Less variability in TTE across the group might be expected when athletes perform at a fixed percentage of CS. However when athletes perform at a fixed percentage of vVO_{2max} the within group variability might be expected to be higher, as each individual participant's vVO_{2max} may fall at a different percentage of their CS. Future research into such areas may help better inform the use of the distance-time relationship as a tool to normalise training intensity, hence better informing applied practice in the field.

8.4 Conclusions

The overall aim of this thesis was to develop a time efficient field test of the distance-time relationship that could be utilised to monitor endurance performance and prescribe training. The main conclusions from this thesis are that the single visit field test is a reliable and valid test that is sensitive enough to detect small changes in CS. The single-visit field test therefore provides a favourable alternative to multi-visit laboratory-based testing of CS. This thesis also concludes that the variability in D′, using the current modelling techniques, limits the ability of the single-visit field test to monitor changes in D′ and prescribe interval training based on the distance-time relationship.

References

Achten, J., & Jeukendrup, A. E. (2003). Heart rate monitoring. *Sports medicine*, *33*(7), 517-538.

Alberty, M., Sidney, M., Huot-Marchand, F., Dekerle, J., Bosquet, L., Gorce, P., & Lensel, G. (2006). Reproducibility of performance in three types of training test in swimming. *International journal of sports medicine*, *27*(8), 623-628.

Alvarez-Ramirez, J. (2002). An improved Peronnet-Thibault mathematical model of human running performance. *European journal of applied physiology*, *86*(6), 517-525.

Amann, M., Hopkins, W. G., & Marcora, S. M. (2008). Similar sensitivity of time to exhaustion and time-trial time to changes in endurance. *Medicine and science in sports and exercise*, *40*(3), 574-578.

ÅStrand, I., ÅStrand, P. O., Christensen, E. H., & Hedman, R. (1960). Intermittent muscular work. *Acta Physiologica Scandinavica*, *48*(3- 4), 448-453.

Atkinson, G., & Nevill, A. M. (1998). Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports medicine*, *26*(4), 217-238.

Bailey, S. J., Vanhatalo, A., Wilkerson, D. P., DiMenna, F. J., & Jones, A. M. (2009). Optimizing the "priming" effect: influence of prior exercise intensity and recovery duration on O2 uptake kinetics and severe-intensity exercise tolerance. *Journal of Applied Physiology*, *107*(6), 1743-1756.

Bangsbo, J., Johansen, L., Quistorff, B., & Saltin, B. (1993). NMR and analytic biochemical evaluation of CrP and nucleotides in the human calf during muscle contraction. *Journal of Applied Physiology*, *74*(4), 2034-2039.

Beaver, W. L., Wasserman, K., & Whipp, B. J. (1986). A new method for detecting anaerobic threshold by gas exchange. *J Appl Physiol*, *60*(6), 2020-2027.

Beneke, R. (2003). Methodological aspects of maximal lactate steady state—implications for performance testing. *European journal of applied physiology*, *89*(1), 95-99.

Beneke, R., Hutler, M., von Duvillard, S. P., Sellens, M., & Leithauser, R.M. (2003). Effect of test interruptions on blood lactate during constant workload testing. *Medicine and science in sports and exercise*, *35*(9), 1626-1630.

Bergstrom, H. C., Housh, T. J., Zuniga, J. M., Traylor, D. A., Lewis Jr, R. W., Camic, C. L., & Johnson, G. O. (2014). Differences among estimates of critical power and anaerobic work capacity derived from five mathematical models and the three-minute all-out test. *The Journal of Strength & Conditioning Research*, *28*(3), 592-600.

Berthoin, S., Baquet, G., Dupont, G., & Van Praagh, E. (2006). Critical velocity during continuous and intermittent exercises in children. *European journal of applied physiology*, *98*(2), 132-138.

Billat, V., Binsse, V., Petit, B., & Koralsztein, J. J. (1998). High level runners are able to maintain a $\dot{V}O_2$ steady-state below $\dot{V}O_{2\,max}$ in an all-out run over their critical velocity. *Archives of physiology and biochemistry*, *106*(1), 38-45.

Billat V.L., Demarle A., Paiva M., & Koralsztein J.P. (2002) Effect of Training on the Physiological Factors of Performance in Elite Marathon Runners (Males and Females). *International Journal of Sports Medicine 23*: 336–341

Billat, V. L., Flechet, B., Petit, B., Muriaux, G., & Koralsztein, J. P. (1999). Interval training at $\dot{V}O_{2\,max}$: effects on aerobic performance and overtraining markers. *Medicine and Science in Sports and Exercise*, *31*, 156-163.

Billat, V. L., Hill, D. W., Pinoteau, J., Petit, B., & Koralsztein, J. P. (1996). Effect of protocol on determination of velocity at $\dot{V}O_{2\,max}$ and on its time to exhaustion. *Archives of physiology and biochemistry*, *104*(3), 313-321.

Billat, V., Renoux, J. C., Pinoteau, J., Petit, B., & Koralsztein, J. P. (1994). Reproducibility of running time to exhaustion at $\dot{V}O_{2\,max}$ in subelite runners. *Medicine and science in sports and exercise*, *26*(2), 254-257.

Birch, R., Noble, D., & Greenhaff, P. L. (1994). The influence of dietary creatine supplementation on performance during repeated bouts of maximal isokinetic cycling in man. *European journal of applied physiology and occupational physiology*, *69*(3), 268-270.

Bland, M.J., & Altman, D. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *The lancet*, *327*(8476), 307-310.

Bogdanis, G. C., Nevill, M. E., Boobis, L. H., Lakomy, H. K., & Nevill, A. M. (1995). Recovery of power output and muscle metabolites following 30 s of maximal sprint cycling in man. *The Journal of physiology*, *482*(Pt 2), 467-480.

Borg, G. (1998). *Borg's perceived exertion and pain scales*. Champaign, IL: Human kinetics.

Bosquet, L., Duchene, A., Lecot, F., Dupont, G., & Leger, L. (2006). V max estimate from three-parameter critical velocity models: validity and impact on 800 m running performance prediction. *European journal of applied physiology*, *97*(1), 34-42.

Bragada, J. A., Santos, P. J., Maia, J. A., Colaço, P. J., Lopes, V. P., & Barbosa, T. M. (2010). Longitudinal study in 3,000 m male runners: relationship between performance and selected physiological parameters. *Journal of sports science & medicine*, *9*(3), 439.

Broxterman, R. M., Ade, C. J., Wilcox, S. L., Schlup, S. J., Craig, J. C., & Barstow, T. J. (2014). Influence of duty cycle on the power-duration relationship: Observations and potential mechanisms. *Respiratory physiology & neurobiology*, *192*, 102-111.

Bull, A. J., Housh, T. J., Johnson, G. O., & Perry, S. R. (2000). Effect of mathematical modeling on the estimation of critical power. *Medicine and science in sports and exercise*, *32*(2), 526-530.

Bull, A. J., Housh, T. J., Johnson, G. O., & Rana, S. R. (2008). Physiological responses at five estimates of critical velocity. *European journal of applied physiology*, *102*(6), 711-720.

Burnley, M., Davison, G., & Baker, J. R. (2011). Effects of priming exercise on $\dot{V}O_2$ kinetics and the power-duration relationship. *Medicine and science in sports and Exercise*, *43*(11), 2171-2179.

Burnley, M., Doust, J. H., & Jones, A. M. (2005). Effects of prior warm-up regime on severe-intensity cycling performance. *Medicine and science in sports and exercise*, *37*(5), 838-845.

Burnley, M., Doust, J. H., & Vanhatalo, A. (2006). A 3-min all-out test to determine peak oxygen uptake and the maximal steady state. *Medicine and science in sports and exercise*, *38*(11), 1995-2003.

Burnley, M., & Jones, A. M. (2007). Oxygen uptake kinetics as a determinant of sports performance. *European Journal of Sport Science*, *7*(2), 63-79.

Carter, H., Grice, Y., Dekerle, J., Brickley, G., Hammond, A. J., & Pringle, J. S. (2005). Effect of prior exercise above and below critical power on exercise to exhaustion. *Medicine and science in sports and exercise*, *37*(5), 775-781

Cheng, B., Kuipers, H., Snyder, A. C., Keizer, H. A., Jeukendrup, A., & Hesselink, M. (1992). A new approach for the determination of ventilatory and lactate thresholds. *International journal of sports medicine*, *13*(07), 518-522.

Chidnok, W., Dimenna, F. J., Bailey, S. J., Vanhatalo, A., Morton, R. H., Wilkerson, D. P., & Jones, A. M. (2012). Exercise tolerance in intermittent cycling: application of the critical power concept. *Medicine and science in sports and exercise*, *44*(5), 966-976.

Chidnok, W., DiMenna, F. J., Bailey, S. J., Burnley, M., Wilkerson, D. P., Vanhatalo, A., & Jones, A. M. (2013). $\dot{V}O_{2\,max}$ is not altered by self-pacing during incremental exercise. *European journal of applied physiology*, *113*(2), 529-539.

Chidnok, W., DiMenna, F. J., Fulford, J., Bailey, S. J., Skiba, P. F., Vanhatalo, A., & Jones, A. M. (2013a). Muscle metabolic responses during high-intensity intermittent exercise measured by 31P-MRS: relationship to the critical power concept. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, *305*(9), R1085-R1092.

Chidnok, W., Fulford, J., Bailey, S. J., DiMenna, F. J., Skiba, P. F., Vanhatalo, A., & Jones, A. M. (2013b). Muscle metabolic determinants of exercise tolerance following exhaustion: relationship to the “critical power”. *Journal of Applied Physiology, 115*, 243-250.

Christensen, E. H., Hedman, R., & Saltin, B. (1960). Intermittent and continuous running (A further contribution to the physiology of intermittent work.). *Acta Physiologica Scandinavica*, *50*(3- 4), 269-286.

Clarke, A. C., Presland, J., Rattray, B., & Pyne, D. B. (2014). Critical velocity as a measure of aerobic fitness in women's rugby sevens. *Journal of Science and Medicine in Sport*, *17*(1), 144-148.

Clarke, D. C., & Skiba, P. F. (2013). Rationale and resources for teaching the mathematical modeling of athletic training and performance. *Advances in physiology education*, *37*(2), 134-152.

Clark, I. E., West, B. M., Reynolds, S. K., Murray, S. R., & Pettitt, R. W. (2013). Applying the Critical Velocity Model for an Off-Season Interval Training Program. *The Journal of Strength & Conditioning Research*, *27*(12), 3335-3341.

Cleuziou, C., Perrey, S., Lecoq, A. M., Candau, R., Courteix, D., & Obert, P. (2005). Oxygen uptake kinetics during moderate and heavy intensity exercise in humans: the influence of hypoxia and training status. *International journal of sports medicine*, *26*(05), 356-362.

Clingeleffer, A., Mc Naughton, L. R., & Davoren, B. (1994). The use of critical power as a determinant for establishing the onset of blood lactate accumulation. *European journal of applied physiology and occupational physiology*, *68*(2), 182-187.

Coats, E. M., Rossiter, H. B., Day, J. R., Miura, A., Fukuba, Y., & Whipp, B. J. (2003). Intensity-dependent tolerance to exercise after attaining $\dot{V}O_{2\,max}$ in humans. *Journal of applied physiology*, *95*(2), 483-490.

Conley, D. L., & Krahenbuhl, G. S. (1980). Running economy and distance running performance of highly trained athletes. *Medicine and science in sports and exercise*, *12*(5), 357-360.

Constantini, K., Sabapathy, S., & Cross, T. J. (2014). A single-session testing protocol to determine critical power and W′. *European journal of applied physiology*, *114*(6), 1153-1161.

Dekerle, J., Baron, B., Dupont, L., Vanvelcenaher, J., & Pelayo, P. (2003). Maximal lactate steady state, respiratory compensation threshold and critical power. *European journal of applied physiology*, *89*(3-4), 281-288.

Dekerle, J., Brickley, G., Hammond, A. J. P., Pringle, J. S. M., & Carter, H. (2006). Validity of the two-parameter model in estimating the anaerobic work capacity. *European journal of applied physiology*, *96*(3), 257-264.

Dekerle, J., Pelayo, P., Clipet, B., Depretz, S., Lefevre, T., & Sidney, M. (2005). Critical swimming speed does not represent the speed at maximal lactate steady state. *International journal of sports medicine*, *26*(07), 524-530.

Dekerle, J., Sidney, M., Hespel, J. M., & Pelayo, P. (2002). Validity and reliability of critical speed, critical stroke rate, and anaerobic capacity in relation to front crawl swimming performances. *International Journal of Sports Medicine*, *23*(02), 93-98.

Demarle, A. P., Slawinski, J. J., Laffite, L. P., Bocquet, V. G., Koralsztein, J. P., & Billat, V. L. (2001). Decrease of O2 deficit is a potential factor in increased time to exhaustion after specific endurance training. *Journal of Applied Physiology*, *90*(3), 947-953.

Denadai, B. S., Gomide, E. B. G., & Greco, C. C. (2005). The relationship between onset of blood lactate accumulation, critical velocity, and maximal lactate steady state in soccer players. *The Journal of Strength & Conditioning Research*, *19*(2), 364-368.

Drust, B., Waterhouse, J., Atkinson, G., Edwards, B., & Reilly, T. (2005). Circadian rhythms in sports performance-an update. *Chronobiology international*, *22*(1), 21-44.

Eckerson, J. M., Stout, J. R., Moore, G. A., Stone, N. J., Nishimura, K., & Tamura, K. (2004). Effect of two and five days of creatine loading on anaerobic working capacity in women. *The Journal of Strength & Conditioning Research*, *18*(1), 168-173.

Farrell, P. A., Wilmore, J. H., Coyle, E. F., Billing, J. E., & Costill, D. L. (1979). Plasma lactate accumulation and distance running performance. *Medicine and science in sports*, *11*(4), 338-344.

Ferguson, C., Rossiter, H. B., Whipp, B. J., Cathcart, A. J., Murgatroyd, S. R., & Ward, S. A. (2010). Effect of recovery duration from prior exhaustive exercise on the parameters of the power-duration relationship. *Journal of applied physiology, 108*(4), 866-874.

Ferguson, C., Whipp, B. J., Cathcart, A. J., Rossiter, H. B., Turner, A. P., & Ward, S. A. (2007). Effects of prior very-heavy intensity exercise on indices of aerobic function and high-intensity exercise tolerance. *Journal of applied physiology*, *103*(3), 812-822.

Ferguson, C., Wilson, J., Birch, K. M., & Kemi, O. J. (2013). Application of the speed-duration relationship to normalize the intensity of high-intensity interval training. *PloS one*, *8*(11), e76420.

Fitts, R. H. (1994). Cellular mechanisms of muscle fatigue. *Physiological reviews*, *74*(1), 49-94.

Florence, S. L., & Weir, J. P. (1997). Relationship of critical velocity to marathon running performance. *European journal of applied physiology and occupational physiology*, *75*(3), 274-278.

Foster, C. (1983). $\dot{V}O_{2\,max}$ and training indices as determinants of competitive running performance. *Journal of Sports Sciences*, *1*(1), 13-22.

Francis, A. W. (1943). Running records. *Science (New York, NY), 98*(2545), 315.

Fry, R. W., Morton, A. R., & Keast, D. (1992). Periodisation of training stress--a review. *Canadian journal of sport sciences, 17*(3), 234-240.

Gaesser, G. A., Carnevale, T. J., Garfinkel, A., & Walter, D. O. (1990). Modeling of the Power-Endurance Relationship for High-Intensity Exercise. *Medicine & Science in Sports & Exercise*, *22*(2), S16.

Gaesser, G. A., Carnevale, T. J., Garfinkel, A., Walter, D. O., & Womack, C. J. (1995). Estimation of critical power with nonlinear and linear models. *Medicine and science in sports and exercise*, *27*(10), 1430-1438.

Gaesser, G. A., & Wilson, L. A. (1988). Effects of continuous and interval training on the parameters of the power-endurance time relationship for high-intensity exercise. *International journal of sports medicine, 9*(06), 417-421.

Galbraith, A., and Dabinett, J. (2009). Accuracy of performance estimation using critical velocity determined on the treadmill and track. *Journal of Sports Sciences,* 27(2): S91-S92.

Galbraith A., Hopker J., Cardinale, M., Cunniffe, B., Passfield L. (2014) A 1-Year Study of Endurance Runners: Training, Laboratory Tests and Field Tests. *International Journal of Sports Physiology and Performance, 9(6),*1019-25.

Galbraith, A., Hopker, J.G., Jobson, S.A., & Passfield, L. (2011). A Novel Field Test to Determine Critical Speed. *Journal of Sports Medicine and Doping Studies,* 1 (01): 1-4.

Galbraith, A., Hopker, J., Lelliott, S., Diddams, L., & Passfield, L. (2014a). A Single-Visit Field Test of Critical Speed. *International journal of sports physiology and performance*, *9*, 931-935.

Gamelin, F. X., Coquart, J., Ferrari, N., Vodougnon, H., Matran, R., Leger, L., & Bosquet, L. (2006). Prediction of one-hour running performance using constant duration tests. *The Journal of Strength & Conditioning Research*, *20*(4), 735-739.

Gibala, M. J., & McGee, S. L. (2008). Metabolic adaptations to short-term high-intensity interval training: a little pain for a lot of gain. *Exercise and sport sciences reviews*, *36*(2), 58-63.

Hagberg, J. M., & Coyle, E. F. (1983). Physiological determinants of endurance performance as studied in competitive racewalkers. *Medicine and science in sports and exercise*, *15*(4), 287-289.

Hampson, D. B., Gibson, A. S. C., Lambert, M. I., & Noakes, T. D. (2001). The influence of sensory cues on the perception of exertion during exercise and central regulation of exercise performance. *Sports Medicine*, *31*(13), 935-952.

Hanley, B. (2014). Senior men's pacing profiles at the IAAF World Cross Country Championships. *Journal of sports sciences*, *32*(11), 1060-1065.

Harris, R. C., Soderlund, K., & Hultman, E. (1992). Elevation of creatine in resting and exercised muscle of normal subjects by creatine supplementation. *Clinical Science*, *83*(3), 367-374.

Hill, A. V. (1925). The physiological basis of athletic records. *The Lancet*, *206*(5323), 481-486.

Hill, D. W. (1993). The critical power concept. *Sports Medicine*, *16*(4), 237-254.

Hill, D. W., Alain, C., & Kennedy, M. D. (2003). Modeling the relationship between velocity and time to fatigue in rowing. *Medicine and science in sports and exercise*, *35*(12), 2098-2105.

Hill, D. W., & Ferguson, C. S. (1999). A physiological description of critical velocity. *European journal of applied physiology and occupational physiology*, *79*(3), 290-293.

Hill, D. W., Rose, L. E., & Smith, J. C. (1993). Estimates of Anaerobic Capacity Derived Using Different Models of the Power-Time Relationship. *Medicine & Science in Sports & Exercise*, *25*(5), S108.

Hinckson, E. A., & Hopkins, W. G. (2005). Reliability of time to exhaustion analyzed with critical-power and log-log modeling. *Medicine and Science in Sports and Exercise*, *37*(4), 696-701.

Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports medicine*, *30*(1), 1-15.

Hopkins W.G. A new view of statistics. *Internet Society for Sports Science*. 2000a; http://www.sportsci.org/resource/stats/.

Hopkins, W. G., Edmond, I. M., Hamilton, B. H., Macfarlane, D. J., & Ross, B. H. (1989). Relation between power and endurance for treadmill running of short duration. *Ergonomics*, *32*(12), 1565-1571.

Hopkins, W. G., & Hewson, D. J. (2001). Variability of competitive performance of distance runners. *Medicine and Science in Sports and Exercise*, *33*(9), 1588-1592.

Hopkins, W., Marshall, S., Batterham, A., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, *41*(1), 3.

Hopkins, W. G., Schabort, E. J., & Hawley, J. A. (2001). Reliability of power in physical performance tests. *Sports Medicine*, *31*(3), 211-234.

Housh, D. J., Housh, T. J., & Bauge, S. M. (1989). The accuracy of the critical power test for predicting time to exhaustion during cycle ergometry. *Ergonomics*, *32*(8), 997-1004.

Housh, T. J., Cramer, J. T., Bull, A. J., Johnson, G. O., & Housh, D. J. (2001). The effect of mathematical modeling on critical velocity. *European journal of applied physiology*, *84*(5), 469-475.

Housh, T. J., Devries, H. A., Housh, D. J., Tichy, M. W., Smyth, K. D., & Tichy, A. M. (1991). The relationship between critical power and the onset of blood lactate accumulation. *The Journal of sports medicine and physical fitness*, *31*(1), 31-36.

Housh, T. J., Johnson, G. O., McDowell, S. L., Housh, D. J., & Pepper, M. (1991a). Physiological responses at the fatigue threshold. *International journal of sports medicine*, *12*(03), 305-308.

Hughson, R. L., Orok, C. J., & Staudt, L. E. (1984). A High Velocity Treadmill Running Test to Assess Endurance Running Potential. *International journal of sports medicine*, *5*(01), 23-25.

Jenkins, D. G., & Quigley, B. M. (1990). Blood lactate in trained cyclists during cycle ergometry at critical power. *European journal of applied physiology and occupational physiology*, *61*(3-4), 278-283.

Jenkins, D. G., & Quigley, B. M. (1992). Endurance training enhances critical power. *Medicine and Science in Sports and Exercise*, *24*(11), 1283-1289.

Jenkins, D. G., & Quigley, B. M. (1993). The influence of high-intensity exercise training on the Wlim-Tlim relationship. *Medicine and science in sports and exercise*, *25*(2), 275-282.

Jeukendrup, A. E., & Currell, K. (2005). Should time trial performance be predicted from three serial time-to-exhaustion tests. *Medicine and science in sports and exercise*, *37*(10), 1820.

Jeukendrup, A., Saris, W., Brouns, F., & Kester, A. D. (1996). A new validated endurance performance test. *Medicine and Science in Sports and Exercise*, *28*(2), 266-270.

Johnson, M. A., Mills, D. E., Brown, P. I., & Sharpe, G. R. (2014). Prior upper body exercise reduces cycling work capacity but not critical power. *Medicine and science in sports and exercise*, *46*(4), 802-808.

Johnson, T. M., Sexton, P. J., Placek, A. M., Murray, S. R., & Pettitt, R. W. (2011). Reliability analysis of the 3-min all-out exercise test for cycle ergometry. *Medicine and science in sports and exercise*, *43*(12), 2375-2380.

Jones, A. M. (1998). A five year physiological case study of an Olympic runner. *British journal of sports medicine*, *32*(1), 39-43.

Jones AM. Middle and long-distance running. In: Winter EM, Jones AM, Davison RCR, Bromley PD, Mercer TH, eds. *Sport and exercise physiology testing guidelines. volume one: Sport testing*. Oxford: Routledge; 2008:147-154.

Jones, A. M., & Carter, H. (2000). The effect of endurance training on parameters of aerobic fitness. *Sports medicine*, *29*(6), 373-386.

Jones, A. M., & Doust, J. H. (1996). A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. *Journal of sports sciences*, *14*(4), 321-327.

Jones, A. M., & Doust, J. H. (1998). The validity of the lactate minimum test for determination of the maximal lactate steady state. *Medicine and Science in Sports and Exercise*, *30*(8), 1304-1313.

Jones, A. M., Koppo, K., & Burnley, M. (2003). Effects of prior exercise on metabolic and gas exchange responses to exercise. *Sports medicine*, *33*(13), 949-971.

Jones, A. M., Vanhatalo, A., Burnley, M., Morton, R. H., & Poole, D. C. (2010). Critical power: implications for determination of V O2max and exercise tolerance. *Medicine and science in sports and exercise*, *42*(10), 1876-1890.

Jones, A. M., Wilkerson, D. P., DiMenna, F., Fulford, J., & Poole, D. C. (2008). Muscle metabolic responses to exercise above and below the “critical power” assessed using 31P-MRS. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, *294*(2), R585-R593.

Jones, A. M., Wilkerson, D. P., Burnley, M., & Koppo, K. (2003). Prior heavy exercise enhances performance during subsequent perimaximal exercise. *Medicine and Science in Sports and Exercise*, *35*(12), 2085-2092.

Joyner, M. J., & Coyle, E. F. (2008). Endurance exercise performance: the physiology of champions. *The Journal of physiology*, *586*(1), 35-44.

Kachouri, M., Vandewalle, H., Billat, V., Huet, M., Thomaïdis, M., Jousselin, E., & Monod, H. (1996). Critical velocity of continuous and intermittent running exercise. An example of the limits of the critical power concept. *European journal of applied physiology and occupational physiology*, *73*(5), 484-487.

Karlsson, J., Bonde-Petersen, F., Henriksson, J., & Knuttgen, H. G. (1975). Effects of previous exercise with arms or legs on metabolism and performance in exhaustive exercise. *J Appl Physiol*, *38*(5), 763-767.

Kendall, K. L., Smith, A. E., Graef, J. L., Fukuda, D. H., Moon, J. R., Beck, T. W., ... & Stout, J. R. (2009). Effects of four weeks of high-intensity interval training and creatine supplementation on critical power and anaerobic working capacity in college-aged men. *The Journal of Strength & Conditioning Research*, *23*(6), 1663-1669.

Kennelly, A. E. (1906, December). An approximate law of fatigue in the speeds of racing animals. In *Proceedings of the American Academy of Arts and Sciences* (pp. 275-331). American Academy of Arts and Sciences.

Kohrt, W. M., O'connor, J. S., & Skinner, J. S. (1989). Longitudinal assessment of responses by triathletes to swimming, cycling, and running. *Medicine and Science in Sports and Exercise*, *21*(5), 569-575.

Kolbe, T., Dennis, S. C., Selley, E., Noakes, T. D., & Lambert, M. I. (1995). The relationship between critical power and running performance. *Journal of sports sciences*, *13*(3), 265-269.

Koppo, K., & Bouckaert, J. (2002). The Decrease in the $\dot{V}O_2$ Slow Component Induced by Prior Exercise Does Not Affect the Time to Exhaustion. *International journal of sports medicine*, *23*(04), 262-267.

Kranenburg, K. J., & Smith, D. J. (1996). Comparison of critical speed determined from track running and treadmill tests in elite runners. *Medicine and science in sports and exercise*, *28*(5), 614-618.

La Torre, A., Fiorella, P., Santos, T. M., Faina, M., Mauri, C., & Impellizzeri, F. M. (2012). Criterion and longitudinal validity of a fixed-distance incremental running test for the determination of lactate thresholds in field settings. *The Journal of Strength & Conditioning Research*, *26*(1), 146-151.

Laursen, P. B., Francis, G. T., Abbiss, C. R., Newton, M. J., & Nosaka, K. (2007). Reliability of time-to-exhaustion versus time-trial running tests in runners. *Medicine and science in sports and exercise*, *39*(8), 1374-1379.

Laursen, P. B., & Jenkins, D. G. (2002). The scientific basis for high-intensity interval training. *Sports Medicine*, *32*(1), 53-73.

Leger L, & Boucher R. (1980). An indirect continuous running multistage field test: the Universite de Montreal track test. *Canadian Journal of Applied Sport Science.* 5:77–84.

Londeree, B. R. (1997). Effect of training on lactate/ventilatory thresholds: a meta-analysis. *Medicine and science in sports and exercise*, *29*(6), 837-843.

Manzi, V., Iellamo, F., Impellizzeri, F., D’Ottavio, S., & Castagna, C. (2009). Relation between individualized training impulses and performance in distance runners. *Medicine and science in sports and exercise, 41*(11), 2090-2096.

Margaria, R., Aghemo, P., & Pinera Limas, F. (1975). A simple relation between performance in running and maximal aerobic power. *Journal of Applied Physiology, 38*(2), 351-2.

Margaria, R., Oliva, R.D., di Prampero, P.E. & Cerretelli, P. (1969). Energy utilization in intermittent exercise of supramaximal intensity. *Journal of Applied Physiology,* 26, 752-756.

Mauger, A. R., Jones, A. M., & Williams, C. A. (2009). Influence of feedback and prior experience on pacing during a 4-km cycle time trial. *Medicine and science in sports and exercise*, *41*(2), 451-458.

Mauger, A. R., & Sculthorpe, N. (2012). A new $\dot{V}O_{2\,max}$ protocol allowing self-pacing in maximal incremental exercise. *British journal of sports medicine*, *46*(1), 59-63.

McDermott, K. S., Forbes, M. R., & Hill, D. W. (1993). Application of the critical power concept to outdoor running. *Journal of the American College of Sports Medicine*, *25*(5), S109.

McLellan, T. M., & Cheung, K. S. (1992). A comparative evaluation of the individual anaerobic threshold and the critical power. *Medicine and Science in Sports and Exercise*, *24*(5), 543-550.

Micklewright, D., Papadopoulou, E., Swart, J., & Noakes, T. (2010). Previous experience influences pacing during 20 km time trial cycling. *British journal of sports medicine*, *44*(13), 952-960.

Miura, A., Kino, F., Kajitani, S., Sato, H., & Fukuba, Y. (1999). The effect of oral creatine supplementation on the curvature constant parameter of the power-duration curve for cycle ergometry in humans. *The Japanese journal of physiology*, *49*(2), 169-174.

Miura, A., Sato, H., Sato, H., hipp, B. J., & Fukuba, Y. (2000). The effect of glycogen depletion on the curvature constant parameter of the power-duration curve for cycle ergometry. *Ergonomics*, *43*(1), 133-141.

Miura, A., Shiragiku, C., Hirotoshi, Y., Kitano, A., Endo, M. Y., Barstow, T. J., ... & Fukuba, Y. (2009). The effect of prior heavy exercise on the parameters of the power-duration curve for cycle ergometry. *Applied Physiology, Nutrition, and Metabolism*, *34*(6), 1001-1007.

Monod, H. (1972). How muscles are used in the body. *The structure and function of muscle*, *1*(Part I).

Monod, H., & Scherrer, J. (1965). The work capacity of a synergic muscular group. *Ergonomics*, *8*(3), 329-338.

Moritani, T., Nagata, A., Devries, H. A., & Muro, M. (1981). Critical power as a measure of physical work capacity and anaerobic threshold. *Ergonomics*, *24*(5), 339-350.

Morton, R.H. (1996). A 3-parameter critical power model. *Ergonomics, 39*(4), 611-619.

Morton, R. H. (2006). The critical power and related whole-body bioenergetic models. *European journal of applied physiology*, *96*(4), 339-354.

Morton, R. H., & Billat, L. V. (2004). The critical power model for intermittent exercise. *European journal of applied physiology*, *91*(2-3), 303-307.

Mujika, I., & Padilla, S. (2003). Scientific bases for precompetition tapering strategies. *Medicine and Science in Sports and Exercise*, *35*(7), 1182-1187.

Murgatroyd, S. R., Ferguson, C., Ward, S. A., Whipp, B. J., & Rossiter, H. B. (2011). Pulmonary O2 uptake kinetics as a determinant of high-intensity exercise tolerance in humans. *Journal of applied physiology*, *110*(6), 1598-1606.

Nebelsick-Gullett, L. J., Housh, T. J., Johnson, G. O., & Bauge, S. M. (1988). A comparison between methods of measuring anaerobic work capacity. *Ergonomics*, *31*(10), 1413-1419.

Nevill, A. M., & Atkinson, G. (1997). Assessing agreement between measurements recorded on a ratio scale in sports medicine and sports science. *British Journal of Sports Medicine*, *31*(4), 314-318.

Nicholson, R. M., & Sleivert, G. G. (2001). Indices of lactate threshold and their relationship with 10-km running velocity. *Medicine and science in sports and exercise*, *33*(2), 339-342.

Nummela, A., Hämäläinen, I., & Rusko, H. (2007). Comparison of maximal anaerobic running tests on a treadmill and track. *Journal of sports sciences*, *25*(1), 87-96.

Palmer, C. D., Jones, A. M., Kennedy, G. J., & Cotter, J. D. (2009). Effects of prior heavy exercise on energy supply and 4000-m cycling performance. *Medicine and science in sports and exercise*, *41*(1), 221-229.

Penteado, R., Salvador, A. F., Corvino, R. B., Cruz, R., Lisbôa, F. D., Caputo, F., & de Lucas, R. D. (2014). Physiological responses at critical running speed during continuous and intermittent exhaustion tests. *Science & Sports*. doi.org/10.1016 /j.scispo. 2014.02.003

Pepper, M. L., Housh, T. J., & Johnson, G. O. (1992). The accuracy of the critical velocity test for predicting time to exhaustion during treadmill running. *International journal of sports medicine*, *13*(02), 121-124.

Péronnet, F. A., & Massicotte, D. (1991). Table of nonprotein respiratory quotient: an update. *Canadian journal of sport sciences*, *16*(1), 23-29.

Pironnet, F., & Thibault, G. (1989). Mathematical analysis of running performance and world running records. *Journal of Applied Physiology*, *67*, 453-465.

Pettitt, R. W., Jamnick, N., & Clark, I. E. (2012). 3-min all-out exercise test for running. *International journal of sports medicine*, *33*(06), 426-431.

Poole, D. C. (1986). Dear Editor-in-Chief. *Medicine and Science in Sports and Exercise*, *18*(6), 703.

Poole, D. C., Ward, S. A., Gardner, G. W., & Whipp, B. J. (1988). Metabolic and respiratory profile of the upper limit for prolonged exercise in man. *Ergonomics*, *31*(9), 1265-1279.

Poole, D. C., Ward, S. A., & Whipp, B. J. (1990). The effects of training on the metabolic and respiratory profile of high-intensity cycle ergometer exercise. *European journal of applied physiology and occupational physiology*, *59*(6), 421-429.

Price, M., & Moss, P. (2007). The effects of work: rest duration on physiological and perceptual responses during intermittent exercise and performance. *Journal of sports sciences*, *25*(14), 1613-1621.

Pringle, J. S., & Jones, A. M. (2002). Maximal lactate steady state, critical power and EMG during cycling. *European journal of applied physiology*, *88*(3), 214-226.

Robinson, D. M., Robinson, S. M., Hume, P. A., & Hopkins, W. G. (1991). Training intensity of elite male distance runners. *Medicine and Science in Sports and Exercise*, *23*(9), 1078-1082.

Rossiter HB (2010) Exercise: Kinetic Considerations for Gas Exchange. *Comprehensive Physiology*: John Wiley & Sons, Inc.

Saltin, B., & Astrand, P. O. (1967). Maximal oxygen uptake in athletes. *Journal of applied physiology*, *23*(3), 353-358.

Scarborough PA, Smith JC, Talbert SM, Hill DW (1991) Time to exhaustion at the power asymptote critical power in men and women. *Medicine and Science in Sports and Exercise*. 23:S12

Seiler, S. (2010). What is best practice for training intensity and duration distribution in endurance athletes. *International Journal of Sports Physiology and Performance*, 5(3), 276-291.

Skiba, P. F., Chidnok, W., Vanhatalo, A., & Jones, A. M. (2012). Modeling the expenditure and reconstitution of work capacity above critical power. *Medicine and science in sports and exercise*, *44*(8), 1526-1532.

Skiba, P. F., Fulford, J., Clarke, D.C., Vanhatalo, A., & Jones, A. M. (2014). Intramuscular determinants of the ability to recover work capacity above critical power. *European journal of applied physiology*, http://dx.doi.org/10.1007/s00421-014-3050-3.

Smith, C. G., & Jones, A. M. (2001). The relationship between critical velocity, maximal lactate steady-state velocity and lactate turnpoint velocity in runners. *European journal of applied physiology*, *85*(1-2), 19-26.

Smith, J. C., & Hill, D. W. (1992). Mathematical Models of the Power-Time Relationship in High Intensity Cycling: 443. *Medicine and Science in Sports and Exercise*, *24*(5), S74.

Smith, J. C., & Hill, D. W. (1993). Stability of parameter estimates derived from the power/time relationship. *Canadian Journal of Applied Physiology*, *18*(1), 43-47.

Smith, T. P., Coombes, J. S., & Geraghty, D. P. (2003). Optimising high-intensity treadmill training using the running speed at maximal O2 uptake and the time for which this can be maintained. *European journal of applied physiology*, *89*(3-4), 337-343.

Smith, T. P., McNaughton, L. R., & Marshall, K. J. (1999). Effects of 4-wk training using Vmax/Tmax on $\dot{V}O_{2\,max}$ and performance in athletes. *Medicine and Science in Sports and Exercise*, *31*(6), 892-896.

Spurway N, Jones AM. Lactate testing. In: Winter EM, Jones AM, Davison RCR, Bromley PD, Mercer TH, eds. *Sport and exercise physiology testing guidelines. volume one: Sport testing.* Oxford: Routledge; 2008:112-119.

Stokes, M. (1985). Reliability and repeatability of methods for measuring muscle in physiotherapy. *Physiotherapy Theory and Practice*, *1*(2), 71-76.

Svedenhag, J., & Sjödin, B. (1985). Physiological characteristics of elite male runners in and off-season. *Canadian journal of applied sport sciences*, *10*(3), 127-133.

Talbert, S. M., Smith, J. C., Scarborough, P. A., & Hill, D. W. (1991). Relationships between the power asymptote and indices of anaerobic and aerobic power. *Medicine and Science in Sports and Exercise*, *23*(4), S27.

Tanaka K, Matsuura Y, Matsuzaka A, Hirakoba K, Kumagai S, O.Sun S, Asano K. A longitudinal assessment of anaerobic threshold and distance-running performance. *Medicine and Science in Sports and Exercise*, 1984;16(3):278-282.

Taylor, S. A., & Batterham, A. M. (2002). The reproducibility of estimates of critical power and anaerobic work capacity in upper-body exercise. *European journal of applied physiology*, *87*(1), 43-49.

Thoden, J.S. (1990). Testing aerobic power. *In Physiological Testing of the High-performance Athlete* (edited by J.D.MacDougall, H.A. Wenger and H.J. Green), pp. 107-175. Champaign, IL: Human Kinetics.

Vandewalle, H., Vautier, J. F., Kachouri, M., Lechevalier, J. M., & Monod, H. (1997). Work-exhaustion time relationships and the critical power concept. A critical review. *The Journal of sports medicine and physical fitness*, *37*(2), 89-102.

Vanhatalo A (2008). The application of the power-duration relationship to all-out exercise. PhD thesis, Aberystwyth University, UK.

Vanhatalo, A., Doust, J. H., & Burnley, M. (2007). Determination of critical power using a 3-min all-out cycling test. *Medicine and science in sports and exercise, 39*(3), 548.

Vanhatalo, A., Doust, J. H., & Burnley, M. (2008). A 3-min all-out cycling test is sensitive to a change in critical power. *Medicine and science in sports and exercise*, *40*(9), 1693-1699.

Vanhatalo, A., Fulford, J., DiMenna, F. J., & Jones, A. M. (2010). Influence of hyperoxia on muscle metabolic responses and the power–duration relationship during severe-intensity exercise in humans: a 31P magnetic resonance spectroscopy study. *Experimental physiology*, *95*(4), 528-540.

Vanhatalo, A., & Jones, A. M. (2009). Influence of prior sprint exercise on the parameters of the 'all-out critical power test'in men. *Experimental physiology*, *94*(2), 255-263.

Whipp, B. J., Huntsman, D. J., Storer, T. W., Lamarra, N., & Wasserman, K. (1982, January). A constant which determines the duration of tolerance to high-intensity work. In *Federation Proceedings* (Vol. 41, No. 5, pp. 1591-1591). 9650 Rockville Pike, Bethesda, Md 20814-3998: Federation Amer Soc Exp Biol.