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A novel approach to the application of critical velocity within soccer

Gordon Dunlop B.Sc. (Hons)
0404728D

Submitted in fulfilment of the requirements for the degree of M.Sc. in Exercise Science

Institute of Biomedical & School of Life Sciences
University of Glasgow

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TABLE OF CONTENTS

ABSTRACT

The relationship between velocity and time to exhaustion is hyperbolic and is defined by two parameters: critical velocity (CV), which represents the highest sustainable work rate; and the curvature constant (*D'*), which is the maximum amount of work that can be performed above CV. An important challenge that needs to be addressed however, before more research is conducted on both the importance of, and understanding of the physiology underlying CV and *D'*, is the protocol implemented for the measurement of these two parameters. At present, the number of exhaustive test bouts required restricts its use in intervention studies and makes its application within team based sports highly impractical.

The main aim of the present study was to validate a novel critical velocity field test protocol that would allow the determination of CV in a single testing session.

Twelve healthy male soccer players (mean ± SD) (22 ± 3yrs; 179 ± 7 cm; 74 ± 9 Kg; 4.5 ± 0.6 $l.min^{-1}$) participated in this study and were randomly assigned to one of two intervention groups: a high intensity aerobic training group (INT) that completed two sessions per week comprising of 4x4 minute high intensity interval training at 90-95% of maximum heart rate (Hf_{max}); or alternatively, a controlled training group (CON), wherein habitual training practices were maintained throughout the 6 week training period. As outlined by the investigation testing protocol, both prior to, and following the completion of each respective 6-week intervention, all subjects performed an incremental exercise test for estimation of peak oxygen uptake (VO_{2peak}) and peak treadmill running velocity (V_{peak}) respectively. Having established V_{peak}, a randomised series of four constant velocity treadmill tests to the limit of tolerance (t_{lim}) were performed for the estimation of CV and *D'*. Each test was separated by a minimum period of 24 hours and was performed at designated work rates elected to span a t_{lim} range of 3 to 20 minutes. Forming the novel element of this investigation, a field based test was also performed pre- and post-intervention. In contrast to the laboratory protocol however, 3 constant velocity tests to t_{lim} were performed simultaneously, separated only by a 15minute recovery period for the determination of the V-t relationship and CV and *D'* respectively.

The results indicated that following the 6 week high intensity aerobic intervention, while a mean significant difference in peak oxygen uptake was displayed in the intervention group pre- to post-intervention (4.36 ± 0.67 vs. 4.50 ± 0.58 $l.min^{-1}$; $P = 0.020$), this was not supported by a mean significant increase in critical velocity (3.65 ± 0.24 vs. 3.72 ± 0.25 $m.sec^{-1}$; $P = 0.355$), post-intervention (lab determined CV values). No significant differences where displayed in either mean peak oxygen uptake (4.65 ± 0.45 vs. 4.56 ± 0.56 $l.min^{-1}$; $P = 0.225$) or CV (3.66 ± 0.49 vs. 3.72 ± 0.52 $m.sec^{-1}$; $P = 0.216$) (lab determined CV values) following the 6 week control intervention. While both protocol estimates for the determination of critical velocity displayed no significant difference pre- to post-intervention for either study group, (3.65 ± 0.24 vs. 3.72 ± 0.25 $m.sec^{-1}$; $P = 0.355$) (INT lab) vs. (3.44 ± 0.10 vs. 3.44 ± 0.22 $m.sec^{-1}$; $P = 0.935$) (INT field) and (3.66 ± 0.49 vs. 3.72 ± 0.52 $m.sec^{-1}$; $P = 0.216$) (CON lab) vs. (3.42 ± 0.28 vs. 3.44 ± 0.32 $m.sec^{-1}$; $P = 0.640$) (CON field) respectively, disparity between laboratory and field derived estimates was evident for both groups, with a significant difference between post-intervention protocol estimates being presented for CV within the INT group (3.72 ± 0.25 vs. 3.44 ± 0.22 $m.sec^{-1}$; $P = 0.018$). Closer inspection of the data revealed little to no agreement between lab and novel field protocols estimates, with the field protocol inherently underestimating CV. Overall the lab protocol performed better than the field protocol, displaying a narrower interval (0.35$m.sec^{-1}$) from which to detect a possible intervention effect relative to that of the field protocol (0.42$m.sec^{-1}$). In concurrence it also provided better reproducibility for CV estimation, exhibiting a higher reproducibility coefficient relative to the field protocol (0.94 vs. 0.81)

The key finding from the present study was that little evidence exists to validate the application of the novel field based protocol to determine critical velocity from a single testing session. The current results indicate that little to no agreement was found between laboratory derived and field test estimates of critical velocity, with the field test inherently underestimating critical velocity. Analysis of the results reveal that the novel field test, relative to the laboratory protocol, offers limited sensitivity and reproducibility to accurately estimate and track changes in critical velocity following a high intensity aerobic training intervention. The large disparity displayed between lab and field protocol estimates implies more research is required into the development of a novel field test that facilitates the accurate estimation of critical velocity from a single test sitting before its application within team based sporting environments can be justified.

LIST OF TABLES

List of Figures

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AUTHOR'S DECLARATION

I declare that this thesis embodies the results of my own special work, that it has been composed by myself and that it does not include work forming part of a thesis presented successfully for a degree in this or another University

DEFINITIONS & ABREVIATIONS

AC – Anaerobic Capacity

ATP – Adenosine Triphosphate

TH_{an} – Anaerobic Threshold

BMI – Body Mass Index

C – Work Economy

CON – Control Group

CP – Critical Power

CV – Critical Velocity

D' – Curvature Constant of Hyperbolic Relationship of Velocity against Time

EP – End-Test Power

ES – End-Test Speed

GPS – Global Positioning System

$[H^+]$ – Hydrogen Ion Concentration

Hf_{max} – Maximum Heart Rate

INT – Intervention Group

$[La^-]$ – Lactic Acid Concentration

LT – Lactate Threshold

MLSS – Maximal Lactate Steady State

MRS – Magnetic Resonance Spectroscopy

P – Power

P_i – Inorganic Phosphate

PCr – Phosphocreatine

Q – Cardiac Output

SV – Stroke Volume

$TAVO_{2\ max}$ – Time To Achieve Maximal Aerobic Capacity

t_{lim} – Time to Exhaustion

V – Velocity

V_e – Ventilation

V_{peak} – Peak Treadmill Running Velocity

vLT – Velocity at Lactate Threshold

VO_2 – Oxygen Uptake

$VO_{2\ max}$ – Maximal Oxygen Uptake

vVO_2 – Velocity at Maximal Aerobic Capacity

W' – Curvature Constant of the Hyperbolic Relationship of Power against Time

WR – Work Rate

CHAPTER 1 - INTRODUTION

1.1 - The Modern Game

Soccer match play has also evolved, and as it is played today, given its acyclical nature and intensity, is presently classified as a high intensity intermittent team sport (McMillan et al., 2004) characterised by its short repeated sprints, rapid accelerations, decelerations, turning, jumping, kicking and tackling (Arnason et al., 2004).

Indeed, three main closely inter linked components of soccer have been identified by Hoff and Helgerud (2004) to provide the required foundation for success within the modern game. They are notably; tactics, individual technique and physical conditioning. In this light, it is now considered a prerequisite that a modern day professional soccer player should ultimately possess high levels of technical skill, tactical understanding, and physical conditioning encapsulating attributes of aerobic endurance (Bishop and Spencer, 2004; Dupont et al., 2005; McMahon and Wenger, 1998), strength (Stolen et al., 2005), power (Wisloff et al., 2004), speed and repeated sprint ability (Bangsbo, 1994; Dupont et al., 2005; Dupont et al., 2010) in order to complement the increasing intensity and performance demands modern match play now requires.

In spite of the literature's emphasis upon the aforementioned components and their importance in achieving success, traditional soccer practices and approaches have tended to gravitate towards and focus primarily on technical and tactical enhancement of players, at the expense of physiological development of physical capacities. An explanation for this predisposition towards traditional practices was offered by Hoff and Helgerud (2004) who explained that a specificity principle has a stronghold within soccer training and also within physiological adaptations in soccer. A logical extension of this would therefore imply that traditional practices would follow the assumption that the most effective strength and endurance training for soccer performance would be playing itself.

However, given the current body of research now established on training responses, it is shown that this is simply not the case, and the relatively modest physiological capacities of top-level soccer players point towards the potential for performance enhancement (Hoff and Helgerud, 2004). Subsequent developments in our understanding of adaptive processes to the circulatory system and endurance performance as well as muscular adaptations to training and performance as a result of this research have given rise to more effective and efficient soccer specific training interventions and practices. This in turn has prompted a transformation in coaching philosophies with a shift towards the use of multipurpose sessions with the intention of maximising the technical, physical development collectively. Additionally, it has also elicited a greater potential in the ability of sports scientists to stress the physiological capacities of modern day elite soccer players and in doing so challenge the physiological limitations related to developing high levels of endurance.

It is imperative that continued emphasis is focused on building upon this existing knowledge of optimising training strategies. This will contribute to further develop our understanding, and ultimately improve the standard and precision to which physical conditioning training can not only be delivered, but individualised, in order to facilitate a more comprehensive physiological assessment and player profiling within professional soccer. It is hoped that in this study, by assessing a broader range of performance indices to provide a more sensitive and detailed physiological profile of soccer players, that the foundations can potentially be laid for the future evaluation of the effectiveness of training practices to elicit a training response in aerobic endurance capacity and essentially match performance.

1.2 – Match Analysis & Physiological Demands of Soccer

In order to gain an accurate impression of the physiological load imposed on players during competitive soccer, observations have to be made during competitive match play and training based scenarios representative of match intensity. In this light, the capacity to understand and analyse match play demands represents an area of great interest to coaches and scientists alike.

Over the last three decades, and particularly in recent years, interest in match analysis of soccer has risen markedly. Technological innovations of data acquisition systems underlie the improvements with respect to type of data and data quality that are becoming readily available to coaches (Bangsbo et al., 1991; Mohr et al., 2003). Evidently, the ability to quantify training and match loading is critical, not only to the process of performance analysis but also training periodisation (Rampinini et al., 2007; Rebelo et al., 2012). Of late, global positioning system technology (GPS) has been extensively implemented within soccer to assist in the delivery of an improved and comprehensive breakdown of the current demands encompassing competitive match play. Recent studies examining the match demands of top level team sports have provided an improved understanding of the requirements encompassing competitive match play in the modern game (Di Salvo et al., 2009; Di Salvo et al., 2010; Bradley et al., 2009; Carling et al., 2012). Importantly these findings tend to identify and agree with the aforementioned philosophy of Hoff and Helgerud (2004) suggesting that the physical, technical and tactical demands of the modern game are intensifying.

Data currently offered on performance and positional benchmarking, as collated via ProZone©, of match analysis from UEFA Champions League and FA Premier League campaigns respectively, highlight that elite soccer players, typically cover in the region of 9500 to 12000m during a standard 90minute match (Di Salvo et al., 2009; Di Salvo et al., 2010; Bradley et al., 2009; Bloomfield et al., 2007) at an average intensity close to the anaerobic threshold, reflecting 80-90% of heart rate max (Hf_{max}), or 70-80% of maximal oxygen uptake ($VO_{2\ max}$) (Helgerud et al., 2001; Hoff and Helgerud, 2004; Hoff and Helgerud, 2002). A review of the literature shows agreement in these recent findings (Bangsbo et al., 1991; Mohr et al., 2003; Rampini et al., 2009; Silva et al., 2011) and follows, that a considerable proportion of this distance will be covered by walking and low intensity running.

Reports have highlighted that collectively, such low energetically taxing (limited energy turnover) activities signify as great as 60-70% of total distance covered during match play (Bloomfield et al., 2007). Values reflecting match performance of top class level Danish soccer players show conformity with this testimony, identifying that walking (41.8%) and jogging (16.7%) activities consolidate to signify a considerable proportion of player activity during match play (Mohr et al., 2003).

While the expression of work rate as a value of total distance covered will provide an insight into the volume of work undertaken and physiological load experienced during match play, in essence, the breakdown of match data in this way will invariably result in the substantial loss of specific information (Helgerud et al., 2001). The breakdown of the work rate activities into defined categories, as displayed above, can provide information more specific to the demands of match play which would otherwise be hidden when only limited match performance data is taken into analytical consideration.

The capacity to communicate high intensity distance covered against performance in soccer is of great benefit, and strong associations have been reported to exist between high intensity distance covered, playing standard and training status (Krustrup et al., 2003; Krustrup et al., 2005). Distance covered at ‘high intensity’ is seen as a valid measure of performance and has been shown to display the sensitivity to differentiate between elite and non-elite opposition and within the top elite professional domain itself respectively (Weston et al., 2011; Harley et al., 2010; Rampinini et al., 2007). A clear example of this is provided by Mohr et al., (2003) who identified that elite high standard international players, categorised by the FIFA ranking of their national team, performed more high intensity running (28%) and sprinting (58%) comparative to their moderate standard international playing counterparts. Moreover, when taking into consideration that total distance covered was only 5% greater in higher standard players relative to their moderate standard contemporaries, Mohr’s findings only serve to accentuate that total distance alone does not adequately discriminate physical performance among different standards of soccer players (Mohr et al., 2003).

Despite only typically accounting for 10% of the total distance covered within competitive match play (Carling et al., 2012; Bradley et al., 2009; Di Salvo et al., 2007; Rampinini., 2009), high intensity and sprinting activity are crucial elements of soccer performance and such efforts are encapsulated within the most decisive moments of match play which are invariably key to shaping the outcome of matches (Di Salvo et al., 2009; Mohr et al., 2003; Bradley et al., 2009). Importantly, in addressing the physical characteristics underlying success within elite professional soccer, both Bangsbo (1994), and more recently Carling et al., (2012) concluded that in addition to possessing the capacity to perform prolonged intermittent exercise (aerobic endurance capacity), elite level players must display the ability to exercise at high intensity and subsequently reproduce these efforts (repeated sprint ability (RSA) (Carling et al., 2012; Iaia et al., 2009).

High intensity and sprinting bouts are of short duration, normally in the region of 2-5s (Stolen et al., 2005)**.** They are frequent in nature with evidence reporting that, per game, between 150-250 intense actions will be performed by the elite level player, with on average, a high intensity effort occurring every 72s (Mohr et al., 2003; Bradley et al., 2009). Significantly, the profound reliance upon anaerobic metabolism to drive these bouts of high intensity activity induces a high rate of adenosine triphosphate (ATP) and phosphocreatine (PCr) breakdown in addition to an accumulation in lactate (facilitating metabolic acidosis via an increase in proton concentration [H^+]) which contributes to the observed development of fatigue during and towards the end of matches and necessitates that a subsequent reduction in playing intensity is required (Krustrup et al., 2003; Boone et al., 2012; Bangsbo et al., 1994; Bangsbo et al., 2007).

Given the cyclical intermittent profile that competitive match play displays, in conjunction with limited recovery between intense bouts, it is therefore unsurprising that Carling and associates (2012) have revealed that as great as 60% of the motion characteristics displayed between consecutive high-intensity actions across match performance is spent walking. The periods of low intensity activities that proceed these high intensity bouts, are of marked importance as they enable players to ‘physiologically’ recover by promoting the removal of fatiguing metabolites and driving the resynthesis of PCr (Bangsbo , 1994), with the speed of this recovery in [PCr] being reflected in the power of the aerobic metabolic capacity possessed by the athlete (Bishop et al., 2004). The capacity to enhance recovery following the performance of high intensity intermittent bouts during match play will effectively contribute to the ability to sustain a high work rate throughout a full competitive match (Helgerud et al., 2001; Balsom, 1994; Bradley et al., 2009).

In consideration of the pivotal role match analysis now plays within modern elite level soccer, it is pertinent that coaches and sport scientists fully utilise the information provided to understand how the increase in the modern match play impacts on players and their respective physiological and performance capacities. By formulating an improved understanding of player and position specific activity profiles in response to match play, sports practitioners will be better placed to focus the way conditioning methods are implemented and prescribed to elicit the intended physiological adaptations necessary to maximise performance and contend with the demands imposed by match play (Hill-Hass et al., 2011).

To summarise, resistance to fatigue is a key factor in the effectiveness of a player's ability to perform at elite level. The modern player should ideally be able to maintain a high level of intensity throughout the entire game. In this respect soccer players should therefore, as a prerequisite of performance, possess high capacities of the aerobic and anaerobic metabolic pathways to contend with match demands. The combined importance of these physical determinants is specific to soccer and in this way soccer training needs to be well balanced and structured to enable adaptation of both these metabolic systems in order optimise player performance.

1.3 – Physiological Determinants of Cardiorespiratory Endurance Performance

For sports such as soccer, in which the aspects underlying performance are heavily reliant on the aerobic capacity of their players, knowledge of how best to develop this component of fitness is essential (Bishop et al., 2004; Dupont et al., 2005; McMahon et al., 1998). Within the construct of the modern game, given the limited time frame amidst a congested schedule, it is imperative that optimal player conditioning can be facilitated within a periodised training structure, to chiefly promote (pre-season) and essentially maintain (in-season) the physiological parameters determining performance throughout a competitive season.

Pate and Krista (1984) have described a model that to date incorporates the three major factors accounting for the inter-individual variance in aerobic performance within soccer. These are namely, maximal oxygen uptake ($VO_{2\ max}$), the “anaerobic threshold” (TH_{an}) [commonly measured as a lactate threshold (LT)], and the work economy (C), with numerous publications supporting this model (Bunc et al., 1989; Helgerud., 1994, Hoff et al., 2002). Essentially a change in any one of these physiological elements will affect performance and as a result, this model has served as a useful framework for the comprehensive study of the aerobic endurance performance of soccer players.

Importantly, as the precision of training interventions implemented within soccer increases, it is necessary to distinguish between changes in the physiological mechanisms that determine aerobic endurance performance (Hoff and Helgerud, 2004). Burnley and Jones (2007), in accordance with their research exploring oxygen uptake kinetics as a determinant of sports performance have proposed the following model:

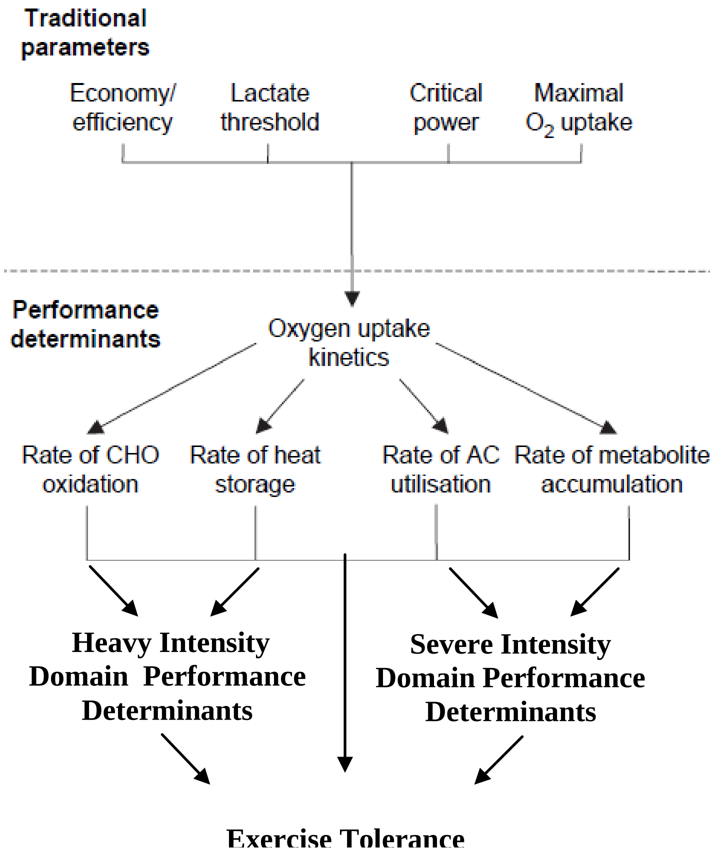


Figure 1: The role of oxygen uptake kinetics in heavy and severe intensity exercise tolerance (Adapted from Burnley and Jones, 2007).

In the model presented above, Burnley and Jones (2007) expanding upon the framework of the aerobic endurance model provided by Pate and Krista (1984), propose that these traditional parameters of physiological function are important because they combine to determine the character of, and place constraints upon, the kinetics of the VO_2 during exercise. The kinetics of oxygen uptake in turn, serves as a channel linking the traditional parameters of aerobic fitness to exercise tolerance by determining a number of performance determinants i.e. the rate if carbohydrate (CHO) oxidation during exercise within the heavy intensity domain or the rate of anaerobic capacity (AC) utilisation and metabolite accumulation during exercise encompassing the severe intensity domain.

As Burnley and Jones (2007) recommend, only by appreciating how these ‘traditional’ parameters of physiological function interact with the kinetics of $VO_{2,}$ to shape the oxygen uptake response profile, across the intensity domains of exercise, can the physiological determinants of performance be fully understood.

Significantly, contrary to the plethora of available literature demonstrating the importance of these 'traditional' aerobic endurance markers within soccer, with numerous investigations presenting the respective significance of maximal oxygen uptake (Stolen et al., 2005; Helgerud et al., 2001), lactate threshold (Edwards et al., 2003; McMillan et al., 2005, Ziogas et al., 2011) and work economy (Hoff and Helgerud, 2002; Saunders et al., 2004; Osteras et al., 2002) to performance, to our knowledge, no research assessing the feasibility of utilising critical power, or more appropriately termed, critical velocity (the running analogue of the critical power concept) as a performance marker within elite professional soccer presently exists.

The tolerable duration of high intensity exercise has been well described as a hyperbolic function of external power which asymptotes at critical power (Moritani et al., 1981; Poole et al., 1988). More pertinently, it has been proposed that critical power (velocity) demarcates the boundary between the heavy and severe intensity domains (Poole et al., 1988; Whipp, 1996) and thus, has been suggested to maintain an important role in determining the character of, and placing constraints upon the kinetics of VO_2.

The theoretical construct of the critical power concept, as offered through the hyperbolic relationship between power (P) and velocity (V) and time to exhaustion (t_{lim}) is seen as a fundamental property of exercise performance (Monod and Scherrer, 1965; Moritani et al., 1981; Poole et al., 1988; Jones et al., 2008; Burnley and Jones, 2007; Ferguson et al., 2010) and is described by the following equation:

$$t_{lim} = W' / (P - \mathrm{CP})$$

With this relationship being defined by two constants: the previously mentioned power-asymptote termed critical power, and the curvature constant *W'*. The curvature constant of the hyperbola, *W'*, is mathematically equivalent to the total amount of work that can be performed above critical power (CP) such that the magnitude of this work capacity remains constant regardless of the chosen work rate above critical power (Monod and Scherrer, 1965; Moritani et al., 1981; Whipp et al., 1981; Hughson et al., 1984; Poole et al., 1988). Traditionally, the literature has considered *W'* to reflect the finite energetic contributions from muscle phosphocreatine (PCr), stored O_2 and muscle glycogen (Hill, 1993; Monod and Scherrer, 1965; Moritani et al., 1981). However, more recent evidence suggests *W'* may be related to the accumulation of fatigue inducing metabolites (e.g. intramuscular inorganic phosphate and H^+, interstitial K^+) to a fixed critical limit during high intensity exercise (Coats et al., 2003; Ferguson et al., 2010).

In turn, critical power has been defined as the upper limit for which a steady state in $VO_{2,}$ arterial acid-base status and intramuscular phosphocreatine and inorganic phosphate can be achieved, without drawing continuously on *W'* (Poole et al., 1988; Jones et al., 2008; Ferguson et al., 2010; Ferguson et al., 2007). Critical power thereby constitutes a crucial threshold for intramuscular energetics control.

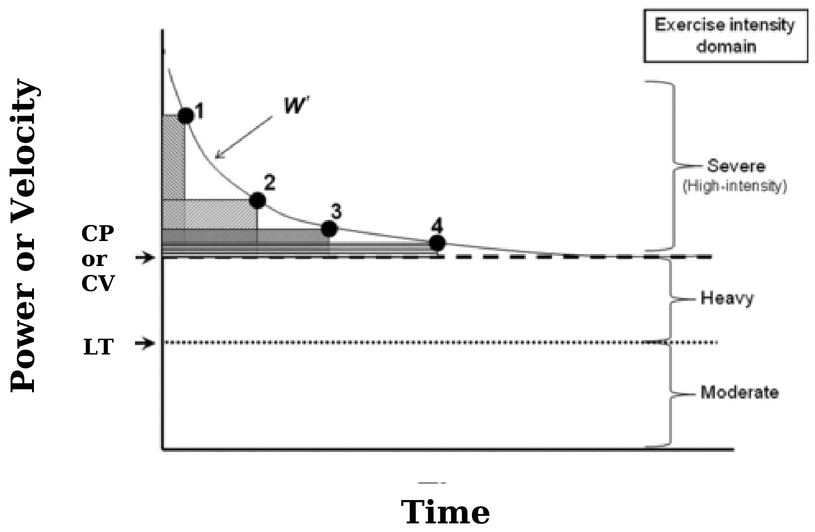


Figure 2: Schematic of the power-time (*P-t*) relationship for high intensity exercise illustrating the location of the lactate threshold (LT) relative to critical power (CP) for healthy, physically active young men across the intensity domains of exercise (taken from Jones et al., 2010).

Because of the functional significance of critical velocity, its position relative to other signatory parameters of aerobic function, namely the lactate threshold and $VO_{2\,max}$ is of great importance. Critical velocity therefore represents a significant parameter of aerobic function and one that provides an invaluable framework in which to study and explore more fully the mechanisms of fatigue and exercise intolerance (Jones et al., 2010).

In consideration of the wider research goal of this thesis, to develop the physiology based sport science strategy implemented within soccer, it is our philosophy that the incorporation critical velocity as a marker of aerobic endurance capacity within soccer is merited, and will assist in providing a more sensitive and detailed physiological profile of elite professional soccer players.

This in turn forms the main research focus of the present investigation with the subsequent chapters providing an insight to the historical and mechanistic bases of the critical power concept while using the supporting literature available to offer justification to its potential application within soccer

CHAPTER 2 – LITERATURE REVIEW

2.1 Origins of Critical Power Concept

In the latter half of the twentieth century it was recognised that, for high intensity exercise, time to exhaustion increases as a predictable and hyperbolic function of decreasing velocity (V) or power (P) (Moritani et al., 1981; Poole et al,. 1988). Inspired by the pioneering research of Monod and Scherrer (1965), through which the origin of the critical power model was first derived. The succeeding investigations of Moritani et al., (1981) and Hughson et al., (1984) thereafter, facilitated the extension of Monod and Scherrer's two-parameter linear work time relationship model concept to whole body exercise for cycling and running respectively and importantly helped support that the proposed shape of this relationship represented the properties and capabilities of both aerobic and anaerobic energy systems as originally elucidated by Monod and Scherrer (1965).

Exercise energetics has since been extensively researched (Busso et al., 2010; Morton, 2006), with numerous post hoc interpretations of the critical power concept allowing a more comprehensive understanding of its proposed physiological underpinnings and importantly its implications with respect to exercise performance (Dekerle et al., 2008).

As offered, the work rate asymptote of this hyperbolic relationship has been termed the critical power, while the curvature constant represents the total amount of work that can be performed above the CP and is referred to as the *W'*. Moritani et al., (1981) proposed that the CP represented the highest sustainable rate of aerobic metabolism and that exercise below the critical power could be sustained indefinitely. In contrast, sustained exercise above critical power requires the utilisation of the finite *W'* at a predictable rate until it is expended, at which point exercise cannot be maintained at the same intensity.

The examination of the boundaries between fatiguing and non-fatiguing whole body exercise has subsequently been thoroughly investigated, and as demonstrated in the previous chapter, it is now established that exercise can be performed within, and across three distinct intensity domains. Defined on the basis of their characteristic metabolic profile responses during constant-work rate exercise, these domains have been classified as moderate, heavy and severe (Vanhatalo et al., 2007; Carter et al., 2002; Dekerle et al., 2008). Imperatively the physiological responses which encompass these domains are very specific and consequently promote different adaptations to training (Carter et al., 2002; Caputo and Denadai, 2009).

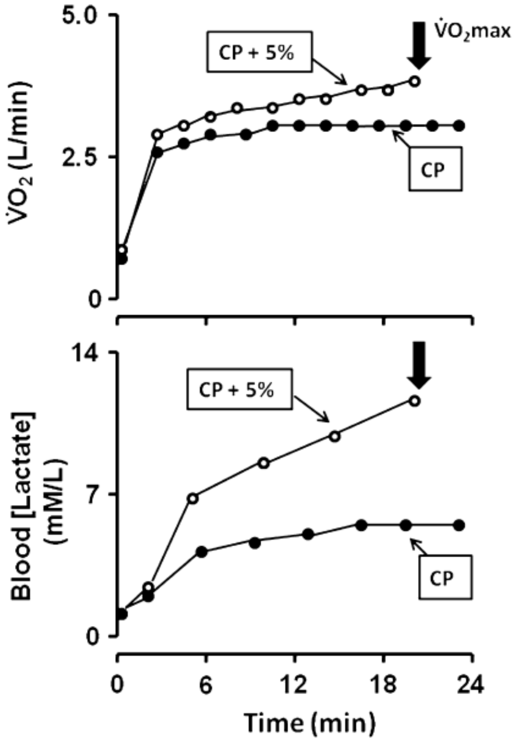
The boundary demarcating the transition from the heavy to the severe exercise intensity domain has been proposed to represent the highest exercise intensity that can be sustained without a progressive increase of anaerobic contribution. In agreement, the literature has demonstrated that at exercise intensities corresponding to the severe domain, a physiological steady state cannot be maintained, with blood [lactate] and VO_2 being shown to progressively increase reaching their maximum at exhaustion (Caputo and Denadai, 2009; Gaesser and Poole, 1996; Dekerle et al., 2005). Understanding how the different exercise intensity domains and their corresponding VO_2 profiles and metabolic responses link with the mechanisms of fatigue and manipulate exercise tolerance is of particular importance and therefore, the measurement of the boundary between each exercise intensity domain is fundamental for optimising training design.

It has been advocated that critical power represents this boundary separating those exercise intensities for which a physiological steady state is attainable (heavy intensity domain) from those exercise intensities for which it is not (severe intensity domain)(Poole et al., 1988; Gaesser and Poole, 1996; Jones et al., 2010; Jones et al., 2008). Support for this position was demonstrated with respect to the correlations displayed between critical power and the maximal lactate steady state (MLSS), a physiological indice also considered to demarcate this boundary (Whipp et al., 2005; De Lucas et al., 2012; Mclellan and Cheung, 1992; Beneke et al., 2003).

To endorse this belief, it has been essential to examine the physiological responses of exercise at CP in order to discern its physiological underpinnings and confirm the theoretical foundation of this concept. Poole et al., (1988), in attempting to elucidate a physiological basis of critical power, demonstrated that when undertaking cycle ergometer exercise at critical power, ~ 80% $VO_{2\ max,}$ approximately midway between the lactate threshold and $VO_{2\ max,}$ subjects failed to achieve maximal aerobic capacity, with $VO_{2,}$ blood [La^-] and pH attaining steady state values. Specifically, at critical power, the VO_2 profile demonstrated a delayed yet pronounced slow component rise that was superimposed on the rapid initial primary phase II increase, which following several minutes of exercise at critical power, levelled off. The emergence of the VO_2 slow component, with the heavy intensity domain represents an additional O_2 cost higher than that predicted from the linear relationship between VO_2 and intensity characterising the moderate domain, which drains the body of its fuel stores more rapidly than if it were not present (Ferguson et al., 2007; Burnley and Jones, 2007). While the mechanistic basis for this apparent metabolic inefficiency is not fully understood, with authors suggesting that is development is located at the muscular level with the fatigable type II muscle fibres being offered as a plausible catalyst for its emergence (Gaesser and Poole et al., 1996; Hull et al., 2008; Barstow et al., 1996; Carter et al., 2000). What is understood is that exercise which elicits the development of the VO_2 slow component is poorly tolerated (Burnley and Jones, 2007)

As depicted below in Figure 2, a markedly contrasting metabolic response profile was displayed when Poole and associates (1988) manipulated exercise intensity to represent a work rate 5% above the critical power threshold. The previously observed stabilisation in VO_2, when exercise was performed at critical power was no longer evident, with the amplitude of the slow component being much higher than those characterising heavy intensity domain intensities. As such, a steady state response in VO_2 failed to materialise resulting in an inexorable rise in VO_2 toward its maximum, which was mirrored by a progressive decrease in pH and an increase in blood [lactate] until exercise cessation.

Figure 3: Group mean oxygen uptake (VO_2) (*top panel*) and blood [lactate] (*bottom panel*) responses to constant-power exercise at CP (*solid symbols*) and 5% above CP (*open symbols*). Arrows denote point of fatigue for CP +5% bout (taken from Jones et al., 2010).



On the bases of Poole's investigation, critical power was systematically shown to represent the upper boundary of the heavy exercise intensity domain and the lower boundary of the severe intensity domain, with distinct pulmonary gas exchange and blood acid-base profiles above and below critical power. Moreover, it was further demonstrated that when the power output was adjusted to represent a work rate greater than critical power, $VO_{2\ max}$ was attained, with the tolerable duration of work being highly predictable from the P-t relationship (Jones et al., 2010).

In contrast to these findings, there exists a degree of contention within the literature to suggest that critical power may not actually accurately define this boundary, with research not always supporting the physiological responses that are expected to be evoked at critical power. Investigators have reported blood [La^-] and VO_2 to increase over time during constant load exercise performed at critical power and therefore contradict the strong correlation previously shown with MLSS (Brickley et al., 2002; Jenkins and Quigley, 1990). This finding is line with many authors who argue that critical power represents an intensity threshold that slightly exceeds that of the MLSS (Housh et al., 1991) and implies that critical power may not be the maximal steady state exercise that can be maintained for a very long time (Brickley et al., 2002; Bull et al., 2000), with Brickley et al., (2002) proposing that critical power represents the "*highest non-steady-state intensity that can be maintained for a period in excess of 20 minutes, but generally no longer than 40 minutes"*.

The original belief that CP (CV) was sustainable for a very long period of time therefore seems to be misinterpretation of its mathematical and not physiological definition of CP (CV) (i.e. the intensity that can be maintained indefinitely) (Dekerle et al., 2008). The research of Hill and Smith, (1994), Hill and Ferguson (1999) and Hill et al., (2002) who investigated the hyperbolic relationship between power and the time to achieve $VO_{2\ max}$ ($TAVO_{2\ max}$) to establish the intensity domains at which $VO_{2\ max}$ can be attained, provide direct support for Poole et al., (1988) hypothesis. Both investigations confirmed, that the asymptote of this new relationship which they donated ($P'_{critical}$), represented a sustainable threshold intensity above which $VO_{2\ max}$ could, in theory, be elicited and corresponded to the lower boundary of the severe intensity domain. This asymptote was found to be identical to critical power. Gaesser and Poole (1996) reinforced these findings through their investigations of [La^-] and VO_2 kinetics across a variety of exercise intensities, encapsulating all three exercise domains. They confirmed that the transition from steady state to non-steady state exercise was demarcated by critical power. In recognition of these findings it may be more appropriate to affine the definition of CP as the highest intensity that is sustainable for a prolonged duration without eliciting $VO_{2\ max}$, that is, the lower boundary for severe exercise.

As described above, whether a metabolic steady state is attained or not has important implications for the development of muscular fatigue and exercise tolerance. While on the basis of the these distinct blood acid-base and pulmonary gas exchange profiles, CP (CV) has now been accepted as an important boundary of exercise intensity, with corresponding implications for the predominant mechanism(s) of muscular fatigue and the tolerable duration of exercise (Jones et al., 2008; Jones and Poole, 2005; Whipp and Rossiter, 2005). Only recently, has the mechanistic bases of the critical power boundary, at the level of the contracting muscle been addressed.

Having originally been established for small muscle group exercise, the contention that underpinning the P-t relationship is muscle energetics seems reasonable. Jones et al., (2008) investigated this contention using ^{31}P magnetic resonance spectroscopy (^{31}P MRS) to examine the temporal profile of the muscle metabolic response profile to prolonged exercise above and below critical power during separate knee extension trials.

In line with the findings of Poole et al., (1988), all subjects completed the exercise protocol, exhibiting only slight metabolic perturbations with steady state responses in [PCr], pH and [P_i] being achieved within 1-3mins of exercise, when the exercise protocol was performed 10% below critical power. In contrast, when the intensity of the protocol was increased to encompass a work rate 10% above critical power, thereby signalling a transition in the severe intensity domain, the tolerable duration incurred within the subject cohort was on average, 14.7 ± 7.1 minutes. This evident inability to complete the knee extension protocol was married with the concurrent fall in [PCr] and pH and progressive increase inorganic phosphate [P_i]. These findings established CP as a boundary above which intramuscular [PCr], [P_i] and pH cannot be stabilised. The distinct response recorded above and below CP within a very narrow range of work rates (CP ± 2W) demonstrate the existence of a critical threshold at CP for muscle metabolic control beyond which a physiological steady state is unattainable.

In view of the fact that Jones et al., (2008) did not resolve whether these variables would reach the same low values at exhaustion at different work rates within the severe domain. Vanhatalo et al., (2010) performed exhaustive single-leg knee extensions across a range of work intensities encompassing the severe intensity domain. It was identified that upon exhaustion, no significant difference was observed in intramuscular [PCr] and pH across a range of severe domain work rate intensities, with measures of these markers consistently achieving a low, potentially limiting value respectively. These findings helped solidify the research of Jones et al., (2008) and demonstrate the existence of a critical threshold at CP for muscle metabolic control beyond which a physiological steady state is unattainable.

In acknowledgement of these studies, performance of high intensity exercise above critical power therefore signifies the utilisation of *W*'. As previously suggested, the physiological equivalents of *W*' are primarily reflected by the available intramuscular PCr and glycogen thereby characterising a fixed anaerobic reserve, whose depletion is thought to exhibit some degree of proportionality to the magnitude of the velocity or power output requirement above critical power or velocity, thus shaping high intensity exercise tolerance (Moritani et al., 1981; Poole et al., 1988). This therefore corresponds well with suggestion by some investigators that *W'* is synonymous with the maximal O_2 deficit (Hill, 1993), anaerobic work capacity (Moritani et al., 1981; Jenkins and Quigley, 1991; Dekerle et al., 2005; Green et al., 1994).

The observations that *W'* can be influenced by interventions such as creatine loading to elevated muscle phosphocreatine concentration (Miura et al 1999), while the depletion of muscle glycogen stores (Miura et al., 2000) and prior exhaustive exercise (designed to reduce intramuscular PCr stores) decrease *W'* in the absence of altered CP (Ferguson et al., 2010, Ferguson et al., 2007) demonstrate consistency with the theory that *W'* represents a finite energy store, whose utilisation shapes high intensity exercise tolerance.

The physiological basis of *W'* however, remains controversial and as such, alternative proposals have been offered to explain the physiological correlates underpinning *W'*. In accordance Jones et al., (2008) findings, that in combination with progressive decreases in [PCr] and pH, metabolite accumulation, as demonstrated through marked rise in [Pi], may have possibly been responsible for, or at least contributed to, the limited exercise tolerance above CP. The complex recovery kinetics of W' displayed by Ferguson et al., (2010) suggests W' reconstitution is not linear as the mathematical definition of this model would suggest, but it rather curvilinear with its physiological basis thereby more closely reflecting the build-up of fatigue inducing metabolites to some critical limit rather than the expenditure of a simple source of stored energy. As offered by Ferguson et al., (2010) it is possible however that an integrated function of the depletion of immediate energy stores in combination with the accumulation of fatigue related metabolites better reflects exercise tolerance during exercise encompassing the severe intensity domain. It does seem that the model of *W'* as a depletable energy pool is likely to be too simplistic.

Collectively, the recent MRS investigations have extended our knowledge of the mechanistic bases of the P-t relationship. Specifically it is now known that critical power represents a critical threshold for intramuscular metabolic control, above which exhaustive exercise results in the attainment of consistently low end-exercise pH and [PCr] values irrespective of the chosen work rate within the severe domain.

By means of this introduction to the field of VO_2 kinetics, the relative position of critical power in relation to the exercise intensity domains has been established and has allowed an improved understanding of the determinants limiting exercise performance to be attained. In recognising how the key physiological variables influence the dynamic profile of the VO_2 response to exercise across different intensity domains, and how, in turn, these differences relate to exercise tolerance, allows for a more comprehensive understanding and of exercise physiology.

2.2 The Proposed Applications of Critical Velocity within Soccer

While its implementation may be novel, the application of critical velocity within soccer offers significant promise. In embracing the fundamental physiological elements encompassing modern match play (i.e. the requirement for the elite player to possess high capacities in both aerobic and anaerobic metabolic pathways), and assimilating it with our understanding of the domains of exercise, particularly that of pulmonary gas exchange kinetics and intramuscular metabolic profiles encompassing the transition from heavy to severe exercise intensity domains. It would seem valid to propose that greater attention should be directed towards obtaining a better understanding of critical velocity and its potential utilisation within soccer (Bull et al., 2008).

Pertaining to the earlier evidence justifying the use of high intensity activity (Mohr et al., 2003) within soccer as a key performance indicator of match play much more emphasis is being focused on the capacity to individualise high intensity interval training in intermittent training (Abt et al., 2009). In attempting to define exercise intensity, studies have successfully prescribed intensities based on % Hfmax (95% Helergud et al., 2007; Hoff et al., 2002) a % of VO2 max (Rognmo et al., 2004; Bartlett et al., 2011) or vVO2 max (Billat et al., 1995; Grant et al., 1997; Lacour et al., 1990). It is our opinion which is in line with that of Ferguson et al., (2013) that this practice is totally inadequate if the intended physiological response to the applied conditioning stimulus is to be normalised across a group, as would be warranted within soccer training.

It is the author's interpretation, having established the premise of specific intensity boundaries, that exercising at a generic percentage of $VO_{2\ max}$ or Hf_{max} may not ensure the same exercise stress is experienced. Thus, it is therefore proposed that establishing exercise intensities based on the measurement of the V-t relationship is potentially more functionally valuable than using a discrete physiological construct such as the velocity associated with VO_2 max or a percentage of $VO_{2\ max.}$ This would be a better way within which to ensure every individual is exercising at the same relative intensity and within the same exercise domain, thereby facilitating greater control over the intended physiological response.

The capacity to establish work intensities based on the characterisation of the V-t relationship offers great potential in developing the aerobic capacities of athletes and gives rise to new strategies and approaches with respect to the most effective ways to implement aerobic based training sessions within soccer. Hoff and Helgerud, (2004) argue that specific endurance training regimes of soccer should be targeted towards improving VO_2 max and have proposed that high intensity interval training for 3-8 minutes with a working intensity of 90-95% of Hf_{max} should increase $VO_{2\ max}$, by supporting improvements in maximal cardiac output as a consequence of increasing stroke volume. The effectiveness of using this aerobic interval training design has been well recognised within soccer (Helgerud et al., 2001; Helgerud et al., 2003; Impellizzeri et al., 2006; Ferrari Bravo et al., 2008; Sporis et al., 2008; McMillan et al., 2004)

In appreciating that $VO_{2\ max}$ can be attained when exercising over a range of intensities encapsulating the severe intensity domain, the premise of incorporating critical velocity for prescribing aerobic training becomes evident (Hill et al., 2002). The selection of exercise intensities that are above critical velocity, but constitute an intensity which is closer to lower boundary of severe intensity domain would be more efficient in eliciting $VO_{2\ max}$ for a long duration. This would presumably make the improvements in aerobic capacity more pronounced as the time spent at $VO_{2\ max}$ would be more appreciable, with the cardiovascular system being maximally stressed for longer (Hill et al., 1999).

In consideration of the wider research focus of this thesis, the assessment of a broader range of performance indices to provide a more sensitive and detailed physiological profile of soccer players. There is growing evidence that critical velocity is a better predictor of exercise tolerance than the traditionally measured $VO_{2\ peak}$ and lactate threshold in clinical settings, as well as in determining athletic performance, with strong correlations being demonstrated with 10km and marathon performance respectively (Gamelin et al., 2006; Jenkins and Quigley, 1992; Florence and Weir, 1997). While a wealth of research indicates that a high $VO_{2\ max}$ is a prerequisite for elite level aerobic endurance performance (Reilly et al., 2000), the application of sub-maximal parameters to examine aerobic capacity may actually provide a more sensitive marker of endurance performance when compared against $VO_{2\ max}$ (Bergh et al., 1991; Bently et al., 2007; Grant et al., 1997). The ability to identify and utilise critical velocity as additional sub-maximal aerobic index may be important for the assessment and monitoring of aerobic performance within elite level soccer, particularly in-season, when a plateau in the development of maximal aerobic capacity has been reported to occur (Bangsbo et al., 1994; Edwards et al., 2003).

The recent position taken by Ziogas and associates (2011) offers that sub-maximal aerobic indices may provide greater discriminatory power relative to $VO_{2\ max}$ in the assessment of soccer teams from divisions of differing playing standard. They found that, the velocity associated with the lactate threshold (vLT) was the only physiological marker that showed a significant difference throughout all teams across the pre-season period, with a higher velocity being inferred with respect to the division of the team. In light of these findings, more emphasis may now be placed upon the adoption of sub-maximal aerobic parameters within elite level soccer.

Critical velocity has been demonstrated to increase as a consequence of short continuous endurance based training (Jenkins and Quigley, 1992) or following the undertaking high intensity interval training (Poole et al., 1990; Gaesser and Wilson, 1988; Vanhatalo et al., 2008; Machado et al., 2011; Clark et al., 2013). By comparison *D'* has been reported not to change following high intensity interval training (Vanhatalo et al., 2008; Poole et al., 1990) with this parameter seemingly more receptive to sprint training, with enlargement of this capacity demonstrated following short term sprint interval training (Jenkins and Quigley, 1993). The measurement of changes in the V-t relationship after a training intervention is likely to be functionally more valuable than measurements of discrete physiological constructs such as maximal aerobic capacity or the lactate threshold (Jones et al., 2010). Essentially, when taking the parameters of CV and *D'* to reflect distinctive aerobic and anaerobic qualities respectively, the application of the critical velocity concept could potentially allow metabolic strengths or weaknesses to be addressed as has recently been conducted by Clark et al., (2013).

It is paramount to understand how different training intensities and practices will influence adaptations in physiological parameters when selecting an optimum training regimen, and how in turn these adaptations will potentially manifest themselves in actual performance. In this light, it is proposed that the application of the critical velocity construct to soccer, while novel, could be potentially advantageous in respect to refining the physiological profiling of players, serving as a physiological marker of aerobic and anaerobic capacities and as conditioning tool in aiding the formulation of individualised high intensity interval running sessions (Aguiar et al., 2012, Berger et al., 2006).

However, a major challenge which needs to be addressed before more work is conducted on both the importance of, and understanding of the physiology underlying CV and *D'* is the protocol adopted for their determination. Presently, the number of tests required limits its use in intervention studies and makes further investigations of CV and *D'* hugely difficult and potentially subject to a training effect. In this light, within the construct of the modern game, given large playing squads and the limited time frame amidst a congested schedule, it comes as no real surprise that the application of the critical velocity concept has not been merited.

With this in mind, we introduce the main aim of this study, the development a novel critical velocity field test protocol that would allow the determination of critical velocity in a single test. To assess the validity of this novel protocol, the field test estimations of CV will be compared against the estimates of a gold standard gold standard laboratory based protocol, both before and following a high intensity running intervention.

CHAPTER 3 - METHODOLOGY

3.1 Subjects

12 male soccer players participated in the study. All players were in good health and free from injury at the time of testing and were considered to be all physically active, participating in regular aerobic training at least twice a week. Their mean ± standard deviations (SD) for age, body mass, height and maximal aerobic capacity were 22 ± 3 years, 74 ± 9 kg and 179 ± 7 cm, 4.51 ± 0.6 $l.min^{-1}$ respectively. The sample of players collected in the study represented all outfield playing positions, that is: central defenders (N = 3), fullbacks (N = 2), central midfielders (N = 3), wide midfielders (N = 2), and attackers (N = 2) and were assigned to one of two groups, the intervention group (INT, N = 6) or the control group (CON, N = 6).

All players were informed of the testing procedures and protocols, without disclosing the aims of the study, and were required to provide written informed consent, approved by the University of Glasgow Ethical Committee, to participate in the study. According to the guidelines of this committee, players were required to complete an approved Medical Questionnaire to identify any medical condition(s) which may predispose them to risk during subsequent exercise testing. Based on the findings of this questionnaire and a mandatory blood pressure examination prior to assessment, any players deemed unsuitable, were excluded from participation within the study.

The study was initiated during the competitive soccer season (September - May) and required the completion of a battery of laboratory and field based assessments at the commencement and completion of a 6 week high intensity aerobic interval training program. Data collected from those players who missed one or more testing sessions was also excluded from the analysis. In total (N = 12) players were available at all of the testing sessions and their physical characteristics are presented in Table 1 (see result section 4.2).

3.2 Equipment

Prior to the commencement of any test performance, all equipment was thoroughly checked and where appropriate, calibrated against appropriate known standards to minimise any possible measurement error when measuring and analysing results.

Laboratory:

All laboratory testing procedures took place in the Human Exercise and Performance Laboratory in the West Medical Building at the University of Glasgow and were conducted on a motorised, programmable treadmill (PPS55 Med – I, Woodway, Birmingham, UK). During all testing sessions, subjects were required to breathe through a two-way, non-rebreathing Hans-Rudolf mouthpiece into a Douglas bag for expired gas collection (collection time typically 60 seconds). Following the completion of the required test expired gas samples were then analysed for O_2 and CO_2concentrations (Servomex 4100, Servomex, Sussex, UK), with gas volume determined using a dry gas metre (Harvard Dry Gas Meter, Birmingham, UK), thus, enabling calculation of pulmonary gas exchange variables VO_2, VCO_2, V_e. Additionally, subjects were required to wear heart rate monitors throughout the duration of testing (S610i, Polar, Kempele, Finland) with heart rate being monitored and recorded after every minute.

Field and High Intensity Aerobic Intervention:

Field based testing and the high intensity aerobic intervention took place at the training facilities (3rd generation artificial field-turf pitch) of the players involved in the study. In both testing protocols, subjects were required to run on specifically designed tracks (Figure 6) whilst wearing heart rate monitors throughout the duration of testing (S610i, Polar, Kempele, Finland). Heart rate was continuously monitored and recorded via a telemetry heart rate monitoring system (Fitpulse, TechnoElletraImpianti, Italy).

3.3 Protocols

For each subject, only one exercise test was conducted on a given day, therefore requiring a total of 12 testing sessions per subject (i.e. 5 lab based tests and 1 field based test pre and post completion of the high intensity intervention), with each individual participating in no more than 3 experimental sessions in any given week.

In an attempt to minimise any extraneous influence on performance, subjects were tested as near as possible to the same time of day on each occasion and were required to refrain from participating in strenuous physical activity and alcohol ingestion in the preceding 24hr and 48hr periods respectively prior to testing. On the day of testing they were to refrain from caffeine ingestion and arrive following a 3 hour fast.

Protocol 1 – Determination of $VO_{2\ max}$ and $vVO_{2\ max}$ (Laboratory Test)

All subjects were required to perform a maximal incremental ramp test (Figure 4) to the limit of tolerance (t_{lim}) to measure and identify $VO_{2\ peak}$ baseline values. It should be noted that the tolerable limit was defined, for the purposes of this investigation, as the point at which subjects were unable to maintain the required treadmill speed despite strong verbal encouragement to continue running.

The maximal incremental ramp test itself was initiated with a 5 minute stage at a treadmill speed of 2.77 $m.sec^{-1}$ [10$km.h^{-1}$] and gradient incline of 1% to simulate that of the wind resistance experienced from running outdoors. Thereafter the speed of the treadmill was increased in increments of 0.28$m.sec^{-1}$ [1$km.h^{-1}$] every minute, while maintaining the selected 1% gradient until each subject arrived at their limit of tolerance. At this point, when the running speed could no longer be maintained, subjects were required to safely straddle the treadmill belt using the hand rails provided to support their weight, and thus in doing so, signalled the end of the incremental ramp test. The treadmill speed was then reduced to a slow cadence walk (1.11$m.sec^{-1}$ [4$km.h^{-1}$]) allowing the commencement of a period of active recovery until the subject had sufficiently recovered and felt comfortable to stop.

In addition to determining $VO_{2\ peak}$, the maximal incremental test allowed the identification max heart rate (Hf_{max}) and also importantly peak treadmill running velocity (V_{peak}), which provided an appropriate starting work rate for the determination of the V-t relationship (Protocol 2) to be established.

Protocol 2 – Determination of the V-t relationship (Laboratory Test)

Having established V_{peak}, subjects then completed a randomised series of four constant velocity tests to the limit of tolerance (Figure 4), with each test implemented at a different work rate elected to span a t_{lim} range of ~ 3 to 20 minutes.

The test was initiated with a warm up comprising of a low cadence walk (1.53 $m.sec^{-1}$ [5.5$km.h^{-1}$] with 1% gradient incline) for a duration of 6 minutes. The adoption of a significantly low intensity was essential in the prescription of the warm up, a work rate below critical velocity, as it was vital to ensure predominantly aerobic energy transfer. Having completed the warm up, the speed of the treadmill automatically accelerated to the pre-programmed speed and subjects were required to run to t_{lim} at the selected velocity.

Critical velocity (CV) and curvature constant (*D'*) were estimated as the y-intercept and slope of the line respectively, by linear regression from the velocity vs. t_{lim}^{-1} relationship i.e. $V = (D'/t_{lim}) + CV$ (Hill, 1993; Poole et al., 1988; Ferguson et al., 2007). In instances where the four point V-t relationship was not adequately characterised (defined as the standard error (SE) of the estimate being less than 5% for CV) an additional test was performed at another work rate to improve the confidence of the estimation.

Protocol 3 – Determination of V-t relationship (Field Test)

With reference to three of the studies principal aims:

1. To examine and validate the accuracy of a novel field based test to estimate critical velocity in comparison to that of the gold standard laboratory protocol estimation (protocol 2)

2. To assess the ability of a novel field based test to track improvements in critical velocity following the completion of a 6 week high intensity aerobic training intervention

3. To investigate the sensitivity of a novel field based test to track improvements in critical velocity.

A novel field based test was developed. This test was intended to mimic that of the lab based protocol (Protocol 2) to determine the V-t relationship. Similarly, a randomised series of three constant velocity tests to the limit of tolerance, with each test implemented at a different work rate to span a t_{lim} range of ~ 3 to 20 minutes was performed. The use of three constant velocity tests to estimate CV has been vindicated within the literature (Wilkie, 1980; Brickley et al., 2002); Jones et al., (2008)). Essentially, the four speeds implemented in the establishment of protocol 2 (laboratory protocol) provided a platform from which to assist in speed selection for the field test protocol. Conversely, unlike the lab based test however, where each test was separated by a mandatory minimum period of 24 hours, all 3 constant velocity tests undertaken in the field test were performed in the same session.

The field test itself, took on the form of a continuous shuttle based running test whereby the pre-determined constant velocity speeds were measured out and marked by cones in a specifically designed course (Figure 5). Subjects were required to keep pace with a tape recording of a series of bleeps interspersed by a period of 3 seconds wherein they had to have reached the next shuttle before the time had elapsed, signified by another bleep. Notably, as multiple constant velocity runs were performed, the appropriate running speed of each test was insured by altering the distance between cones, thus producing a required adjustment in subjects running speed to allow them to reach the next shuttle within the designated three seconds.

The session commenced with a warm up of light jogging for 5 minutes proceeded by a period of stretching. Throughout the entire testing session subjects wore heart rate monitors (S610i, Polar, Kempele, Finland) with heart rate being continuously monitored via a telemetry heart rate monitoring system (Fitpulse, TechnoElletraImpianti, Italy). Upon starting, the tape recording counted subjects down with a simple 3, 2, 1, GO, instruction and the test commenced. Subjects, as previously stated, were required to run continuously with the aim of reaching each shuttle within the required 3 second period until achieving t_{lim}. For the purposes of this particular protocol the tolerable limit was defined as the point at which subjects were unable to maintain the required running speed. This was characterised by either voluntary cessation or falling more than one shuttle behind the pace of test maintained by the tape recording, despite strong verbal encouragement to continue running. At cessation, peak heart rate and test duration were recorded.

Upon termination of each test, subjects actively recovered (walking) for 15 minutes before undertaking the subsequent constant velocity test. The 15 minute rest period applied in this protocol is based on evidence in the study by Ferguson et al, (2010) which investigated the effect of recovery duration from prior exhaustive exercise on the parameters of the power-duration relationship. In this study, subjects similarly performed a maximal incremental ramp test and a series of constant load tests to t_{lim}. As the studies central focus was to determine the recovery kinetics of *W'*, further exhaustion tests were performed each being preceded by an exhausting conditioning bout, with intervening recoveries of 2, 6, and 15 minutes. The findings of this study highlighted that post conditioning; the P-t_{lim} relationship remained well characterized by a hyperbola, with critical power remaining unchanged irrespective of rest period duration. However findings suggested, *W'* recovered to 37±5, 65±6 and 86±4 % of control value (control being the anaerobic work capacity (*W'*) value estimated from initial series of constant load tests to t_{lim}) following 2, 6 and 15 minutes of intervening recovery respectively.

Exploration of these results suggests it is evident that a minimum of 15 minutes will be required between field test performances in the present study to produce a large if not full reconstitution in *W'*. To date Ferguson et al, (2010) investigation is the first study to attempt the characterisation of *W'* recovery kinetics and so forms the basis for the methodical structure of the present novel field based critical velocity test.

Training Intervention

The high intensity aerobic training intervention consisted of interval training; comprising 4 sets of 4 minute work intervals running on a specifically designed circuit (Figure 6) (Hoff et al., 2002) on an artificial field-turf pitch. Training cones were used in the design of the circuit, with hurdle height fixed at a height of 30cm. Training intensity was set at 90-95% of each player's Hf_{max} (determined from Protocol 1), with the work periods separated by active recovery periods of 3 minutes at 60 -70% of $Hf_{max,}$ in which subjects were informed to jog slowly around the perimeter of the circuit. All players wore a Polar heart rate belt (Polar Electro, Finland) and heart rates were recorded and monitored continuously using a telemetry heart rate monitoring system (Fitpulse, TechnoElletraInpianti, Italy) throughout the interval training session to ensure that the intensities were being maintained by each subject. In instances where subjects were operating at an intensity which elicited divergence from their pre-determined training zones, subjects were informed to simply either speed up or slow down to produce the appropriate corrective response. As demonstrated by Hoff et al., (2002) the application of heart rate monitoring to observe and maintain player work rate intensity has been established to be a valid measure of actual exercise intensity during training sessions.

The training intervention was performed twice a week at the beginning of the soccer training session, following a comprehensive warm up, on the same days and time of day throughout the intervention period. This is in line with literature suggesting that an increase in aerobic capacity is dependent upon a minimum of two sessions a week (Hoff, 2005). The 6-week intervention period was carried out during the competitive in-season period (March to April).

For subjects assigned to the control group, participation in soccer training sessions and match play was continued in accordance with their habitual soccer training routine, without the supplementation of any additional high intensity endurance training. Subjects were required to adhere to this routine throughout the duration of the study, limiting any additional exercise which may elicit a training effect.

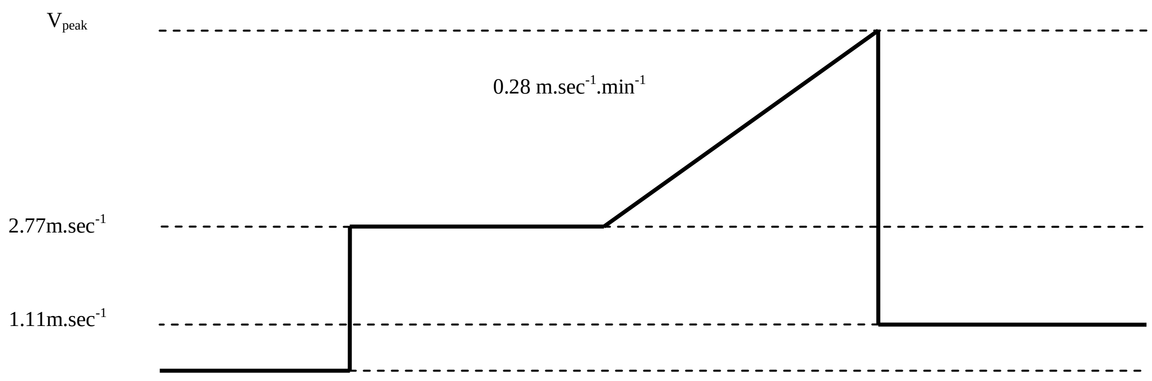
3.4 Analysis

For all laboratory protocols, serial Douglas bag sampling was conducted from the point at which subjects were deemed to be close to achieving exhaustion, with VO_{2peak} taken as the value obtained from the sample taken if VO_{2max} was not achieved. In instances where t_{lim} was achieved with less than 20 seconds into the gas collection period, the previous 60 second sample was taken as VO_{2peak}. If in cases subjects were unable to fulfil the criteria establishing the attainment of VO_{2max}, defined in accordance with the British Association of Sport and Exercise Sciences (BASES) guidelines, VO_{2peak} was denoted. When undertaking Protocol 2, the VO_{2peak} value obtained from the incremental exercise test (Protocol 1) served as a reference value, which helped verify the attainment of VO_{2peak} across each of the 4 constant velocity treadmill tests performed. Taking into account the inter-individual daily variation reported within VO_{2max}, 0.2l was set as the accepted range for certifying VO_{2peak} attainment.

3.5 Statistical Analysis

All results are reported as mean values and standard deviations (SD). Differences from pre- to post training intervention were calculated using paired and 2 sample T-tests, with results accepted as significant at $P < 0.05$. To detect a change pre-to post-treatment or possible bias, scatterplots with the line of equality are provided to assess visually a departure of the estimates from the line of equality (*which represents perfect agreement*). In calculating the reproducibility coefficient for each protocol, reproducibility was defined as the fraction of total variance (i.e. between-subject plus within-subject variance) explained by the between subject variance. Appropriate estimates of these variances were obtained using a generalised linear model incorporating treatment effect, time effect and subject effects. A Bland and Altman plot was produced to assess the level of agreement between the critical velocity estimation protocols. Bland and Altman plots, where the individual subject differences between the two values for each protocol were plotted against the respective individual means, are provided. If the two measurements are comparable, the differences should be small, distributed around zero, and show no systemic variation within the mean of the measurement pairs. These plots allow examination of the direction and magnitude of the scatter around the zero line allowing an informal assessment of possible bias. In order to supplement the Bland-Altman plot with a formal analysis, a 95% confidence interval for the mean difference was calculated and superimposed on the plot.

A



B

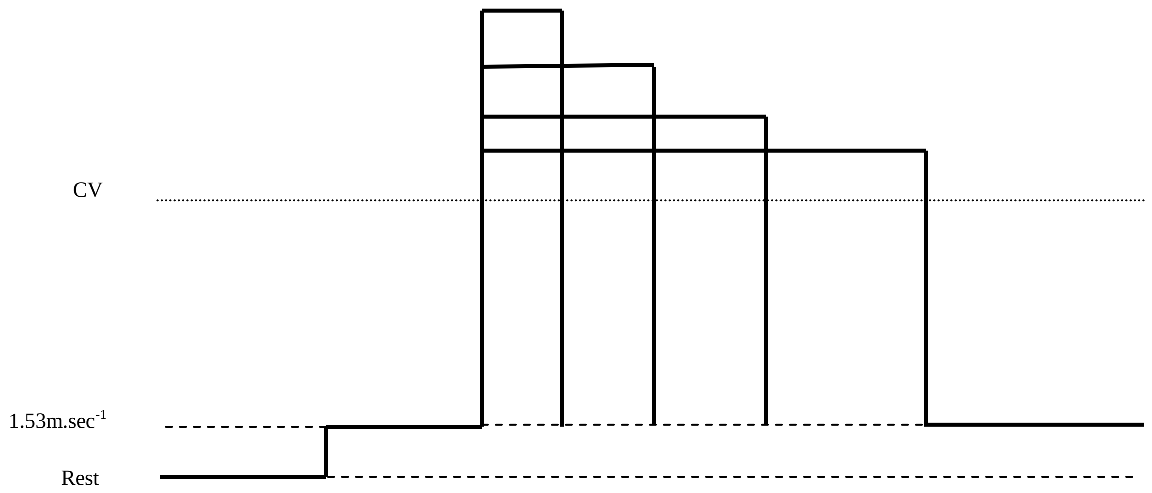


Figure 4: Schematic representation of the protocols performed during each laboratory exercise testing session. *A: Protocol 1*, maximal incremental exercise test. *B: Protocol 2*, series of 4 constant velocity tests, each at different work rates, for determination of the V-t relationship. All tests were performed to the limit of tolerance (t_{lim}). V_{peak}, peak treadmill running velocity; CV, critical velocity.

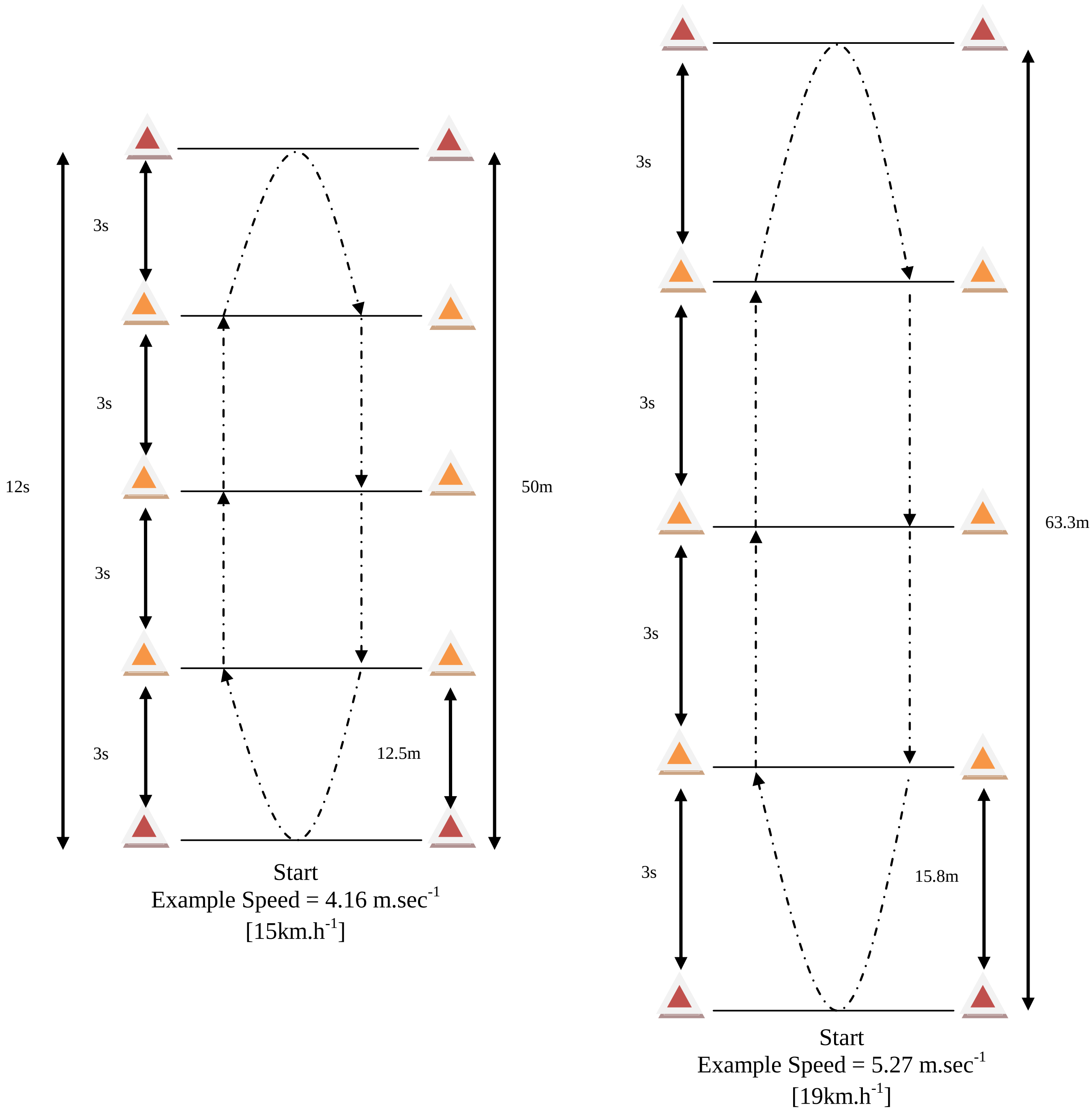


Figure 5: Schematic representation of the novel field based test protocol for the determination of the V-t relationship. The illustration demonstrates an example of 2 potential running speeds utilised to estimate the V-t relationship when adopting the novel field test protocol. Subjects were required to keep pace with a tape recording of a series of bleeps interspersed by a period of 3 seconds wherein they had to have reached the next shuttle before the time had elapsed. Note as the running velocity increases the required distance to be covered in 3 seconds also increases. All tests were performed to the limit of tolerance, with each run being performed consecutively following a 15 minute recovery period.

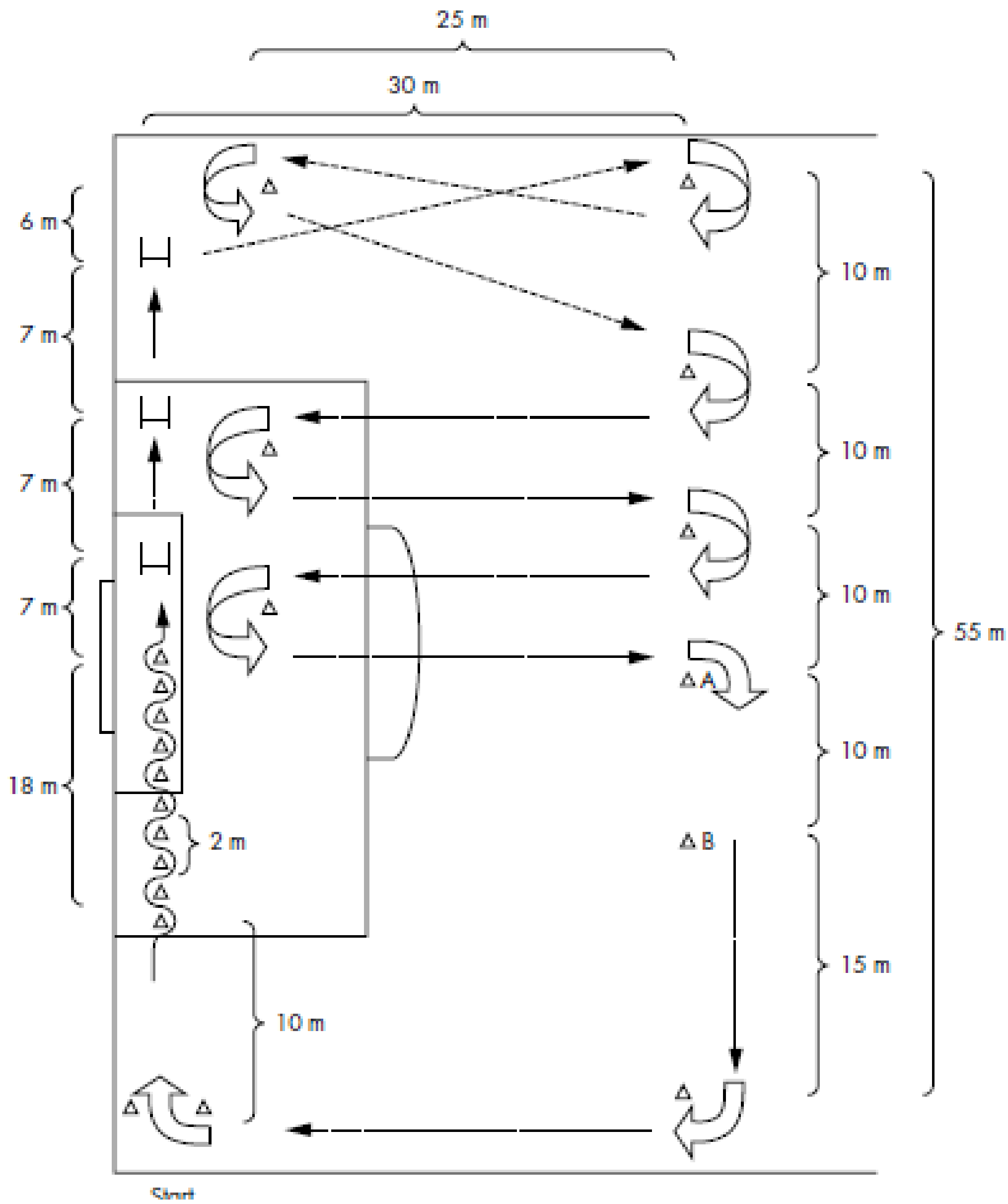


Figure 6: Schematic representation of the soccer specific track for the 6 week high intensity aerobic training intervention (based on Hoff et al., 2002). Players follow the route indicated by arrows. Backwards running occurs between point A and B. Players undertake 4x4 minute work intervals running at an intensity which elicits 90-95% Hf_{max} with each being separated by 3 minutes active recovery at 60-70% Hf_{max}. △ cones; H hurdles 30 cm in height. (Taken from McMillan et al., 2004)

CHAPTER 4 – RESULTS

4.1 Training Compliance

Intervention Group (INT)

During the training period, 4 of the original 10 subjects tested pre-intervention, were excluded from the study due to injuries unconnected with the high intensity training intervention and/or unavailability during post-intervention assessment. The 4 subjects excluded, were withdrawn from statistical analysis.

Of the 6 remaining subjects, each performed the block of 12 high intensity interval sessions scheduled (2 $d.wk^{-1}$) and completed the testing protocols outlining both pre and post intervention assessment. All pre- and post-intervention data from the 6 players are detailed in Table 2

Control Group (CON)

As part of the study protocol, the control group was required to maintain their habitual training activities for a 6 week period. All 6 control subjects completed pre- and post-intervention assessment and their data is described in Table 2

Evaluation of the training diaries of the controls revealed no excess physical activity over the six week intervention period. All subjects conformed well to their habitual training routine as outlined to the investigator prior to undertaking the investigation.

4.2 Physical and Anthropometric Characteristics

Descriptive data of the physical and anthropometric characteristics for both the high intensity aerobic training and control groups, prior to initiating their respective six week intervention programs, is presented in Table 1.

Table 1: A Comparison of the Physical and Anthropometric Attributes Displayed in the High Intensity Training Intervention Group and the Control Group Pre Intervention. Values are sample mean (sample standard deviation; SD).* Significantly different between groups ($P < 0.05$).

Pre intervention	**Intervention Group**	**Control Group**
Age (years)	20.3 (1.0)	23.7 (3.5)
Anthropometric Characteristics		
Height (cm)	180 (7)	177 (7)
Body Mass (kg)	70.6 (9.1)	76.5 (8.4)
Maximal Oxygen Uptake (VO_{2peak})		
$l.min^{-1}$	4.36 (0.67)	4.65 (0.45)
$ml.kg.min^{-1}$	61.7 (3.3)	60.9 (5.9)
Lab Critical Velocity Test Response		
CV ($m.sec^{-1}$)	3.65 (0.24)	3.66 (0.49)
D' (m)	229 (57)	276 (117)

No significant differences ($P < 0.05$) were found between the intervention group and control treatment groups for any of the pre-intervention physical or anthropometric markers derived from laboratory based measurements. While well matched, in terms of anthropometric characteristics, the subjects that formed the intervention group tended to be taller (180 ± 7 vs. 177 ± 7 cm), and lighter (70.6 ± 9.1 vs. 76.5 ± 8.4 kg) in stature than their respective control group counterparts. Comparisons of maximal aerobic capacity as determined via a maximal incremental ramp test (Protocol 1), revealed no significant difference between groups, (4.36 ± 0.67 vs. 4.65 ± 0.45 $l.min^{-1}$; $P = 0.409$). This was also reflected in the investigation's other marker of aerobic capacity critical velocity. Derived from protocol 2 (lab based protocol), critical velocity represented very similar values (3.65 ± 0.24 vs. 3.66 ± 0.49 $m.sec^{-1}$; $P = 0.990$). *D'*, albeit non-significantly, was found to be larger in the control group relative to the intervention group (276 ± 117 vs. 229 ± 57 m; $P = 0.407$).

4.3 Analysis of 6-Week High Intensity Aerobic Training and Control Interventions

A comprehensive breakdown of the results following the implementation of each respective 6 week training intervention (INT group: 6-week high intensity aerobic training, CON group: 6-week controlled training) is provided in the succeeding tables and figures.

Table 2: A comparative analysis of the physiological performance indices measured both pre- and post- intervention for each respective intervention treatment group. Values are sample mean (sample standard deviation; SD); n=6 per group. * Significantly different from pre-intervention; # Significantly different from Laboratory Protocol critical velocity estimate (*P* < 0.05).

	INT (N=6) Training Intervention		**CON (N=6) Training Intervention**	
Physiological Variable	**Pre**	**Post**	**Pre**	**Post**
Body Mass (kg)	70.6 (9.1)	69.7 (8)	76.5 (8.4)	75.8 (7.8)
Maximal Incremental Exercise Test				
VO_{2peak} ($l.min^{-1}$)	4.36 (0.67)	4.50 (0.58)*	4.65 (0.45)	4.56 (0.56)
VO_{2peak} ($ml.kg.min^{-1}$)	61.7(3.3)	64.6 (3.6)*	60.9 (5.9)	60.2 (5.4)
Peak Velocity ($m.sec^{-1}$)	4.91 (0.23)	5.14 (0.23)*	4.96 (0.54)	4.86 (0.46)
Tolerable Duration (s)	720 (45)	774 (45)*	745 (104)	732 (105)
Laboratory Critical Velocity Test				
CV ($m.sec^{-1}$)	3.65 (0.24)	3.72 (0.25)	3.66 (0.49)	3.72 (0.52)
D' (m)	229 (57)	242 (42)	276 (117)	263 (95)
VO_{2peak} $l.min^{-1}$	4.39 (0.58)	4.45 (0.68)	4.58 (0.50)	4.58 (0.54)
VO_{2peak} $ml.kg.min^{-1}$	62.1 (3.2)	63.9 (4)	60.5 (5.8)	60.5 (5.6)
Field Test Critical Velocity Test				
CV ($m.sec^{-1}$)	3.44 (0.10)	3.44 (0.22) #	3.42 (0.28)	3.44 (0.32)
D' (m)	238 (94)	222 (38)	215 (50)	224 (79)

Effect of Intervention Treatment on Maximal Oxygen Uptake & Maximal Incremental Ramp Test

Protocol 1 – Maximal Incremental Exercise test

The 6 week high intensity aerobic training intervention performed by the intervention group (4x4 min at 90-95% Hf $_{max}$) manifested significant improvements in absolute mean peak oxygen uptake of 3.12% (*P* = 0.020). Mean VO_{2peak} increased from 4.36 ± 0.67 to 4.50 ± 0.58 $l.min^{-1}$ (Table 2, Figure 7, 8). In contrast, following the 6 week control intervention, no significant improvement was elicited in absolute mean peak oxygen uptake pre- to post-intervention (4.65 ± 0.45 vs. 4.56 ± 0.56 $l.min^{-1}$; *P* = 0.225)(Table 2, Figure 7, 8).

As body mass was not significantly altered following training in either treatment group INT (70.6 ± 9.1 vs. 69.7 ± 8 kg; *P* = 0.782), CON (76.5 ± 8.4 vs. 75.8 ± 7.8 kg; *P* = 0.298), relative $VO_{2\ peak}$ represented a 4.51 % significant increase from 61.7 (3.3) to 64.6 (3.6) $ml.kg.min^{-1}$ pre- to post-intervention respectively within the INT group (*P* = 0.002). No significant change in relative $VO_{2\ peak}$ was established for the CON treatment group, with values remaining very stable from pre to post analysis (60.9 ± 5.9 vs. 60.2 ± 5.4; *P* = 0.493). No significant difference was reported post-intervention in mean $VO_{2\ peak}$ (4.5 ± 0.58 vs. 4.56 ± 0.56 $l.min^{-1}$; *P* = 0.875) between INT and CON treatment groups.

In line with these findings, significant improvements post-intervention were displayed in V_{peak} (4.91 ± 0.23 vs. 5.14 ± 0.23 $m.sec^{-1}$; *P* = 0.041) and tolerable duration (720 ± 45 vs. 774 ± 45 s; *P* = 0.037) respectively within the INT group, while the CON group displayed no significant change pre- to post-intervention in either V_{peak} (4.95 ± 0.54 vs. 4.86 ± 0.46 $m.sec^{-1}$; *P* = 0.175) or tolerable duration (745 ± 104 vs. 732 ± 105 s; *P* = 0.403) respectively (Figure 9, 10). No significant difference was reported between treatment groups, both pre intervention (4.91 ± 0.23 vs. 4.95 ± 0.54 $m.sec^{-1}$; *P* = 0.848) (720 ± 45 vs.745 ± 104s; *P* = 0.611) and post intervention (5.14 ± 0.23 vs. 4.89 ± 0.46 $m.sec^{-1}$; *P* = 0.224) (774 ± 45 vs. 732 ± 105 s; *P* = 0.406) in V_{peak} or tolerable duration respectively (Table 2, Figure 9, 10).

Figure 7: A scatterplot representation of the change in peak oxygen uptake ($l.min^{-1}$) from pre- to post-intervention in both, the high intensity aerobic training group (INT) and the control group (CON) respectively, following the completion of the maximal incremental treadmill exercise test, n =12. Line of equality illustrated (where pre-intervention VO_{2peak} estimate = post-intervention VO_{2peak} estimate).

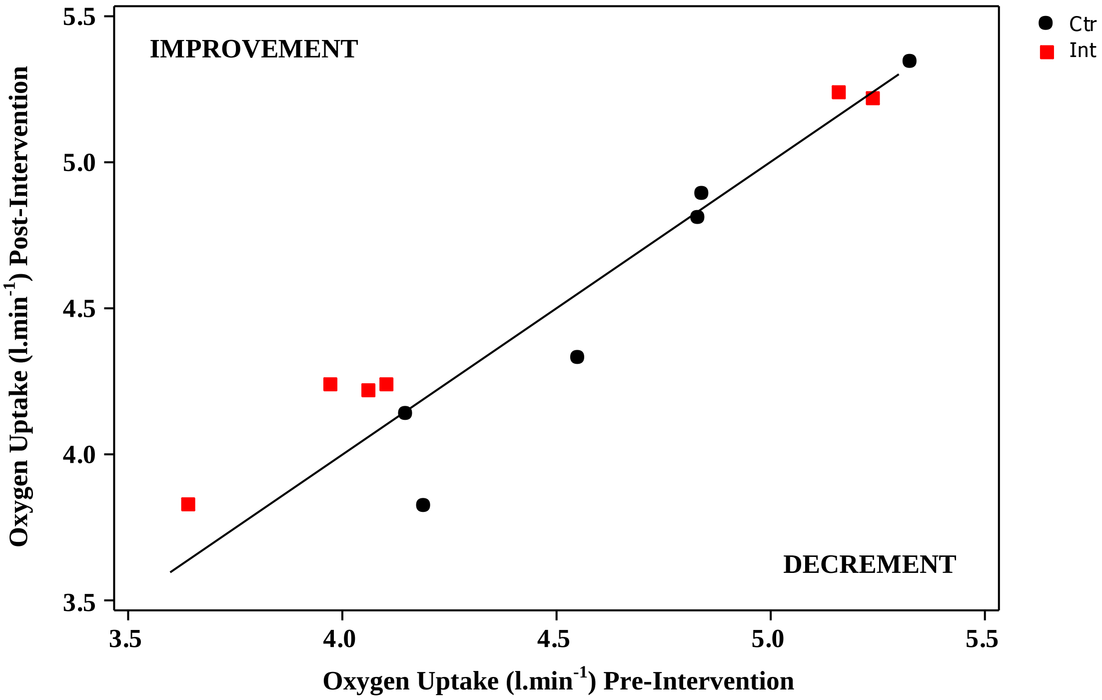
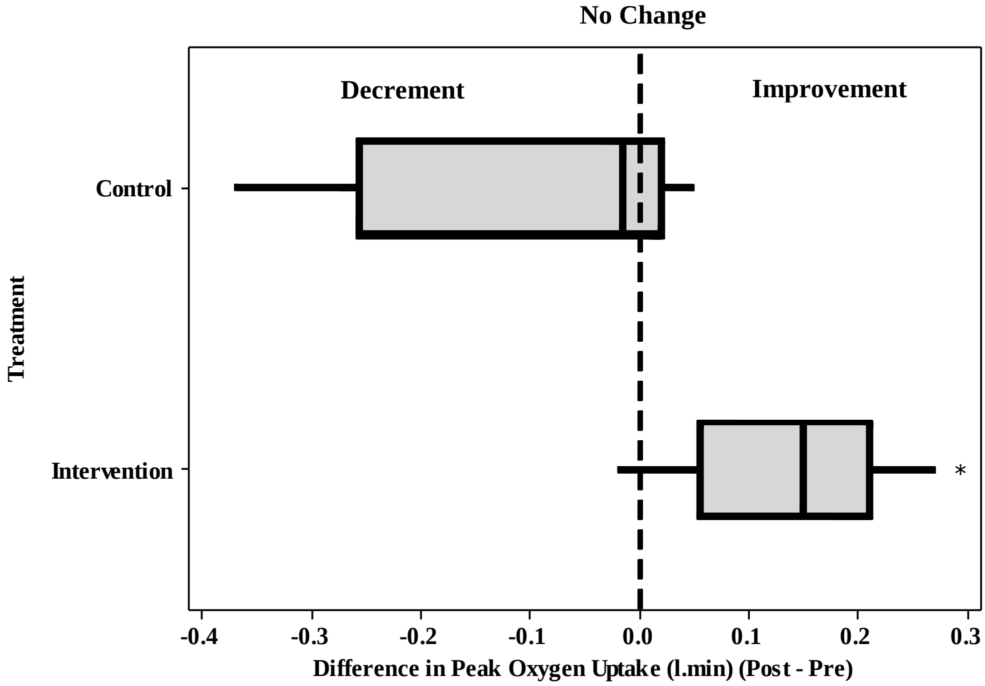


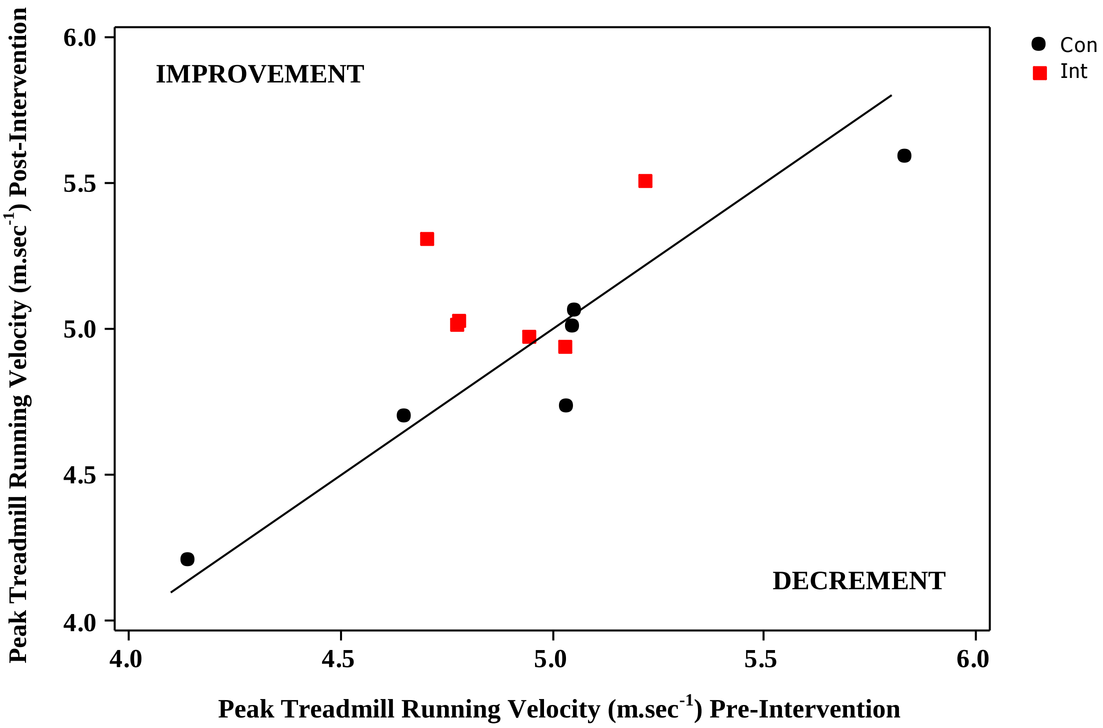
Figure 7 clearly demonstrates that the majority (5 out of 6) subjects undertaking 6 weeks of high intensity aerobic training improved their peak oxygen uptake post intervention. This observed improvement in peak oxygen uptake post exercise is however, not reflected within the control group. Significantly, following the completion of 6 weeks habitual training which was not supplemented with additional high intensity aerobic interval training, the majority of control subjects are found to lie very close to the line of equality, displaying little or no improvement in peak oxygen uptake measured post-intervention. Of note, 2 CON group subjects display noticeable depreciations in $VO_{2\ peak}$ post-intervention.

Figure 8: A box plot representation of the peak oxygen uptake following the completion of either the 6 week control or the high intensity aerobic training intervention. The x-axis represents the difference (post minus pre) in peak oxygen uptake for each of the training regimes documented on the y-axis. The box plot indicates the sample median, the interquartile range (IQR) and the maximum and minimum range values for the difference in peak oxygen uptake ($l.min^{-1}$) recorded pre- to post-intervention.* Significantly different pre- to post-intervention ($P < 0.05$).



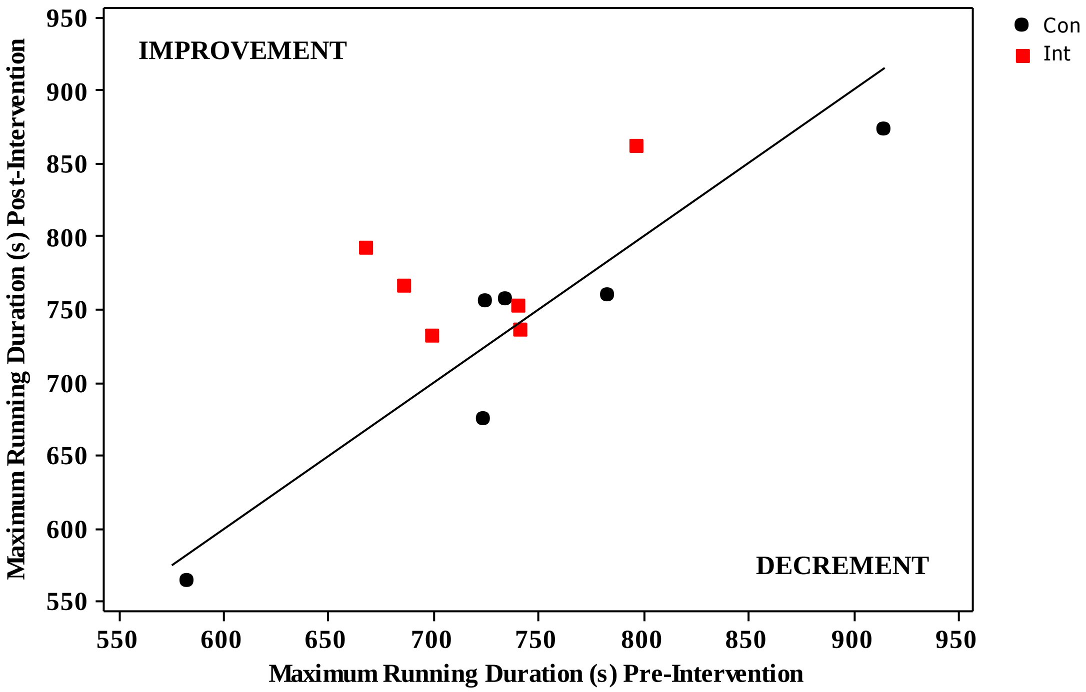
The box plot illustrated in Figure 8, displays agreement with the improvement depicted in the scatter plot representation of the change in peak VO_2 for the INT group following their 6 week high intensity aerobic training interventions (Figure 7) with a median change of 0.15 $l.min^{-1}$ being displayed pre- to post-training intervention. Following the high intensity aerobic intervention, the greatest improvement $VO_{2\ peak}$ was in the region of 0.3 $l.min^{-1}$. In contrast, following 6 weeks of habitual training, there is a very slight depreciation displayed in control subjects' peak oxygen uptake, with the median of the difference being a fall of -0.02 $l.min^{-1}$. Equally, while the control median stays close to the line representing no change pre- to post-intervention, larger reductions up to 0.4 $l.min^{-1}$ can be seen post-intervention and supports the noticeable depreciation in $VO_{2\ peak}$ presented by 2 CON subjects in particular in figure 7.

Figure 9: A scatterplot representation of the peak treadmill running velocity (V_{peak}) ($m.sec^{-1}$) from pre- to post-intervention in both the high intensity aerobic training group (INT) and the control group (CON) respectively, following the completion of the maximal incremental treadmill exercise test, n =12. Line of equality illustrated (where pre intervention V_{peak} ($m.sec^{-1}$) estimate = post intervention V_{peak} ($m.sec^{-1}$) estimate).



In agreement with the increase in peak aerobic capacity (Table 2), significant improvements were also displayed in peak treadmill running velocity (V_{peak}) post-intervention for the INT group as presented in Figure 9. Clear progression in V_{peak} attained can be seen for the INT group subjects (4 of 6) following the completion of maximal incremental exercise test (Protocol 1) post-intervention. By comparison, no appreciable improvements were observed in the CON treatment group following post-intervention assessment, with the majority of subjects grouping close to the line of no change.

Figure 10: A scatterplot representation of the tolerable duration (t_{lim}) (s) from pre- to post-intervention in both the high intensity aerobic training group (INT) and the control group (CON) respectively, following the completion of the maximal incremental treadmill exercise test, n =12. Line of equality illustrated (where pre intervention tolerable duration (s) estimate = post intervention tolerable duration (s) estimate).



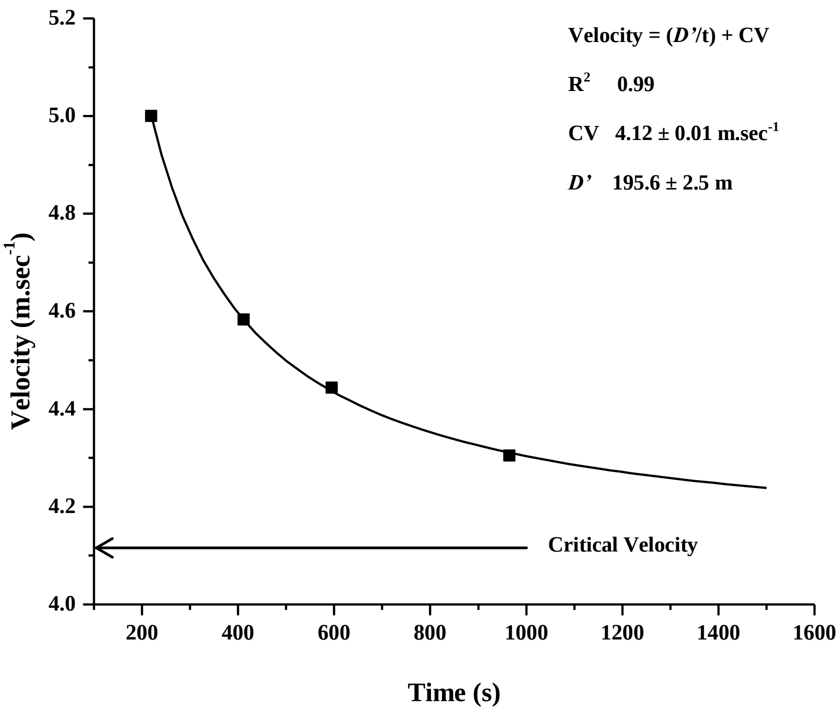
As Figure 10 highlights, an improving trend is characterised in the maximal incremental treadmill exercise test by those subjects who undertook 6 weeks of high intensity aerobic training. Consistent with the increase in V_{peak}, as expected, time to exhaustion (i.e. tolerable duration of exercise) is extended within the INT group pre-to post-intervention. The same however cannot be observed for the CON treatment group. Following the completion of their respective 6 week intervention, CON subjects were more inclined to perform worse post-intervention with respect to the tolerable duration achieved when undertaking the maximal incremental exercise test.

Effect of Intervention Treatment on the V-t_{lim} *Relationship*

Protocol 2 – Laboratory Based Estimation

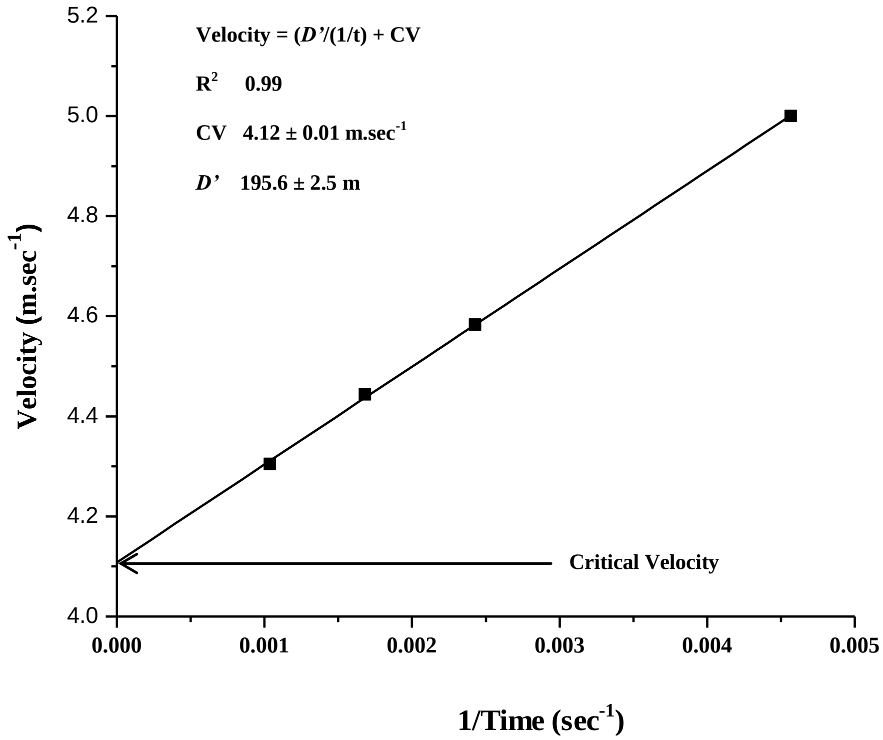
Defined as the time period for a given exercise intensity with which exercise intolerance is induced, the tolerable duration for each subject across both treatment groups conformed well to a hyperbolic function of the external treadmill velocity. In all cases the SE of CV estimates consistently fell within the 5% acceptable limits across both pre- and post-assessment for the INT (Pre < 0.04 m.sec^{-1} (Range 0.3 – 3.9%); Post < 0.04 m.sec^{-1} (Range 0.2 – 1.8%) and CON (Pre < 0.08 (Range 0.5 – 5%); Post < 0.1 (Range 1.5 – 4.7%) groups respectively. The hyperbolic relationship between velocity and time to exhaustion, along with the corresponding linear relationship of velocity and the reciprocal of time to exhaustion are shown for a representative subject in Figures 11 and 12.

Figure 11: The relationship between velocity and tolerable duration for constant velocity tests performed to t_{lim}. A hyperbolic relationship has been fitted to these data allowing the estimation of critical velocity (CV) and D'.



For both parameters of the V-t_{lim} relationship, no significant difference was found following the 6 week high intensity aerobic intervention. The laboratory derived sample mean and (SD) for CV and *D'* were (3.65 ± 0.24 $m.sec^{-1}$; 229 ± 57s vs. 3.72 ± 0.25 $m.sec^{-1}$; 242 ± 42s) (CV (P=0.355); *D'* (P=0.583)) for pre- and post-intervention estimations respectively. Correspondingly no significant difference was displayed within the CON group for CV (3.65 ± 0.49 vs. 3.72 ± 0.52 $m.sec^{-1}$; P = 0.216) or *D'* (276 ± 117 vs. 263 ± 95 m; P = 0.448) pre- to post-assessment following 6 weeks habitual training.

Figure 12: The linear transformation of the V-t relationship when work rate is plotted against the inverse of time to exhaustion (1/time). The slope of the regression line represents the curvature constant (*D'*), while the *y*-axis intercept, donates critical velocity (CV).



The VO_{2peak} values attained across the 4 constant-velocity tests when estimating the V-t_{lim} relationship averaged 4.39 ± 0.58 and 4.45 ± 0.68 $l.min^{-1}$ for the INT treatment group and 4.58 ± 0.50 and 4.58 ± 0.54 $l.min^{-1}$ for the CON group respectively following pre- and post-intervention determination of CV. For each group these values were found not to be significantly different to the respective mean $VO_{2\ peak}$ values attained following maximal incremental test assessment (Protocol 1) (P < 0.05 in all cases) pre and post-intervention.

These findings conform well to the criterion for attainment of $VO_{2\ peak}$ within this study and insinuate that all subjects achieved a VO_{2peak} upon t_{lim} across the 4 constant velocity tests that was representative of their maximal incremental exercise test $VO_{2\ peak}$ value. Further, this negates, with particular emphasis upon pre-intervention assessment, any potential training effect as a result of these tests in determining the V-t relationship prior to the commencement of the high intensity aerobic intervention.

Effect of Training Intervention on the V-t_{lim} Relationship

Protocol 3 – Field Based Estimation

The SE of CV estimates did not consistently fall within the 5% acceptable limits pre- or post-intervention for either the INT (Pre < 0.19 m.sec^{-1} (Range 1.2 – 9.7%); Post < 0.15 (Range 2.6 – 5.6%) or CON (Pre < 0.20 (Range 1.4 – 17.5%); Post < 0.15 (Range 1 – 6.3%) groups respectively, and thus, subjects did not conform as strongly to the hyperbolic V-t_{lim} relationship as observed when adopting Protocol 2.

As was shown following the lab based estimation, both parameters of the V-t_{lim} relationship as measured utilising the field test protocol (Protocol 3), expressed no level of significant difference pre- to post-intervention, with CV and *D'* averaging (3.44 ± 0.10 m.sec^{-1}; 238 ± 94m vs. 3.44 ± 0.22 m.sec^{-1}; 222 ± 38m) (CV ($P = 0.935$); *D'* ($P = 0.616$)) for pre- and post-intervention respectively.

Comparatively, the CON group showed no significant difference pre- to post-intervention, with CV and *D'* averaging (3.42 ± 0.28 m.sec^{-1}; 215 ± 50 vs. 3.44 ± 0.32 m.sec^{-1}; 224 ± 79) (CV ($P = 0.640$); *D'* ($P = 0.738$)) for pre- and post-intervention respectively.

4.4 Analysis of Agreement between Field Test & Laboratory Test Estimation of Critical Velocity

Pre-intervention analysis revealed no level of statistical significance between Protocol 2 (Lab) and Protocol 3 (Field) for the INT (3.65 ± 0.24 vs. 3.44 ± 0.10 m.sec^{-1}; P = 0.072) or CON (3.66 ± 0.49 vs. 3.42 ± 0.28 m.sec^{-1}; P = 0.125) groups respectively. While similarly, no significant difference was reported for the CON group following 6 weeks habitual training (3.72 ± 0.52 vs. 3.44 ± 0.32 m.sec^{-1}; P = 0.064). A significant difference was found however, between protocol estimates of CV post-intervention within the INT group (3.72 ± 0.25 vs. 3.44 ± 0.22 m.sec^{-1}; P = 0.018).

Figure 13: A scatter plot illustrating the comparison between field and lab based derived estimations of critical velocity from the V-t_{lim} relationship both pre- and post-intervention within the high intensity aerobic training group and control group respectively. n=12. Line of equality illustrated (field derived CV estimate = lab derived CV estimate)

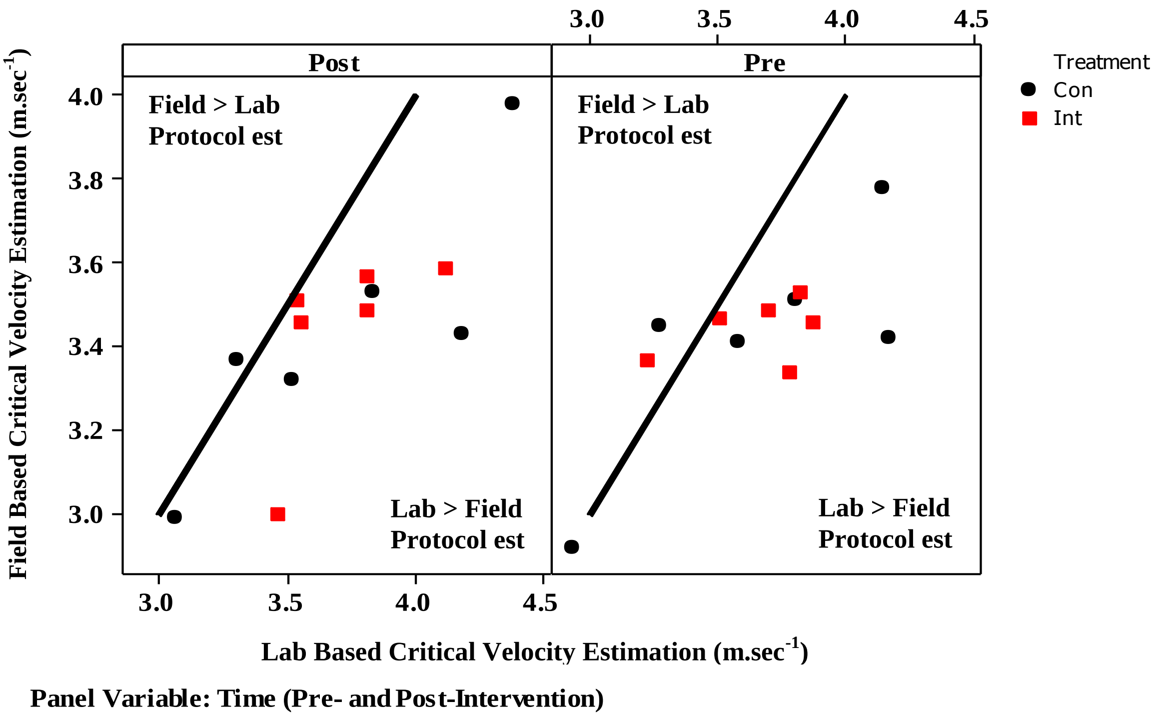
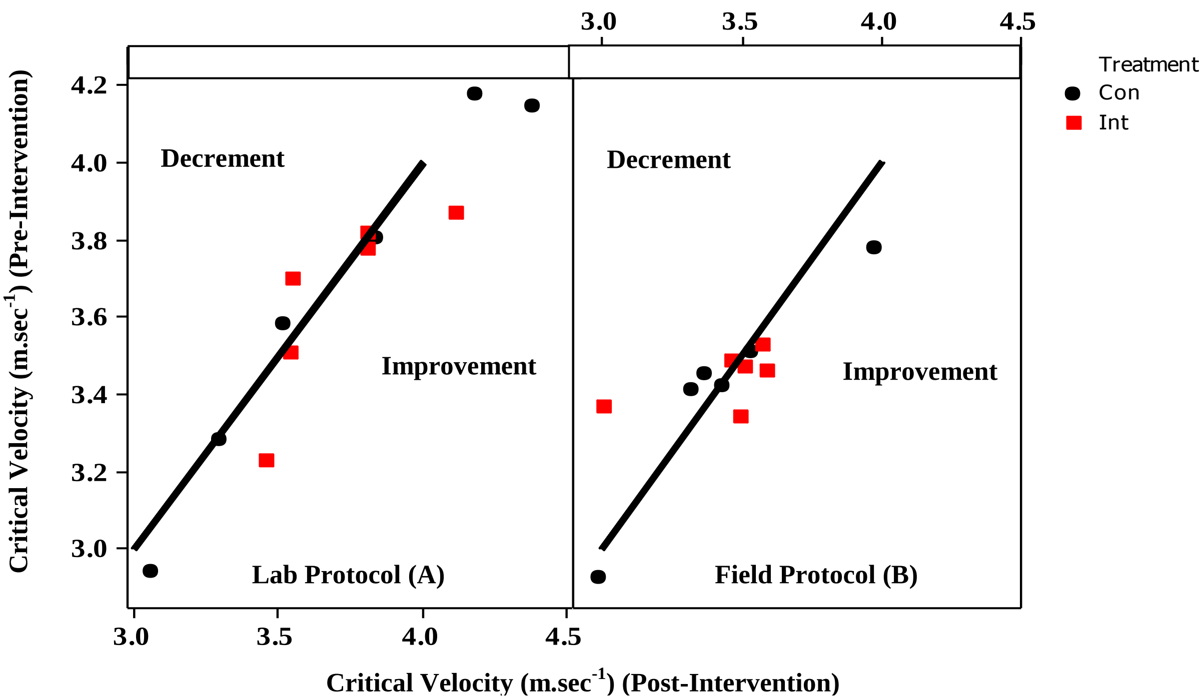


Figure 13 provides a comparison of the critical velocity value estimated when adopting the laboratory and field test protocols both pre and post intervention. Those values displayed right of the line of equality represent a higher estimation provided by the laboratory protocol, while those left of the line similarly represent a higher estimation in CV provided by the field protocol.

It can be inferred that there was limited to no agreement between lab and field estimations of critical velocity. The distribution of the CV values for both treatment groups, irrespective of the 6-week intervention implemented, highlights little to no sample variability across (all but 3 of the 12) subjects for CV estimations derived through field based assessment. By comparison, measurement obtained via the lab based protocol, displays on the whole, a much wider spread in the values of CV collected across pre and post intervention for both treatment groups under investigation. For the most part, there is a much greater variability in CV provided by the laboratory protocol relative to that provided by the novel field test protocol.

Figure 14: A scatterplot illustrating the pre- to post-intervention change in critical velocity derived from both lab and field based protocols from the V-t_{lim} relationship. Panel A represents the change in critical velocity pre- to post-intervention for critical velocity values estimated from laboratory based protocol. Panel B represents the change in critical velocity pre- to post-intervention for critical velocity values estimated from field based protocol. n=12. Line of equality illustrated (pre intervention = post intervention)

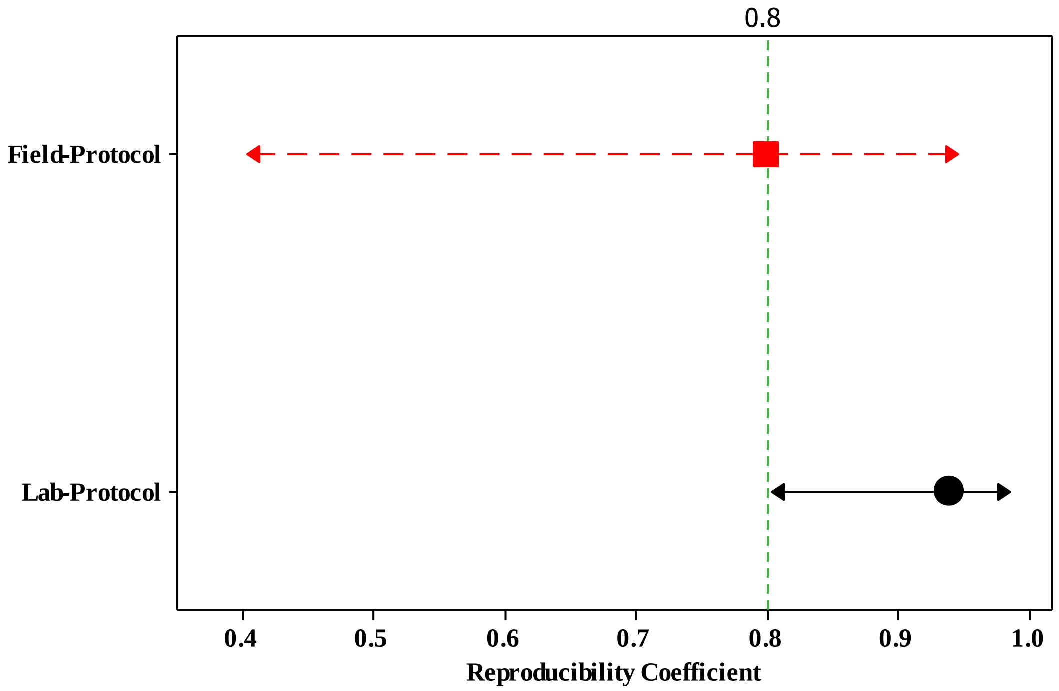


As Figure 14 illustrates, no sizable training effect in critical velocity was manifested following the high intensity intervention. As displayed in both plots, CV values for both control and intervention samples are located close to the line of equality signifying limited or no adaptation in CV following post-intervention assessment in either study population.

While the field based test demonstrates similarity to that of the lab based protocol in displaying a limited training effects post-intervention for each respective treatment group. As previously highlighted in Figure 13, the field based measurement of CV again tends to result in a clustering of individual values irrespective of the treatment. It appears that, when CV values are derived via lab based assessment, a greater spread in the range of values observed pre to post assessment is evident, while this is not the case for the field test.

In line with these findings, analysis of the interval estimates (95% CI) displayed by each respective protocol confirmed that no significant difference was evident in each respective protocol, pre-to post-intervention ($P > 0.05$). The narrower interval estimate width presented for the laboratory protocol (i.e. the difference in population mean changes between INT and CON (post minus pre)) of $0.35 m.sec^{-1}$ (the 95% CI is from 0.18 to + 0.17 giving a width of 0.17 – (-0.18) = 0.35), relative to $0.42 m.sec^{-1}$, produced for the field protocol do however indicate a greater capability of the laboratory protocol in detecting any discernible training effect pre-to post intervention compared to that of the novel field test protocol.

Figure 15: The Reproducibility Coefficients and corresponding 95% confidence intervals for critical velocity (CV) estimation for both the laboratory and field test protocols.



In quantifying a measure of reliability and reproducibility displayed by each protocol to estimate CV, a general linear model allowing for possible treatment, time and subject effects was fitted to each measure of CV and the between subject and within subject variability estimated. From the application of this general linear model, the between subject variability and the within subject variability were estimated as 0.15 and 0.01 respectively for the lab based protocol, and 0.05 and 0.01 respectively for the field based protocol. As presented in Figure 15 the reproducibility coefficient calculated for the lab based derived estimate of CV was 0.94 (i.e. 0.15/(0.15+0.01)) while by comparison the field based protocol produced reproducibility coefficient of 0.80 (i.e. 0.05/(0.05+0.01)). The closer the reproducibility coefficient is to 1(representing perfect reproducibility with no within-subject variability) the better the re-test reliability of the protocol.

In addition to the higher reproducibility coefficient displayed for the lab based protocol, Figure 15 also highlights, that the 95% CI for the reproducibility coefficient for the lab based protocol covers a much smaller range than that of the field test (0.81 - 0.98 as opposed to 0.41 - 0.94) and does not cross the threshold of 0.80 below which the reliability of a protocol is considered poor. The much wider 95% CI width presented by the field test protocol, with a possible reproducibility coefficient well under the 0.80 threshold, implies the field protocol is of questionable value as a practical tool.

Figure 16: Bland-Altman plot with estimated mean bias and limits of agreement for the difference in critical velocity (CV) estimates (pre-intervention only) between the field and laboratory based protocols for the determination of the V-t_{lim} relationship. The *dotted lines* represent the estimated 95% limits of agreement, which provide a range that is likely to capture 95% of the differences between any two measurements. The *dotted blue line* is the zero line, i.e. an observation on this line signifies that there is no difference between the two protocols in their respective estimation of CV.

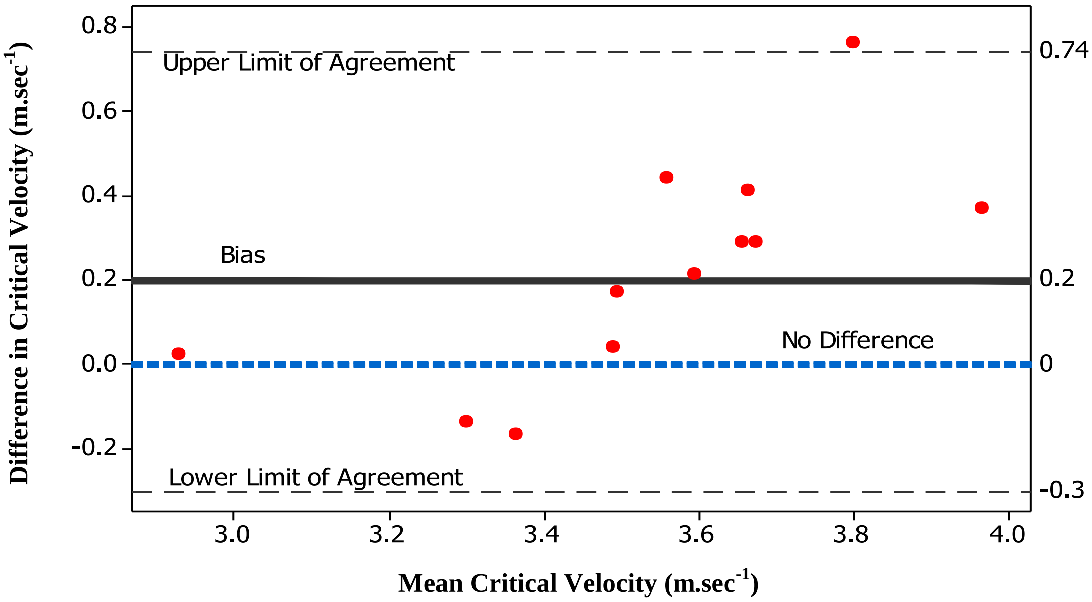


Figure 16 illustrates the relationship, possible bias and 95% limits of agreement between lab and field protocol estimations of critical velocity. As seen, there is a tendency that as the critical value increases beyond 3.5m.sec^{-1}, the difference between protocol estimates becomes more pronounced, i.e. the bias in the field test derived value of CV gets progressively worse. On average, the field test appears to underestimate CV by 0.2m.sec^{-1} compared to the lab based protocol; however, in line with the upper limit of agreement this underestimation can be as large as ~ 0.75m.sec^{-1}.

CHAPTER 5 – DISCUSSION

An important challenge that needs to be addressed before more research is conducted on both the importance of, and understanding of the physiology underlying CV and *D'* is the protocol implemented for the measurement of these two parameters. At present, the number of exhaustive test bouts required restrict its use in intervention studies and makes it application within team based sports highly impractical.

The development of a single test protocol would provide a very efficient and applicable means of establishing critical velocity, a crucial parameter of exercise physiology that can be used to demarcate the heavy from severe exercise intensity domains, assess aerobic fitness, optimise training intensities and predict exercise performance.

The primary aim of the present investigation was to validate the application of a novel field based test to estimate critical velocity, the asymptote of the hyperbolic relationship between velocity and time to exhaustion. In fulfillment of this aim, the novel field test was evaluated against an established gold standard laboratory protocol, on both, its proficiency to accurately estimate critical velocity, and its sensitivity to detect any potential training effect elicited in critical velocity following the completion of a high intensity aerobic training intervention. The secondary aim of this investigation was to examine the effectiveness of a six week high intensity aerobic training intervention to improve physiological indices associated with aerobic capacity including critical velocity.

The key finding to be inferred from the present study was that little evidence was shown to support the application of a novel field based protocol to determine critical velocity from a single testing session. With pertinence to the ability to detect a potential training effect in critical velocity following the 6 week training intervention, while the novel field test, in correspondence to laboratory estimates displayed no significant increase in critical velocity post training intervention for both the INT and CON treatment groups respectively ($P > 0.05$), relative to the laboratory protocol, it offered limited capacity to accurately estimate critical velocity.

5.1 Evaluation of the 6 Week High Intensity Aerobic Training Intervention

-Main Findings-

Peak Aerobic Capacity ($VO_{2\ peak}$)

In consideration of the key findings, post-intervention analysis revealed that the high intensity aerobic training intervention adopted within the current investigation to improve aerobic endurance, elicited a significant increase ($P < 0.05$) in peak aerobic capacity. As presented in Table 2 and supported by Figures 7 and 8 , this constituted to a 0.14 $l.min^{-1}$ improvement (4.36 ± 0.67 to 4.50 ± 0.58 $l.min^{-1}$; $P = 0.020$) within the INT treatment group and equated to a 2.9 $mk.kg.min^{-1}$ (61.7 ± 3.31 to 64.6 ± 3.56 $ml.kg.min^{-1}$; $P = 0.002$) increase in relative $VO_{2\ peak}$ pre-to post-intervention respectively. In line with the findings of Helgerud et al., (2001) no significant change in $VO_{2\ peak}$ was observed in the CON treatment group (4.65 ± 0.45 vs. 4.56 ± 0.56 $l.min^{-1}$; $P = 0.225$) following the completion of 6 weeks habitual training (Table 2, Figures 7, 8).

Significantly, while the playing standard of the subject cohort considered for this study was not indicative of elite professional level, with reference to the available literature, the mean peak aerobic capacity ascertained within the INT group post-intervention compares favorably with those encompassing the higher echelons of the game (Helgerud et al., 2001; Wisloff et al., 2004; Dupont et al., 2004) and encouraging coincides with Reilly and associates (2000) proposed prerequisite threshold of 60 $ml.kg.min^{-1}$. The expression of a maximal aerobic capacity below this threshold as advocated by Reilly et al., (2000), insinuates a player is unlikely to possess the physiological attributes necessary for success in elite level soccer.

Such encouraging parallels, however, cannot be drawn when evaluating the relative magnitude of improvement observed in peak aerobic capacity following the completion of the high intensity aerobic training intervention to those displayed within the literature adopting the same intervention protocol. While only a 4.5% (2.9 $mk.kg.min^{-1}$) improvement was displayed in $VO_{2\ peak}$, within the current study, Helgerud et al., (2001) reported improvements in mean $VO_{2\ max}$ of elite youth soccer players of 11% (6 $ml.kg.min^{-1}$), albeit during an 8week intervention study. In supporting research, Helgerud et al., (2003), applying the identical 8 week intervention within an elite professional champions league team reported an 8%

improvement in $VO_{2\ max}$ (60.5 to 65.7 ml.kg.min^{-1}), while comparatively, Impellizzeri et al., (2006) displayed a 8.3% increase in junior elite soccer players maximal aerobic capacity after 12 weeks high intensity aerobic interval training.

While statistically significant, the above findings make it perhaps appropriate to question the physiological significance of the 0.14l.min^{-1} improvement displayed in peak aerobic capacity within the INT group (Figure 8). While it could be argued significant improvements in V_{peak} (4.91 ± 0.23 vs. 5.14 ± 0.23 m.sec^{-1}; P = 0.041) and an extended tolerable duration (720 ± 45 vs. 774 ± 45 s; P = 0.037) (Table 2, Figure 9, 10) complement the enhanced peak aerobic capacity presented for the INT treatment group post-intervention, similarly these improvements, in most instances, are again not marked, and in agreement with this were not found to be significantly different from the CON group post-intervention for V_{peak} (5.14 ± 0.23 vs. 4.89 ± 0.46 m.sec^{-1}; P = 0.224) or tolerable duration (774 ± 45 vs. 732 ± 105 s; P = 0.406) respectively. It seems unlikely therefore, that a mean 0.14l.min^{-1} $VO_{2\ peak}$ increase will manifest itself into any appreciable improvement in soccer performance as has been previously reported (Helgerud et al., 2003; Impellizzeri et al., 2006). Supplementing the 11% VO_2 max increase in elite youth players, Helgerud et al., (2001) saw a 20% increase in total distance covered during competitive match play, along with a 100% increase in the number of sprints performed by each player which coincided with a 24% increase in the number of involvements with the ball. Similarly Impellizzeri et al., (2006) documented a 6.4% increase in total distance covered and a 23% increase in high intensity activity performed during match play.

The adoption of the short training period in conjunction with the season phase in which the high intensity aerobic intervention was implemented are important factors to deliberate in offering rational for the limited improvement exhibited in peak aerobic capacity observed. Svensson and Drust (2005) attest, training programs should be between 8-12 weeks in duration to allow structural and functional physiological adaptations to the training stimulus to occur. Consistent with the 6 week training period implemented within this investigation, shorter interventions in the region of 6-8 weeks do not always produce significant physiological improvements (Maughan et al., 1997; Svensson and Drust, 2005). Bangsbo (1994) following a 5 week pre-season training intervention reported no change in maximal aerobic capacity in 7 professional soccer players pre-to post-intervention, while after 7 weeks of speed endurance training Hill-Hass et al., (2009) reported no improvement in maximal aerobic capacity.

Within the construct of the modern game, given the limited time frame amidst a congested schedule, the pre-season phase offers the only real window of opportunity wherein the training goal can be primarily focused toward physiological development of the physical capacities encompassing performance. As such, the majority of published literature reporting significant improvements in maximal aerobic capacity in response to a training intervention captures this specific seasonal preparation phase (Helgerud et al., 2001, Sporis et al., 2008; McMillan et al., 2004, Chamari et al., 2005), unlike this study that was carried out in-season.

Significantly, it is therefore plausible that the appreciable improvements in $VO_{2\ max}$ manifested within these studies could in part be attributable to players returning to pre-season deconditioned following the summer intermission period. When taken in conjunction with Impellizzeri et al., (2005), whereby central factors governing aerobic capacity (i.e. $VO_{2\ max}$) were shown to be restored rapidly in a short period of time (4 weeks pre-season training), it could be argued that the marked improvements in $VO_{2\ max}$ reported in interventions implemented during this period are essentially in part masking the initial decrease in aerobic capacity displayed by returning players following a long summer intermission (McMillan et al., 2005).

As a result, due to the difficulties associated with adopting control groups within elite soccer intervention studies it is difficult to determine the independent effects of high intensity training beyond the accustomed adaptations associated with early pre-season training as it also is reasonable to assume conventional soccer training (e.g. small-sided games) will provide a physiological stimulus which will elicit improvements in maximal aerobic capacity (Iaia et al., 2009) particularly within this pre-season period.

In view of the limited improvement in $VO_{2\ peak}$ within the INT group. The initiation of the training intervention in-season when the current subjects will have already established an aerobic base (following a pre-season conditioning phase), could therefore have reduced the ability to facilitate any appreciable physiological development in peak aerobic capacity relative to the aforementioned studies reporting notable improvements. This assumption is supported in the literature for elite players (Bangsbo, 1994), and elite junior players with

Impellizzeri et al., (2006) reporting no in-season post-intervention improvement following 8 weeks of aerobic interval training (4x4 min at 90-95% Hf $_{max}$) (4.14 ± 0.38 vs. 4.20 ± 0.40 $l.min^{-1}$). Conversely it has been shown that in-season aerobic interval training can be effective, with the findings Chamari et al., (2005) and Ferrari Bravo et al., (2008) exhibiting notable improvements in maximal aerobic capacity of 7.5% and 6.6% respectively. The longer training periods implemented within these studies relative to that of the present study may attribute to larger improvements presented.

Critical Velocity

Importantly, both INT and CON groups across the 4 constant velocity tests (Protocol 2) performed, demonstrated no significant difference from $VO_{2\ peak}$ established following Protocol 1, either pre- or post-intervention respectively (Table 2). This holds particular significance in allowing us to negate the potential of any training effect upon peak aerobic capacity with respect to INT group prior to undertaking the training intervention (4.36 ± 0.67 vs. 4.39 ± 0.58 $l.min^{-1}$; P = 0.939).

Fundamentally, it also lends support to the theoretical construct of the critical velocity concept, that exercise performed above this domain boundary will result in the attainment of VO_{2max} ($VO_{2\ peak}$ in this instance) if continued to t_{lim} with the tolerable duration of the exercise being performed dependent of the rate of *D'* depletion, with this rate of depletion increasing proportionally with the intensity of exercise (Figure 11). The results of the present study conform well to the plethora of available literature maintaining the position of critical velocity as the lower boundary of the severe intensity domain (Poole et al., 1988; Gaesser and Poole, 1996; Jones et al., 2010; Jones et al., 2008).

Disagreement within the literature remains however, and in contrast to these findings, Sawyer et al., (2012) and Billat et al., (1988) have demonstrated that constant load exercise to exhaustion above critical power did not result in the attainment of $VO_{2max.}$ In this respect, while the estimation of CV for both INT and CON groups were within acceptable limits (defined as the standard error being within 5% of CV) this study would have benefited from the additional performance of constant velocity tests to t_{lim} at CV and selected velocities slightly above and below this threshold. This would have allowed us to confirm with greater accuracy that the velocity estimated to denote CV represented the boundary domain between the heavy and severe intensity domains. However in light of the large number of tests being undertaken, this was deemed impractical.

In conjunction with the wider research focus of this thesis: the development of a more comprehensive physiological profiling strategy within soccer. The findings that critical velocity (power) displays sensitivity to aerobic endurance training (Poole et al., 1990; Gaesser and Wilson, 1988;Jenkins and Quigley, 1992; Vanhatalo et al., 2008; Machado et al., 2011; Clark et al., 2013) provides support for its application within intervention studies as a potential physiological marker of sub-maximal aerobic capacity. However, to date, while the estimation of critical velocity has not been routinely conducted within intermittent based sports, there is growing evidence to suggest its inclusion to the physiological testing battery adopted within intermittent sports is merited.

High intensity interval training, in a variety of forms, is today one of the most effective means of improving cardiorespiratory and metabolic function and, in turn, the physical performance of athletes. It has been offered that the capacity to establish work intensities based on the characterisation of the V-t relationship offers great potential for the prescription of high intensity interval training (Clark et al., 2013; Fergusson et al., 2013). The requirement for elite soccer players to possess highly developed aerobic and anaerobic capacities to contend with the demands of modern match play pinpoints to the fantastic functional utility offered through critical velocity testing, as the distinctive aerobic and anaerobic qualities possessed by a player are reflected in the parameters of CV and *D'* respectively. In this light, as was the approach adopted by Clark et al., (2013), conditioning practitioners have the capacity to assess metabolic strengths and weaknesses, and accordingly, employ specific high intensity training interventions to target aerobic or anaerobic development dependent on individual training needs. As both Machado et al., (2011) and Clark et al., (2013) attest, implementing protocols shorter in duration but of higher intensities will presumably be necessary for evoking improvements in *D'*, while the adoption of training interval intensities located closer to the lower boundary of the severe intensity domain, will contribute to aerobic development, as exercise duration can be maintained thereby allowing the cardiovascular system to be stressed for longer.

In light of the limited data corresponding to CV within soccer, review of the available literature shows good agreement with the pre-intervention velocity estimated to correspond to CV within the study for both INT (3.65 $m.sec^{-1}$) and CON (3.66 $m.sec^{-1}$) groups (Table 1), with Clark et al., (2013) and Denadai et al., (2005) reporting mean critical velocities of 3.27 ± 0.29 $m.sec^{-1}$ and 4.00 ± 0.31 $m.sec^{-1}$ in elite female and male soccer players respectively. In relation to the wider spectrum of elite endurance athletes, these values are relatively modest however, with markedly higher running speeds associated with CV being displayed (4.25 – 4.46 $m.sec^{-1}$) (Kranenburg and Smith, 1996; De Lucas et al., 2012; Fukuda et al., 2012; Pettitt et al., 2012), with values as high as 5.85 $m.sec^{-1}$ being reported (Paula Radcliffe, current world record holder for woman's marathon) (Burnley and Jones, 2007).

As advocated, the modest physical capacities demonstrated for soccer players in comparison to other sporting disciplines may in part be explained by the high volume of matches completed over a season thereby reducing the opportunity for aerobic fitness development. Conversely, as Edwards et al., (2003) attests, it is also likely that elite soccer players are successful because they possess good, but not exceptional, all round physical strengths (aerobic and anaerobic capacities) and are thus able to effectively respond to the diverse and multifaceted demands of the game.

Post-intervention analysis revealed no significant improvement in CV (estimates determined via Protocol 2) within the INT group (3.65 ± 0.24 vs. 3.72 ± 0.25 $m.sec^{-1}$; P = 0.355) (Table 2, Figure 14 – Panel A) and provides further evidence to support the limited training effect elicited following 6 weeks of high intensity aerobic interval training. These findings are in contrast to those exhibited within the literature. An investigation by Gaesser and Wilson (1988), applied two types of training intervention, with the first group performing submaximal continuous training (40 minutes at 50% $VO_{2\ max}$ 3 $d.wk^{-1}$) and the second group performing high intensity interval training (10x 2 minutes at $VO_{2\ max}$, 3 $d.wk^{-1}$). After 6 weeks, both groups showed significant increases in CP by 13% and 15% respectively. In response to 7 weeks of high intensity interval training (10x 2minutes at 105% $VO_{2\ max}$, 3 $d.wk^{-1}$) a 10% increase in CP was found (Poole et al., 1990), while Jenkins and Quigley (1992) reported a 31% increase in CP following 8 weeks of continuous endurance exercise (30- 40 minutes at CP 3 $d.wk^{-1}$).

More pertinently, Clark et al., (2013) presented significant improvements in CV within elite female footballers when consigned to either a short (3.53 to 3.78 $m.sec^{-1}$) or a long intensity interval training group (3.11 to 3.32 $m.sec^{-1}$). While acknowledging the different methods implemented to estimate CV, thereby limiting direct comparison, the magnitude of the improvement presented by 2 INT subjects (Figure 14 – Panel A) is in line with those reported by Ida and provides a degree of support for a potential intervention effect elicited in CV within this study. However given the small sample size the power to discern any intervention effects is severely hindered within this study.

It has been advocated by numerous authors that while $VO_{2\ max}$ assessment is applicable for physiological evaluation when changes in aerobic capacity are expected to be pronounced (pre-season), the application of sub-maximal indices of aerobic fitness could be more sensitive to discerning an intervention effect relative to $VO_{2\ max}$, particularly in-season, when changes in aerobic capacity are likely to be small and be a reflection of peripheral, rather than central adaptation (Svensson and Drust, 2005; Hoff et al., 2005; McMillan et al., 2005; Kalapotharakos et al., 2011; Impellizzeri et al., 2006; Ziogas et al., 2011).

Given the limited adaptation in $VO_{2\ peak}$ exhibited in this study, a platform from which to assess the value of CV as a marker of submaximal of aerobic capacity was provided. In view of the close agreement displayed in the magnitude of improvement in CV between both INT (3.65 ± 0.24 vs. 3.72 ± 0.25 $m.sec^{-1}$; $P = 0.355$) and the CON groups (3.66 ± 0.49 vs. 3.72 ± 0.52; $P = 0.216$) (Table 2, Figure 14 – Panel A) with pre and post-intervention differences between groups displaying no statistical difference ($P > 0.05$), its application within soccer, with respect to providing a sensitive sub-maximal marker to identify changes in aerobic conditioning is potentially limited. Importantly, the findings of Vanhatalo et al., (2008) who investigated the effects of 12 high intensity interval training sessions (performed $3.d.wk^{-1}$) on critical power within habitually trained cyclists highlighted that a large improvement in VO_{2peak} (10%) may be required in order to support a significant improvement in critical power. In consideration of the limited improvement in VO_{2peak} displayed by the INT group, whereby the combination of a short training phase in unison with the implementation of an in-season intervention have been offered as plausible mediators. The non-significant improvement in critical velocity displayed by the INT group post-intervention plausibly echoes this.

These findings are in contrast to other sub-maximal indices of aerobic capacity implemented to monitor changes in training state within the competitive soccer season when maximum aerobic power is unchanged (Edwards et al., 2003; Bangsbo, 1994). However, when expressed relative to $VO_{2\ max}$ or Hf_{max} no significant change in relative lactate threshold was reported despite representing higher running velocities at the same lactate values pre-to post-intervention assessment (Helgerud et al., (2001); McMillan et al., (2005). In this light it could be argued that the lactate threshold changes in tandem with $VO_{2\ max}$ in soccer players, and in terms of $\%Hf_{max}$ and $\%VO_{2max}$ the adaptability seems minor. Therefore in agreement with McMillan et al., (2005) interventions within soccer should always look to improve $VO_{2\ max.}$ While the expression of CV relative to $VO_{2\ peak}$ was not determined within this study and is a drawback of the current investigation, the minimal adaptation in the velocity associated with CV therefore likely reverberates the limited improvement found in $VO_{2\ peak}$ within the INT group.

5.2 Evaluation of the Proficiency of the Novel Field Test

The traditional measurement protocol for the determination of the V-t relationship (Protocol 2) requires the performance of multiple constant velocity tests to exhaustion with a considerable recovery period provided between each exercise bout. In view of this, the identification of the boundary demarcating the heavy and severe intensity domains is rendered time consuming and problematic for certain study designs and resultantly limits its application within the athletic population. The development of a single-testing session for the determination of CV would therefore be of great practical utility and a useful addition to the exercise testing battery. The current study sought to address this issue by developing a novel field test which would establish CV from a single testing session.

Critical Velocity Estimation

A principal aim of this study was to validate the accuracy of a novel field test (Protocol 3) to estimate critical velocity. In agreement with laboratory estimates, the novel field protocol reported no significant improvement within the INT group pre- to post-intervention (3.44 ± 0.10 vs. 3.44 ± 0.22 $m.sec^{-1}$; P = 0.935) (Table 2, Figure 14 – Panel B) demonstrating no appreciable intervention effect following the high intensity aerobic training, with the INT sample predominantly being located close to the line of equality. Correspondingly, the control group reported no appreciable change in CV following 6 weeks post habitual training (3.42 ± 0.28 vs. 3.44 ± 0.32 $m.sec^{-1}$; P = 0.640) (Table 2, Figure 14 – Panel B) with comparisons between INT and CON groups revealing no significant difference ($P > 0.05$) in CV either prior to, or following, 6 weeks of high intensity interval or habitual training respectively when adopting the novel field protocol.

Comparative analysis of CV estimates derived between protocols however, highlights an inherent underestimation in the velocity associated with CV when derived from the novel protocol across both pre- and post-6 week assessment within each study group. While pre-intervention observations found no statistical significance between protocol estimates within both the INT (3.65 ± 0.24 vs. 3.44 ± 0.10 $m.sec^{-1}$; P = 0.072) and CON (3.66 ± 0.49 vs. 3.42 ± 0.28 $m.sec^{-1}$; P = 0.125) groups respectively, performance of the novel field test produced a lower estimate of CV relative to that of the lab based protocol. While suitably depicted in Figure 13, with a predominant rightward distribution away from the line of equality, indicative of an underestimation in CV when adopting the novel protocol. The Bland-Altman plot (Figure 16) supplemented with 95% limits of agreement provides a more formal analysis from which to compare and assess potential bias between protocol CV estimations. In confirmation of the poor agreement between protocol estimates, the novel protocol was recognised to typically underestimate the running velocity representing CV by 0.2 $m.sec^{-1}$ (~ 6%), with the upper limit of this underestimation potentially being as large in 0.75 $m.sec^{-1}$(~ 20%).

On the basis of this evidence, while the sample study again reduces the power with which to discern any significant relationships between protocol estimates of critical velocity. A potential upper limit of this underestimation in the region of 0.75 $m.sec^{-1}$ provides a basis in which to question the accuracy of the novel field protocol to estimate CV. This has important implications of potential functional value offered by this novel protocol when establishing training intensities based on the asymptote of the V-t relationship as earlier proposed. The estimation of the velocity demarcating the heavy-severe boundary must be accurate to ensure the prescription of the intended physiological stimulus and thus, in this light, the practical utility of the novel protocol is therefore reduced. In view of its liable nature to underestimate CV and therefore presumably wrongly define the velocity demarcating the heavy-severe domain boundary, establishing and prescribing training intensities based on this protocol would not be warranted as the intended physiological stimulus may not be guaranteed.

An overview of the available research does not however maintain this assertion. Within the literature, critical velocity is re-emerging as an important determinant of exercise tolerance in high intensity domains, and as such, in accordance with this study, concerted emphasis has been placed on the development of single test protocols that potentially provide a more efficient means of extracting the parameters of the power (velocity) – time relationship.

Most notable, has been the development of a 3 minute all-out cycling test (Vanhatalo et al., 2007; Burnley et al., 2006). Theoretical basis for the all-out test is in accordance with the mathematical underpinnings of the power-time relationship. In performing 3 minutes of all-out cycling, Burnley et al., (2006) Vanhatalo et al., (2007) postulated that this finite work capacity (*W'*), after ~ 2.5 minutes, would be entirely depleted and consequently the maximal power output maintained over the remaining duration of the test (30s) should in theory reflect an aerobically sustainable power output that is equivalent to CP. In contrast to the present findings, the mean power output over the last 30 seconds of this test protocol (end-test power (EP)) has shown good agreement when compared against traditionally determined CP (Vanhatalo et al., 2007) and correlated well with other proxies proposed to represent the heavy-severe domain boundary (MLSS) with EP displaying consistency with the response profiles above and below CP (Burnley et al., 2006).

Only very recently however, has the rationale behind the 3 minute all-out cycling test been applied to running (Broxterman et al.,2013; Pettitt et al., 2012). While Pettitt et al., (2012) utilised a 3 minute all-out running test to predict outdoor racing performance, Broxterman et al., (2013) in line with the present investigation attempted to validate the accuracy of their novel field protocol (400m running track, with speed recorded using a second by second accelerometer) against the traditional determination of the CV and *D'*. Broxterman found end-test speed (ES) (i.e the average speed across the final 20 seconds of the 3 minute run) to be strongly correlated with CV (R = 0.92) with mean CV and ES being 13.3 ± 2.8km.h^{-1} and 13.4 ± 2.8km.h^{-1} respectively. In conjunction with Vanhatalo et al., (2007), Broxterman's et al., (2013) 3 minute all-out running test encouragingly provides strong agreement with traditional protocol measures of CV and future research is strongly warranted to further validated the early promise displayed by this protocol.

In light of the recent nature of Broxterman et al., (2013) research publication, this all-out running protocol as yet, to our knowledge, has not been used within a training intervention study from which to assess its sensitivity to detect a change in critical velocity. However, adopting the 3 minute all-out cycling protocol, Vanhatalo et al., (2008) found that in response to 12 high intensity interval sessions over a 4 week period, significant improvements ($P <$ 0.05) in CP (230 ± 53 vs. 255 ± 50 W) were mirrored in EP (225 ± 52 vs. 248 ± 46 W), with respective protocol estimates of CP and EP being highly correlated both pre- and post-intervention. Importantly the increase in EP was strongly correlated with and not different from the increase in CP suggesting that the 3-minute all-out test is sensitive to training-induced changes in CP.

These findings are however not supported by the current study. In line with the pre-intervention disparity observed between protocol estimates, post-intervention analysis expressed pronounced discrepancies between CV values in both groups, with a significant difference being found within the INT group (3.72 ± 0.25 vs. 3.44 ± 0.22 m.sec^{-1}; P = 0.018)

(Table 2). Coupled with poor agreement in the magnitude of change following the high intensity training intervention (3.65 to 3.72 $m.sec^{-1}$ vs. 3.44 to 3.44 $m.sec^{-1}$), irrespective of the non-significant improvement displayed pre-to post-intervention, the present results imply that the novel field protocol is not sensitive to training induced changes in CV. The narrower interval estimate width presented for the lab protocol (0.35 $m.sec^{-1}$) relative to the novel field protocol (0.42 $m.sec^{-1}$) maintains this assertion, and is indicative of a greater sensitivity and capability of the laboratory protocol to detect any discernible training effect pre-to post-intervention.

Interpretation of these findings suggests that had the training intervention elicited a significant improvement in CV, we are in a position of little confidence to suggest that the field protocol would detect this change and further still, reflect the same magnitude of improvement in CV as displayed by the lab protocol. Fundamentally, this evidence insinuates that were a conditioning practitioner seeking to add CV examination to their exercise testing battery, they would be strongly encouraged to adopt the traditional laboratory measurement protocol (Protocol 2). In reality, given the adjoining impracticalities of such assessment, its implementation would therefore unlikely be viable within a team environment. Moreover, such outcomes essentially highlight the failure of the novel field test in addressing the underlying issue pertaining to critical velocities restricted implementation to date as a physiological marker of aerobic capacity.

In view of these findings, it is important to address the reasons which potentially impede the novel field tests capacity to accurately determine CV. Relative to laboratory protocol estimates (Table 2), the novel protocol implemented within the current study offers limited to no sample variability, with both pre- to post- assessment displaying little change within either group (INT – 3.44 ± 0.10 vs. 3.44 ± 0.22 $m.sec^{-1}$) (CON – 3.42 ± 0.28 vs. 3.44 ± 0.32 $m.sec^{-1}$) ($P > 0.05$). In support of these findings, novel protocol performed poorer with respect to reproducibility of CV, displaying a reproducibility coefficient of 0.81. In contrast to the much higher reproducibility coefficient presented by the lab protocol (0.94), the lower between-subject variability in concurrence with a larger within-subject variability offered by the field test implies that this test is not nearly as good at ‘separating’ out individuals and as such, would not be as effective as the lab protocol in detecting an intervention effect.

This explanation is better depicted through Figures 13 and 14. Compared to laboratory estimates wherein a much greater spread in the range of velocities characterising CV estimates is evident across subjects. The narrower distribution of CV values derived through field test performance, irrespective of the treatment undertaken, is reflected in its predisposition to cluster and group individuals and likely accounts for the poorer measure of sensitivity displayed by this protocol to detect an intervention training effect.

For a testing protocol to be considered good, it needs to able to differentiate between subjects and display minimal within subject variability across days or tests. While 3 subjects are seen to lie out with this cluster (Figure 14 – Panel B), thus providing some potential for the field to differentiate between individuals. This interpretation should be approached with caution. As Figure 15 highlights, the 95% CI for the reproducibility coefficient for the field test covers a much larger range than that of the lab based protocol (0.41 – 0.94 as opposed to 0.81 – 0.98). In concurrence with reproducibility coefficients potentially as low as 0.41, suggestive of larger within-subject variability, SE errors out-with 5% accepted limit for critical velocity estimation signifies a high degree of uncertainty and inaccuracy envelopes the CV estimates produced when field test performance is undertaken. This position is further reinforced by the finding that in light of the much wider 95% CI width presented by the field protocol, with a possible reproducibility coefficient well under the 0.80 reliability threshold, the field protocol provides a poor measure of reliability and as such is of questionable value as a practical tool.

It was hoped that a high level of agreement in the estimation of CV would accompany the performance of the novel field test, relative to the lab protocol from which a basis could be established to implement this protocol within soccer. However, as a result of the poor sensitivity exhibited with respect to the consistent inability of the novel field test to differentiate between individuals in addition to the poor test-re-test reliability, the scope from which to utilise the novel field test within soccer, particularly for physiological assessment is severely limited.

4.5 Limitations

Given the nature of intervention studies, training compliance is often difficult to maintain. Over the duration of the present investigation, unavailability during testing and across the training intervention period meant that the initial sample size was altered, resulting in only 12 completed sets of data being obtained. Given the small sample, the power of the study to discern any significant intervention effects or relationships between the field and laboratory test measures of critical velocity was therefore reduced. As a result, this investigation can only really at best, be considered as a pilot study. Retrospective power calculations identified over 100 subjects would have had to been tested in order to achieve a 90% chance of inferring that a 0.07 $m.sec^{-1}$ increase in CV displayed within the INT group was significant. Given the number of tests required for 1 individual, a sample size of over 100 would be extremely impractical and thus effectively limits CV application within soccer until an accurate single test protocol can be developed.

In light of the limited practicality associated with the gold standard laboratory protocol for the measurement of the parameters of the hyperbolic V-t relationship, this study sought to develop a novel field test that would facilitate the determination of critical velocity in a single testing session. An inherent drawback however, that could be associated with the novel field test protocol design, was the inability to maintain a constant velocity throughout each run until t_{lim} was achieved. The confinement to a shuttle run design for the field test necessitated that accelerations, decelerations and change of directions were required in order to maintain pace with the bleep for each speed selected.

While it could be argued that the incorporation of such actions is indeed specific to soccer performance, coincidently they may have negatively impacted on test performance. As proposed by some authors within the literature, *D'* is believed to represent a finite energy store whose rate of utilisation rate is thought to bear some degree of proportionality to the magnitude of the velocity requirement above critical velocity, with exhaustion occurring when this store is depleted (Moritani et al., 1981; Poole et al., 1988). In this light, as Buchheit et al., (2010) attests, the requirement to perform such additional actions clearly presents a different physiological loading relative to the performance of the laboratory protocol, whereby a constant running velocity could be maintained. Running with directional changes represents a greater physiological load which is likely associated by an increased cardiorespiratory response, muscular VO_2 uptake and blood lactate concentration. As a result, the inclusion of such actions may have elicited a greater taxation of *D'* above that necessary to sustain the selected running velocity, thus decreasing the duration that feasibly could be achieved upon reaching t_{lim} for the given running speed. It could therefore be postulated that the shuttle based design was a limitation of this study and possibly contributed to the underestimation in critical velocity displayed by the field test relative to the laboratory derived estimation.

Another plausible explanation which may account for some of the discrepancy displayed in protocol estimations of CV was the differing environmental conditions to which each testing protocol was conducted. A higher metabolic demand and greater utilization of *D'* could be associated with the forward propulsion required during field test performance due to the need to overcome air resistance and inertia. During field test performance, as a result of protocol design, subjects were required to continually overcome substantial amounts of inertia while accelerating upon performing the change of direction required at the end of each shuttle. While a 1% grade was implemented throughout all laboratory testing to compensate for the effects of air resistance, the impact of inertia could not be simulated. It would seem sensible to suggest that for the same running speed performed across both protocols, the presence of this environmental factor would have presumably resulted in a quicker taxation of *D'* and cessation of exercise during field test performance and contributed to the underestimation of CV relative to that derived from laboratory estimation.

To provide a closer representation of the laboratory protocol implemented to estimate CV, it was originally proposed that the novel field test should be performed on a running track to better ensure the maintenance of a constant running velocity. While it was accepted that this would have reduced the heightened metabolic cost associated with changing direction, thus making the taxation of *D'* more reflective of the selected running velocity, this proposal could not be successfully employed. The restriction to a fixed distance (i.e. 400m running track) meant that the 3 second pacing strategy and elimination criteria would have been difficult to apply. It was for this reason along with the inaccuracy and difficulty associated with measuring out a novel circular running track design for each different running velocity that led to the selection of a shuttle based format for the field protocol.

Another area of limitation could have potentially been the rest duration allocated between runs. Within the current literature, limited evidence exists investigating the use, and or impact, of consecutive bouts of work to volitional exhaustion. Therein, the effects of recovery duration from prior consecutive bouts of exhaustive exercise on the parameters of the velocity-duration relationship are yet to be fully elucidated. Thus, at present, to our knowledge, no technique is currently available for directly assessing the time course of *D'* recovery following prior exhaustive exercise. At the time of developing the field protocol, the work conducted by Ferguson et al., (2010) provided much of the rationalisation for the 15 minute recovery period employed between each of the successive three runs. The findings from Ferguson's research identified that the mean temporal profile of the magnitude of *W'* recovery displayed a $t_{1/2}$ of 4 minutes and following 15minutes recovery, was replenished by 86±4 %. Essentially however, it could be inferred when basing the recovery kinetics of *D'* on these findings, that the adoption of a 15 minute recovery period may not have been sufficient to fully facilitate the reconstitution of *D'* in the subsequent second and third running bouts respectively. Consequently, this may have adversely impacted on subject's performance capacity, with diminished running durations being achieved.

In contrast, a fundamental assumption adopted in the present study was that following the completion of each surpa-critical velocity field test run, upon achieving $t_{lim,}$ *D'* was fully depleted or that its mediator(s) is (are) exhausted to a low but limiting value. As we had no way of verifying this, test performance may not have been a true reflection of an individual's actual limit of tolerance as *D'* may not have been fully utilised.

A reduction in work efficiency has been reported in subsequent exercise bouts following a prior bout of supra-CV exercise to deplete *W'* (Sahlin et al., 2005) and as such, as Ferguson et al., (2010) also postulates, we are unable to rule out the possibility that the recovery profile of *W'* following the undertaking of successive shuttle runs may have been modified as a result of an altered work efficiency effect on the rate of *W'* depletion. Together, a reduction in work economy in conjunction with a potential alteration in the reconstitution rate of *W'* may have again limited field test performance, particularly in the second and third runs respectively.

4.6 Further Study

In view of the limited adaption displayed within the physiological indices of aerobic capacity measured, future study should take into consideration the duration of, and season phase within which the intervention is implemented. Given, the fact that this study was conducted using University soccer players, the duration and season phase (i.e. in-season) were curtailed and dictated by the academic semester. The adoption of a longer training intervention (8-12 weeks) which encompasses the pre-season phase of the soccer season is warranted. This would have presumably facilitate a more marked improvement in maximal aerobic capacity and critical velocity as an aerobic base would not have been previously established. Given the validation nature of this study, it may be more practical to assess the ability of the novel field test to accurately track changes in CV when indeed the magnitude of change is expected to be more substantial.

The restriction to a shuttle run design which necessitated subjects to decelerate and accelerate thereby presumably contributing to a greater taxation of *D'* and a premature t_{lim} as attested, may have contributed to the poor agreement displayed between protocol estimates of CV. While an original proposal was to perform the field test on a running track to better ensure the maintenance of a constant running velocity, the restriction to a fixed distance (i.e. 400m running track) meant the 3 second pacing strategy and elimination criteria would have been difficult and impractical to apply. It is proposed that a longer shuttle length is implemented in further research. While reducing the frequency of the requirement to perform taxing decelerations and accelerations, this would permit the maintenance of a constant velocity for longer. It is presumed, that in response this design adaptation, the tolerable duration of exercise at a given velocity would be increased as the taxation of *D'* would be less pronounced in account of the maintenance of a more consistent running velocity with a reduced frequency with which a change direction is required.

With respect to the limited sensitivity and reproducibility displayed within the novel field test to accurately estimate critical velocity, we were unable to provide validation for the adoption of this protocol as suitable alternative to the traditional laboratory protocol for the demarcation of the heavy-severe domain boundary. Concerted effort must be made to continue to develop protocols which can accurately and efficiently determine both CV and *D'* before more research can be conducted on both the significance of, and understanding of the physiology underlying these two parameters.

In accordance with the growing body of evidence within the literature, highlighting that CP and *W'* can be established in a single laboratory derived 3 minute all-out cycling test (Burnley et al., 2007, Vanhatalo et al., 2007, McClave et al., 2011; Bergstrom et al., 2012), thereby limiting the requirement for multiple testing sessions and directly addressing the time consuming dilemma presented. The investigations of Pettitt et al., (2012) and Broxterman et al., (2013) have sought, through the implementation of GPS and accelerometry respectively, to apply and adapt the single three minute all out concept to running performance for the determination of CV and *D'*.

In close relation to the present study, Broxterman et al., (2013) attempted to validate their method against the traditional determination of the V-t relationship. While the findings presented, provide good agreement between ES and traditionally determined CV, further investigation is warranted to consolidate this testing protocol as a valid alternative to traditional determination of CV estimation before it can be universally implemented.

CHAPTER 6 - CONCLUSION

In concluding, the key finding to be inferred from the present investigation was that given the limited agreement displayed in protocol estimations of critical velocity, little evidence exists to support the application of the novel field test based to determine critical velocity from a single testing session.

The current investigation indicates that no correlation existed between laboratory derived and field tests estimates of critical velocity. From the findings, it was found that the novel field test, relative to the laboratory protocol, inherently underestimated critical velocity for both intervention and control groups respectively, with a significant difference being exhibited in post-intervention comparisons for the INT group respectively.

When taken in combination with the limited sensitivity and test-retest reproducibility displayed within the novel field protocol to accurately estimate and track changes in critical velocity irrespective of experimental group examined. Best practice suggests the continued use of laboratory based protocols to determine critical velocity is merited. More research should be directed towards developing more reliable field tests with the aim of estimating critical velocity in a single test.

While the novel field test implemented within the present investigation fails to accurately address the innate impracticalities associated with estimating the parameters of the V-t hyperbolic relationship via laboratory derived estimates. The respective investigations of both Pettitt et al., (2012) and Broxterman et al., (2013) have recently built upon the original work of Vanhatalo et al., 2007 and have looked to develop an equivalent all-out-3 minute field test for running to estimate critical velocity and *D'*.

The availability of an accurate single test protocol to determining the parameters of the velocity-time relationship would greatly facilitate the utility of the critical velocity concept within exercise science. By reducing the number of testing sessions' necessary, thus minimising disruption to training and competition schedules, a single test protocol would be highly practical within the athletic arena.

The development of a single all-out-3 minute protocol has the capacity to provide a comprehensive analysis of the physiological status of an athlete. In addition to offering an assessment of aerobic fitness, it allows for the demarcation of the heavy and severe domains. By accurately determining this domain boundary, training intensities can be both, individual tailored and standardised across team sporting environments to elicit the desired training response.

The development of a single all-out-3 minute test for running would provide a useful basis from which to progress research within this area, and continued study is strongly warranted.

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