Applications of the Anaerobic Speed Reserve to Elite 800m running

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Gareth Neil Sandford – MSc

Primary Supervisor – Dr Andrew Kilding

Secondary Supervisor – Dr Paul Laursen

Tertiary Supervisor – Dr Angus Ross

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Auckland University of Technology
Faculty of Health and Environmental Sciences

SPORTS PERFORMANCE RESEARCH INSTITUTE, NEW ZEALAND
AN INSTITUTE OF AUT UNIVERSITY

ATHLETICS NEW ZEALAND

HIGH PERFORMANCE SPORT NEW ZEALAND

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Attestation of Authorship

"I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning."

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Publications

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Abbreviations

ADP – adenosine diphosphate

ASR – anaerobic speed reserve

ASR-LAB – ASR where lower component calculated with laboratory derived vVO_2max

ASR-1500_v – ASR where lower component calculated with 1500m race prediction

ATP – adenosine triphosphate

ATP-PC – phosphate system.

CL – confidence limits

CP – critical power

CS – critical speed

CSA – cross-sectional area

CV – coefficient of variation

D’ – D’ prime

e - exponential

E-cost – Energy cost

EMG – electromyogram

ES – effect size

$HCO3^-$ - bicarbonate

HPSNZ – High Performance Sport New Zealand

Hz – hertz (frequency)

Abbreviations

IAAF – International Association of Athletics Federations

kg - kilograms

km – kilometre

km/hr – kilometres per hour

km/week – kilometres per week

LDH – lactate dehydrogenase

LT_2 – lactate turnpoint

m – metres

MAOD – maximally accumulated oxygen deficit

MART – maximal anaerobic running test

MAS – maximal aerobic speed

MBI – magnitude based inferences

MCT's – monocarboxylate transporters

MLSS – maximal lactate steady state

mmol – millimole

m/s – metres/second

MSS – maximal sprinting speed

MTU – muscle tendon unit

NAD^+ – nicotinamide adenine dinucleotide

OG – Olympic games

Abbreviations

PB – personal best time

PCr – phosphocreatine

Pi – inorganic phosphate

RE – running economy

RH – relative humidity

s - seconds

SaO_2 – oxygen saturation

SB – seasons best time

SD – standard deviation

SE_E– standard error of the estimate

SL – stride length

SF – stride frequency

SRR – speed reserve ratio

SSC – stretch shortening – cycle

SWC – smallest worthwhile change

TT– time trial

$\dot{V}O_2$ – oxygen uptake

$\dot{V}O_2max$ – maximal oxygen uptake

$_vLT_2$ – velocity at lactate turnpoint

$v\dot{V}O_2max$ – velocity at $\dot{V}O_2max$

Abbreviations

vMART – final velocity of MART (above)

vOBLA – velocity at onset of blood lactate accumulation

VO_2 peak – peak oxygen uptake

W - watts

W' – W prime

WC – world championships

400-800m – sprint 800m athlete subgroup

800-1500m – endurance 800m athlete sub-group

1500_v – average 1500m race pace

Abstract

Middle-distance running events (800 and 1500m) require a unique interplay of aerobic and anaerobic energetics, meaning athletes with diverse profiles may have an opportunity to win the race. Historically, research of middle-distance running has centred on the aerobic determinants of performance. Preparatory training approaches to meet these demands have naturally followed.

Modern-day international middle-distance standards and depth are becoming increasingly competitive. Within a race, there are tactical moments that differentiate medal outcomes, which are typically underpinned by surges. These moments are supported by high levels of aerobic metabolism, yet potentially concurrent anaerobic, neuromuscular and mechanical characteristics.

The anaerobic speed reserve (ASR) represents the speed range an athlete possesses from their velocity at $\dot{V}O_2max$ ($v\dot{V}O_2max$) to their maximal sprint speed (MSS). The degree to which the ASR is required within middle-distance events is yet to be investigated. Therefore, an overarching aim of my thesis was to explore the tactical behaviours that differentiate World and Olympic medallists over 800m in the modern era and to analyse the potential importance of the ASR as it relates to these critical moments. To address these aims, the following studies were conducted. Study 1 assessed the evolution of tactical behaviour in the men's 800m at Olympic Games and World Championships in the modern competition era (2000-2016). Study 2 evaluated the tools currently available to measure the anaerobic qualities underpinning modern day tactics found in study 1. Following the findings of studies 1 and 2, the ASR was determined as the most reliable and practical measure for field application. Study 3, through theoretical modelling, determined whether ASR differences existed between and within middle-distance event groups. To directly address these findings, study 4 involved travel to locations around the

world to test elite participants to determine the relationship between ASR and elite 800m performance and further understanding of 800m profile variability. Study 5 aimed to contextualise application of the ASR construct to 800m running, specifically by focusing on the neuromuscular and mechanical determinants of ASR. Study 6 offered sample training data from elite male 800m runners, providing insight into how coaches might apply knowledge of ASR to the different 800m sub-groups identified in study 4. In study 7, it was important to validate the $v\dot{V}O_2max$ prediction equation I used in study 4 based on a runner's 1500m race performance; this variable was instrumental in calculating the ASR construct.

Collectively these studies showed: 1) faster sector speed demands than in previous eras of 800m running for Olympic and world medallists, 2) that ASR, as a function of MSS, seems to differentiate faster 800m performers in an elite population, 3) that ASR is a key component of 800m running performance, with additional application for surging in 1500m-10,000m 4) that ASR is a useful tool for categorizing runners into one of three distinct athlete sub-groups (400-800m speed types, 800m specialists and 800-1500m endurance specialists), which may assist coaches to individualise their training approach, and 5) mechanical efficiency of middle-distance runners may be a critical factor limiting surge capability.

CHAPTER 1: INTRODUCTION

Chapter 1

1.1 Background

Distance running has a large cultural significance in New Zealand following the global success of athletes such as Jack Lovelock (1930's), Peter Snell, Murray Halberg, Barry McGee (1960's) and John Walker (1970's). One man's tutelage has largely been credited for the majority of these achievements, and that is the great Sir Arthur Lydiard. Indeed, Lydiard coached Peter Snell (800m Gold), Murray Halberg (5000m Gold) and Barry McGee (Marathon Bronze) (Lydiard & Gilmour, 2000) to success at the 1960 Rome Olympic Games. The training methods of Lydiard, which eventually reached international reputation, placed a large emphasis on training volume (up to 160km/week) and maximising aerobic fitness that was considered beneficial to performance in events as short as 800m and up to the Marathon. Lydiard shaped the culture of distance running in New Zealand, with many of his methods used by disciples around the world today.

Middle-distance running at the Olympic level considers events ranging from 800m to 5000m (Lacour et al. 1990). The physiological demands of these events are particularly unique with close interplay between aerobic and anaerobic energetics (Brandon, 1995), whereby, the shorter the race distance, the greater the anaerobic contribution, with a maximal effort of 75s providing approximately equal aerobic/anaerobic energy contribution (Gastin, 2001). The aerobic energetic contribution to men's 1500m and 800m has been reported as 80-85% and 66% respectively (Duffield & Dawson, 2003; Spencer & Gastin, 2001). Despite their considerable differences, the 800m is often grouped alongside the 1500m event in terms of the event demands and subsequent determinants of performance (Ingham et al., 2008). Brandon (1995) suggests that athletes can be successful over middle-distance events with varying aerobic and anaerobic dominant profiles. This is highlighted by the diversity of athlete profiles believed to appear in the event, alongside the complexity of training approaches needed to maximise performance across the speed-to-endurance 800m profile continuum (Gamboa et al.,

1996; Horwill, 1980). To date, characterising the diversity and importance of these profiles for success in modern-day 800m running has received little scientific attention.

Early work on power-duration relationships recognised that energy supply, and therefore aerobic metabolism, may not be the only important contributor to middle-distance running performance (Hill, 1925). Hill stated that both oxygen requirement (above and beyond oxygen uptake), and 'non-metabolic' determinants of maximal speed (efforts under 40s), such as ground reaction force orientation (Weyand, Sternlight, Bellizzi & Wright, 2000; Morin, Eduard & Samozino, 2011) were important considerations to performance, that may hold key relevance to middle-distance running where surges (defined as a noticeable raise in velocity from the front of the race, or passing ≥3 opponents) differentiate medallists (Mytton et al. 2015). However, to date, research has largely focused on the aerobic contribution to middle-distance performance (Barnes & Kilding, 2015; Bassett & Howley, 2000; Ingham et al., 2008; A. Jones & Carter, 2000; Joyner & Coyle, 2008; Saunders, Pyne, Telford, & Hawley, 2004), with $\dot{V}O_2max$, running economy and lactate threshold gaining the large share of attention. By way of example, a PubMed online search on 25th July 2018 revealed the number of articles related to the following search terms by total, then in brackets with middle-distance added e.g. '$\dot{V}O_2max$' ('$\dot{V}O_2max$ middle-distance'). '$\dot{V}O_2max$' 7653 (58), 'Critical Speed' 6,381 (3), 'Lactate Threshold' 3,752 (29), 'Running Economy' 2391 (26), 'Anaerobic work capacity' 782 (5), 'Velocity at $\dot{V}O_2max$' 460 (21) and 'Anaerobic speed reserve (ASR)' 11 (0). As a result, it was clear that the middle-distance literature would benefit from exploration of the anaerobic speed reserve (where the upper limit maximal sprint speed (MSS) is limited primarily by ground reaction force, Weyand et al. 2000; Morin et al. 2011) and its potential contribution to performance.

The term ‘speed reserve’ in the middle-distance context was first defined as the difference between the average speed per 100m of a race event and the person’s best 100m time (Ozolin, 1959). Using this interpretation, a larger speed reserve was deemed an indicator of greater athlete potential, believed to allow more headroom to develop the aerobic system (Schmolinsky, 1983). In addition, development of speed reserve was seen as an important component for allowing fast finishing speed (Schmolinsky, 1983). More recently, the term ASR was coined to define the speed range across an athlete's velocity at maximal oxygen uptake ($v\dot{V}O_2max$) to their MSS (Blondel, Berthoin, Billat, & Lensel, 2001;Buchheit & Laursen, 2013). These two moving parts may be underpinned by distinct performance determinants, with $v\dot{V}O_2max$ primarily influenced by metabolism (Bundle & Weyand, 2012) and MSS more by force orientation/mechanics (Rabita et al., 2015; Weyand, Sternlight, Bellizzi, & Wright, 2000). ASR changes as a function of MSS and $v\dot{V}O_2max$, thus its role as a determinant of performance will be driven by changes in the respective upper (MSS) and lower ($v\dot{V}O_2max$) bounds. Therefore, a key application of ASR is to concurrently assess both metabolic and mechanical limitations of an athlete’s profile in context of the other components, with the 800m requiring developed characteristics across aerobic, anaerobic neuromuscular and mechanical characteristics (Spencer & Gastin, 2001; Ingham et al 2008; Bachero-Mena et al. 2017).

However, beyond using ASR as a discrete test measure, the ASR could be considered a construct that potentially offers promise in a number of areas with reference to middle-distance running. For example, the ASR framework may help advance understanding of the complexity of athlete profiles in middle-distance running by concurrently taking into account *both* metabolic and mechanical/neuromuscular locomotor limitations (Buchheit & Mendez-Villanueva, 2014), rather than in isolation. Further, the ASR domain (speed range from $v\dot{V}O_2max$ to MSS) may allow for faster race pace running (Buchheit, Hader & Mendez-Villaneuva, 2012), account for individual differences in prescription of high

intensity interval training (Buchheit & Laursen, 2013) or uncover individual training density and recovery approaches. Utilising the ASR framework (both $v\dot{V}O_2max$ and MSS) within middle-distance running could provide insight into the diversity of profiles that athletes often present with to get to the same performance, as shown previously in world-class pursuit riders (4000m, 4 min 19s duration) (Schumacher & Mueller, 2002).

Within sprint coaching circles, the ASR is a regularly discussed construct (D. Pfaff, K. Tyler, T. Crick, personal communication). The foundation of this concept is that to run a certain time, the athlete must have the speed capacity to execute a particular pacing strategy. A commonly used approach by coaches to predict 400m potential is to double their athletes' best 200m time and add 3.5s (Schiffer, 2008). Schiffer (2008) states that "when comparing heterogeneous groups of runners characterised by a very high anaerobic capacity, those who are faster over shorter distances tend to be faster in the 400 metres". Despite evidence in events from 800m-10,000m, showing that surges in pace and the 'last lap kick' are key differentiators between Olympic and World Championship medallists (Mytton et al., 2015; Ross Tucker, Lambert, & Noakes, 2006), the ASR, which may in part underpin this race tactic, has received very little attention in the middle-distance context throughout the scientific literature.

1.2 Rationale and Thesis Aims

At the time this thesis was proposed, Athletics New Zealand had prioritised middle-distance as a focus event group for the 2016 Olympics and 2020 Olympic cycle. Federation and coaching observations of race performance throughout the Rio de Janeiro Olympic cycle (2012-2016) was that speed demands were substantially increasing, exemplified by new world records in the Men's 800m (1:40.91) and women's 1500m (3:50.07), and last lap surges differentiating medal outcomes (Mytton et al. 2015). It was therefore crucial to develop a research question that could potentially contribute to the

development of a framework for ensuring New Zealand athletes had the required speed demands to compete in race surges on the world stage. Therefore, the overarching objective of this thesis was to further develop understanding of the physical qualities and tactical behaviours underpinning race surging in the men's 800m, with specific reference to use of the anaerobic speed reserve.

To address this overarching objective, several subsequent aims were developed for this thesis:

1. Better understand the tactical behaviours of modern day world-class male 800m runners
2. Evaluate the tools available for quantifying the ASR domain in middle-distance runners
3. Determine the relationship between the ASR and its components ($v\dot{V}O_2max$ & MSS) in elite male 800m performances
4. Define best practice application of ASR in middle-distance running context
5. Provide frameworks for better understanding the complexity of middle-distance running profiles that may lead to guiding more individual training approaches
6. Provide practical field alternatives to measuring the lower component of the ASR – $v\dot{V}O_2max$

1.3 Thesis Structure

To address the thesis aims, a series of studies were undertaken as illustrated in Figure 1.1.

Figure 1.1. Overview of thesis structure

1.4 Overview of Studies

Chapter 3 – Study 1

This chapter assessed the evolution of tactical behaviour in the M800 at Olympic Games (OG) and World Championships (WC) in the modern competition era (2000-2016). We aimed to determine clear tactical determinants of medal winning on the world stage.

Chapter 4 – Study 2

This chapter evaluated the tools currently available to measure the anaerobic qualities underpinning modern day tactics found in study 1.

Chapter 5 – Study 3

Following the findings of studies 1 and 2, the anaerobic speed reserve (ASR) was determined to be the most reliable and practical measure for field application. The aim of this paper was to model the ASR in world class male 800m and 1500m runners, to determine hypothetically whether ASR differences existed between and within middle-distance event groups.

Chapter 6 – Study 4

This chapter followed up study 3 by profiling the ASR of 19 world-class 800m and 1500m runners. The aim of this study was to determine the relationship between ASR and 800m performance, as well as how ASR might be used as a tool for understanding 800m profile variability.

Chapter 7 – Study 5

This chapter contextualises application of the ASR construct to 800m running. The aim was to focus on the neuromuscular and mechanical determinants of ASR, in doing so provoking interest in less frequently considered areas in developing the modern-day 800m runner.

Chapter 8 – Study 6

This chapter provides sample training data from elite 800m runners, with the aim of providing principles for applying ASR to the different 800m sub-groups identified in study 4.

Chapter 9 – Study 7

Following on from the maximal aerobic speed prediction used in study 4, we aimed to validate $v\dot{V}O_2max$ prediction from 1500m race performance in elite middle-distance runners.

1.5 Significance of Thesis

The aim of the research that forms my thesis was to provide an evidence base and assessment tool for 800m training paradigm selection for Athletics New Zealand and wider middle-distance community. Profiles of ASR characteristics have yet to be reported together in national and international middle-distance runners, and would serve as a substantial contribution to knowledge in this space. Re-assessing the key determinants of distance running success, and specifically middle-distance was a key driver for initiation of this project. With that in mind, it was deemed important for this research project to further investigate a relatively unexplored, but potentially key performance determinant of middle-distance running; the ASR.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The anaerobic physiology of running performance has received relatively little scientific attention in the literature, particularly in the middle-distance events (Brandon, 1995). Indeed, Berg (2003) describes the state of the literature as having "a relative neglect of anaerobic power and physical structure as determinants of performance". Perhaps whilst attention and consideration towards anaerobic energetic understanding has improved in long-distance events (≥ 5km) (Baumann, Rupp, Ingalls, & Doyle, 2011; Beattie, Kenny, Lyons, & Carson, 2014; Nummela, Mero, Stray-Gundersen, & Rusko, 1996), a paucity of information pertaining to the anaerobic qualities of middle-distance runners remains (Brandon, 1995). Factors affecting technical, tactical and physical development in middle-distance running are displayed in figure 2.1, including the all-important anaerobic and neuromuscular characteristics. Research focus on the anaerobic characteristics contributing to middle-distance running performance may be disproportionate relative to its importance. Therefore, the aim of this review is to provide a landscape of the middle-distance running research to date and by doing so illustrate the importance of the research undertaken in the current thesis.

2.2 Defining Middle-Distance Running Determinants and Energetic Demands

Middle-distance running at the Olympic level considers events ranging from 800m to 5000m (Lacour, Padilla-Magunacelaya, Barthélémy & Dormois, 1990). This review however will focus on the 800 and 1500m events due to their average relative race intensities beyond v$\dot{V}O_2$max shown in Figure 2.2. For context, current world record performance times for men's and women's 800m and 1500m (mm:ss:ms) are 1:40:91/1:53:28 and 3:26:00/3:50:07, respectively. The individual contribution of the ATP/PCr, anaerobic glycolytic and aerobic energy systems to ATP production is

dependent upon both the demands of the exercise and the capacity of the respective systems. ATP/PCr has the highest rate of ATP production, while the aerobic system the largest capacity (Maughan & Gleeson, 2010).

The energetic demands of middle-distance running surpass that which can be met solely by aerobic glycolysis and lipolysis, leaving metabolic limitations in elite-level middle-distance running performance residing partially from an individual's anaerobic capabilities (Maughan & Gleeson, 2010). Moreover, there may be an important difference between energetic demands of the event (e.g 66% aerobic) and the determinants underpinning race surges. For example, Rio 2016 Olympic Gold medal winning time was 1:42.16 (average of 28.19km/hr), with the fastest 100m sector – 11s (average of 32.73km/hr). In the following sections, I will revisit the 'classic' physiological determinants underpinning distance running performance, before reviewing the modern-day technical/tactical factors of middle-distance racing, in order to establish the relative importance of a concurrent focus on biomechanical and neuromuscular development in middle-distance runners.

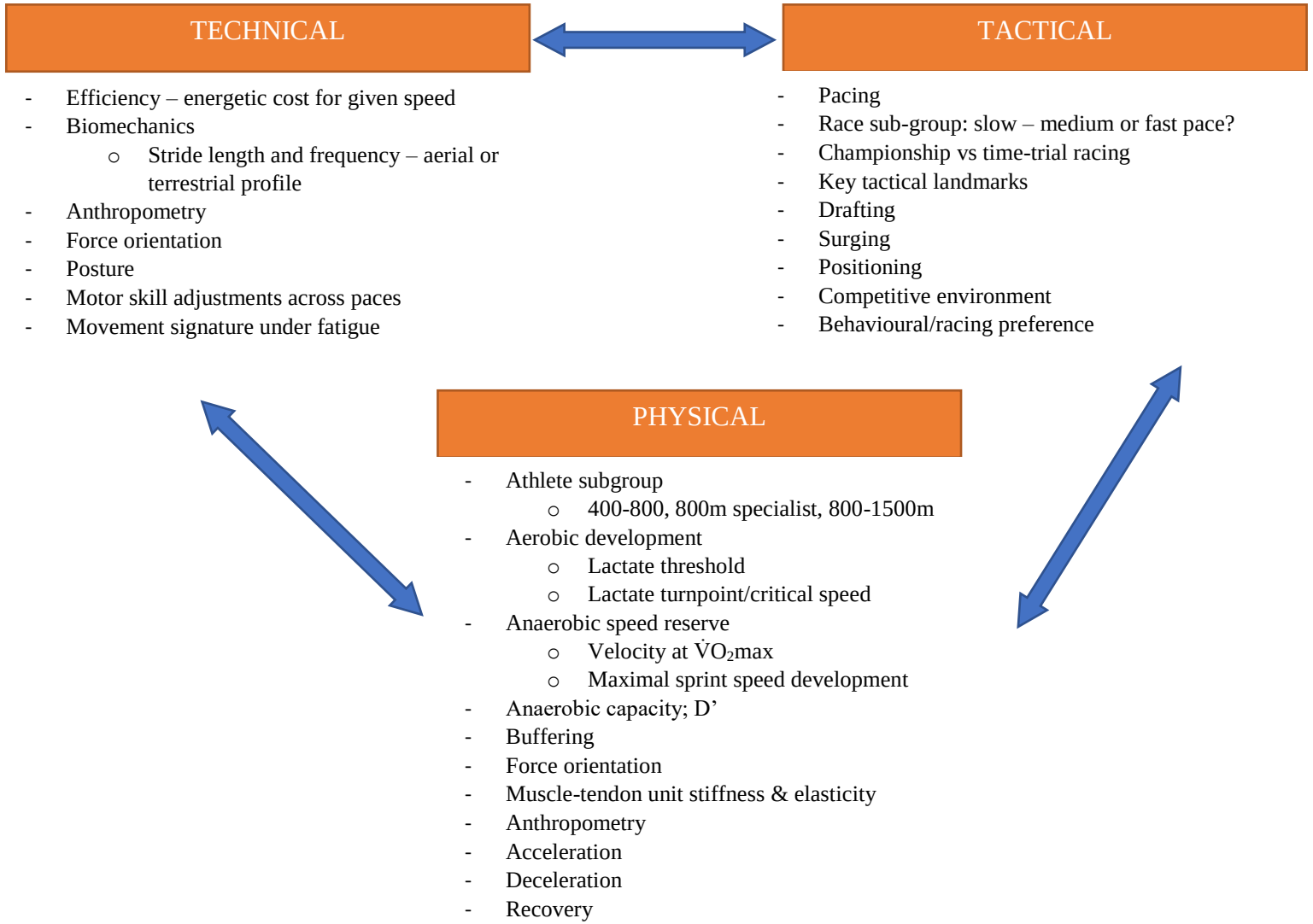

Figure 2.1 Factors affecting technical, tactical and physical development in middle-distance running

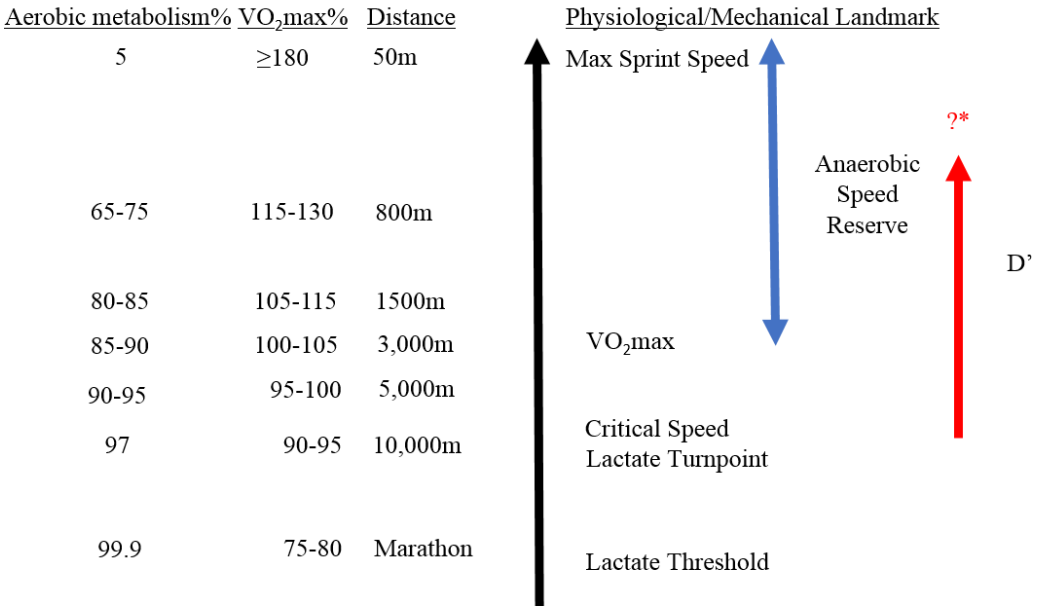

Figure 2.2 Relative work intensities and energetic contributions to energy metabolism as they relate to distance running races. Modified from (Billat, 2001), (Buchheit & Laursen, 2013), (Maughan & Gleeson, 2010).

2.3 'Classic' Physiological Determinants of Distance Running Performance

The aerobic physiology of running performance is well described within the scientific literature (Bassett & Howley, 2000; Joyner & Coyle, 2008; Baumann, Rupp, Ingalls, & Doyle, 2011). Largely, the research has focused on maximal oxygen uptake ($\dot{V}O_2max$), running economy (RE) and lactate threshold (Berg, 2003). The reason for this research emphasis may be due to the following three factors. First, there is a predominance of aerobic energy contribution to middle-distance race performance (Duffield & Dawson, 2003), making this the most logical area to explore. Second, the progressive exercise tests where these aerobic parameters are measured is a reliable and accessible physiological testing battery (Bundle, Hoyt, & Weyand, 2003). Last, it is possible that there may have been a researcher bias towards the longer distance running events (5km to marathon). This section will briefly revisit the three 'classic physiological determinants of distance

running performance': namely, $\dot{V}O_2$max, RE and lactate threshold and the transition from heavy to severe intensity exercise. For a more extensive review on these parameters, see Bassett & Howley, (2000) and Joyner & Coyle, (2008).

Maximal Oxygen Uptake

$\dot{V}O_2$max can be defined as the maximum oxygen carrying capacity of an individual (Hill & Lupton, 1925). $\dot{V}O_2$max is calculated through measurements of the air concentrations and volumes of expired air measured from the mouth, and relate to the amount of oxygen taken up by the lungs, transported around the body via the heart and blood, and consumed by the body's mitochondria to produce ATP via oxidative phosphorylation.

Not only does $\dot{V}O_2$max differentiate endurance capability within a heterogeneous athlete group, but also between middle-distance (800 & 1500m) and long-distance international athletes (Costill, Thomason, & Roberts, 1973; Rabadán et al., 2011). Indeed, higher $\dot{V}O_2$max values have been shown in long-distance compared to middle-distance runners (Rabadán et al., 2011), suggesting that an athlete's physiological profile may help inform event specialisation to some extent. For example, the $\dot{V}O_2$max values of five former world-class middle-distance athletes are shown in Table 2.1 (adapted from Noakes, 2001). Across the 800m to 1 mile event distance, a vast difference in $\dot{V}O_2$max can be seen between elite athletes, however there appears to be a minimum requirement of aerobic capability to be an elite middle-distance athlete. The naturally high $\dot{V}O_2$max requirement in elite middle-distance running is further demonstrated from examples of National French juniors (18-19), where $\dot{V}O_2$max values for males and females average 71.4ml/kg/min and 60.1 ml/kg/min, respectively (Billat, Lepretre, Heugas, & Koralsztein, 2004). Furthermore in 16-year-old male and female English county 800m runners, mean $\dot{V}O_2$ peak was 65.2 ml/kg/min and 56.2 ml/kg/min respectively. In the 1500m, a similar

$\dot{V}O_2$ peak was found for boys 65.5ml/kg/min and 56.9 ml/kg/min for girls (Almarwaey, Jones, & Tolfrey, 2003).

Table 2.1. Physiological and performance characteristics of 5 world class middle-distance runners

Athlete	$\dot{V}O_2$max (ml/kg/min)	1 Mile Personal Best (mm:ss:ms)	1500m Personal Best (mm:ss:ms)	800m Personal Best (mm:ss:ms)	World Record
Steve Prefontaine	84.4	3:54.6	3:38.10	n/a	-
Jim Ryun	81.0	3:51.1	3:33.10	1:44.90	1500m (1967) 1 Mile (1967)
Steve Scott	80.1	3:47.69	3:31.76	1:45.05	-
Sebastian Coe	77.0	3:47.33	3:29.77	1:41.73	800m (1981) 1500m (1980) Mile (1981)
Peter Snell	72.3	3:54.4	3:37.60	1:44.30	800m (1962) 1 Mile (1964)

Combined, it may be assumed that having $\dot{V}O_2$max values below ~70 ml/kg/min for males and ~60 ml/kg/min for females is unlikely to result in medal winning performances at a world-class level.

Running Economy

RE is defined as the oxygen cost of movement for a given running speed, and a large degree of inter-individual variability has been shown across athletes (Barnes & Kilding, 2015). As such, RE can be a performance differentiator amongst elite athletes groups with homogeneous $\dot{V}O_2$max values (Costill et al., 1973). RE for British male national and international 800m and 1500m have been recorded as 209±14 and 207±9.7 ml.kg.km respectively (Ingham et al., 2008). By comparison, the current world half-marathon world

record holder Zerisenay Tadese possesses a RE of 150 ml.kg.km (Lucia, Oliván, Bravo, González-Freire, & Foster, 2008), one of the best RE ever reported. Typically RE is better in 5-10km and marathon performers at slower paces than 800-1500m athletes (J Daniels & Daniels, 1992; Fink, Costill, & Pollock, 1977; Lucia et al., 2006a; Saltin et al., 1995), reflecting performance determinants of the event.

RE variability between individuals may in part be explained by differences between two moving factors: a) the oxygen uptake and utilisation and b) the muscle tendon unit (MTU) properties of the lower extremities (Arampatzis et al., 2006; Saunders et al., 2004). With respect to oxygen uptake and delivery, these might be altered by any adaptation that modifies the absolute amount of oxygen the body can utilise at a given speed, including those that modify $\dot{V}O_2max$ (cardiorespiratory, haematological, metabolic). This is exemplified by the fact that training strategies such as altitude training have been documented to improve RE and various oxygen transport/utilisation factors, including angiogenesis and aerobic enzyme activity (Gore, Clark, & Saunders, 2007). MTU, refers to contractile and passive properties that modify muscle tendon stiffness (see Spring mass characteristics for full description), which have been shown to relate to superior RE (Arampatzis et al., 2006; Dumke, Pfaffenroth, Mcbride, & McCauley, 2010). Interventions such as strength and plyometric training have been shown to improve RE in well trained cohorts (Beattie et al., 2014; Paavolainen et al., 1999; Saunders et al., 2006), likely as a result of developing the MTU component of the economy equation. For extensive reviews on determinants of RE see Barnes & Kilding, (2015) and Saunders et al. (2004). Further discussion on RE application to middle-distance is expanded on in Chapter 7.

Velocity at $\dot{V}O_2$max

v$\dot{V}O_2$max can be defined as the minimal velocity at which $\dot{V}O_2$max is attained (Billat & Koralsztein, 1996). v$\dot{V}O_2$max may have relevance to event groups from 800m to the marathon and represents the interplay between $\dot{V}O_2$max and RE, which can differentiate between categories of runners (Costill et al., 1973). Typical v$\dot{V}O_2$max values of world-class middle-distance and long-distance runners are scarcely available within the scientific literature compared to absolute $\dot{V}O_2$max. Veronique Billat (2001) estimated the v$\dot{V}O_2$max of Haille Gebreselassie (Double Olympic and 4-time World Champion over 10km) at 25.5km/h based upon his 3000m time. In comparison, Jones (2006) reports a v$\dot{V}O_2$max of 23.5km/h in the female marathon world record holder, in the year the record was set. Alejandro Legaz-Arrese et al. (2011) demonstrated that the v$\dot{V}O_2$max of 3000m national steeplechase athletes was faster than that of marathon specialists. Within the literature, Peter Snell (800m Double Olympic Champion & 1x 1500m Olympic Champion) recorded a v$\dot{V}O_2$max of 22km/h (Carter et al., 1967). For comparison, one male international 1500m runner (3:32.80) had a v$\dot{V}O_2$max of 23.1 km/h (Ingham, Fudge, & Pringle, 2012). Thus, both the Peter Snell and the Ingham, Fudge & Pringle (2011) example present with a substantially lower v$\dot{V}O_2$max than 10km specialist Gebreselassie. Possible explanations include training approach for different event demands and differences in reliability of kit and calibration procedures from 1967 compared to 2012 (Hopkins, 2000). Further, both Snell and the British case study (Ingham et al., 2012) may be athlete's with exceptional anaerobic qualities or maximal sprint speed (MSS) , although this data is to my knowledge unreported. Relative to more aerobically gifted athletes such as Haille Gebreselassie or Steve Prefontaine (Billat, 2001; Fink, Costill, & Pollock, 1977), Peter Snell's $\dot{V}O_2$max and v$\dot{V}O_2$max capability is particularly low (table 2.1). This may in part be due to his uncharacteristic endomorph physique for middle-distance runners, with potentially associated heightened anaerobic capabilities (Carter et

al., 1967). The extensive work of Veronique Billat to introduce this concept and demonstrate its importance is well acknowledged by the author (Billat, Hill, Pinoteau, Petit, & Koralsztein, 1996; VL Billat & Koralsztein, 1996; Blondel et al., 2001). However, in recent times, reporting of this value in the scientific literature despite its importance in middle-distance running appears largely overlooked. One explanation may be that a reductionist approach to multi-factorial performance outcomes may have contributed to a perceived 'reliance' on $\dot{V}O_2$max, RE and lactate threshold to explain running performance, without further consideration of other factors.

Lactate Threshold

Lactate threshold can be defined as the first rise in lactate above baseline levels, and indirectly reflects the exercise intensity where the rate of lactate production in the muscle exceeds its removal into the blood (Bassett & Howley, 2000). Specifically, this may be the point where glycolytic energy production surpasses the rate at which pyruvate can be oxidised in the mitochondria, leading to the accumulation of lactic acid (dissociated to lactate and H^+ ions). H^+ ion accumulation within the muscle and blood is widely considered as one contributor to fatigue (Kicker, Renshaw, Oldham, & Cairns, 2011; Maughan & Gleeson, 2010), although its relative importance as a contributor is debated (Robergs, Ghiasvand, & Parker, 2004). For example, Robergs et al. (2004) have shown that the metabolic intermediates from glycolysis do not release protons (H^+) that are acidic in nature, but instead form as salts. In fact, the lactate dehydrogenase (LDH) reaction reduces pyruvate to lactate, and alkalises the cell. This contrasts the basis of the lactic acid theory, where ultimately metabolic acidosis is slowed, and is not causal to its initiation (Robergs et al., 2004). Proton release during glycolysis occurs from NAD, a crucial intermediate in facilitating ATP regeneration by maintaining the redox potential of the cell (transfer of electrons or ions), in this case H^+. Simultaneously, as lactate is

removed from the cell, excess protons are able to leave the cell, thus alkalising the environment. Nielsen, Paoli, & Overgaard, (2001) demonstrated in an isolated rat muscle under electrical stimulation, that the addition of lactate actually prevents the potassium-induced decline in force, further supporting the case that lactate production actually prolongs exercise duration during metabolic acidosis. Intra and extracellular based buffers provide a further tool for the body to maintain metabolic homeostasis. Bicarbonate (HCO^{3-}) is an extracellular buffer that quenches the protons produced by the exercising muscle to form carbonic acid, which dissociates to carbon dioxide and water (Stellingwerff et al., 2011).

The mechanism by which lactate leaves the muscle cell is via monocarboxylate transporters (MCT's) may also be important (Pilegaard, Terzis, Halestrap, & Juel, 1999). Pilegaard et al. (1999) demonstrated that fibre type predominance may influence MCT1 and MCT4 distribution in the muscle with more MCT4 transporters found in type ll muscle fibres. A short-term adaptation to training is an increase in MCT density which increase the rate of lactate clearance, as seen frequently in training studies with untrained or physically active individuals (Bonen et al., 1998; Burgomaster et al., 2005; Dubouchaud et al., 2000; Juel et al., 2004; Pilegaard et al., 1999; Thomas et al., 2005). Additionally, further MCT increases are less prominent in well trained individuals following high intensity training, suggesting further pH tolerance may come from alternative mechanisms involved in excitation contraction coupling (Iaia & Bangsbo, 2010; Iaia et al., 2008).

Years of consistent aerobic training increases the mitochondrial density and aerobic enzyme activity in the muscle enhancing the ability of the mitochondria to oxidise pyruvate (Coyle et al. 1988). Improving mitochondrial capacity to use cytosolic protons and electrons retards a dependence on glycolytic ATP production and thus reduces lactate

accumulation. These training adaptations 'raise' the lactate threshold and increase the fractional utilisation of $\dot{V}O_2$max that can be sustained before performance duration becomes limited. Typically, in elite endurance athletes, lactate threshold tends to occur at ~80% of $\dot{V}O_2$max (Coyle, 1988). The ability to sustain a high percentage of $\dot{V}O_2$max in a race is a key performance determinant long-distance running. Specifically, for the marathon, raising the lactate threshold as high as possible is a key training objective. Subsequently monitoring the movement of this 'threshold' is a good indicator of aerobic adaptation and potential performance velocity in long distance running events (Bassett & Howley, 2000; Coyle, Coggan, Hopper, & Walters, 1988; M J Joyner, 1991). Typically elite endurance athletes can maintain critical speed (CS) at 90% $\dot{V}O_2$max (Poole, Burnley, Vanhatalo, Rossiter, & Jones, 2016b), which in a former international male 1500m runner was 18.0 km/hr (Ingham et al., 2012) and in the women's marathon world record holder was 20.0 km/hr. The higher value in the latter case is likely a reflection of the respective determinants of performance (Jones, 2006).

Critical Speed - Transitioning from Heavy to Severe Exercise

Lactate turnpoint (LT_2), Maximal Lactate Steady State (MLSS) and CS represent a 'similar' physiological landmark, describing the transition from 'heavy' to 'severe' exercise (Poole et al., 2016b; Pringle & Jones, 2002). The consistency of terminology for defining physiological landmarks and exercise zones is of ongoing challenge to the coach and sport scientist (Binder, Wonisch, Corra, & Cohen-solal, 2008; Seiler & Tonnesson 2009). LT_2 is defined as the second deflection point in a lactate curve, beyond which a non-linear rise in lactate occurs for a given speed, usually between 2-5 mmol lactate (Hoffman, Bunc, Leitner, Pokan, & Gaisl, 1994; Smith & Jones, 2001). MLSS is defined as the highest speed at which lactate accumulation and removal may be equal, and can be sustained for 30-60 minutes (Beneke, Leithäuser, & Ochentei, 2011). Assessment of

MLSS over LT_2 is recommended because LT_2 is likely to over or underestimate MLSS values, with large variability seen between individuals (i.e., 54-83% max power; (Beneke et al., 2011). By comparison CS describes 'the tolerable duration of severe-intensity exercise' and is founded on the basis that the tolerance to sustain a particular speed is hyperbolic (ability to sustain exercise at higher intensities falls away sharply compared to low intensities) (Monod & Scherrer, 1965; Poole et al., 2016b).

The physiological changes for each aforementioned landmark are similar, but subtly different. For example, beyond CS, steady state can no longer be established, as with LT_2 and MLSS, with durations to exhaustion at CS reported lasting approximately 30 minutes (Jones, Vanhatalo, Burnley, Morton, & Poole, 2010; Smith & Jones, 2001). Here, net lactate is produced as a function of time (Beneke et al. 2010) and there is a preferential recruitment of type ll muscle fibres leading to a reduced exercise economy that drives the $\dot{V}O_2$ slow component and attainment of $\dot{V}O_2$max (Billat, Binsse, Petit, & Koralsztein, 1998; Poole, 1994).

Broadly speaking, a 3-zone model, expressing low, moderate and heavy training intensities is most commonplace (Figure 2.3), which can be practically raised to a 5 zone model in the applied setting (Seiler & Tonnessen, 2009). For accurate training zone determination, both MLSS and CS require multiple visits to the laboratory, which might be impractical in most applied settings. Attempted field-based alternatives are promising in terms of their predictive capacity to calculate critical speed, but their level of accuracy required may be questioned (i.e., coefficient of variation = 13%) (Galbraith, Hopker, Lelliott, Diddams, & Passfield, 2014).

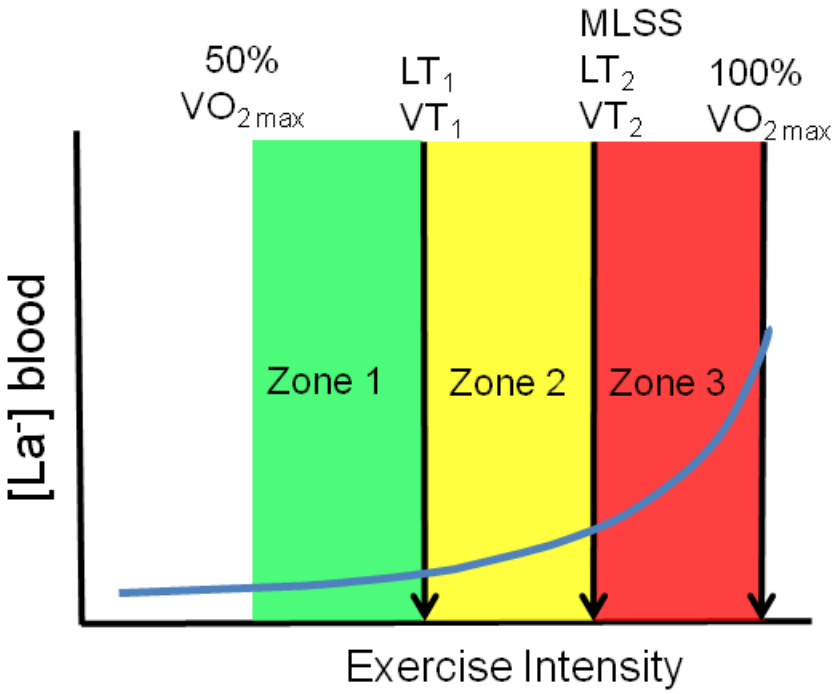

Figure 2.3. Training intensity zones and physiological landmarks (Seiler & Tonnessen, 2009). Maximal lactate steady state, Lactate Turnpoint and Critical speed would all reflect the demarcation of Zone 2 to Zone 3. La – Lactate, LT_1 – Lactate Threshold, VT_1 – Ventilatory Threshold, LT_2 – Lactate Turnpoint, VT_2 – Ventilatory Turnpoint

LT_2 has importance for 5-10km runners, as the higher the velocity related to LT_2 (vLT_2) pace, the longer one will be able to delay exponential accumulation of metabolic acidosis, which may inhibit one's ability to execute surges in pace or a last lap 'kick'. With middle-distance running intensities largely occurring above $v\dot{V}O_2max$, the density of training prescription between $v\dot{V}O_2max$ and $_vLT_2$ is an important programming consideration for the coach. Many of the training distribution models designed for endurance are often applied to middle-distance running, without full consideration of the anaerobic capabilities. Whether or not the '80:20' distribution, often considered optimal for many endurance sports, remains optimal for elite middle-distance running performance, remains to be determined. Further, clarity around the priority of importance of needed

physiological adaptations for middle-distance athletes remains to be fully elucidated, and will be discussed further in Chapters 7 and 8.

2.4 Race Analysis

Pacing Strategies of One-Off Time Trial vs. Championship Racing

Pacing in sport as it relates to performance refers to the distribution of work applied across a set distance or period of time, as used to achieve optimal performance for an individual athlete (Abbiss & Laursen, 2008). For key reviews on pacing, the author refers the reader to Abbiss & Laursen, 2008; Roelands, De Koning, Foster, Hettinga, & Meeusen, 2013; Mauger, 2014. Briefly, research has shown that a fast start pacing strategy in cycling and speed-skating may present a performance advantage over the 1500m distance (duration ~2 mins) (Stoter et al., 2015), this is not consistently demonstrated, perhaps in part due to differences in mechanical and postural demands (Hettinga, Koning, Hulleman, & Foster, 2012). A complex integrated model describes optimal pacing strategies (maximising speed and minimising fatigue), including consideration for biomechanics, exercise physiology, neurophysiology, and psychobiology, which are largely sport and event specific (Hettinga et al., 2010; Stoter et al., 2015; Tucker & Noakes, 2009). Of particular focus within this thesis will be determining clear tactical determinants of medal winning performance.

Two common middle-distance race strategies are generally observed in competition. One is a sustained and consistent high-speed strategy from ‘gun-to-tape’. The alternate is a slow race from the beginning of the race with a sprint finish (Jones & Whipp, 2002). One-off races can influence race energetics in several ways. First, the presence of a pacemaker can create more of a ‘gun-to-tape’ or time-trial race plan, whereby athletes use pacemakers to guide the optimal pacing strategy, which theoretically maximises an athlete’s aerobic and anaerobic energy reserves to sustain the highest possible pace, as

often seen in world record attempts (Tucker et al., 2006) and diamond league racing (Filipas, Nerli Ballati, Bonato, La Torre, & Piacentini Maria, 2018).

In national and international Tunisian runners, Zouhal & colleagues (2015) found a 9s improvement in 3km time when runners drafted behind two pacemakers versus the non-drafting control condition. No differences in physiological parameters were found between paced and non-paced trials. However, Pugh (1971) demonstrated that drafting 1m behind a pacemaker may reduce oxygen consumption at middle-distance speed by 6.5%. Therefore, Ardigo and Padulo (2016) suggest that the measures taken by Zouhal & colleagues may not be sensitive enough to reflect the extra metabolic expenditure in a non-drafting condition, calculated through kinematic energy and work changes in the respective conditions (Ardigo & Padulo, 2016). Additionally psychological factors, such as not having to think about lap splits, as well as consistency of lap splits following a pacemaker might have contributed to the finding (Zouhal et al., 2015). Indeed, Bath et al. (2012) showed that performance perception improved in club runners merely due to the presence of another runner, despite no physiological or performance difference when running a 5km time-trial alone. Clearly, the benefits of drafting are multifactorial and explanations likely reside in psychological, biomechanical and aerodynamic factors (Davies & Kingdom, 1980; Zouhal et al., 2015).

In comparison, championship racing tends to be approached more conservatively, whereby athletes tactically execute the minimum race speed required to qualify through to the next round, as they aim to minimise feelings of fatigue to ensure readiness for future rounds (Hanley & Hettinga, 2018; Noakes, 2012). Successfully negotiating preliminary rounds for finalist-level runners requires a work capacity equivalent to performing 3x800m races in four days, or 3x1500m in four days. Often due to the depth of the field and qualification standard, the semi-finals, particularly in the 800m, are often as fast as,

or faster than the final itself (International Association of Athletics Federations). Historically, 'doubling up' across the middle-distance events (performing both the 800m and 1500m events at a meet) was often performed, but in recent times this approach has become far less common, at least in female runners (Brown, 2005).

Evidence from the Beijing Men's 800m (M800m) final suggests the presence of an end spurt with 200m left to run (Thiel, Foster, Banzer, & De Koning, 2012). In contrast, Billat et al. (2009) describe the 800m as more of a long sprint, thereby likely requiring a large anaerobic capacity. The inability to perform a 'gun-to-tape' strategy for the M800m has critical implications for championship round qualification. Using London 2012 Olympics data, Renfree, Mytton, Skorski, & Clair Gibson (2014) showed that positioning outside the top three athletes with 400m remaining results in less than a 50% probability of qualifying through to the next round. Therefore, determination of the tactical behaviours and the physiological and mechanical underpinning of modern-day racing warrant further investigation.

1500m Championship Race Analysis

In contrast to the 800m event at major championships, 1500m medallists are consistently differentiated by their last lap speed (Hanon & Thomas, 2011; Mytton et al., 2015; Renfree et al., 2014; Thiel et al., 2012). From a tactical standpoint, Aragón, Lapresa, Arana, Anguera, & Garzón, (2015) suggest that an athlete needs to be within the first four athletes when the last lap kick is initiated to have a medal-winning outcome. Preliminary analysis suggests this to be most common with 300m to go, where several factors influence the ability to kick. The likely most important of these is a high critical speed and aerobic capacity so as to delay anaerobic utilisation (Billat et al., 2009). Possessing a large anaerobic speed reserve (ASR) may also allow an athlete to respond to fast changes in pace (Buchheit & Laursen, 2013), however the influence of anaerobic, neuromuscular

and mechanical capabilities on the ability to respond to surges in pace requires further investigation.

Evidence for Neuromuscular/Mechanical Importance

The relative race intensity (running speed) of 800m and 1500m races are typically above v$\dot{V}O_2$max and considered high-intensity in nature (figure 2.3) (Billat, 2001; Buchheit & Laursen, 2013). Relative race intensities have been reported as 106-126% v$\dot{V}O_2$max and 95-111% v$\dot{V}O_2$max for 800m & 1500m events, respectively (Billat et al., 2009; Duffield, Dawson, & Goodman, 2005b; Spencer & Gastin, 2001). In contrast, the relative race intensity of events 3km and longer are typically below v$\dot{V}O_2$max pace (Duffield, Dawson, & Goodman, 2005a; Støa, Støren, Enoksen, & Ingjer, 2010), as these require a much larger aerobic contribution (figure 2.3). The possible critical exception within these 3km, 5km and 10km events is the 'last lap kick'. For example, Haille Gebreselassie has been estimated to have performed as high as 106% v$\dot{V}O_2$max pace over the closing 400m of a 10,000m Championship final (Billat, 2001).

2.5 Physiological, Neuromuscular & Biomechanical Correlates of Middle-Distance Running – The Current Landscape

With the 'last lap kick' becoming a consistent differentiator between 1500m medallists on the world stage (Mytton et al., 2015), and the 800m seemingly becoming more of a long sprint, it would be amiss to not further investigate the aerobic and anaerobic, neuromuscular and mechanical qualities that may underpin these tactical manoeuvres. One reason the literature in this area may be limited is that the quantification of anaerobic contribution to exercise has often been problematic (Davison, Someren, & Jones, 2009), as explored further in chapter 4. Consequently, there is a poor degree of certainty as to

how exercise economy quantification in the domain above CS and beyond $\dot{V}O_2$max for anaerobic qualities is calculated (Denadai & Greco, 2017).

Brandon & Boileau (1992) revealed in 56 well-conditioned middle-distance runners that $\dot{V}O_2$max was the primary variable of importance for 1500m and 3000m, followed by anaerobic capacity. In contrast, 800m was most influenced by peak velocity from a 60m sprint, with $\dot{V}O_2$max also having an important contribution. Whether these relationships hold true for athletes at and above national level remains to be explored. Further, it is fair to assume with the potential changes seen in the men's 800m event that this event group alone may hold a large diversity of athlete profiles (Gamboa et al., 1996; Horwill, 1980). The following section will review the existing literature assessing the less often considered determinants of middle-distance performance, without extensive review of the anaerobic speed reserve and anaerobic capacity, as these topics are expanded on in detail throughout chapters 4, 6, 7 and 8.

Muscle Power

The role of muscle power, which combines an athlete's anaerobic and neuromuscular capabilities (Beattie et al., 2014), has historically been overlooked as being a large contributor to endurance performance (Baumann et al., 2011; Beattie et al., 2014), despite it's known influence on RE and running speed (Barnes & Kilding, 2015; Barnes, 2014; A Nummela et al., 1996; Saunders et al., 2006, 2004). Motor unit recruitment refers to the ability of the neuromuscular system to recruit slow and fast twitch muscle (Cormie, Mcguigan, & Newton, 2011). The ability to recruit larger (fast twitch) motor units upon demand (during a race surge) influences muscle power output per stride, and during a middle-distance race this must be coordinated whilst energy systems are working at maximal rate and capacity (Paavolainen et al., 1999; Rusko, Nummela, & Mero, 1993).

Anaerobic Work Capacity and Anaerobic Power

Anaerobic power is the maximal rate of work that can be performed in a short burst of maximal exercise (Margaria, Aghemo, & Rovelli, 1966; D. T. Martin, 2014) and is reflected in the maximal sprinting speed (MSS). Whereas AWC is defined as the theoretical quantity of energy or distance that can be covered via ATP resynthesis from non-oxidative phosphorylation (Billat et al., 2009; Green, 1995); Billat et al. 2009). CS is used to depict the onset of the AWC, and time to exhaustion beyond CS is an indicator of an athlete's AWC (Blondel et al., 2001), termed D prime (D') (Poole, Burnley, Vanhatalo, Rossiter, & Jones, 2016a). Within a middle-distance race, the work performed above $\dot{V}O_2max$ is in theory related to the AWC (Blondel et al. 2001; Billat et al. 2009). Previously Blondel et al. (2001) explored the time limit or duration an athlete can spend close to or above $v\dot{V}O_2max$, but this does not consider the amount of work one can do anaerobically relative to their ASR performed at a fixed speed. With the 800m race profile execution considered by some to be a 'long sprint' (Billat et al., 2009), a better resolution on an 800m athlete's anaerobic capabilities and the interplay with $v\dot{V}O_2max$ is needed to better optimise the current approach to 800m training.

The Maximal Anaerobic Running Power (MARP) concept (later known as the Maximal Anaerobic Running Test (MART) (1999)) was introduced by Rusko, Nummela, & Mero, (1993) to quantify the interrelationship between neuromuscular characteristics and anaerobic power during running. In both national level (Nummela et al., 2006; Paavolainen et al., 1999) and NCAA collegiate (Baumann et al., 2011) runners, the MART, and thus muscle power has been shown to be a key determinant of 5 km running performance (Beattie et al., 2014). Interestingly the MART has only once been investigated in 800m and 1500m performance, and showed that middle-distance and 400m runners had greater muscle power and power at 10mmol/l blood lactate than long-

distance runner and control groups (Nummela et al., 1996). MART research from the Jyvaskyla group has focused on differentiating the anaerobic characteristics between event groups (middle-distance vs. 400m), which may in part be explained by differences in training emphasis. Of strong interest in the middle-distance events is differentiating individuals within an event group, where one could hypothesise diverse aerobic and anaerobic characteristics may be found. However at this stage, such presumptions are limited to coach observation (Gamboa et al., 1996; Horwill, 1980), and further research is required.

Spring-Mass Characteristics

Running requires a stretch shortening cycle complex that utilises elastic energy return. Stiffness in this context refers to the compression of the leg during stance phase of the running gate (resistance to a change in length). Stiffness characteristics can be divided into passive (tendon, collagen/titin filaments/fascia) and contractile components (pennation angle, fascicle length, muscle thickness) (Arampatzis et al., 2006; Gajdosik, 2001; Morse, Degens, Seynnes, Maganaris, & Jones, 2008). In general, greater stiffness of the MTU (assuming greater hysteresis doesn't occur) facilitates faster forward propulsion, shorter contact times and more efficient RE, enhancing race speed (Nummela, Keränen, & Mikkelsson, 2007) and MSS (Rogers, Whatman, Pearson, & Kilding, 2017). Greater knee joint stiffness and plantar flexor compliance was observed in the lower limb segments of faster (5km = 14:34 (±10s) compared to slower (5km – 15:14±25s) distance runners (Kubo, Miyazaki, Shimoju, & Tsunoda, 2015). Further, Hébert-losier, Jensen, & Holmberg, (2014) measured counter movement jump, squat jump, standing long jump and repeated hops on a force plate and established that elite orienteers possessed superior stretch shortening cycle (SSC) characteristics to amateur orienteers implying development of SSC characteristics are an important consideration for elite level

performances . In support of these findings, Hudgins, Scharfenberg, Triplett, & McBridge (2013) revealed a strong correlation between three consecutive double leg bounds for distance and 800m race performance in NCAA division one athletes (800m time = 2:07±15 mm:ss:ms). In addition, Rabita et al. (2015) have shown that orientation of force production, and not absolute force production per se to be a differentiator between elite and sub elite sprinters, which may have application to those athletes in the middle-distance events. In summary, these findings extend the possibility that there may be key neuromuscular and spring mass characteristics differentiating elite and sub elite middle-distance runners, which to this point have not been extensively examined.

Sano et al. (2013) demonstrated that elite Kenyan endurance runners weighing 57.9±5 kg possess similar vertical stiffness to physically active controls weighing 71.3±5 kg. One can speculate from this that Kenyan athletes have an exceptional relative stiffness-to-mass relationship. Further, the same group in 2014 revealed during stance phase that Kenyans produce shorter EMG contraction amplitudes than a National level Japanese runner cohort (Sano et al., 2014). These findings suggest that further understanding of the relative spring mass characteristics of middle-distance runners may be another important determinant of middle-distance running performance, and may be a key injury risk factor (Butler, Crowell, & Davis, 2003).

Over the course of a 400m and 800m race, in well and moderately trained populations, vertical stiffness has been shown to decrease as an athlete fatigues, resulting in lengthening contact times and negative postural changes (Girard, Millet, & Micallef, 2017; Hobara, Inoue, Gomi, & Sakamoto, 2010). Of great interest to coaches at an elite level is whether delaying the decline of some of these spring-mass characteristics is of importance. At present, the descriptor of spring-mass model characteristics during the last lap kick is unclear in an elite population, where to increase speed one would expect

shorter contact times and increased vertical stiffness. Under fatigue however, such surging behaviour needs characterising. A measurement tool that can quantify mechanical efficiency within a race is crucial to further understanding the multiple factors contributing to the last lap kick. In particular, of interest is the mechanical limitation of an athlete's anaerobic speed reserve.

Anaerobic Speed Reserve – Origins and Opportunities

A.V Hill's (1925) observations of power-duration relationships using athletic world-records, suggest that other factors than energy metabolism may limit running and swimming competition performance, with particular emphasis for events below 40s in length. Ozolin (1959) first proposed a middle-distance athlete's 100m speed as a determinant of performance. Here, 100m speed was considered an athlete's 'speed-reserve' and was believed to be important for race success in the finishing sprint. The speed reserve in this instance was defined as the difference between the average speed per 100m of a race event and the person's best 100m time (Schmolinsky, 1983). Whilst the term speed-reserve was adopted thereafter in particular by the sprint coaching world (Schiffer, 2008), it laid dormant in the scientific exploration of middle-distance vernacular until 2001, where it resurfaced under an alternative definition (Blondel et al., 2001). Here, Blondel and co-workers defined the anaerobic speed reserve (ASR) as the running speed ranging from $v\dot{V}O_2max$ to an athlete's maximal sprinting speed (MSS) (Blondel et al., 2001; Buchheit & Laursen, 2013a; Bundle et al., 2003).

In this initial study, Blondel et al. (2001) showed time to exhaustion at intensities above $v\dot{V}O_2max$ (i.e. where 800m and 1500m race pace occur, figure 2.2) was better explained by ASR than $v\dot{V}O_2max$, leading to the early belief that ASR represented a measure of anaerobic energetics; the so-called 'anaerobic work capacity' (Bundle et al., 2003). However, the evolution of CS research has provided strong evidence that CS may be the

last physiological work intensity supported predominantly by oxidative – ATP production (Morton, 2006; Poole et al., 2016a). Therefore, beyond CS, anaerobic energetic contributions to exercise augment before attainment of $v\dot{V}O_2max$, dependent on the rate of peripheral fatigue development. Thus, $v\dot{V}O_2max$ does not always represent a consistent physiological landmark (Grassi, Porcelli, Salvadego, & Zoladz, 2011; Grassi, Rossiter, & Zoladz, 2015). More recently, it has become clear that the ASR represents more of a mechanical construct, with $v\dot{V}O_2max$ a measure of efficiency supported metabolically (Billat & Koralsztein, 1996), and MSS limited by ground reaction force and not energetic supply (Bundle & Weyand, 2012).

A resurgence of the ASR construct has been seen in recent years, primarily in team sports, focused on the premise illustrated in figure 2.5 (Buchheit, Hader, & Mendez-Villanueva, 2012; Buchheit & Laursen, 2013b; Buchheit & Mendez-Villanueva, 2014; Buchheit, Simpson, Peltola, Mendez-Villanueva, & Simpson, 2012). In this model, for workloads beyond $v\dot{V}O_2max$, Athlete A would be required to be working at a higher proportion of their ASR, than athlete B. Thus, a larger ASR may afford a lower physiological cost for a given workload, which may have implications for performance and training programme design.

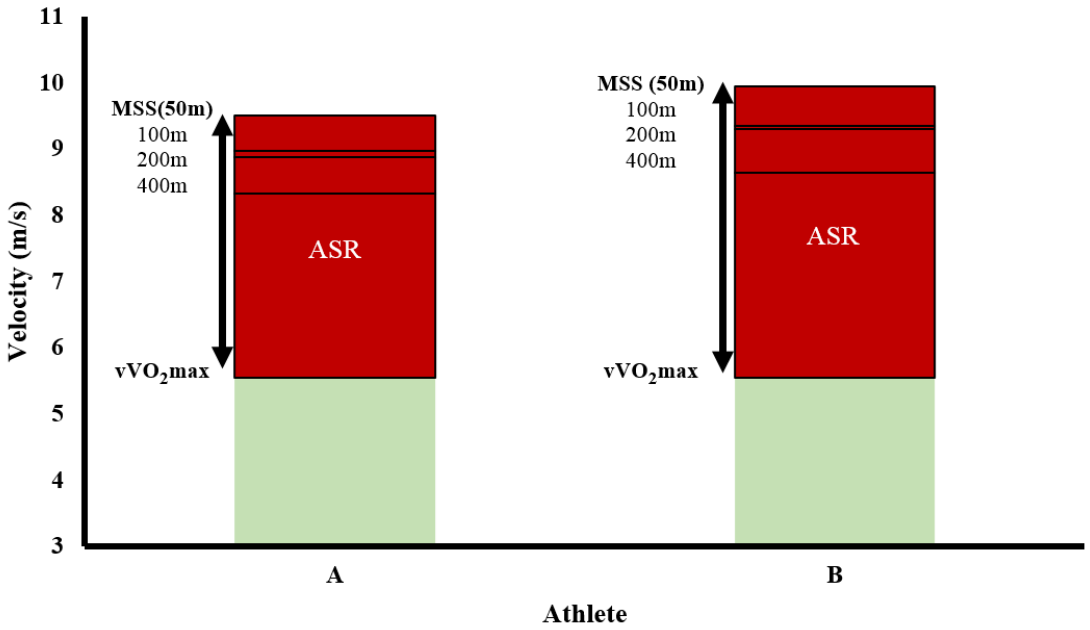

Figure 2.4. Two hypothetical athletes (A+B) presenting with different maximal sprinting speeds (MSS), but possessing the same velocity at maximal oxygen uptake ($v\dot{V}O_2max$). Adapted from (Buchheit & Laursen, 2013b)

Electronic timing gates (Fletcher & Anness, 2007; Mendez-Villanueva, Buchheit, Simpson, Peltola, & Bourdon, 2011; Vescovi & Mcguigan, 2008; Young, McLean, & Ardagna, 1995) and radar technology (Morin, Edouard, & Samozino, 2011; Morin & Seve, 2011) can both be used to quantify MSS. In elite sprinters, typically 60m is required to identify top speed, however Buchheit, Simpson, Peltola, Mendez-Villanueva, & Simpson, (2012) suggest that 40m may be adequate for assessment in youth athletes. MSS is rarely considered across the middle-distance literature despite its likely influence on the relative running speed and time to exhaustion at supramaximal intensities (Blondel et al. 2001; Buchheit & Laursen, 2013). This variable has also been suggested to be a factor that may discriminate across groups of homogenous middle-distance runners (Houmard, Costill, Mitchell, Park, & Chenier, 1991).

Numerous studies (Mytton et al., 2015; Renfree et al., 2014; Schmolinsky, 1983) demonstrate the importance of end spurt speed on 1500m medal success and suggests that

ASR has a potential race-defining role to play in middle-distance events, and should be considered a key component in a middle-distance athlete's annual training programme. However, how these qualities should be specifically trained and periodised for within an annual training cycle to facilitate best outcome for middle-distance athletes requires further investigation.

2.6 Physiological Correlates of Middle-Distance Running

As shown in Table 2.2, only two studies investigating middle-distance running performance have assessed the importance of sprint speed (Brandon & Boileau, 199$_2$; Deason, Powers, Lawler, Ayers, & Stuart, 1991). Whilst Deason et al. (1991) found that anaerobic qualities explained 82% of 800m race performance using stepwise multiple regression, only 11 male track athletes possessing with diverse physiological profiles were used, and illustrates statistical and sample size limitations. A higher-powered study design from Brandon & Boileau (1992) found peak velocity correlated (r = -0.34) with 800m race performance in well-trained males. Thus, it is important to confirm this relationship in elite and sub elite 800m runners. By comparison, Ingham et al. (2008) assessed 62 national and international middle-distance runners in the UK and determined that running economy and $\dot{V}O_2$max explained 95% of middle-distance running performance, but largely overlooked the anaerobic contribution to the race and in particular speed-based 800m runners. A further two studies in junior athletes have found moderate to strong relationships between v$\dot{V}O_2$max and 800m (r= -0.61 to -0.74) and 1500m (r= -0.74 to -0.82) running performance (Almarwaey et al., 2003; Arins, Da Silva, Pupo, Guglielmo, & Dos Santos, 2011). Inconsistency of parameters assessed between studies makes a strong conclusion beyond speculation impossible. Within men's 800m running, there is a clear need to understand the key differentiators to perform a sustained

Table 2.2. Physiological, neuromuscular and biomechanical correlates of middle-distance running

Author	Age	Study Design	Description	$\dot{V}O_2max$	Event	Performance Times	Aerobic Correlates to MD Performance	Anaerobic Correlates	NM & BM correlates
Arins et al. 2011	17.6±1.4	Correlation analysis	11 Juniors	76.9±4.5	800m 1500m	2.05.6 4:22±12.5	$v\dot{V}O_2max$ r=0.74, Tlim =0.65 $v\dot{V}O_2max$ =0.82, Tlim = 0.79	MAOD ns.	CMJ = 0.65
Ingham et al. 2008	21.4±2.9 21.2±2.9 22.1±4.6 22.8±5.1	Performance prediction	62 national and International runners	72.4±6.1 73.3±4.5 61.6±4.7 65.2±3.5	Men's 800m Men's 1500m Women's 800m Women's 1500m	1:48.9±2.4s 3:44.1±6.5s 2:05.8±9.9s 4:12.0±4.1s	$\dot{V}O_2max$ & Running Economy =95% performance variance	n/a	n/a
Boileau 1982	21.7±2.8	Correlation analysis	42 elite MD runners	68.9±6.0	800m 1500m	1:48 (range 1:45-1:55) 3:44 (range 3:37-3:57)	$\dot{V}O_2max$ (r=0.70)	n/a	n/a
Bachero-Mena et al. 2017	22.9±5.3	Correlation analysis	14 national and international	n/a	800m	1:52 (range 1:43 – 1:58)	n/a	10m r=0.59 20m r=0.72 200m r=0.84	CMJ r=- 0.69 JS r=-0.65 SQ r=0.58

Fuji et al. 2012	20.2±1.6	Correlation analysis	13 University MD runners	64.7±4.3	800m 1500m	1:54.94 (1:49.82-2:02.89) 4:00.33 (3:50.54 -4:11.94)	$\dot{V}O_2$max n.s vLT ns vOBLA n.s	Vmax on MART r= -0.88 PP Wingate = -0.87 AP 60s Wingate = -0.60 AP 30s= -0.73	n/a
Deason et al. 1991	30±3.9	Correlation analysis	11 male track athletes	61.6±5.09	800m	2:12.6 (2:00.8 – 2:23.6)	n/a	300m & 100m time = 86% performance variance	n/a
Brandon & Boileau 1992	26.6±4.5	Performance prediction	56 well-conditioned males	62.5±6.1	800m 1500m 3000m	2.21± 0.12 4.48±0.3 10.37±0.72	$\dot{V}O_2$max r = -0.33 $\dot{V}O_2$max r= - 0.62 $\dot{V}O_2$max r= - 0.66	Peak velocity r= -0.34 Anaerobic Power r=0.27 Anaerobic Power r=0.27	Stride Length r= - 0.28 Stride length r= - 0.24
Almarwaey, Jones & Tolfrey, 2003	16.1±0.6 16±0.8	Correlation analysis	Boys n=23 Girls n=17 English County Level	65.2±4 65.5±4 56.6±4.9 56.9±4.8	Boys 800m Boys 1500m Girls 800m Girls 1500m	2:10.4±0:008 4:33.9±0:22 2:25.8±0:08 5:12.8±0.22	$\dot{V}O_2$@ 12km/hr r=0.62, v$\dot{V}O_2$peak r= -0.62 $\dot{V}O_2$peak r=0.43 v$\dot{V}O_2$peak = 0.74,	Mean Power =-0.49 (Wingate)	n/a

NM & BM – Neuromuscular & Biomechanical, n/a – none assessed, Ns. Non-significant, vLT – Velocity at Lactate Threshold, vOBLA – Velocity at onset of blood lactate accumulation, AP – Average Power PP – Peak Power, MART – Maximal Anaerobic Running Test (for review see Nummela, Alberts, Rijntjes, Luhtanen, & Rusko, 1996), MAOD – Maximally accumulated oxygen deficit (for review see Noordhorf et al. 2010.) CMJ – countermovement jump, JS – jump squat with load of 20cm height, SQ – squat jump – full squat with load reached at 1m/

long sprint in elite 800m runners compared to sub-elite counterparts where race pacing strategies may differ.

2.7 Summary and Conclusion

Aerobic determinants of performance (RE, LT, $\dot{V}O_2max$) and their normative values in elite middle-distance runners are well established (Barnes & Kilding, 2015; Bassett & Howley, 2000; J Daniels & Daniels, 1992; Ingham et al., 2008; Joyner & Coyle, 2008; Noakes, 2001; Saunders et al., 2004). Several studies show the possibility for $\dot{V}O_2max$ (Costill et al., 1973; Rabadán et al., 2011), $v\dot{V}O_2max$(Alejandro Legaz-Arrese et al., 2011) and RE (J Daniels & Daniels, 1992; Fink et al., 1977; Lucia et al., 2006b; Saltin et al., 1995) to help differentiate between event specialists. However, with 34% of an 800m coming from anaerobic sources (Duffield & Dawson, 2003; Spencer & Gastin, 2001), a third of the qualities underpinning 800m race performance are unaccounted for by 'classic' physiological profiling. Therefore, potential resolution on the athlete profile and opportunities that could support athlete sub-group specialisation and training approach warrant further investigation.

The current literature illustrates a clear gap in research focus in the ASR domain. That is, exploration of the anaerobic, neuromuscular & mechanical components of elite 800m running. With surges differentiating medal outcomes, there is a clear need to investigate this potential medal defining skill. Whilst it is clear that there is a minimum aerobic requirement ($\dot{V}O_2max$) to be competitive in middle-distance running on the international stage (Legaz-Arrese et al., 2007), it may be the anaerobic capabilities, alongside $v\dot{V}O_2max$, that differentiate amongst homogenous groups of middle-distance runners (Arins, Da Silva, Pupo, Guglielmo, & Dos Santos, 2011; Brandon & Boileau, 1992; Houmard et al., 1991; Lacour, Padilla-Magunacelaya, Barthelemy, & Dormois, 1990).

ASR may be an important tool in 1) being able to determine typical speed ranges required to be competitive in modern-day elite competition, which are currently unknown, and 2) differentiating between athlete profiles, as shown previously (Sanders, Heijboer, Akubat, Meijer, & Hesselink, 2017), and therefore provide resolution on coaching observation of potential 800m sub-groups (Gamboa et al., 1996; Horwill, 1980). Furthermore, there is a paucity of studies investigating both aerobic, neuromuscular and mechanical qualities of 800m and 1500mrunners. The ASR, in two simple measures, considers both metabolic ($v\dot{V}O_2max$), and neuromuscular/mechanical (MSS) components of an athlete's profile.

Finally, advancing the understanding as to what differentiates elite 800m athletes is a much-needed point of comparison for national talent ID and individualized training strategies for diverse presenting athlete phenotypes. Ultimately, there is a clear need to further investigate the underlying characteristics of middle-distance runners and 800m race performance in order to provide clear recommendations for coaches and practitioners on supporting this complex event.

CHAPTER 3: TACTICAL BEHAVIOURS IN MEN'S 800M OLYMPIC AND WORLD CHAMPIONSHIP MEDALLISTS: A CHANGING OF THE GUARD

3.1 Abstract

Purpose: To assess the longitudinal evolution of tactical behaviours used to medal in Men's 800m (M800) Olympic Games (OG) or World Championship (WC) events in the recent competition era (2000-2016).

Methods: Thirteen OG and WC events were characterised for first and second lap splits using available footage from YouTube. Positive pacing strategies were defined as a faster first lap. Season's best M800 time and world ranking, reflective of an athlete's 'peak condition', was obtained to determine relationships between adopted tactics and physical condition prior to the championships. Seven championship events provided coverage of all medallists to enable determination of average 100m speed and sector pacing of medallists.

Results: From 2011 onwards, M800 OG and WC medallists showed a faster first lap by 2.2 ±1.1s (mean, ±90% confidence limits; large difference, *very likely*), contrasting a *possibly* faster second lap in 2000-2009 (0.5, ±0.4s; moderate difference). A positive pacing strategy was related to a higher world ranking prior to the championships (r=0.94, 0.84 to 0.98; extremely large, *most likely*). After 2011, the fastest 100m sector from M800 OG and WC medallists was faster than before 2009 by 0.5, ±0.2m/s (large difference, *most likely*).

Conclusions: A secular change in tactical racing behaviour appears evident in M800 championships; since 2011, medallists have largely run faster first laps and have faster 100m sector speed requirements. This finding may be pertinent for training, tactical preparation and talent identification of athletes preparing for M800 running at OG and WC.

3.2 Introduction

In middle-distance running, an athlete's tactical execution is a key element of race performance (Abbiss & Laursen, 2008; A. Jones & Whipp, 2002). Historical examples of men's 800m (M800) championship running from the Beijing 2008 Olympic Games (OG) suggests the presence of an end spurt with 200m left to run (Thiel et al., 2012). By contrast, both Sebastian Coe (1:41.73, Florence, 1981) and Wilson Kipketer's former M800 world record (WR) (1:41.11; Cologne, 1997) demonstrate a positive pacing approach whereby an end spurt appears limited by the preceding efforts earlier in the race (Thiel et al., 2012). The Rio 2016 OG saw current WR holder David Rudisha (1:40.91) retain his M800 Olympic title, the first man since Peter Snell (1960-64), and fourth ever athlete to do so across the two-lap event. In a new era of dominance, it is pertinent to investigate whether tactical behaviours in the M800 follow the end spurt seen in Beijing 2008 or the positive approach of Kipketer's and Coe's former WR (Thiel et al., 2012).

Analysis of the London 2012 OG M800 heats revealed that positioning outside of the top three positions with 400m remaining results in less than a 50% probability of qualifying through to the next round (Renfree et al., 2014). Thus, M800 runners and coaches require a clear understanding of the tactics required for successful performance execution. However, a comprehensive assessment characterising the evolution of tactical behaviours of M800 OG and World Championship (WC) medallists is lacking. Therefore, the primary aim of this study was to assess the longitudinal evolution of M800 tactical behaviours used to medal at an OG or WC event in the recent competition era (2000-2016).

3.3 Methods

The tactical behaviours of M800 medallists across thirteen championships (five OG and eight WC from Sydney 2000 – Rio de Janeiro 2016) were characterised using readily

available footage from YouTube. In total, coverage of twelve championship events enabled recording of first and second lap splits. For Osaka 2007 WC, pacing could only be described using the race leader's lap time from readily available data (www.iaaf.org/results). A positive pacing strategy was defined as a faster first lap (Abbiss & Laursen, 2008). Where longitudinal changes were revealed, the season's best prior to the championship, reflective of the eventual gold medallist's form leading into the championship, was used to determine the relationship between the adopted pacing strategy and pre-championship form. All season's best data were attained from readily available sources (http://www.tilastopaja.org/ and http://www.all-athletics.com/).

For part two of the analysis, 21 observations were made (three medallists, across seven championships; Sydney 2000 OG, Athens 2004 OG, Beijing 2008 OG, London 2012 OG, Moscow 2013 WC, Beijing 2015 WC, Rio de Janeiro 2016 OG) to establish resolution on 100m splits and sector pacing of medallists. Only seven championships provided coverage of all medallists to enable determination of all 100m splits. Videos were downloaded via YouTube and analysed using a frame-by-frame playback method in Kinovea analysis software. Error of technical measurement was within 0.02s as reported previously (Mytton, Archer, Thompson, Renfree, & St Clair Gibson, 2013).

To account for potential historical doping violations amongst medallists in the current sample, medallists disqualified after the event, or from nations revealed to be systematically doping, were removed and replaced with the fourth placed athlete. However, the effect on overall pacing from excluding one potential cheat from the medal roster did not alter whether the race had a positive or negative strategy, with mean lap times only altered by 0.1-0.3s.

Statistics

Data are presented as means and 90% confidence limits (CL) unless otherwise stated. Logarithmic regression was used to determine relationships between athletes' form prior to the championship and pacing strategy adopted. The magnitude of correlation was rated using; 0.1 (small), 0.3 (moderate), 0.5 (large), 0.7 (very large) and 0.9 (extremely large) (Hopkins, Marshall, Batterham, & Hanin, 2009).

Between championship comparisons of lap differentials (delta) were assessed using magnitude based inferences (Hopkins et al., 2009). The following threshold values used for effect size (ES) statistics were ≥0.2 (small), >0.6 (moderate), >1.2 (large) and >2.0 (very large). The smallest worthwhile change (SWC) for lap differential and 100m sector speed over time was determined as the standard deviation (SD) of a medallist's first lap, second lap or a medallist's 100m sector speed respectively, multiplied by the ES. For example, a moderate effect for a 100m sector change over time would use the following formula:

SD of medallist's sector speed * 0.6 (moderate ES)

= 0.367 m/s * 0.6

SWC for moderate effect = 0.22 m/s

Practically speaking, any value found below a moderate SWC would unlikely be representative of a secular change in pacing e.g. 0.22m/s for 100m sector difference or 0.96s first lap differential. Therefore, a moderate SWC was chosen for both lap differentials and 100m sector speed over time (Buchheit, 2016). For consistency, a moderate smallest worthwhile effect was also used for correlation analysis.

3.4 Results

From 2011, M800 OG and WC medallists showed a faster first lap of 2.2, ±1.1s (large effect, *very likely*; Figure 3.1), contrasting a possibly faster second lap in 2000-2009 (0.5, ±-0.4s; moderate difference, *62% possibly, 38% trivial*).

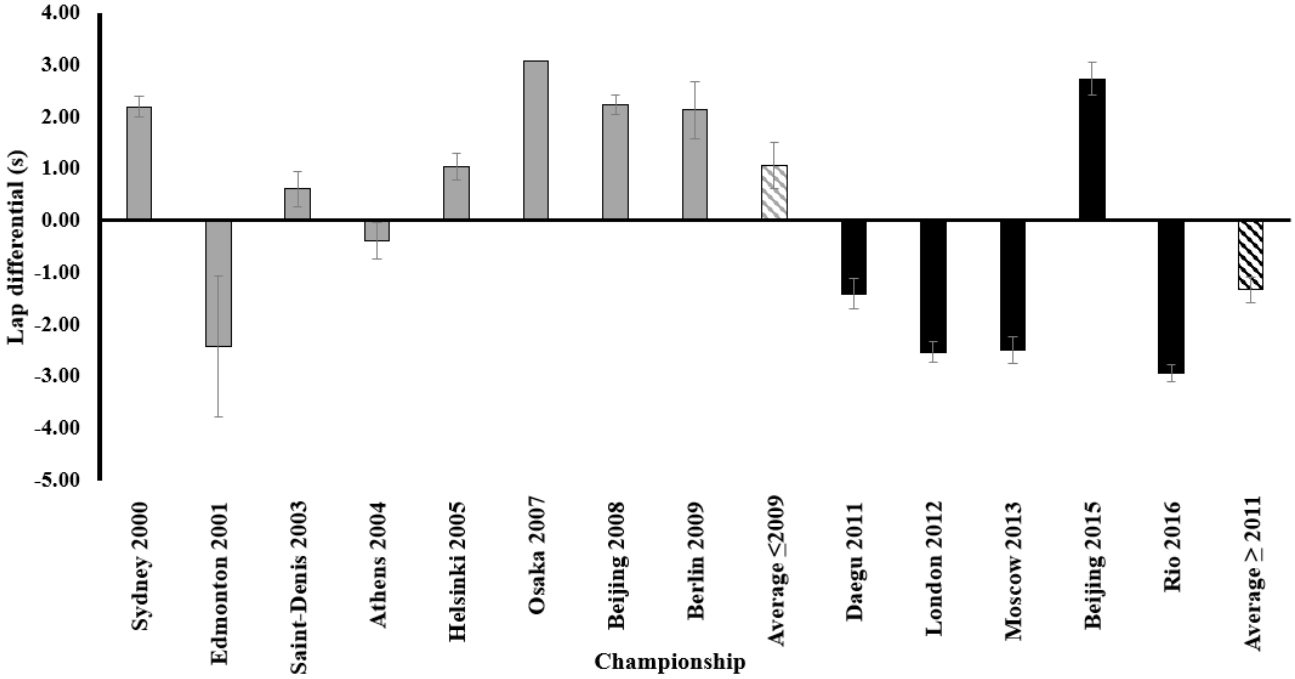

Figure 3.1. Mean and SD lap differentials for Men's 800m medallists. A negative value represents a faster first lap. * Osaka 2007 value representative of gold medallist only due to incomplete footage.

Figure 3.2 describes the relationship between world ranking prior to the championship and pacing strategy adopted by the gold medallists (r=0.94, 0.84 to 0.98; extremely large, *most likely*), whereby a higher world ranking prior to the championship was related to a positive pacing strategy. Four of the last five OG and WC were completed using a positive pacing strategy (all but 2015).

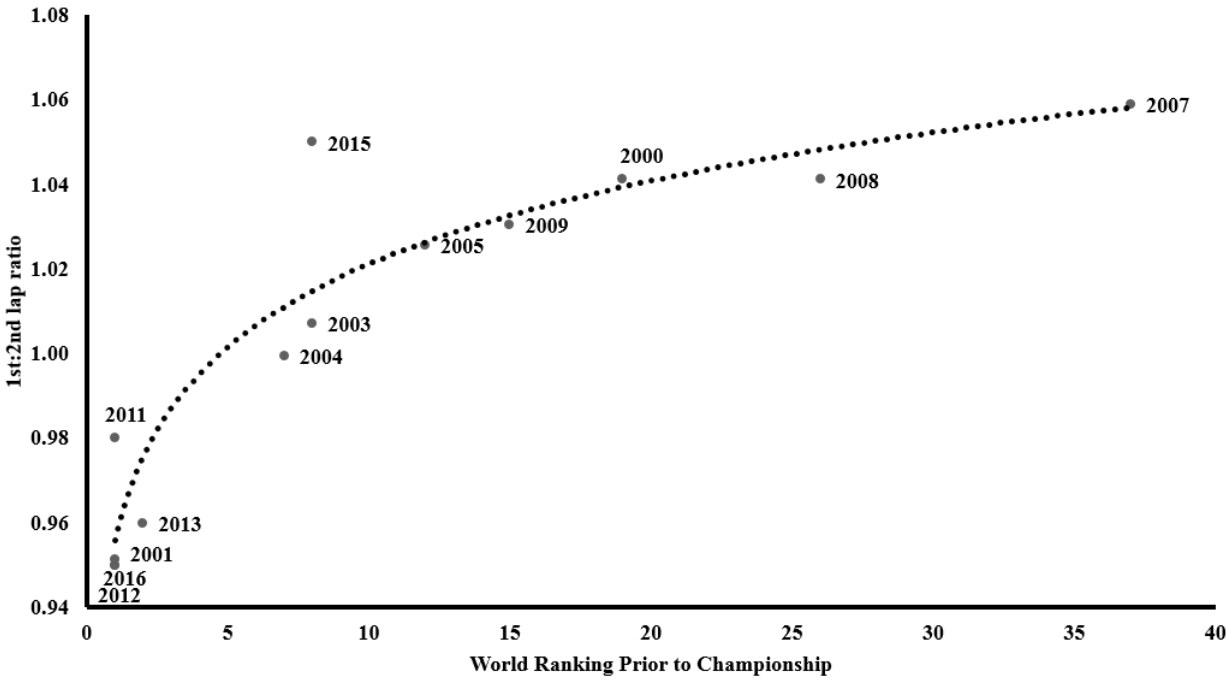

Figure 3.2. Gold medal winner's pacing strategy vs. their world ranking ahead of championships. A ratio <1 depicts a positive pacing strategy (faster first lap).

Figure 3.3 describes the fastest 100m sector of championship medallists across seven OG and WC. The fastest 100m sector from 800m championship medallists was faster after 2011 than before 2009 by 0.5, ±0.2m/s (large effect, most likely). In 2012 OG, 2013 WC and 2016 OG, the fastest 100m sector occurred between 100-200m. By comparison, the 2015 WC showed a negative strategy with the 700-800m sector as fastest.

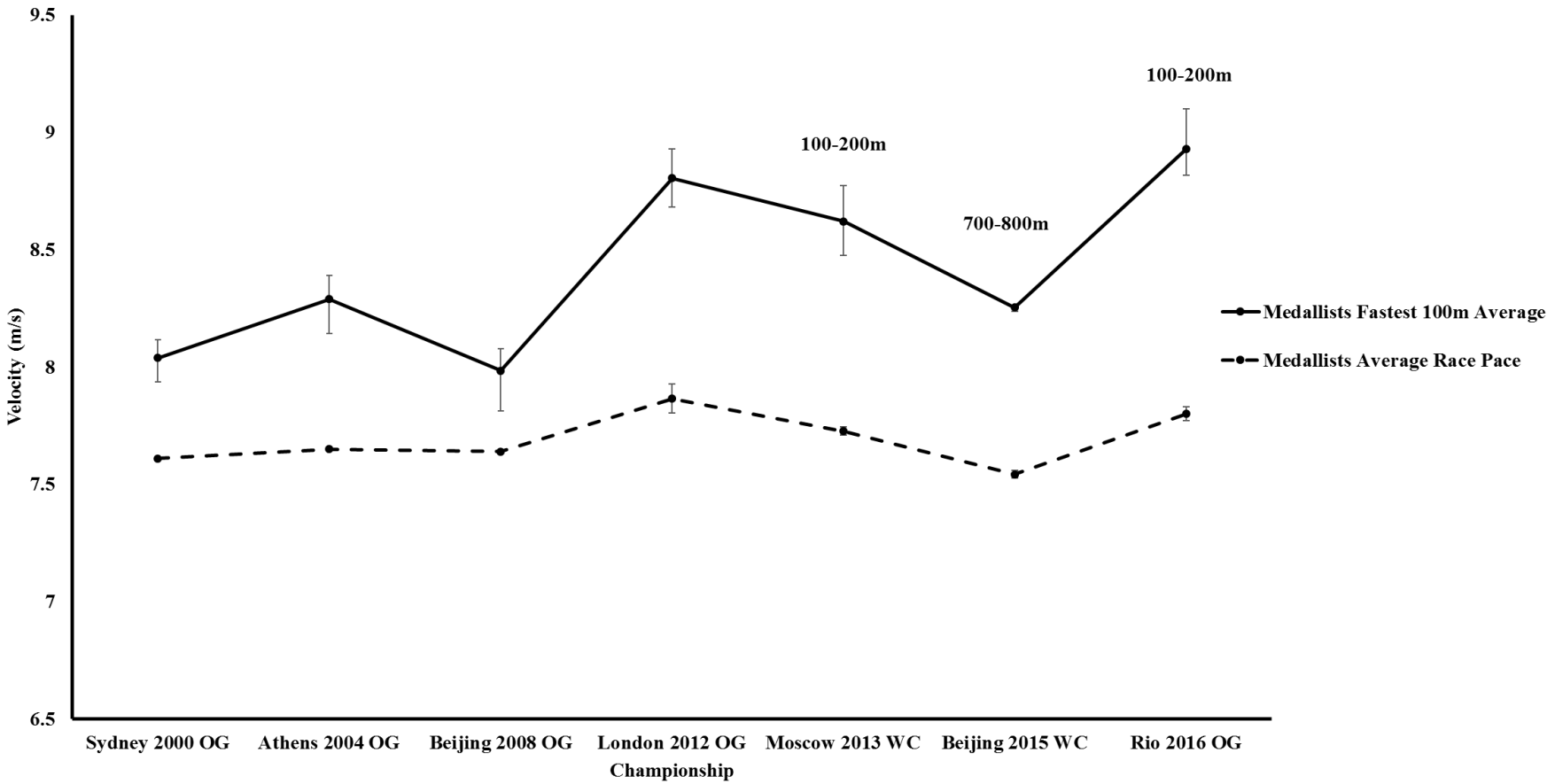

Figure 3.3. Fastest 100m sector of the Men's 800m medallists, compared to their average 800m race pace across championship finals

3.5 Discussion

Results from this technical report reveal for the first time, an increased adoption of positive pacing in OG and WC M800 medallists since 2011. Interestingly, this tactical shift from gold medallists appears contingent, in part, on the athlete possessing a high world ranking prior to the championship event. Not only does the pacing approach appear increasingly positive (Figure 3.1), but the range of speed required to medal in M800 OG and WC racing has increased (Figure 3.3).

It is clear that M800 championship racing has transitioned. Prior to 2009, OG and WC M800 championship finals were approached more conservatively over the first lap. Pressure to perform at a championship, accumulation of fatigue from heats and a higher calibre of opposition may affect 'doubt' in an athlete's decision to execute a positive 'gun-to-tape' approach in a final. The transition aligns with a new era of 800m runners, who perhaps possess different physiological characteristics that enable more positive pacing approaches. A notable characteristic of the recently adopted positive pacing approach is the faster speed demand between 100- 200m, with another 600m to run (Figure 3.3), with very similar second lap closing demands from 2000-2016, posing clear questions around the underpinning qualities required to successfully compete against the modern-day demands.

Literature across middle distance running has largely focused on the aerobic determinants of performance. Previously in a 2008 publication (Ingham et al., 2008), it was reported that running economy and $\dot{V}O_2max$ predicts 95.9% of 800m and 1500m running performance in national and international athletes. As shown in the present study, it may be necessary to revisit this paradigm, to investigate whether anaerobic qualities may be more important for success in modern-day M800 championship events than previously thought. Additionally, it is noteworthy that less athletes appear to be 'doubling up' and

performing both M800 and 1500m events, as unique pacing strategies, tactics and associated energetics may now be required to attain medal success in the M800 (Mytton et al., 2015).

Despite his eighth-place world ranking prior to 2015 WC, Rudisha's gold medal demonstrates the influence a frontrunner with the 'aura' that a WR holder can have, which may have enabled him to control the race from the front using a negative pacing strategy. Figure 3.2 reveals that a negative pacing approach may 'open the door' in the end spurt to the whole field; for example, in 2007, where an athlete ranked 37th prior to the WC won the gold medal. The increased adoption of positive pacing may be the result of more M800 athletes possessing superior speed capability (figure 3.3). Indeed, success in the M800 might be limited to those who can best regulate their pacing in accordance with their physiological, psychological and tactical limitations in the moment (De Koning et al., 2011; De Koning et al., 2011). Ultimately, it would appear that if an athlete is unable to run with the new speed demands of the first lap, then their probability of success in the modern era will be low.

Due to the strict inclusion criteria to depict 100m sector splits, only seven of thirteen global championships were included in the 100m speed sector sample. However, personal observations across the remaining incomplete footage of the other M800 championship events, showed no 100m sector faster than that seen over the medallists from Figure 3 before 2009.

3.6 Conclusion and Practical Application

In summary, a change in tactical behaviour has occurred in M800 championship racing, whereby since 2011, medallists have largely run faster first laps. This finding may be pertinent for training, tactical preparation and talent identification of athletes preparing for M800 running at WC and OG.

3.7 Chapter Link

A key finding of chapter 3 was the faster speed demand between 100-200m of the men's 800m in the modern era (2011-2016). This timepoint in the race is critical for attaining favourable tactical position near the front and being able to dictate the pace of the race. Second lap speed demands are very similar across 2000-2016, suggesting perhaps that the modern day 800m runner has some different underlying qualities to that seen in the 2000-2009 era.

Specifically, the qualities underpinning surge capability are of important interest. To better understand surge capability we must understand determinants and limitations of the metabolic input and the mechanical output to 800m performance (Bundle & Weyand, 2012). Anaerobic energy yield measured directly from muscle biopsy has been shown to be ~40% of total energy cost for all out exercise in the 90-120s time frame (similar to an 800m) (Bangsbo et al., 1990). However, current valid, reliable and easy to implement indirect measurements of the metabolic input beyond $\dot{V}O_2max$ (and accurately beyond critical speed) have evaded applied practice.

This important area of interest is still very much the 'elephant in the room' when it comes to resolution on the determinants of performance. The following chapter will provide an overview of the tests currently available to quantify the anaerobic energetics relevant to middle distance running performance, as well as providing awareness of the important neuromuscular and mechanical contributors.

CHAPTER 4: ANAEROBIC ENERGETICS OF MIDDLE-DISTANCE RUNNING PERFORMANCE – THE ELEPHANT IN THE ROOM?

Chapter 4

4.1 Abstract

Middle-distance running events (800-1500m) present a unique metabolic challenge for an athlete, demanding high levels of aerobic and anaerobic energy system development for optimal performance. The ability to perform work above those intensities supported predominantly by aerobic metabolism is often a distinguishing factor that decides a contest. Historically, the importance of such high-intensity work has been realised in the last mile of longer distance events (10,000m), and on the last lap in 800-5000m events, though in the modern era, this appears to be occurring from the start of the 800m, as well as during longer sustained surges for the finish in the 1500m-5000m. Thus, to maximise the systems that support these surges over middle-distance events, a better understanding of the potential qualities that underpin them is required. Measurement of anaerobic energetics has long been problematic for the sport scientist, with reliability, ecological design and direct measurement all challenging the creation of a gold standard test. However, until greater resolution into the work that is believed to be met by anaerobic energetic processes can be achieved, a critical piece of the performance puzzle for middle distance performance remains unresolved. This article reviews tests currently available to quantify the anaerobic energetics relevant to middle distance running performance, as well as providing awareness of the important neuromuscular and mechanical contributors.

4.2 Introduction

Middle-Distance running at the Olympic level encompasses events ranging from 800m-5000m (Lacour et al., 1990). The physiological demands of these events are particularly unique, with close interplay between aerobic and anaerobic energetics (Brandon, 1995). Typically, the shorter the race distance, the greater the anaerobic contribution, with a maximal effort of 75s thought to require approximately equal aerobic/anaerobic energy contribution (Gastin, 2001). As the majority of energetic contribution to middle-distance events is aerobic in nature (Spencer & Gastin, 2001), coupled by the relative ease of aerobic assessment (Midgley, McNaughton, & Wilkinson, 2006), we are left with a middle-distance literature described almost exclusively by aerobic parameters (Baumann et al., 2011; Brandon, 1995).

Measurement of the contributions made to high-intensity exercise performance by the anaerobic energetics, namely the short-term phosphate system (ATP-PC) and the anaerobic glycolytic system, have challenged physiologists for years (Davison, van Someren, & Jones, 2009). Direct measurement of anaerobic energetics from muscle biopsy (Bangsbo et al., 1990) are impractical and have led to several indirect measurement methods with their own nomenclature. Terms such as ‘anaerobic power, anaerobic capacity, anaerobic work capacity and anaerobic distance capacity’, have left scientists, practitioners and coaches without a consistent gold standard framework from which they can measure and interpret within. Several methods of measuring the anaerobic component to high-intensity exercise in the 2-10-minute range have been trialled, with limited success in providing acceptable levels of reliability and validity (Noordhof, De Koning, & Foster, 2010; Pettitt, Jamnick, & Clark, 2012), leaving determination of its contribution to performance still very much the ‘elephant in the room’.

The individual contribution of the phosphagen, anaerobic glycolytic and aerobic energy systems to adenosine triphosphate (ATP) production is dependent upon both the demands of the exercise and the capacity of the respective systems. The phosphagen system has the highest rate of ATP production, while the aerobic system has the largest capacity (Maughan & Gleeson, 2010). Aerobic energy contribution to middle-distance running have been reviewed extensively (Bassett & Howley, 2000; Duffield et al., 2005a, 2005b; Joyner & Coyle, 2008; Spencer & Gastin, 2001). Further, average race intensity of men's 800m, 1500m and 5000m have been profiled at 113, 103, and 97% of VO_2peak respectively (Gastin, 2001; Lacour et al., 1990), or 126 and 111% of the velocity at $\dot{V}O_2$max ($v\dot{V}O_2$max) for 800 and 1500m events (Billat, 2001). Thus, the energetic demands of middle-distance running surpass that which can be met solely by oxidative phosphorylation, leaving metabolic limitations in elite-level middle-distance running performance residing partially from an individual's anaerobic capabilities (Maughan & Gleeson, 2010). For example, In trained 800-5000m runners, Zagatto et al., (2011) showed a 73.5% total anaerobic energy contribution across 20s efforts during the Maximal Anaerobic Running Test (MART, see below). Furthermore, Parolin et al., (1999) showed that other than the first 15s bout during repeated 30s maximal cycling bouts in healthy males (4 minutes recovery), subsequent repetitions beyond 6s were supplied from aerobic sources (>50%). Importantly, the metabolic support of exercise performance is a synonymous interaction of aerobic and anaerobic energetics (Poole et al., 2016a), and to distinctly separate and measure the anaerobic systems accurately, across their short time frame, is a substantial technical challenge.

An athlete's ability to surge within races, is likely explained in part by their anaerobic energy capacities (Fukuba & Whipp, 1999), alongside important neuromuscular/mechanical contribution that is less considered (Bundle & Weyand, 2012). Such tactical events of high work intensity within races are known to be key

differentiators between medallists across 800-10,000m distances (Enomoto, Kadono, Suzuki, Chiba, & Koyama, 2008; Mytton et al., 2015; Sandford et al., 2018; Chapter 3; Thiel et al., 2012). Therefore, this current opinion aims to provide a brief overview of the main laboratory tests used in research settings to quantify the anaerobic energetics alongside the neuromuscular and mechanical contributors that may support this high-intensity exercise performance, with specific reference to middle-distance running.

4.3 Methods of Determining Anaerobic Energy Contribution to High Speed Running

Critical Power (Speed) Modelling

A. V. Hill, (1925) first described the relationship between exercise duration and maximum sustainable speed across world record event performances, which became known as the power-duration relationship. Specifically, a sustainable performance velocity was proportional to the time of the effort. From this beginning, the critical power (CP) concept was born. CP (or speed (CS) in running) has been defined as a mathematical construct with physiological significance representing the divide between steady state and non-steady state exercise (Poole et al., 2016a),occurring between 85-90% of $\dot{V}O_2$max in well trained runners (Skiba, 2014) (Figure 4.1). The finite work capacity that occurs beyond CS has been termed D prime (D') for the distance run above CS (Vanhatalo, Jones, & Burnley, 2011). D' is the current best estimate of anaerobic capacity, whereby the sustainable aerobic power (represented by CS) and total work above CS (D') that can be completed, ultimately determines high-intensity running performance.

Using this energetic model, the assumption made is that CS is the rate limiter of aerobic supply, which is unlimited in capacity, whilst D' is not rate limited, but limited in capacity. Exhaustion above CS and associated exercise termination occurs when D' is exhausted (Morton, 2006). In the short duration 800m event, this becomes complex to

model, as almost immediate utilisation of D' occurs from the gun whilst VO_2 kinetics amplitude rises (Bosquet, Duchene, Dupont, Leger, & Carter, 2007). VO_2 kinetics time-lag (25-35s (Bosquet et al., 2007)) is highly variable in part due to muscle fibre efficiency (Grassi et al., 2015) alongside a high neuromuscular component inducing metabolic acidosis (Bundle & Weyand, 2012).

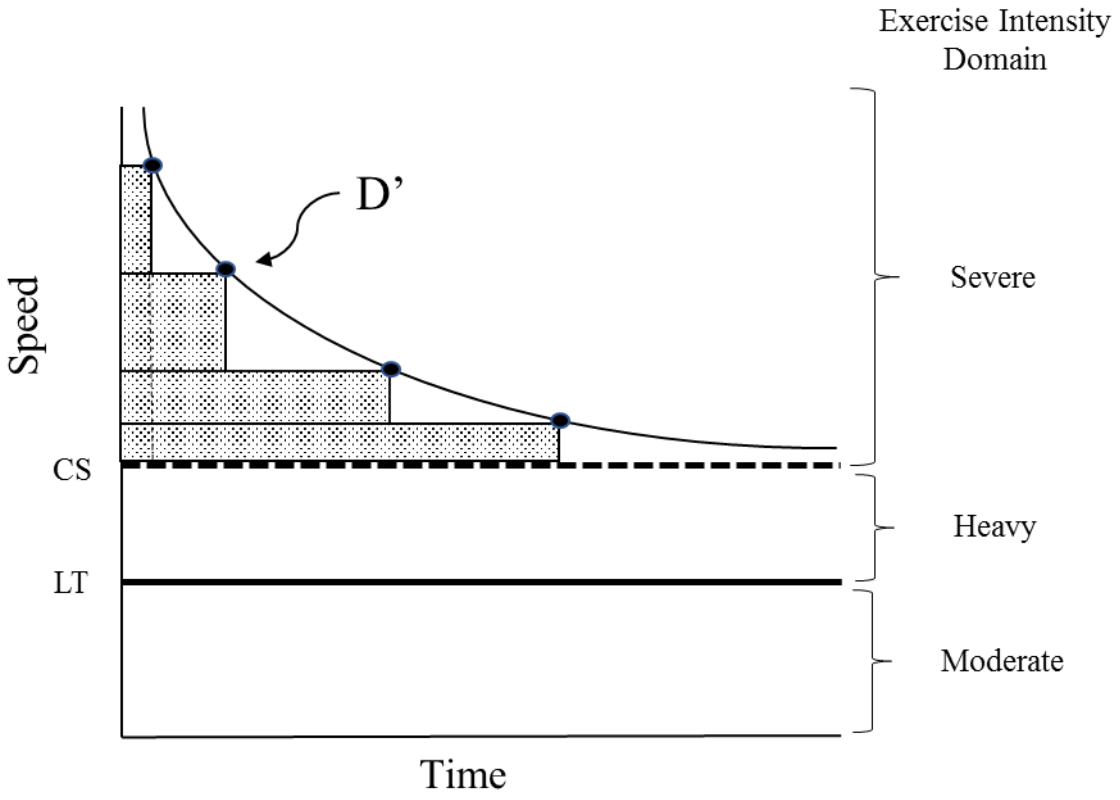

Figure 4.1. The critical speed(CS) model (Adapted from Poole et al. 2016) demonstrating the power duration relationship of sustainable exercise performance. CS demarcates a threshold for steady state exercise. Above which no steady state can be attained, and the exercise duration is determined by utilisation of D'. Note the multitude of theoretical D' intensity/duration variations that could occur above the CS, yet for all cases, available energy-related speed is finite.

CS model application has been suggested to be most appropriate for events 2-30 minutes (Vanhatalo et al., 2011). However, while D' estimates have shown acceptable levels of prediction accuracy over longer distance events (Fukuba & Whipp, 1999; Kolbe, Dennis, Selley, Noakes, & Lambert, 1995; Pettitt et al., 2012; Skiba, 2014), it appears to have

limited application for 800m runners with 7.96s (5.4%) error shown in 800m prediction (Pettitt et al., 2012). In part this may stem from CS measuring very different physiology to an 800m race, where larger aerobic contributions (78%, Bangsbo, Michalsik, & Petersen, 1993) are found across 3 minutes, compared to 1 min 53 800m race (66%, Spencer & Gastin, 2001).

Further, with the sprint-based 400-800m subgroup (Gamboa et al., 1996; Horwill, 1980), where accurate CS measures require repeated time-to-exhaustion tests over 2-15 minutes (Vanhatalo et al., 2011), or in the field over 3600m, 2400m and 1200m in one training session is unlikely (Galbraith et al., 2014). There are only a few exceptional athletes who would be able (or willing) to produce such maximal performances in events ranging from 800m through to 5km, completed within the frequency required for model validity. Therefore, use of CS with middle-distance running events from both a model accuracy and practical standpoint is questionable.

Maximally Accumulated Oxygen Deficit

The maximally accumulated oxygen deficit (MAOD) method is a laboratory-based assessment that typically uses a graded exercise test to determine the VO_2 workload relationship, from which total anaerobic capacity can be estimated by extrapolating the predicted oxygen demand knowing the duration of exercise and the athlete's maximal oxygen uptake ($\dot{V}O_2max$) (figure 4.2) (Medbø et al., 1988; Noordhof et al., 2010). Accordingly, MAOD has been used to estimate the 'anaerobic capacity' across numerous 'middle-distance -related sports', including kayak and sprint skiing (Bishop, Bonetti, & Dawson, 2002; Losnegard, Myklebust, & Hallén, 2012; Ramsbottom, Nevill, Nevill, Newport, & Williams, 1994). Furthermore, with respect to performance, Ramsbottom et al. (1994) showed a large relationship between MAOD and 800m performance (r=-0.61) in 12 subjects ($\dot{V}O_2max$=64.4 ±7.2 ml/kg/min, range: 57.1-81.6) and Billat et al. (2009) reported an inverse relationship between 800m running specialists and MAOD (r = -0.70).

Conversely, however, Olesen, Raabo, Bangsbo, & Secher, (1994) found no relationship (value not reported) between MAOD and competitive middle-distance runners ($\dot{V}O_2max$, 72ml/kg/min, range: 61-82.4). Whilst some large negative relationships have been shown in 800m (Billat, Hamard, Koralsztein, & Morton, 2009; Ramsbottom et al., 1994), the relationships between research groups are inconsistent.

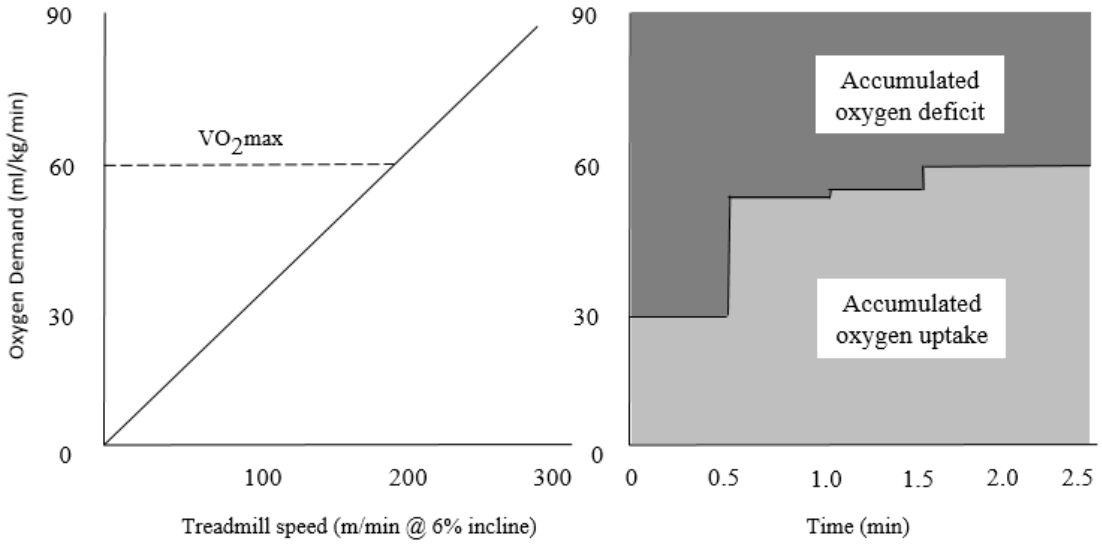

Figure 4.2. Overview of the maximal accumulated oxygen deficit (MAOD) method, which uses the submaximal oxygen extrapolation methodology to estimate anaerobic capacity. Adapted from Medbø et al.(1988).

Several methodological considerations may explain the disparate findings, including heterogeneous populations, different protocols (test duration, step increments, gradient) and inappropriate methods for assessing reliability (Atkinson & Nevill, 1998; Noordhof et al., 2010). First, Pringle, Doust, Carter, Tolfrey, & Jones, (2003) have shown an increase in the amplitude of the VO_2 slow component (gradient of oxygen uptake) above CS, leads to faster attainment of $\dot{V}O_2max$, with differences in slow components between individuals due presumably to variations in muscle recruitment patterns and muscle fibre composition (thus mechanical efficiency). Considering the different population sub-groups of middle-distance runners (Gamboa et al., 1996; Horwill, 1980; Sandford, Allen,

Kilding, Ross, & Laursen, 2018; Chapter 6), and their large differences in maximal sprint speed (MSS) (reflective in part, of fibre composition differences (Baguet et al., 2011), means the MAOD's validity is questionable. Second, submaximal VO_2 measurement at 16km.h^{-1} in a 400-800m athlete is unlikely to accurately predict efficiency above CS, where an elite 800m athlete's race pace (e.g. 1:45(min: s) is 27.4km/hr. Indeed, Daniels & Daniels, (1992) demonstrated that elite 800 and 1500m runners were more economical at speeds greater than 19km/h, but less economical at slower speeds compared with marathon runners. Therefore, MAOD may under- or over-estimate anaerobic capacity based on differences in running economy above and below CS and this would indicate that a more valid and reliable method of assessing anaerobic energetics in middle-distance athletes is needed.

Maximal Anaerobic Running Test

An alternative test of anaerobic contribution to running is the 'Maximal Anaerobic Running Test' (MART) designed by Nummela et al. (1996), which specifically assesses the neuromuscular and metabolic components of anaerobic performance (Nummela et al., 1996). The laboratory test protocol requires 10x20s efforts, with 100s recovery intervals, starting at 3.41m/s (<3 mmol lactate) on a 4% gradient with increments of 0.35 m/s per stage. Exhaustion is attained within 12 runs, and the vMART power (proposed measure of anaerobic capacity) is calculated from the last completed stage, where if exhaustion occurred >10s into the stage above, every additional 2s completed adds an extra 1/6th (m/s) to the vMART speed. A practical field alternative has been used, where 20s efforts are replaced by 150m runs (Nummela, Hämäläinen, & Rusko, 2007) .

The vMART has been found to explain 31% of 5km performance in collegiate female runners and 15% of 5km performance in elite cross country runners (Paavolainen et al., 1999). Furthermore, Nummela et al. (2006) found a very large relationship between vMART and 5km running velocity (r=0.77) in well trained distance runners, and a

moderate relationship with last lap speed (r=0.54). Zagatto et al. (2011) suggest that the phosphagen system makes the highest energy contribution during 20s MART efforts (62.6%), but there is additionally high-aerobic energy contribution when the entire test is considered (65.4%). Limitations lie in laboratory testing protocol consistency across the literature, with the test conducted on a 4% (Nummela et al., 1996) or 10.5% (Maxwell & Nimmo, 1996) gradient, which adjusts the active muscle mass involvement and limits ecological validity for middle-distance track running performance. Throughout the studies that have used this method, step increments are also inconsistent, occurring at 0.41 m/s (Nummela, Hämäläinen, et al., 2007), 0.38 m/s (Nummela et al., 1996), or 0.35 m/s (Maxwell & Nimmo, 1996), adding further uncertainty across study comparisons.

While the field test version offers higher ecological validity, its consistent recovery duration (100s) is likely to favour aerobic sub-groups (Gamboa et al., 1996; Horwill, 1980; Sandford et al., 2018, Chapter 6), expected to recover faster between repetitions (Tomlin & Wenger, 2002), subsequently limiting the validity of between sub-group comparisons. Whilst Nummela et al. (1996) attempted to individualise the test by working back from MSS, the incremental process is not individualized and does not consider differences in mechanical efficiency, which is likely a key determinant of performance in this test.

4.4 Anaerobic Speed Reserve

Blondel et al. (2001) introduced the term anaerobic speed reserve (ASR) to describe the difference between the velocity at $\dot{V}O_2max$ ($v\dot{V}O_2max$), or maximal aerobic speed (MAS) in the field, and the MSS (Figure 4.3). The authors showed how estimation of an athlete's time-to-exhaustion at supramaximal intensities (above $\dot{V}O_2max$) was better estimated using MSS and ASR versus $v\dot{V}O_2max$, per se. However, problems arise when the ASR is considered as a metabolic construct, as the anaerobic energetic contribution to exercise

commences at an intensity above CS (Figure 4.3); well before $v\dot{V}O_2max$. In addition, $v\dot{V}O_2max$ is partially dependent on the rate of peripheral fatigue development, with increases in adenosine diphosphate (ADP) and inorganic phosphate (Pi) in the muscle impairing excitation-contraction coupling, reducing rate of muscle shortening velocity and force production (Grassi et al., 2011, 2015). Therefore, as previously stated, MAS and $v\dot{V}O_2max$ may be better described as markers of running efficiency, as opposed to a consistent physiological landmark (Billat & Koralsztein, 1996; Buchheit, 2010; Jones & Carter, 2000). For middle-distance performers, this may be a pivotal consideration, due to the proximity of $v\dot{V}O_2max$ to mean 1500m race pace (e.g 57s first lap = 25.3km/hr; Figure 4.3). Indeed, advances in CS modelling of the speed-duration relationship have shown that the finite D' decays proportionately with differences in target pace and CS (Poole et al., 2016a; Vanhatalo et al., 2011) (Figure 4.1). Thus, for a primary measure of aerobic energetics, CS is recommended (Figures 4.1 and 4.3), but probably of most importance, it is evident that the upper limit of the ASR (MSS) is not a function of anaerobic metabolic power (Bundle & Weyand, 2012), but is limited more by ground reaction impulse (Samozino et al., 2015; Weyand, Sandell, Prime, & Bundle, 2010) (see below). Critically, both the upper *and* lower bounds of the so called "ASR" do not actually represent anaerobic energy contribution limitations.

Despite its inability to explain anaerobic energy cost, the ASR has important applications. ASR has shown strong predictive mechanical (speed) duration relationships with performance in cycling and running (Bundle & Weyand, 2012). The decrement in high speed running and cycling performance (all out efforts <300s) has been predicted to within 2-4% in running (Weyand, Lin, & Bundle, 2006; Weyand & Bundle, 2005) and 6.6% in cycling (Sanders et al., 2017; Weyand et al., 2006) when normalised to ASR. Furthermore, differences in sprint performance (<300s) durations for both cycling and running were best explained by impulse (horizontal ground reaction force, expressed as

power output/kg (Rabita et al., 2015) due to stride length and frequency variations (Bundle & Weyand, 2012; Martin, Farrar, Wagner, & Spirduso, 2000), providing further evidence to support the ASR's important mechanical construct. With middle-distance speed demands being faster than ever (Sandford et al., 2018; Chapter 3), ensuring an athlete has the speed range required to meet the demand of their selected event is crucial, as MSS and ASR have been shown to have strong relationships with elite 800m running (Sandford et al., 2018; Chapter 6).

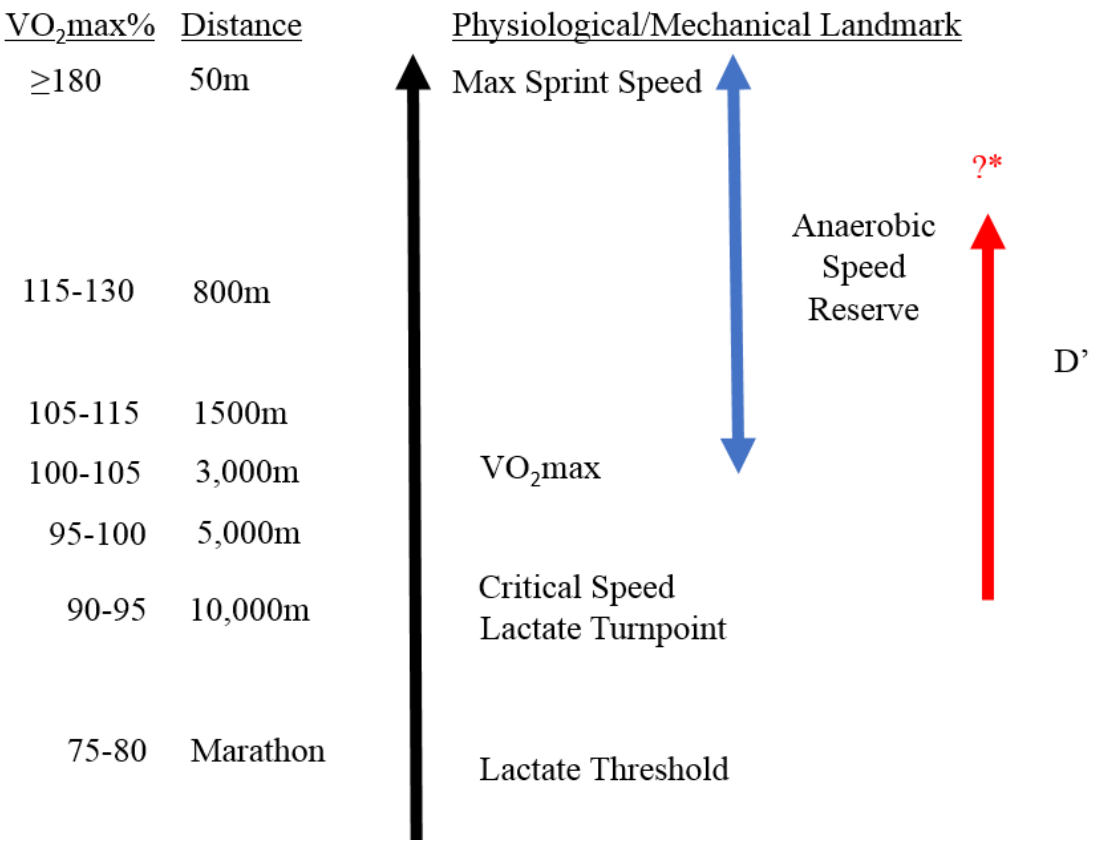

Figure 4.3. Relative work intensities as a proportion of $\dot{V}O_2$max as they relate to distance running races. Modified from Billat, (2001) and Buchheit & Laursen, (2013a). * D' utilisation proportional to difference of race pace and critical speed (see Figure 1).

Sprint Performance (<60s): Mechanical or Metabolic Limitations?

Bundle & Weyand, (2012) provide evidence that running performance of less than 60s is related more to mechanical or neuromuscular limitations, versus metabolic power

availability. In the non-sustainable range (above CS), the neuromuscular demand to maintain external force output (minimise deceleration) increases throughout short duration performances (measured by EMG), with larger rates of increase at higher workloads (Burnley, Vanhatalo, & Jones, 2012). Additionally, no increase in neuromuscular activity (assessed by constant current stimulation and the proportion of maximum voluntary knee extensor contraction) occurs when the workload is predominantly supported by the aerobic system (work below CS) (Bundle & Weyand, 2012; Burnley et al., 2012). Therefore, in distance running, if an athlete possesses a small ASR, then their ability to maintain or increase impulse later in a middle-distance race may be impaired. Enomoto et al. (2008) demonstrated this in the third-place athlete on the last lap of the World Championship 10,000m (2007), providing evidence to suggest this factor limited his ability to compete for the gold medal. Further, impulse and EMG measurements during all-out sprint trials, performed over 300s during cycling and running in moderately trained participants (Weyand et al., 2006; Weyand et al., 2000), revealed performance was limited by the ability to withstand fatigue and sustain external force application from anaerobic metabolism. Specifically, it was deemed more the inability of the contractile apparatus to utilise energy that limited force production, *and not a limitation of metabolic energy supply* (Bundle & Weyand, 2012), countering longstanding assumptions (Bundle & Weyand, 2012) .

The Challenging Middle Ground of Middle-Distance Running

With the 800m lasting ~100s, metabolic power is required to support the 'non-sustainable impulse' (to slow deceleration) as long as possible. With all paces in the 800m in the severe domain above CS (115-130% $\dot{V}O_2max$) (Billat, 2001), the anaerobic metabolism contribution is critical. Weyand et al. (1999) revealed that when oxygen availability was reduced under hypoxic conditions, all-out sprint exercise lasting 100s (in the severe domain) was compensated for by increases in anaerobic metabolism (D') (measured by

MAOD) of up to 18% higher than the same task in normoxia. The decrement in speed over 100s in hypoxia versus normoxia was attributed to the 30% reduction in maximal aerobic power in hypoxia (87±4% SaO_2) (Weyand et al., 1999). Despite the increases in anaerobic metabolism (D') in the hypoxic trial, all-out 100s performance could not be sustained under the supressed aerobic system. These results emphasize the complex 'middle-ground' of the 800m, which likely requires concurrent periodised development of all aspects across neuromuscular, mechanical, anaerobic glycolytic and aerobic oxidative components to sustain impulse in the severe domain and limit deceleration. Interestingly, the 800m participant (1:51PB) in this study had a 1.7% larger increase in anaerobic metabolism than the others (Weyand et al., 1999), supporting the premise that, depending on the strengths of the athlete's profile (Sandford et al., 2018; Chapter 6; Schumacher & Mueller, 2002), the balance between aerobic and anaerobic metabolism may vary on a compensatory basis. More reliable and practical quantification of anaerobic metabolism may facilitate more individualise training approaches towards improving these qualities.

4.5 Perspectives - Where to From Here?

In all-out exercise, such as a gun-to-tape 800m race, the necessary utilisation of anaerobic metabolism will compromise force production, meaning compensatory strategies must be drawn upon by the athlete (Bundle, Ernst, Bellizzi, Wright, & Weyand, 2006). Recruitment of larger motor units ensues, which presents a clear rationale for developing both ASR components; $v\dot{V}O_2max$ and MSS (Bundle et al., 2006). Nummela et al., (1996) revealed that Finnish national 800m and 1500m distance runners and USA 400m athletes (PB range: 44-52.5 s) had superior anaerobic work capacity (as defined by the MART) compared with long distance runners and controls (sprinters and jumpers). The 400m athletes showed superior anaerobic work capacity and the highest MSS compared to the national Finnish 800m and 1500m athletes. Therefore, accurate quantification of

anaerobic energetics may enable more subtle individualisation of training approach and athlete event specialisation. Recent data in elite cyclists show a very large relationship (r=0.87) between peak force and W' (D' equivalent in cycling) (Kordi, Menzies, & Parker Simpson, 2018). Therefore, with larger ground reaction forces determining faster running speeds (Weyand et al., 2000), an important relationship between D' and the ASR may exist, although this requires further study (Denadai & Greco, 2017; Sandford et al., 2018; Chapter 7).

For a comprehensive assessment of physical work capacity of athletes, both aerobic and anaerobic capabilities should be represented across three dimensions, i.e. using an index of power (speed), capacity and efficiency (Volkov, Shirkovets, & Borilkevich, 1975). ASR and D' components may currently be our best tools for capturing this, though clearly not without limitations (Table 4.I). Better quantification of this important area may require a multidisciplinary perspective, incorporating the sciences of biomechanics, physiology and motor control to advance our understanding (Bertuzzi et al., 2018). What is abundantly clear is that anaerobic energetics alongside neuromuscular attributes are critical determinants of performance in events requiring maximal efforts over 2-10 minutes (Brandon, 1995) (Figure 4.3), and make key contributions to the tactical moments that can differentiate outcomes in many longer distance events, e.g 'the last lap kick' in 10,000m (Enomoto et al., 2008).

Table 4.1. Summary of the reliability and practicality of anaerobic tests used in middle distance running performance

Test	Protocol	Reliability			Practicality (+/-)
		Coefficient of Variation	Limits of Agreement	Technical Error (Confidence limits)	
Critical Speed (lab)	3 minute all out test (Pettitt et al., 2012)	5.4% 800m performance 1.7% 1600m performance 2.1% 5000m performance		7.96s (5.17-18.89s) 5.59s (3.63-13.27s) 23.52 (15.80-49.13s)	Large measurement noise render predictions redundant
	5 constant velocity tests at 95,100,105,110 and 120% of Peak treadmill velocity (L. Bosquet, Delhors, Duchene, Dupont, & Leger, 2007)	4.13-4.74% 800m performance			Performed on motorized treadmill but could act as a training session
Critical Speed (field)	3600,2400, 1200 TT (Galbraith et al., 2014)			CS – 0.16m/s (0.09-0.26) D' – 88m (60-169m)	High ecological validity but high workload for one session. Likely restricted in implementation.
MAOD	Treadmill speeds above $v\dot{V}O_2max$, exhaustion achieved after 15s, 30s, 1,2 & 4 minutes on different days (Medbø et al., 1988)	4-10%			Multiple day trials at maximum effort. Not easy to implement within a typical training week.
MART (lab)	Each run lasts 20s, with 100s rest periods. Starting speed of	P_{max} 2.75% P_{10mM-} 4.86%			Poor ecological transfer with differences in muscle mass recruitment on a 4°

		14.6km/hr, increased by 1.37km/hr until exhaustion. Treadmill at 4°gradient (Nummela et al., 1996)	P_{5mM} – 9.67% pBla – 19.21%		gradient. Large psychological and physiological demand.
MART (field)		10 x 150m runs to exhaustion, 100s rest periods. 4.75 m/s starting speed for males and 3.94 m/s for females (Nummela, Hämäläinen, et al., 2007)	Field vs. Lab protocol $V_{max\ -}$ 7.09% V_{10mM} – 9.07% V_{5mM} – 12.79% La_{max} – 26.53%		Dependent on consistent pacing in the field for 150m.
Anaerobic Reserve	Speed	MSS – Peak Speed Radar (Samozino et al., 2015) $v\dot{V}O_2max$ (Billat et al., 1996) MAS – Time Trial (Bellenger et al., 2015)	1.11±0.86% 4-5%	-0.7; 1.3 m/s 1.04±6.4 km/hr for 1600m TT	Easy to measure both Peak Speed and MAS in the field. Not a quantification of energetics, but of neuromuscular/mechanical efficiency.

CS – Critical speed, D' – Anaerobic distance capacity in metres (D prime), Pmax – maximum power in oxygen equivalents. P_{10mM} – power output at 10mmol lactate P_{5mM} - power output at 5mmol lactate, pBla – peak blood lactate at the end of MART. $V_{max\ -}$ maximum velocity at end of test, V_{10mM} – velocity at 10mmol lactate, V_{5mM} – velocity at 5mmol lactate, La_{max} – maximum lactate at the end of MART. MSS – Maximal Sprint Speed, $v\dot{V}O_2max$ – velocity at $\dot{V}O_2max$, MAS – maximal aerobic speed, TT – time trial.

4.6 Conclusion

Various attempts have been made to accurately quantify anaerobic energetics, with CS modelling currently the best estimate for performance durations beyond 4 minutes. The increasing modern day demand for speed early in the 800m (Sandford et al., 2018; Chapter 3) and in the 1500m-10,000m closing stages (Enomoto et al., 2008; Mytton et al., 2015), suggest the interaction of ASR and CS modelling may currently be the most comprehensive method for ensuring athletes have not only the mechanical efficiency, but a well-developed D' for maximising work above CS. Performance in this so called ASR domain appears to be a complex neuromuscular, mechanical and energetic phenomenon (Weyand et al., 2006). Despite the challenges of measurement, scientific advances in anaerobic energetics are critical, with many Olympic sports spanning the 2-10-minute duration. Without further investigation, our understanding of anaerobic energetics in middle-distance performance will remain – the elephant in the room.

4.7 Chapter Link

In absence of an accurate and reliable field measure of anaerobic energetics (shown in chapter 4), a step forward for understanding in this area would be to provide more resolution on the mechanical output and absolute speed capabilities currently required by elite 800m runners. The anaerobic speed reserve (ASR - speed range from velocity at $\dot{V}O_2max$ to maximal sprint speed), provides an easy to implement field measure for capturing these characteristics.

Coaching observations suggest the existence of 3 sub-groups of 800m runners: speed types (400-800m), 800m specialists and endurance types (800-1500m athletes) (Gamboa et al., 1996; Horwill, 1980). A unique part of the ASR is that it represents both the athlete's limits of force production, through MSS, and the fastest speed that can be supported aerobically (Blondel et al., 2001), thus considering both the metabolic and neuromuscular/mechanical limitations of an athlete's profile. Sanders et al (2017) demonstrated substantial differences between the anaerobic power reserve of professional cyclists, suggesting the ASR may provide resolution on athlete sub-groups.

Therefore, Chapter 5 sought to indirectly estimate the ASR of world-class male 800m and 1500m runners from available race personal bests to determine: a) what approximate ASR, MSS and $v\dot{V}O_2max$ values were in world-class middle-distance athletes, and b) to explore whether the ASR may be a suitable measure to differentiate athletes between and within event groups.

CHAPTER 5: ESTIMATING THE ANAEROBIC SPEED RESERVE IN WORLD CLASS MALE 800M AND 1500M RUNNERS

Chapter 5

5.1 Abstract

Purpose: To estimate the anaerobic speed reserve (ASR) in world class male 800m and 1500m runners.

Methods: ASR of the 30 fastest male 800m and 1500m runners from 2016 were selected using performance times from IAAF.org. Personal best times for each athlete across 400, 800 or 1500m were used to estimate the athlete's velocity at $\dot{V}O_2max$ ($v\dot{V}O_2max$) and Maximal Sprint Speed (MSS) using the equations of Bundle, Hoyt and Weyand (2003).

Results: MSS of 800m runners was *most likely* faster than that of 1500m runners (2.8 ±0.9 km/hr; large effect; mean ±90% confidence limits). Further, the ASR of 800m runners was *most likely* greater than that of 1500m runners (3.0 ±0.7 km/hr; large effect). While *trivial* differences in predicted $v\dot{V}O_2max$ existed between 800m and 1500m athletes (-0.3 ±0.5 km/hr; unclear effect), individual data revealed a non-uniform spread of $v\dot{V}O_2max$ for 800m runners, relative to the more homogenous $v\dot{V}O_2max$ of 1500m runners.

Conclusions: These estimations suggest world-class male 800m runners possess a larger MSS than world-class 1500m runners, highlighting the potential importance of ASR in middle-distance runners as a tool to differentiate and identify sub-groups within and between middle-distance events.

5.2 Introduction

Understanding the physiological, mechanical and neuromuscular determinants that underpin running performance is a key objective of researchers, practitioners and coaches working with athletes to reach their athletic potential. Quantification of an athlete's capacities and efficiencies can highlight individual strengths and weaknesses, as well as inform a targeted training approach.

The anaerobic speed reserve (ASR) is a construct that depicts the high-intensity running speed range from an athlete's velocity at $\dot{V}O_2max$ ($v\dot{V}O_2max$) to their maximal sprinting speed (MSS) (Blondel et al., 2001). $v\dot{V}O_2max$ represents the fastest mechanical speed that can be supported aerobically (Weyand et al., 2006), and MSS is determined by horizontal ground reaction impulse (Rabita et al., 2015). Sanders et al., (2017) have shown very large to perfect performance predictions using the related anaerobic power reserve in professional cyclists over 5-300s duration, while work in swimming has shown the swimming speed reserve (maximal intensity freestyle speed across 50m and 400m) to detect changes in swim performance over time (Dalamitros et al., 2015). However, this concept has received limited attention in the middle-distance running literature.

The aim of this study was to estimate the ASR of world class 800m and 1500m males, using predictive equations validated by Bundle et al. (2003) to contribute to understanding of the interrelationship between the aerobic and neuromuscular/mechanical limits of middle distance runners.

5.3 Methods

The 30 fastest male 800m and 1500m runners from 2016 were selected using performance times from https://www.iaaf.org/records/toplists/. Personal best (PB) times across 400m, 800m and 1500m runners from 2016 (table 5.1) were obtained from (http://www.tilastopaja.org/ and http://www.all-athletics.com/). These times were

substituted into previously validated equations (Bundle et al., 2003) to estimate each athlete's $v\dot{V}O_2max$, MSS and ASR (km/hr) as follows:

$$ASR = (distance_1/time_1 - distance_2/time_2)/[e^{(-0.013*time_1)} - e^{(-0.013*time_2)}]$$

$$v\dot{V}O_2max = distance_1/time_1 - (ASR*e^{(-0.013*time_1)}]$$

$$MSS = v\dot{V}O_2max + ASR$$

Where $distance_1$ and $_2$ and $time_1$ and $_2$ refer to known distances (m) and times (s) from two competitive performances. Times used in the model had to be performed within two years of one another to be included for analysis. In the case where there were more than two years between PB times, an athlete's second best time over both distances were used within another two-year window. When an athlete had recorded a performance across all three distances, the two distances with the highest performance standard (judged against IAAF points chart) were selected. If an athlete was in the top 30 for both 800m and 1500m times, they were removed from their lowest ranked event, and replaced by next highest ranked athlete not already included.

Table 5.1. Performance descriptors of world-class male 800m (n=17) and 1500m (n=22) runners

	800m		**1500m**	
Performance times (min:sec:ms)	**2016 SB**	**PB**	**2016 SB**	**PB**
Mean	1:44.06	1:43.62	3:33.46	3:31.60
Range	1:42.20-1:45.16	1:40.91 - 1:45.16	3:29.30-3:35.00	3:26.69-3:34.78

SB = season's best, PB = personal best

Three independent middle-distance running experts examined the anonymised PB times of each athlete. Where two of the three experts highlighted markedly disproportionate times between the two distances, that athlete was excluded from the analysis as these outliers skewed the subsequent estimation of physiological parameters. For example, a

$time_1$ and $time_2$ of 1:42 (800m) and 3:28 (1500m), respectively, were considered of equal standard, whereas 1:42 and 3:45 were considered disproportionate.

Statistics

Estimated $v\dot{V}O_2max$, MSS and ASR of the remaining 800 (n=17) and 1500m runners (n=22) were log-transformed to establish event-distance group means and standard deviations (SDs). Between-athlete SDs for each group and parameter were then combined with the 3.3% error of the prediction equations (Bundle et al., 2003) to establish overall SDs for creation of 90% confidence limits (CL).

Values for the smallest important differences between groups were defined as 0.2 of the overall between-athlete SD for each parameter as follows: $v\dot{V}O_2max$ (0.93 km/hr), MSS (2.24 km/hr) and ASR (2.36 km/hr) (Hopkins, 2007; Hopkins et al., 2009). Thresholds for moderate, large and very large effects were 0.6, 1.2 and 2.0 of these SDs, respectively (Hopkins et al., 2009). Inferences for mean differences between event-distance groups on each parameter were evaluated mechanistically based on the uncertainty in magnitude using these values, and calculated using a spreadsheet (Hopkins, 2007). Overall between-athlete variation (SD) for each group and parameter were also doubled for interpretation of their magnitude using these scales, although the spreadsheets used did not compute CL for inferences.

5.3 Results

Figure 5.1 displays the modelled ASR profiles of world-class male 800m (n=17) and 1500m (n=22) runners. MSS of 800m runners was *most likely* faster than that of 1500m runners (2.8 ±0.9 km/h; mean ±CL; large effect). Trivial and *unclear* differences in predicted $v\dot{V}O_2max$ were shown between 800m and 1500m athletes (-0.3 ±0.5 km/hr). However, the ASR of 800m runners was *most likely* greater than that of 1500m runners (3.0 ±0.7 km/h; large effect).

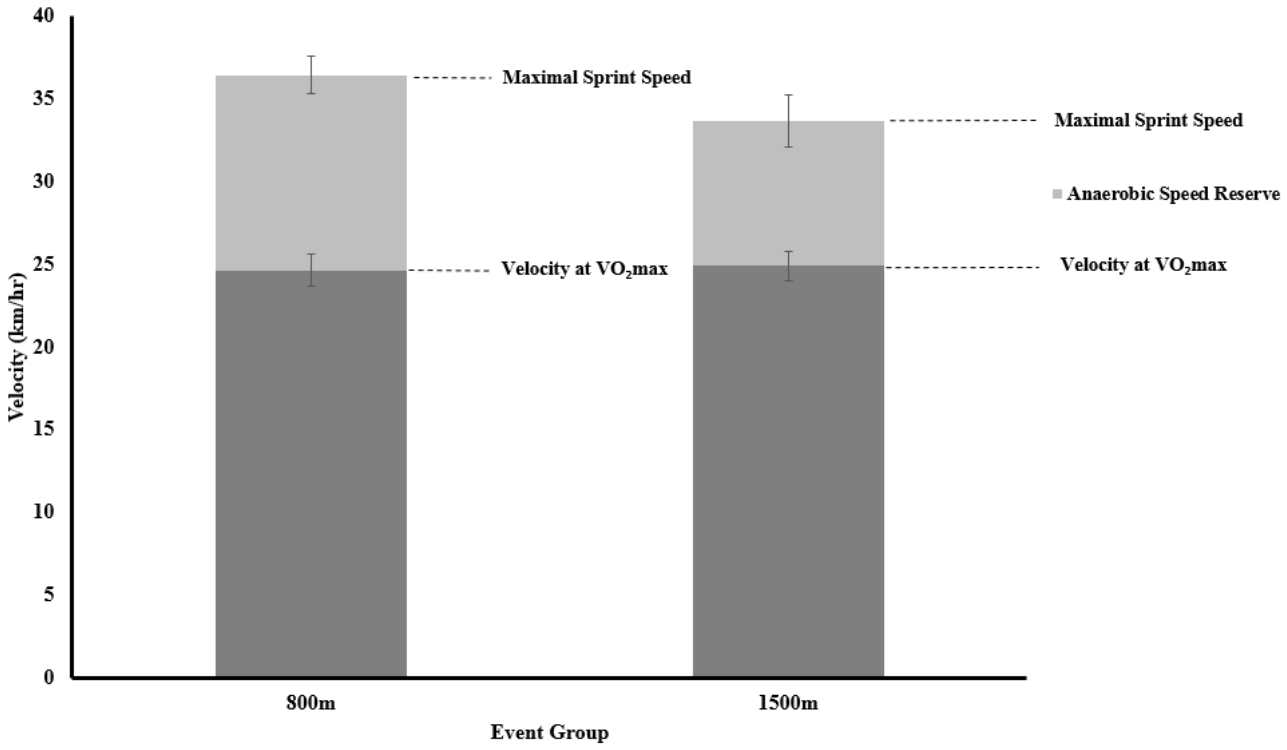

Figure 5.1. Estimated anaerobic speed reserve profiles of world-class male 800m (n=17) and 1500m (n=22) middle-distance runners.

Figure 5.2 profiles the individual v$\dot{V}O_2$max (A) and MSS (B), sorted from fastest to slowest across 800m and 1500m runners. The SDs of MSS and v$\dot{V}O_2$max were 1.69 km/hr (large) and 0.99 km/hr (very large) for 800m and 1.75 km/hr (large) and 0.87 km/hr (large) for 1500m, respectively.

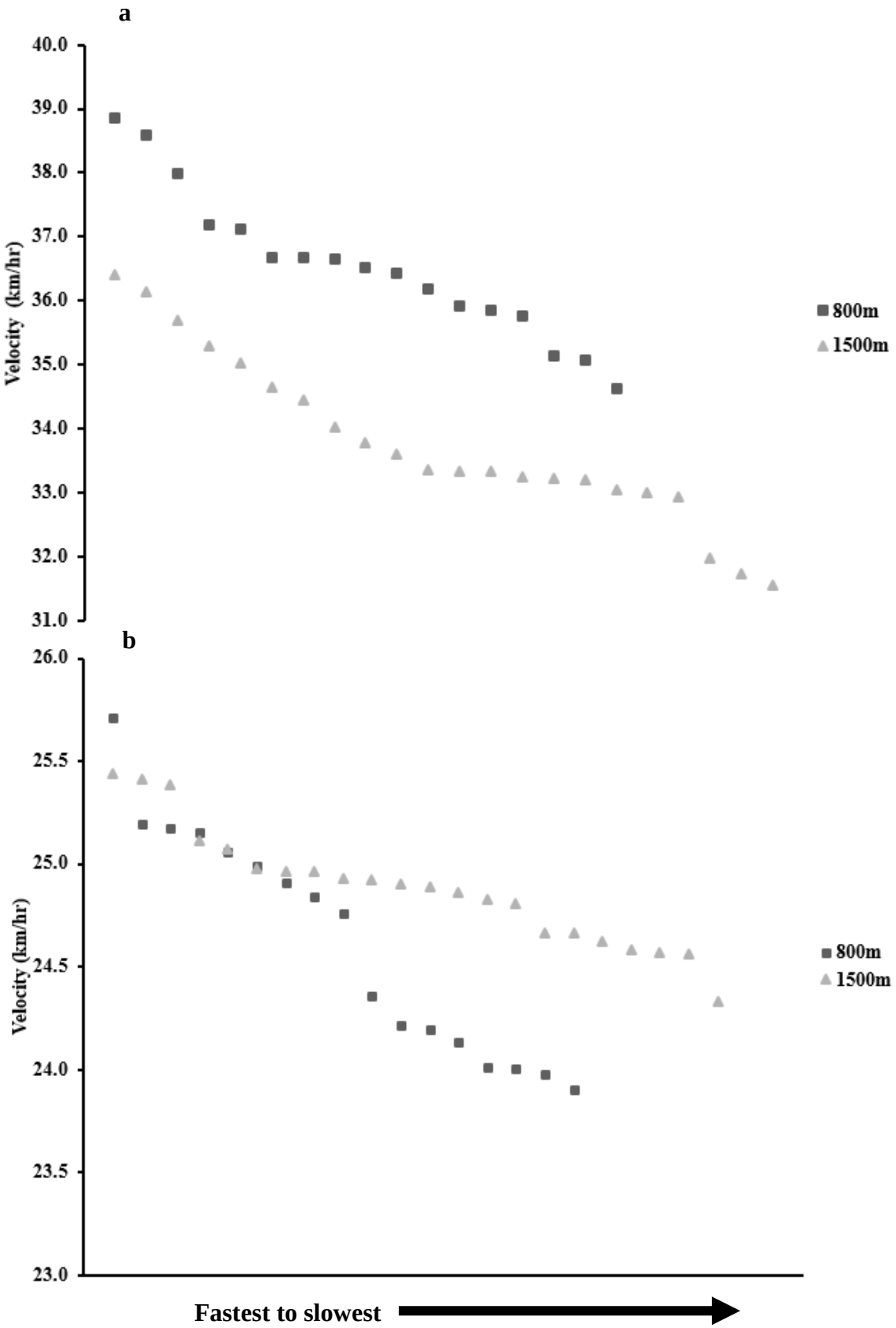

Figure 5.2 a) Individual plot of estimated maximal sprint speed for world-class 800m (n=17) and 1500m (n=22) athletes. **b)** Individual plot of estimated velocity at $\dot{V}O_2max$ for world-class male 800m (n=17) and 1500m (n=22) runners. Note that athletes in the direct vertical plane are not the same individual.

5.4 Discussion

In the present study, we estimated the ASR of world-class male 800m and 1500m runners using Bundle et al 2003) formula to highlight the importance of ASR for middle-distance running event specialists. The analysis highlights the potential of ASR to differentiate middle-distance running event specialists. On average, world-class 800m male runners displayed a *most likely* larger MSS over their 1500m runner counterparts, despite similar v$\dot{V}O_2$max capability. Moreover, the large individual ASR variance displayed in 800m and 1500m runners warrants further investigation.

Last lap speed, or "the kick" (defined as a the decisive and final break from the pace as a sustained pursuit for the finish line) , has been demonstrated to be a key differentiator between medallists and non-medallists in elite 1500m running (Mytton et al., 2015), a phenomenon historically shown as important across 800m to 10,000m distances (Thiel et al., 2012; Tucker et al., 2006). More recently, evidence indicates that not only do elite men's 800m major event medallists possess faster first laps, but additionally faster 100m sections (Sandford et al., 2018; Chapter 3). Results of the present analysis lend support for the premise that a minimum ASR and MSS is required to reach a world-class level in middle-distance running (Figure 5.1). It is acknowledged that several factors within a race (i.e., tactical positioning, pacing, perceived exertion, mechanical efficiency etc.) can influence how an athlete might express their ASR, but this does not forgo the prerequisite level of ASR required to be competitive. The 800m MSS values shown in the present study were as high as 39 km/hr (Figure 5.2), and while larger than expected, are likely explained by the predictive error in the model (Bundle et al., 2003). This study highlights the need to determine these metrics more accurately within a large running population, including elite performers, as seen with established world class benchmarks for $\dot{V}O_2$max and running economy (Daniels, 2005). Such benchmarks would assist with implementing

individualised training approaches and athlete pathways to appropriately develop the complex and diverse middle-distance athlete.

Figure 5.2a highlights the clear uniform differences in MSS between 800m and 1500m groups. In contrast, distinct variation in $v\dot{V}O_2max$ is evident for the 800m group, compared with the more homogenous values in the 1500m group (Figure 5.2b). Whilst more resolution is required, such observations may arise due to the presence of both 'sprint' (smaller $v\dot{V}O_2max$ and larger MSS) and 'endurance' (larger $v\dot{V}O_2max$ and smaller MSS) type 800m runners as observed in elite track cycling (Daniels, 2005; Schumacher & Mueller, 2002).

In the analysis, some 800m athletes were observed to excel only at the 800m distance, with vastly disproportionate 400 or 1500m times. These extreme cases were excluded by our methods, as these outliers skewed the subsequent estimation of physiological parameters. We speculate however that some of these athletes may form a third sub-group, a hybrid of the sprint and endurance-type 800m runners, whose underpinning characteristics remain undetermined. Several reasons can be offered to explain a relatively weak second time (400m or 1500m). First, rarely do athletes run their fastest time of the year at a given distance in their season opener, so the reported PB may not be a true reflection of their physiological capacities. Second, the timing and location where the times were run may also be relevant (e.g. in college vs. Olympics with perfect conditions, crowd size, importance of event, competition, and athlete mind-set i.e., being favourite vs. outsider). Last, the proximity of performance times relative to likely peak form or training phase may also affect the time (e.g. pre-competition versus taper/competition phase). Despite the limitations this places on the present estimates, our results highlight the diversity of athlete profiles presenting in world-class middle-distance running.

Practical Applications

Results from the current report raise important considerations for future investigations in middle-distance running. First, ASR could be used to categorise sub-groups of athletes in future research study designs. Second, the ASR (e.g. 11 km/hr) should always be provided within the context of an athlete's MSS (35 km/hr) and $v\dot{V}O_2max$ (24 km/hr), so that the complete picture of middle-distance running capability is provided; ASR in isolation is not indicative of athlete calibre. Finally, MSS may in the future become part of the routine testing battery for middle-distance runners, as this measure could help coaches, practitioners, athletes and national sporting federations identify potential middle-distance event-group specialisation alongside more commonly adopted aerobic measures.

5.5 Conclusion

The present study indicates world-class male 800m runners possess a larger MSS than world-class 1500m runners, highlighting the potential importance of measuring ASR in middle-distance runners to differentiate and identify sub-groups within and between middle-distance events. Further investigation using direct physiological and mechanical data in a larger middle-distance athlete population is needed to confirm the potential of ASR as a first layer descriptor for middle-distance running capability.

5.6 Chapter Link

Chapter 5 showed the potential role of the ASR construct to a) estimate typical absolute speed ranges in world-class middle-distance runners and b) differentiate between and within athlete subgroup profiles. However, within the estimates developed from Bundle et al. (2003) there is a degree of error. Couple that with the utilisation of personal bests over 400-800 and 1500m to project ASR, the normative absolute values are too variable to be used as normative benchmarks for athletes, coaches and practitioners.

Therefore, it was important to collect ASR directly within an elite middle-distance population. To perform this study (Chapter 6) I travelled to locations around the world to test participants at their local training venue during the late pre-competition/competition phase of the 2017 athletics season. The key aims of chapter 6 were to a) determine MSS and ASR and their relationship to 800m performance in an elite middle-distance cohort and b) using the ASR construct, investigate the athlete profiles within the event and offer possible solutions for coaches and scientists to be able to better categorize 800m athletes.

CHAPTER 6: ANAEROBIC SPEED RESERVE: A KEY COMPONENT OF ELITE MALE 800M RUNNING

6.1 Abstract

Purpose: In recent years (2011-2016), men's 800m championship running performances have required greater speed than previous eras (2000-2009). The "anaerobic speed reserve" (ASR) may be a key differentiator of this performance, but profiles of elite 800m runners and its relationship to performance time have yet to be determined.

Methods: The ASR - determined as the difference between maximal sprint speed (MSS) and predicted maximal aerobic speed (MAS) – of 19 elite 800m and 1500m runners was assessed using 50m sprint and 1500m race performance times. Profiles of three athlete sub-groups were examined using cluster analysis and the speed reserve ratio (SRR), defined as MSS/MAS.

Results: For the same MAS, MSS and ASR showed very large negative (both r=-0.74±0.30, ±90% confidence limits; *very likely)* relationships with 800m performance time. In contrast, for the same MSS, ASR and MAS had small negative relationships (both r=-0.16±0.54), possibly) with 800m performance. ASR, 800m personal best, and SRR best defined the three sub-groups along a continuum of 800m runners, with SRR values as follows: 400-800m ≥1.58, 800m ≤1.57 to ≥1.48, and 800-1500m as ≤1.47 to ≥ 1.36.

Conclusion: MSS had the strongest relationship with 800m performance, whereby for the same MSS, MAS and ASR showed only small relationships to differences in 800m time. Further, our findings support coaching observation of three 800m sub-groups, with the SRR potentially representing a useful and practical tool for identifying an athlete's 800m profile. Future investigations should consider the SRR framework and its application for individualised training approaches in this event.

6.2 Introduction

Preparation for 800m running represents a unique challenge to the middle-distance coach. With close interplay required between aerobic and anaerobic/neuromuscular physiology, athletes with distinctly different profiles have an opportunity for success in the event. Recently, a 'changing of the guard' in the men's championship 800m event was revealed, whereby from 2011 onwards World and Olympic medallists were shown to run predominantly a 'gun-to-tape' type race tactic in the final (Sandford et al., 2018; Chapter 3), requiring 100m sectors that are 0.5m/s faster than in 2000-2009. This raises important questions pertaining to the mechanical speed range required in top athletes relative to their aerobic capabilities.

Previous studies of national and international calibre 800m and 1500m runners reveal opposing findings regarding the physiological requirements of 800m running. For example, Ingham et al. (2008) reported that $\dot{V}O_2max$ and running economy explained 95.9% of running performance in 800m and 1500m runners, however no speed and power measures were collected. In contrast, Bachero-Mena et al. (2017) showed very large relationships between 800m performance and sprints over 20m (r=0.72) and 200m (r=0.84), yet aerobic markers were not reported. Several reasons may explain these contrasting outcomes. First, athletes with diverse physiological profiles may be competing in the same event. For example, Schumacher & Mueller, (2002) showed in Olympic gold medal-winning team pursuit cyclists that the 1st and 2nd position riders presented with markedly different anaerobic and aerobic physiological profiles, yet produced similar individual pursuit performance times (4:18 vs 4:19). Accordingly, it is possible that more aerobic-based 800m runners demonstrate stronger relationships between aerobic-measured variables and performance, while more sprint-based 800m athletes present stronger correlations with anaerobic and neuromuscular qualities, depending on the random phenotype predominance of the sample. Second, it is possible

that a cultural endurance-focused training approach bias has contributed to a production of studies from the more endurance-based 800m running sub-group. Third, while the 800m and 1500m have historically been considered as 'similar events'(Ingham et al., 2008), this belief may require reassessment in light of recent tactical evolution (Sandford et al., 2018). Indeed, heterogeneity of performance standard within 'elite' samples may be misleading when it comes to differentiating elite athlete make-up. For example, conclusions are often drawn on elite performance when samples may contain only one or two truly elite runners (800m performance ≤ 1:46) (Bachero-Mena, Pareja-Blanco, Rodríguez-Rosell, et al., 2017; Ingham et al., 2012).

Middle-distance coaches have long spoken of three sub-groups of middle-distance runners. These include: 1) speed types (400-800m specialists), 2) 800m specialists and 3) endurance types (800-1500m specialists) (Gamboa et al., 1996; Horwill, 1980). Understanding the athlete sub-group has substantial influence on the coach's plan, training program and coaching approach. In contrast, the sport science literature has traditionally treated the 800m cohort as a single athlete type, without assessing individual characteristics that might form a coach's sub-group. While a minimum level of both aerobic and neuromuscular qualities would be required for success in any elite 800m runner, a deficiency in either component is likely balanced by a strength in the other to achieve a two-lap performance (Daniels, 2005). However, without information defining this variability, clarity of training methods for this event group cannot be established to the degree that they have been with runners training for the 1500-10,000m events (Tjelta, 2016).

Sanders et al. (2017) recently showed the usefulness of the anaerobic power reserve construct for predicting sustainable power performance across four professional road cyclists with largely diverse peak power profiles (range=1036-1525 W). Therefore, the anaerobic speed reserve (ASR), defined as the speed range an athlete possesses between

velocity at $\dot{V}O_2max$ ($v\dot{V}O_2max$) in the laboratory (or maximal aerobic speed (MAS) in the field (Bellenger et al., 2015)) and maximal sprint speed (MSS) (Blondel et al., 2001), may likewise prove a useful tool to better understand the apparent diversity of mechanical profiles across the 800m event group. Additionally, ASR may provide the coach and sport scientist a profile for assessing an athlete's mechanical limits supported by their metabolic systems (aerobic and anaerobic) as well as for tracking progress in training (Weyand et al., 2006).

Therefore, the aims of the present study were to a) determine MSS and ASR and their relationship to 800m performance in an elite middle-distance cohort and b) using the ASR construct, investigate the athlete profiles within the event and offer possible solutions for coaches and scientists to be able to better categorize 800m athletes.

6.3 Methods

Study Overview

To perform this study, the primary researcher travelled to locations around the world to test participants at their local training venue during the late pre-competition/competition phase of the 2017 athletics season. At each training location, athletes were tested for their MSS. Within 6 weeks of the MSS assessment, an outdoor 1500m race, used to estimate MAS, was performed in competition.

Participants

A total of 19 elite 800m and 1500m specialists representing 5 different continents (Africa, Europe, North America, Oceania and South America) participated in this study (table 6.1). The study inclusion criteria included an 800m personal best (PB) of ≤1:47.50, and/or a 1500m PB of ≤3:40, as guided by USATF World Championship trial standards (2017). Season's bests (SB) were used throughout the analysis to better reflect an athletes' current

Table 6.1. Description of the participants in the study.

Category of Athlete	Regions Represented	Highest Competition Representation	Other Details	800m PB (mm.ss.ms) (mean±SD)	1500m PB (mm.ss.ms) (mean±SD)
International n=8	Europe, North America, South America, Oceania,	Olympic Games/World Championships n=6 World Indoor Championships n= 1 World Relay Championships n=1	Includes 1 x world record holder, 2 x national record holders	1:45.55±1.18	3:46.69±8.20
European n=3	Europe	European U23 Cross Country European U23 Outdoor Championships European U20 Outdoor Championships	1 x medallist	1:47.07±0.15	3:39.93±3.53
National $n_{=2}$	Oceania	National Championship	5 x national champion 1 x national medallist	1:47.80±1.13	3:42.34±5.04
Collegiate n=6	Africa, Europe, North America	World University Games n=3 NCAA Outdoor Championship n=3	World University Games 2x Medallist Includes African championship finalist	1:47.90±1.84	3:41.40±3.04

shape (e.g. PB could be up to three years prior). Each athlete provided written informed consent to participate in the study, which was approved by the Auckland University of Technology Ethics Committee.

Performance Testing

Maximal Aerobic Speed

For MAS assessment, a 'gun-to-tape' 1500m race performed within 6-weeks of MSS assessment reflective of an athlete's absolute time-trial capacity and current aerobic fitness. In line with the periodisation phase described, data collection aligned well with the period where athletes were targeting qualifying times and 'gun-to-tape' style races led by a pacemaker to 1000-1200m; an aspect that would also have likely enhanced reliability of 1500m times. From these times, MAS was predicted using the 1500m race performance equation of Bellenger et al., (2015):

$$MAS = TT_s\ (0.766 + 0.117\ [TT_d])$$

Here, TT_s was the athlete's average 1500m speed (km/hr) and TT_d was 1.5km.

Maximal Sprint Speed

Upon arrival at the track, participants were informed of the rationale for the 50m MSS assessment and maximal nature of the testing protocol. Athlete performance was measured using a sports radar device (Stalker ATS II System, Radar Sales, Texas, USA Stalker) over a 50m sector on the track straight. The device was placed in the middle of two lanes, 2m behind the start line, on a tripod resting 1.5m from the ground. For live capture of the athlete's acceleration trace, the radar was operated remotely from a laptop to remove the possibility of manual use variability, using a method that has been shown to be highly reliable (CV=1.1%) against gold-standard force plates (Samozino et al., 2015). Instantaneous radar was used to extract MSS (m/s) and split time (s) from each effort, sampling at 46.9 Hz. Custom-built software (Goldmine, HPSNZ, NZ), was used

to remove post-processing error of the acceleration trace from manual inspection of erroneous data points. Previous investigations have shown the reliability limitation of post-processing with 'Lab-view' software (Simperingham, Cronin, Pearson, & Ross, 2017).

Owing to the experienced status of the athletes, and cultural differences in warm-up, a semi-structured framework was used to provide consistency across sites. Here, instructions were to take 10-15 minutes to prepare for a maximal effort, incorporating individual needs to feel ready to go. Athletes were familiarised with the standing start position and instructed to place one foot in front of the other (athlete's preference), with no backward oscillation, though a forward lean into the movement was permitted into the first forward step.

Boundaries for the warm-up included some pulse-raising activity (jogging), some drills (A skips, B skips, etc.), time for any other exercises athletes required and 2-3 progressive strides in flats, before transitioning into race-spikes, where athletes were asked to rehearse the standing start in 1-2 maximal efforts to 30m. Athletes performed the assessment in spikes (n=17), or race flats (n=2).

Once ready to go, an instruction of 'on you' was provided for the athlete to accelerate in their own time maximally through to the end of the cones, along the line at the centre of the two lanes. Athletes performed 2-3 maximal efforts with ~3 minutes rest on rotation at the end of the athlete testing line. The primary variable of interest taken from the radar for analysis was the MSS, representing the ceiling of the athlete's ASR. MSS assessments were conducted where possible in an indoor location, but where not possible (six sites), a wind gauge (Kestrel 5100, Nielsen-Kellerman, USA) was used to measure wind speed. All MSS assessments outdoors were captured with 0.5±0.3m/s tail wind. Environmental

conditions indoors (25.2±3.5°C, 51.4±10.7%RH) and outdoors (26.2±5.0 °C, 42.7±22.8%RH) were similar. One site was at 580m altitude with all others at sea level.

Speed Reserve Ratio

The speed reserve ratio (SRR) was developed from the ASR construct as a potentially practical tool for coaches to display individual athlete profiles in one variable, as used in team sports (Mendez-Villanueva et al., 2010). Whereby:

Speed reserve ratio = Maximal sprint speed (km/hr)/Maximal aerobic speed (km/hr)

Data Analysis

Data are presented as mean ± 90% confidence limits (CL) unless otherwise stated. The relationships between 800m SB performance and MSS, MAS and ASR (n=10) were determined from partial-correlations using SAS 9.4 (SAS Institute, Cary, NC) and described by Magnitude Based Inferences (MBI) (Hopkins et al., 2009). As alluded to in the introduction, the merging of elite and sub-elite athlete data into the same analysis (Bachero-Mena, Pareja-Blanco, Rodríguez-Rosell, et al., 2017; Ingham et al., 2008) may explain disparate outcomes reported previously. Therefore, two 1500m specialists who did not have an 800m SB on record were removed from this part of the analysis. Five athletes with a SB of >1:47.50 for 800m were also removed, with times outside cut-offs for elite status.

A k-means cluster analysis was performed using SAS 9.4 to investigate the variation in physiological and performance characteristics of world-class 800m runners. Athletes excluded from partial-correlation analysis (due to the 800m focus) were included for sub-group clustering (n=19). Instruction was given to fit the collected variables into three clusters, as per the aforementioned coach observations. MAS, MSS, ASR, SRR, body mass, 800m PB & SB, 1500m PB & SB obtained through testing, questionnaire or

competition data collection were standardised and run through the cluster analysis to understand which best explained any differences between groups.

Variables were excluded based on their ability to explain variation between clusters, with the strongest relationships (highest R^2 value) used for final sub-group determination. Differences between clusters were determined using MBI. The following threshold values used for effect size (ES) statistics were ≥0.2 (small), ≥0.6 (moderate), ≥1.2 (large) and ≥2.0 (very large). The smallest worthwhile change for maximum velocity was determined as the standard deviation (SD) of all 19 athletes' MSS, multiplied by the ES (Hopkins et al., 2009). Moderate thresholds were applied across all variables to acknowledge variability in the MAS equation (Bellenger et al., 2015).

To explore the individual variation specifically in the 800m, the SRR was used. For this analysis, 10 athletes with season's best ≤1:47.50, who also had a MAS marker within the 6-week window were assessed. 800m SB times of these participants ranged from 1:44.50–1:47.36.

6.4 Results

ASR and 800m Performance Relationships

Participant details are described in Table 1. MSS and ASR showed very large negative (both r=-0.74±0.30; *very likely)* relationships with 800m performance time for the same MAS. In contrast, ASR and MAS had small negative relationships (both r=-0.16±0.54), possibly) with 800m when MSS was constant (figure 6.1 a, b, c).

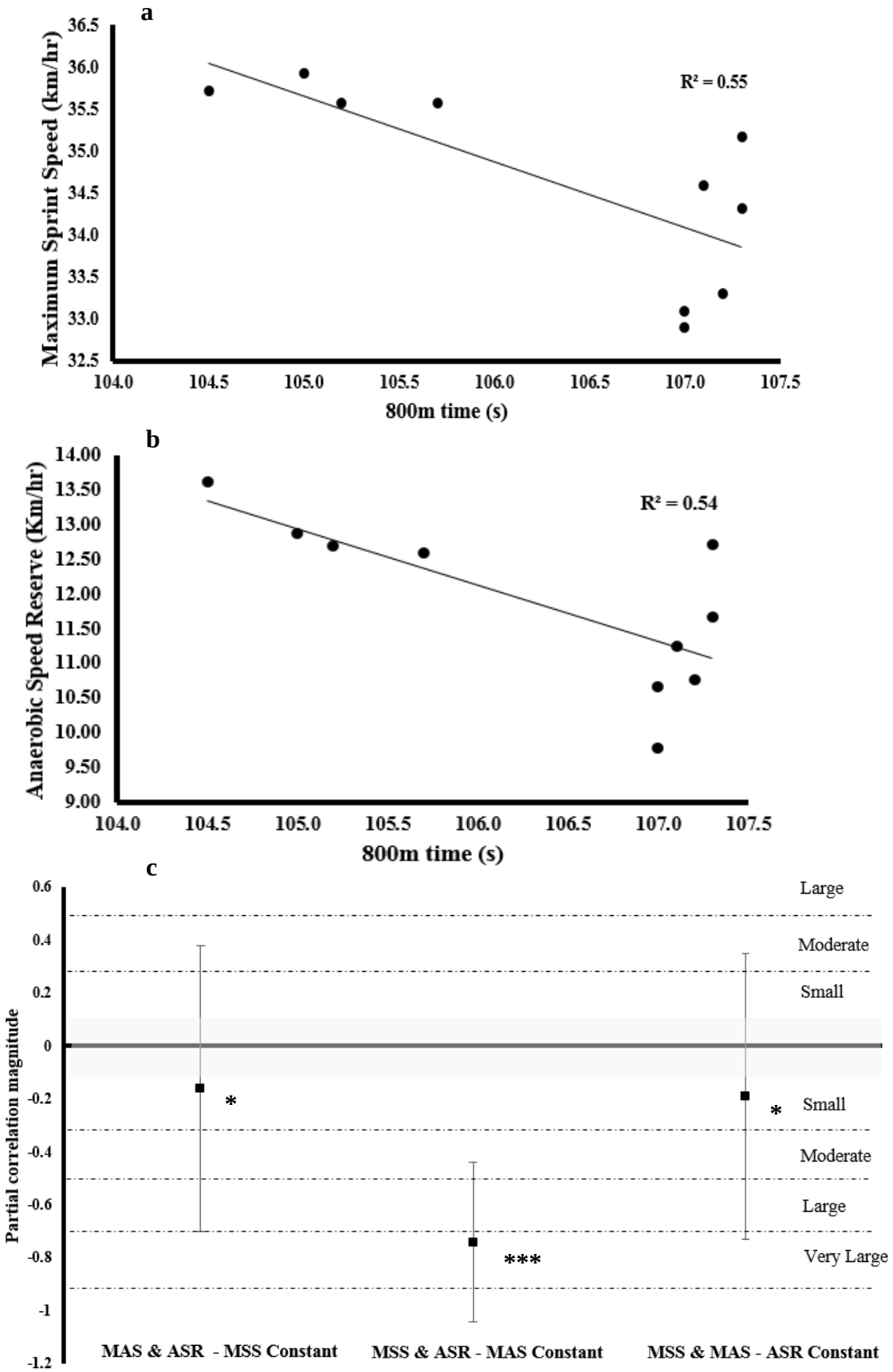

Figure 6.1. Relationships between **a)** Maximal sprint speed and **b)** Anaerobic speed reserve with 800m season's best race performance in ten elite male 800-m runners **c)** Partial correlation magnitudes with 90% confidence limits, grey area represents trivial relationship. Change *possibly **likely ***very likely

800m Sub-Group Variation

ASR, SRR and 800m PB accounted for the greatest variation between the three clusters of 800m athletes (R^2=0.87; *very large*). Sub-group performance characteristics are shown in Table 6.2 and 800m SRR variation in figure 6.2.

Table 6.2. Mean±SD (mm:ss.00) performance and profile characteristics of the 800m sub-groups (n=19)

	400-800m Athlete (n=10)	800m Specialist (n=6)	800-1500m Athlete (n=3)
800m PB	1:46.21±1.16	1:46.37±1.43	1:49.53±1.28
1500m PB	3:44.05±4.33	3:42.13±3.87	3:38.89±0.87
Body mass (kg)	72.2±8.3	65.8±8.3*	66.4±6.9*#
MSS (km/hr)	35.48±0.30###	33.68±0.63***	31.49±0.99***##
MAS (km/hr)	22.41±0.62	22.76±0.50**	23.21±0.06***#
ASR (km/hr)	14.46±1.00###	12.12±0.61***	10.13±0.76****##
SRR	≥1.58	≤1.57-≥1.48	≤1.47 ≥1.36

*possibly different to 400-800m athlete, **likely different to 400-800m athlete, ***very likely different to 400-800m athlete, ****most likely different to 400-800m, #possibly different to 800m specialist, ##likely different to 800m specialist, ###very likely different to 800m specialist.

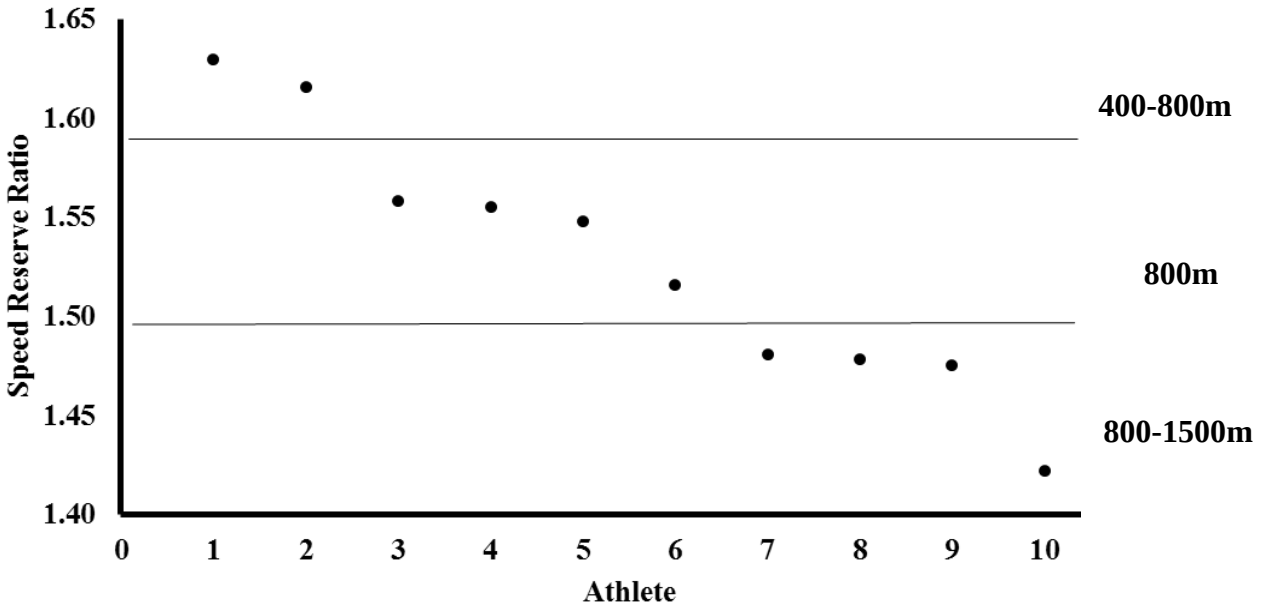

Figure 6.2. Speed reserve ratio [maximal sprint speed (km/hr)/maximal aerobic speed (km/hr)] of ten elite male 800m runners. Lines depict 800m sub-groups from cluster analysis.

MSS of 400-800m athletes was faster than the 800m specialists (1.8±0.6 km/hr, moderate, *very likely*), and 800-1500m athletes (4.0±0.4 km/hr, very large, *very likely*). 800m specialists had faster MSS than 800-1500m athletes (2.2±1.5 km/hr, large, *likely*). MAS in 400-800m athletes was slower than both 800m specialists (-0.5±0.5 km/hr, moderate, *likely*) and 800-1500m athletes (-0.8±0.4, large, *very likely*). MAS of 800m specialists was slower than 800-1500m athletes (-0.3±0.3, moderate, *possibly*). ASR of 400-800 athletes was larger than 800m specialists (2.3±0.7 km/hr, large, *very likely*) and 800-1500m athletes (4.3±1.2 km/hr, very large, *most likely*). ASR of 800 specialists was larger than 800-1500m athletes (2.0±1.2 km/hr, moderate, *likely*).

SRR had a large relationship with 800m performance (r=0.53±0.43, *likely*) whereby faster 800m athletes had a higher ratio. In addition, body mass showed a large relationship with SRR (r=0.62±0.34, *very likely*). 400-800m athletes were heavier than 800m specialists (6.4±7.8 kg, moderate, *possibly*) and 800-1500m athletes (5.8±11.2 kg, moderate, *possibly*), with trivial differences between 800m specialists and 800-1500m athletes (-0.6±11.1 kg, *possibly*).

6.5 Discussion

In the present study, we examined for the first time, the role of the ASR in elite male 800m running performance, in an era where faster top speed appears to be a critical performance requirement (Sandford et al., 2018; Chapter 3). Our findings confirm this observation, with a greater MSS (and therefore ASR) strongly correlated with a faster 800m. Importantly, for the same MSS, having a greater MAS or ASR wasn't strongly related to changes in 800m time. These results support the notion that at an elite level, faster 800m runners have a larger ASR, which is related to a higher MSS (Figure 6.1a, c), along with an already established minimum level of estimated MAS. Additionally, in agreement with longstanding coaching observations (Gamboa et al., 1996; Horwill,

1980), we reveal the profiles of three 800m athlete sub-groups, described along a continuum herein as 400-800m (speed types), 800m (specialists) and 800-1500m (endurance types; Table 6.2). Finally, we present the SRR construct (Figure 6.2) as a practical and easily implemented tool to support a coach's identification of the 800m athlete sub-group, which may aid training approaches and event specialisation.

The unique nature of the global elite study sample (Table 6.1) represents a critical addition to the middle-distance literature, with high relevance to coaches, athletes, scientists, and sports federations. Importantly, we confirm the role of ASR (through function of larger MSS) as a key performance indicator of elite male 800m running. Indeed, for the same MSS, having a greater MAS or ASR wasn't strongly related to changes in 800m time. The paradigm offered by our analysis should consider that once a certain aerobic standard is reached, MSS becomes a differentiating factor in elite 800m runners. In agreement with Bachero-Mena et al. (2017), we found a very large relationship between MSS and 800m running performance (Figure 6.1a). The small relationship with MAS contrasts the study by Ingham et al. (2008), who studied athletes with slower performance times (1:48.9 ± 2.4), where perhaps the aerobic component may be a more important differentiator of slower (≥1:47.50) performance times. As we have shown, in an elite 800m running cohort, the strong relationships between 800m performance times and MSS (Figure 6.1a) and ASR (Figure 6.1b) demonstrate the importance of possessing advanced speed characteristics alongside an already well-developed aerobic capability.

It appears that to be competitive in the modern-day elite 800m era, an MSS of ~10m/s is required to cope with the high speed demands in the first 200m of the race (Sandford et al., 2018; Chapter 3) (Table 6.2). Notwithstanding the complex phenomenon of any middle-distance performance (Glazier, 2015) amid tactics, trips, mis-timed training, injury, illness and other uncertainties that occur (Jones & Whipp, 2002; Raysmith & Drew, 2016), our data suggest that, at the elite level, a baseline level of MSS/MAS

characteristics are required to handle surging in slow, fast or moderate paced 800m events. Critically, considering the energetic demands of the men's 800m (66% aerobic) (Spencer & Gastin, 2001), neither aerobic or anaerobic/neuromuscular components of training can be neglected.

Historically, the most common coaching approaches for differentiating 800m athletes into sub-groups involves using 400m and 1500m personal best times to segregate an athlete into 400-800m or 800-1500m sub-groups (Gamboa et al., 1996; Horwill, 1980). The present investigation offers the SRR as an additional tool for classifying athletes into sub-groups (Table 6.2, Figure 6.2). MAS differences between 400-800m and 800m specialists, and 800m and 800-1500m sub-groups were moderate; while they were large between 400-800m and 800-1500m athletes. However, the differences in MSS were much greater between sub-groups (Table 6.2). Therefore, SRR may be the most effective metric for easily identifying an athlete's sub-group, as evidenced by the cluster analysis, which revealed that ASR, SRR and 800m PB accounted for the greatest amount of sub-group variation. Further studies investigating middle distance running should consider stating the distribution of athlete sub-groups in the methodology sections, and perform data analysis per sub-group to provide readership with outcomes of interventions (e.g. training or nutritional) on specific sub-groups with similar profiles (table 6.2).

Many questions remain across 800m sub-group characterisation, in terms of how mechanical and metabolic components may explain these results. The critical speed (CS) describes the divide between steady state and non-steady state exercise, with the finite work capacity above CS termed D prime (D') (Vanhatalo et al., 2011). D' is our current best estimate of an athlete's so-called anaerobic capacity, a measurement that has challenged physiologists for years (Davison, van Someren, et al., 2009). Previously, it was shown that Finnish national 800m and 1500m distance runners and USA 400m athletes (PB range: 44-52.5s) had superior anaerobic work capacity (as defined from the

maximal anaerobic running test) compared with long-distance runners and control (sprinters and jumpers) groups (Nummela et al., 1996). The 400m athletes had superior anaerobic work capacity and the highest MSS in comparison to the national Finnish 800m and 1500m athletes; however individual event comparisons were not provided. A fast MSS, determines the proportion of ASR an athlete can work at, and may relate to high-intensity training tolerance (Buchheit, Hader, et al., 2012).

Body mass showed a large positive relationship with SRR (r=0.62) which may be explained by the underlying ground force characteristics, with MSS ultimately limited by the impulse an athlete can produce (Weyand & Davis, 2005). Van der Zwaard et al.,(2017) showed that fast-twitch muscle fibre composition and vastus lateralis muscle volume explained 65% of the normalised peak power output in cycling. Therefore, greater muscle mass differences (inferred from body mass measurement) between sub-groups may explain part of their different MSS capability (Table 6.2). Further, muscle composition differences between the sub-groups have implications for VO_2 kinetics, with slower oxygen flux through type lla and llx fibres (Crow & Kushmerick, 1982), as well as smaller capillary density and electron transport chain enzymes versus type l fibres (Jackman, Willis, Willis, & Character, 1996). Differences in metabolic efficiency (lower efficiency in type ll fibres) may have implications for metabolic perturbation during exercise intensities above CS (Pringle, Doust, Carter, Tolfrey, Campbell, et al., 2003), such as in 800m racing, therefore reiterating the need to characterise D' (alongside MSS) in 800m sub-groups. We postulate that perhaps 800m specialist athletes are event experts, in part due to a predominance of lla fibre types, which provide the unique blend of higher force generation characteristics than type l fibres, and greater metabolic efficiency than type llx, though this warrants confirmation using non-invasive muscle fibre type estimation alongside SRR (Baguet et al., 2011).

Limitations

Our current methods used a 1500m race for MAS prediction, potentially creating bias towards a better MAS prediction in 800m rather than 1500m specialists. With the current methods and logistics of the study collection, a race (that was already in most athlete's calendars), was deemed as the most practical method for capturing the MAS estimate in this elite sample during competition. However, specialisation in competition today means that some 800m athletes rarely, if ever, perform 1500m races. The present sample also represents a distribution that unintentionally reflects clustering around the qualifying mark for nationals (1:47.50), similar to the Bannister 4 minute-mile phenomenon (Denison, 2006), in addition to the difficulty of capturing world-class participants for a research study. As such, this should be kept in mind with study interpretation.

The unique nature of this investigation into the speed characteristics of elite athletes in their various locations meant that laboratory assessment of $v\dot{V}O_2max$ was not practically possible, so a sound prediction method was a necessity. In this regard, it is also important to highlight that the variability of elite middle-distance racing is only ~1% (Hopkins, 2005), far less than typical metabolic cart measurements (CV VO_2, ~4.7% (Crouter, Antczak, Hudak, DellaValle, & Haas, 2006). Additionally, athletes may not always produce 'true maximum' results in laboratory settings (Galbraith et al., 2014). While unique, we believe our methodology provides a robust level of ecological validity and practicality for athletes and coaches (Galbraith et al., 2014). Further, the scientific literature has a comprehensive understanding of the aerobic determinants of world-class middle-distance running, but data is scarce with respect to the MSS characteristics of world-class 800m runners.

Practical Application

An athlete's ASR and SRR, showed greatest variation between the three sub-groups of elite male 800m runners, and these variables therefore represent practical markers that coaches can easily measure to categorise their athletes' sub-group profiles. Importantly, many training studies show large individual variation in response to a given intervention, with the 'responder and non-responder concept' often attributed to the outcome (Mann, Lamberts, & Lambert, 2014). Another explanation may be that for some athlete profiles, the stimulus provided could be inappropriate. For example, it is unlikely an anaerobic/neuromuscular-based athlete would respond to high densities of continuous aerobic work. The SRR framework (Table 6.2, Figure 6.2) could advance the profiling of athletes into sub-groups based on their ASR characteristics, which may allow precise selection of more favourable training content. Such an approach has been successfully used in team sports (Buchheit, 2010), and thus provides a fruitful opportunity for further understanding the individual training response required for different 800m sub-groups.

6.6 Conclusion

A larger ASR through the function of a faster MSS, had the strongest relationship with elite 800m performance. When MSS was held constant, MAS and ASR had only small relationships to differences in 800m time. Additionally, the SRR, defined as the MSS/MAS, may represent a useful tool to identify an athlete's 800m sub-group. Future investigations should consider the SRR framework and its application for individualised training approaches in this event.

6.7 Chapter Link

Historically, coach education for middle-distance running has often emphasized aerobic metabolic conditioning, while it relatively lacks consideration for an important neuromuscular and mechanical component (Thompson, 2016). Consequently, coaching nomenclature and application of speed varies considerably between squads (Gamboa et al., 1996). Chapter 6 found a very large relationship between ASR and elite 800m performance, as a function of a faster MSS. When MSS was held constant, MAS and ASR had only small relationships to differences in 800m time. Therefore, with the role of MSS highlighted in elite 800m runners, it was important in chapter 7 to specifically define MSS in contextualising applications of ASR to elite 800m runners.

MSS accounted for 55% of the variance in elite 800m performance. It is likely that a large proportion of the remaining variance lies in the efficiency of the athlete to run at 800m race pace and surge within the ASR domain. However accurate quantification in the domain beyond critical speed has evaded current scientific measurement, and in agreement with field observations, modifications in running economy measured during submaximal exercise may not translate to improved running performance over middle-distance race speeds (Denadai & Greco, 2017). Therefore, in chapter 7 we describe the ASR as it relates to the 800m athlete, the transfer of MSS to race pace performance, and the factors that may underpin this transfer. Finally, we consider the topic of race pace efficiency for 800m runners, and how this may be more motor skill than running economy driven.

CHAPTER 7: MAXIMAL SPRINT SPEED AND THE ANAEROBIC SPEED RESERVE DOMAIN

Chapter 7

7.1 Abstract

Recent evidence indicates that the modern-day men's 800m runner requires a speed capability beyond that of previous eras. In addition, the realisation of different athlete subgroups (400-800, 800, 800-1500m) implies a complex interplay between the mechanical (aerial or terrestrial) and physiological characteristics that enable success in any individual runner. Historically, coach education for middle-distance running often emphasizes aerobic metabolic conditioning, while it relatively lacks consideration for an important neuromuscular and mechanical component. Consequently, many 800m runners today may lack the mechanical competence needed to achieve the relaxed race pace speed required for success, resulting in limited ability to cope with surges, run faster first laps or close fast. Mechanical competence may refer to the skilled co-ordination of neuromuscular/mechanical (stride length/frequency/impulse) and metabolic components needed to sustain middle-distance race pace and adjust to surges efficiently. The anaerobic speed reserve construct (difference between an athlete's velocity at $\dot{V}O_2max$ ($v\dot{V}O_2max$ – the first speed at which $\dot{V}O_2max$ is attained) and their maximal sprinting speed, MSS) offers a framework for assessing a runner's speed range relative to modern-day race demands. While the smooth and relaxed technique observed in middle-distance runners is often considered causal to running economy measured during submaximal running, little empirical evidence supports such an assumption. Thus, a multidisciplinary approach is needed to examine the underpinning factors enabling elite 800m running race pace efficiency. In this current opinion, we argue for the importance of utilising the ASR and MSS measurement to ensure middle-distance runners have the skills to compete in the race-defining surges of modern-day 800m running.

7.2 Introduction

Winning a middle-distance race requires a unique blend of tactical decision-making and physical execution in the moment (Hettinga, Konings, & Pepping, 2017; Konings & Hettinga, 2017). Whilst characterisation of middle-distance events usually starts with global 'energetic demands' (Duffield et al., 2005b; Spencer & Gastin, 2001), there are moments within races that define medal outcomes, such as surges in the first lap of the 800m or the last lap kick in the 1500m (Mytton et al., 2015; Sandford et al., 2018; Chapter 3). To date, race-defining moments and their underpinning qualities have received little attention in the literature. Both 'sit and kick and 'gun to tape tactical approaches can occur (e.g through championship rounds), meaning successful athletes require a robust armoury of abilities to negotiate both 'sit and kick' and 'gun to tape' scenarios, alongside the multitude of other possible surging scenarios (Jones & Whipp, 2002). Herein, a surge is defined as any time point after 100m into the race where an athlete repositions by ≥3 places or noticeably raises the pace from the front, and the kick is defined as a decisive and final break from the pace in a sustained pursuit for the finish line.

In the men's 800m, extreme surge demands (as fast as 11s per 100m) require substantial absolute speed (as fast as 10m/s in elite male 800m runners (Sandford et al., 2018; Chapter 3) alongside concurrent aerobic capability (Sandford et al., 2018; Chapter 6). Recently, the anaerobic speed reserve (ASR; figure 7.1), defined as the speed domain ranging from the velocity at $\dot{V}O_2max$ ($v\dot{V}O_2max$- the first speed at which $\dot{V}O_2max$ is attained) to the maximal sprint speed (MSS the velocity at which an athlete can no longer accelerate when performing an 'all-out' sprint effort, Moir, Brimmer, Snyder, Connaboy, & Lamont, 2017), was used to highlight the physiological and mechanical diversity of elite 800m athletes (Sandford et al., 2018; Chapter 6). As traditional coach education practices continue to prioritise the aerobic conditioning aspect of middle-distance running (Thompson, 2016), these modern-day race demands clearly require significant concurrent

speed capability (Sandford et al., 2018; Chapter 3), bringing forth the need to define the underlying speed qualities that constitute performance in an 800m event (Thompson, 2016).

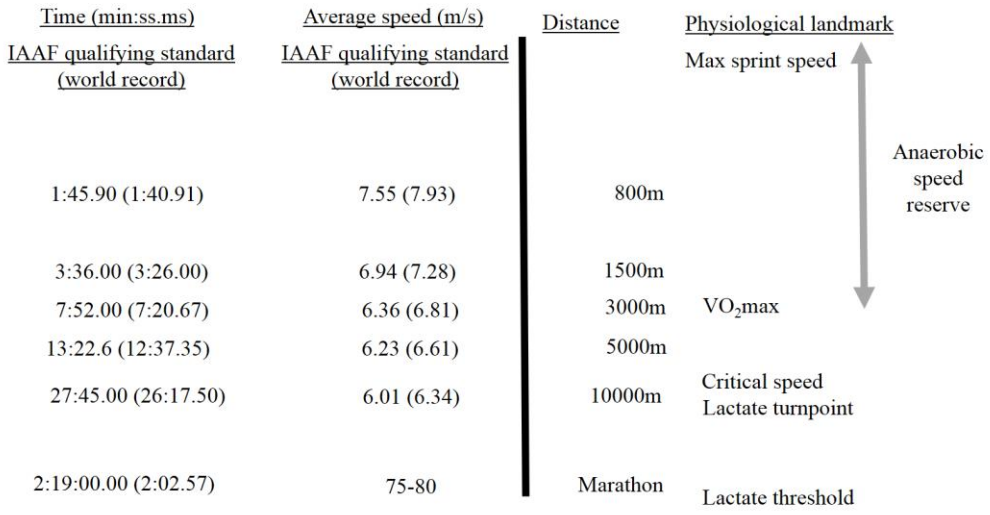

Figure 7.1. Time and average speeds for the IAAF qualifying standards for the London 2017 world championships and world records, as they relate to physiological ($\dot{V}O_2$max, critical speed, lactate turnpoint) and mechanical/neuromuscular (maximal sprint speed), anaerobic speed reserve) markers (assuming even pace running). Modified from Billat [66] and Buchheit and Laursen [12], with permission. IAAF – International Association of Athletics Federations, Max – Maximal, $\dot{V}O_2$max – Maximal Oxygen uptake.

Middle-distance coaching vernacular for a 'speed session' may refer to: 150m efforts, 400m pace, race pace, maximal sprint speed (<80m) or sprint finish (pre-fatigued). Subtle prescription differences across discrete training paces (all of which may be termed 'speed') can lead to large differences in adaptation outcomes (Buchheit & Laursen, 2013b). Therefore, clarification of the role of MSS (the speed ceiling) for 800m running is needed to optimise training preparation for the event (Gamboa et al., 1996). DeWeese & Nimphius, (2008) define speed application as "the skills and abilities required to achieve high velocities". Indeed, how the skill component of speed is trained, taught and emphasised in distance runners is a topic of much debate (Thompson, 2016). Thus, in this Current Opinion article, we describe the ASR as it relates to the 800m athlete, the transfer

of MSS to race pace performance, and the factors that may underpin this transfer. Finally, we consider the topic of race pace efficiency for 800m runners, and how this may be more motor skill- than running 'economy-driven'.

7.3 Anaerobic Speed Reserve – A Framework for Faster Race Pace Running?

The application of the ASR may be considered complex as a result of its two moving parts; one largely limited by metabolism ($v\dot{V}O_2max$) (Bundle & Weyand, 2012), the other more by force orientation/mechanics (MSS) (Rabita et al., 2015; Weyand et al., 2000). The importance of the ASR (via larger MSS) is highlighted by its strong relationship with elite 800m running performance (r=0.74; (Sandford et al., 2018; Chapter 6), with likely implications in the 'last-lap kick' (1500-10,000m) (Enomoto et al., 2008; Mytton et al., 2015). Our recent study (Sandford et al., 2018; Chapter 6) showed that athletes running 1:44/1:45 for men's 800m displayed a larger ASR (as function of larger MSS) over their 1:47 running counterparts (where both groups already have adequate $v\dot{V}O_2max$ (chapter 6), highlighting ASR as an important framework through which to view middle-distance running profiles (considering relative aerobic and neuromuscular/mechanical strengths), that highlight differential characteristics between elite and sub-elite performers.

An 800m runner presenting with a large ASR (with fast MSS) may have the opportunity to run faster race paces relaxed compared to an athlete presenting with a smaller ASR, assuming similar aerobic capability (e.g. figure 7.2). First due to a larger mechanical range across which one can adjust technique to apply more force as race surges demand (Enomoto et al., 2008). Second, if 800m pace sits at a lower proportion of the ASR, the imposed physiological strain of that pace is reduced (Buchheit, Hader, et al., 2012). For example, Bachero-Mena et al. (2017) recently demonstrated in national and international 800m runners (1:43-1:58) that MSS measured using 20m time was strongly related to

800m performance (r= 0.72), with an even stronger relationship shown for 200m speed (r= 0.84). Therefore, MSS may be an important prerequisite for an athlete to achieve faster paces over longer event distances and or closing race sectors.

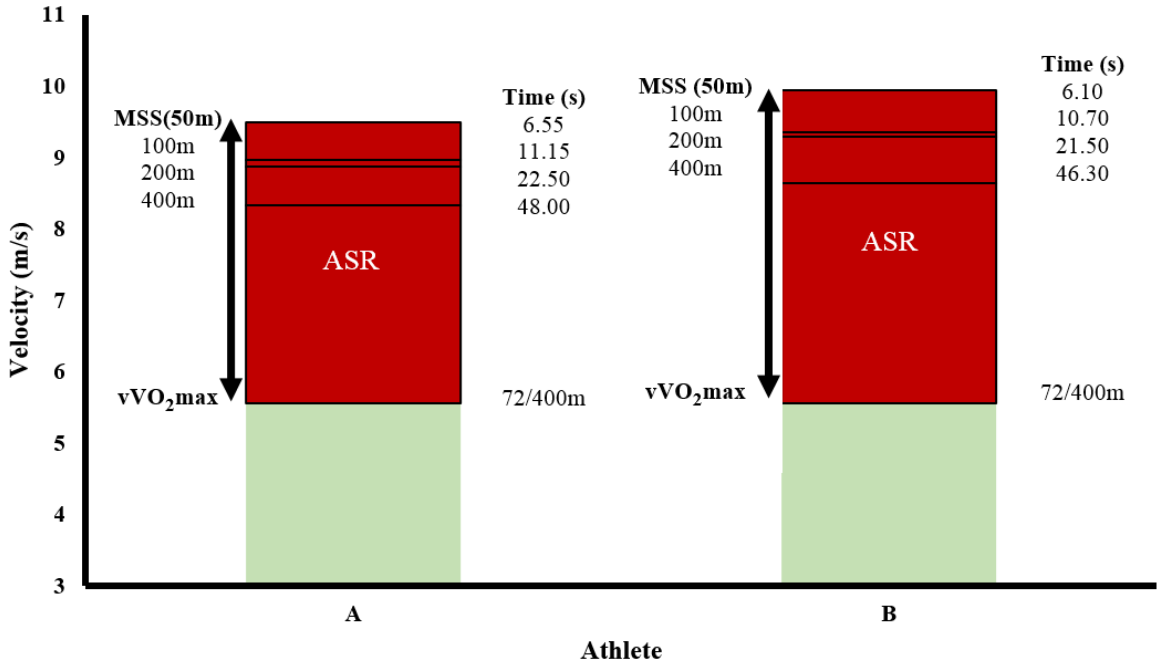

Figure 7.2. Two hypothetical athletes (A+B) presenting with different maximal sprinting speeds (MSS), but possessing the same velocity at maximal oxygen uptake ($v\dot{V}O_2max$). If the race demand of the fastest 100m is 11.0 s, and an athlete's 100m personal best is 11.15 s (athlete A), their anaerobic speed reserve (ASR) limits their ability to meet the event demands. The alternative approach for athlete A may be to perform a relaxed first lap of 50s within their ASR limit. Importantly, however, relying on the latter approach may not be enough for a podium finish in the modern era (Sandford et al., 2018). The successful elite middle-distance athlete needs a high enough ASR, or 'golden ticket' fresh, to be competitive at race velocities under high metabolic perturbation in the closing stages of a race. Modified from Buchheit & Laursen, (2013b), with permission.

Men's 800m tactical analysis from the 2012 Olympics (Renfree et al., 2014) showed a 50% probability of qualifying by being in 3rd place by 400m. With remarkable individual 100m sector speeds attained by world class 800m males between 100 and 200m (Sandford et al., 2018), athletes must possess an ASR to either meet these demands relaxed (and be in the top 3 by 200m), or have a strategy to be in the race at the 400m mark (Renfree et al., 2014) (Figure 7.3) by running a more even first lap of ~50s (i.e. 25s + 25s, rather than 23s+27s). A slow MSS when fresh may prove costly in enabling a 50s first lap, and subsequent tolerance of the second lap, if target race pace is at too high a proportion of

their MSS (Buchheit, Hader, et al., 2012). Therefore, a key strength of the ASR determination for middle-distance athletes may be knowledge of the athlete's mechanical speed bandwidth to begin the process of optimising race pace selection (Buchheit & Mendez-Villanueva, 2014). Indeed, during all-out exercise, such as a gun-to-tape 800m race, reliance on anaerobic metabolism will compromise force production (Bundle et al., 2006), meaning compensatory strategies must be drawn upon by the athlete (Bundle et al., 2006; Sundberg & Bundle, 2015). The necessary recruitment of the larger motor units needed to sustain pace above critical speed (CS) (Burnley et al., 2012) (e.g. 800m race pace), presents a clear rationale for the need to maximise ASR (i.e., both $v\dot{V}O_2max$ and MSS) (Bundle et al., 2006). Importantly a large ASR does not mean athletes are instantly fast or efficient at all paces within the ASR domain (figure 7.4) but offers a potential explanation as to why some fast 400m athletes struggle to transition to the 800m (i.e. a new motor skill patterning is needed for efficiency at 800m race pace, see sections 7.4, 7.5,7.6).

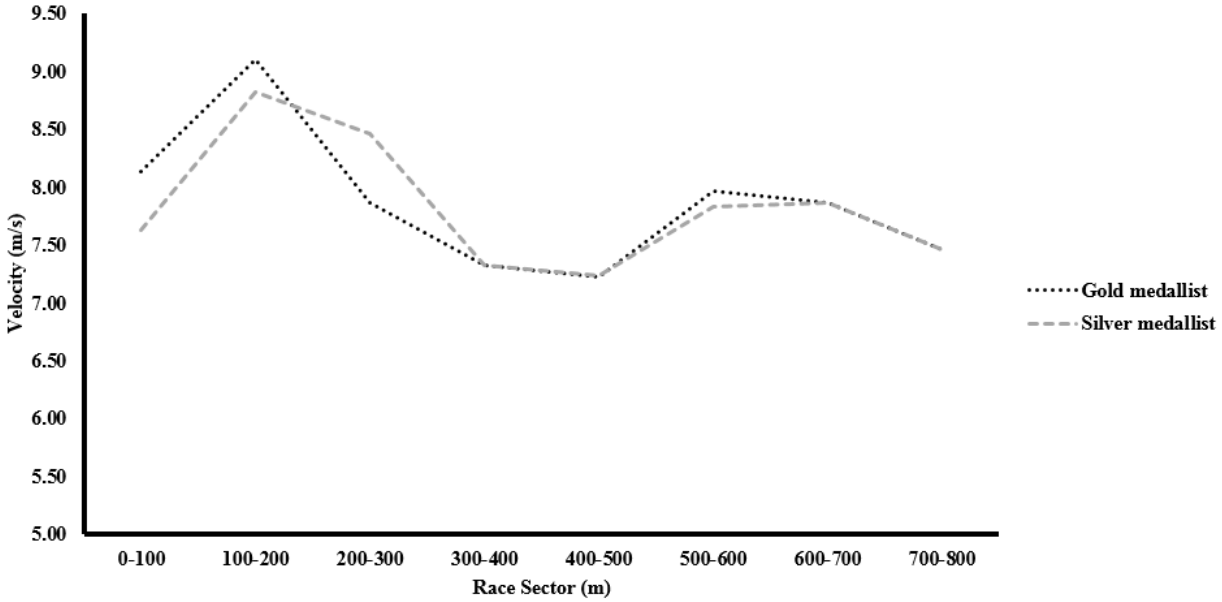

Figure 7.3. Race profile of Rio de Janeiro 2016 men's 800m final Olympic gold and silver medallists, illustrating the mechanical bandwidth of surges occurring during an 800m middle-distance race (winning time 1:42.15). At the 200m mark, the eventual silver medallist (800-1500m subgroup) was 1.28s behind the race leader (800 specialist), shortening the deficit at 400m to 0.37s behind. Many speed transitions are shown within the race, requiring smooth mechanical co-ordination to avoid potentially disastrous increases in energetic cost. This figure represents the need for mechanical running literacy across the race pace bandwidths to maintain smooth technique at or above an even race pace strategy (MacPherson, Collins, & Obhi, 2009).

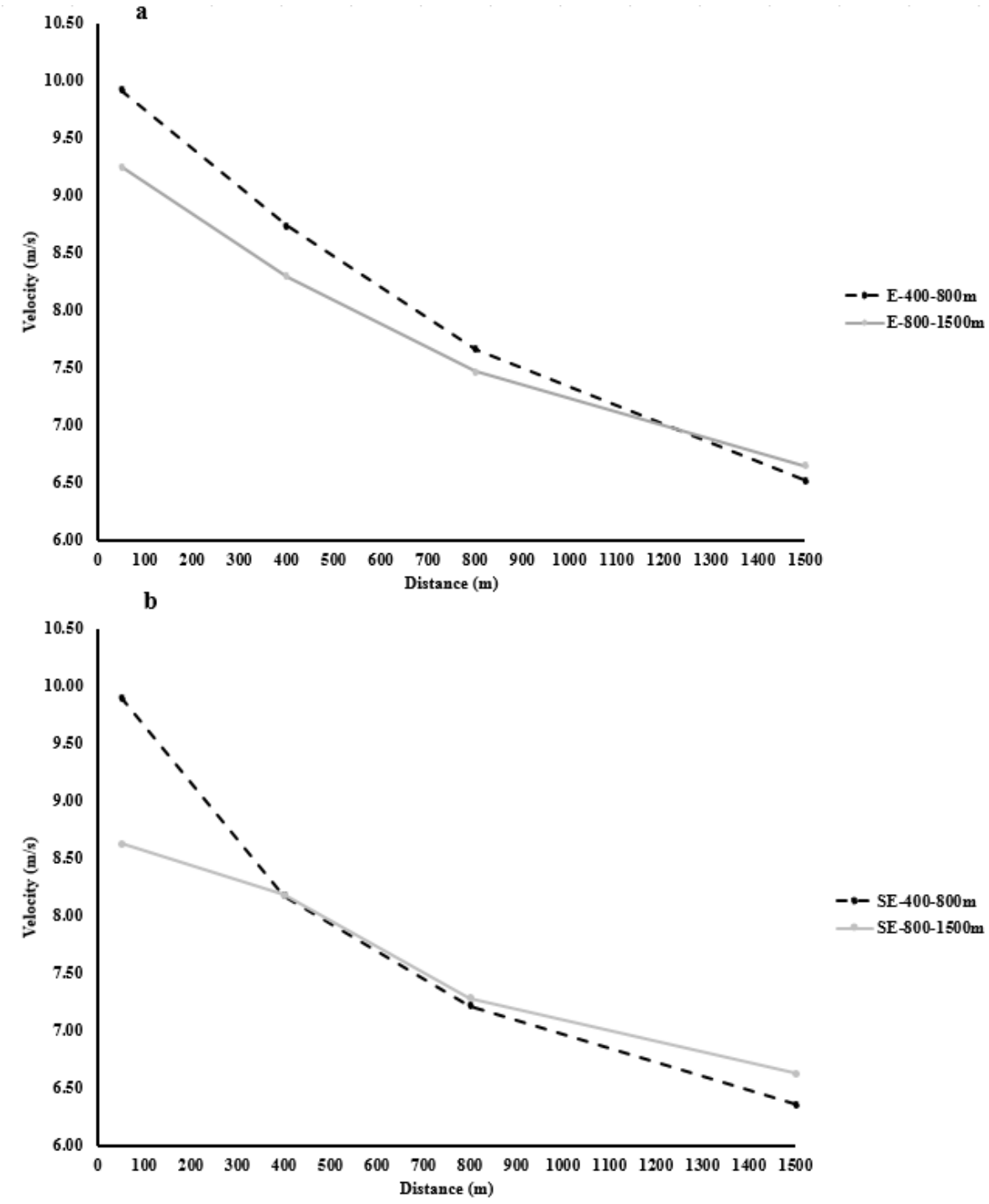

Figure 7.4. A hypothetical speed profile of four 800m athlete's categorised per competitive standard **a)** elite: 800m season's best time <1:47.50, ≥1:44 and **b)** sub elite: 800m season's best time <1:51, ≥1:47.50). Dashed black lines represent 400-800m sub-group, grey lines represent 800-1500m sub-group. Improvement in maximum velocity (50m) or average velocity at a given race distance would be described by an upward shift of that marker on the speed profile to be used to identify mechanical/training/planning gaps in the athletes profile, as illustrated by Quod et al. (Quod, Martin, Martin, & Laursen, 2010). Data collected from methods described in Chapter 6 (Sandford et al., 2018). E- Elite, SE – Sub-elite

MSS Transfer to Race Pace

Improving understanding of MSS characteristics in 800m sub-groups provides a framework to further understand an athlete's 'split potential' in optimising their 800m race strategy. 800m race plans (splits) are usually cordoned into sectors, most commonly over 200m or 400m (Prendergast, 2002). An athlete's ability to run a first lap target time is often judged by their ability to run a specified 200m or 400m split in training or racing (unpublished observation, Gareth Sandford). Without considering the athlete's MSS capability, these splits are used to establish the upper capacity for speed over any given race sector. The problem with this approach is that the transfer of MSS into 400m season's best (SB) time is highly variable (figure 7.5). By comparison, in national USA and Finnish 400m specialists, Nummela et al. (1996) revealed a very large (r=0.88) relationship between 400m time and maximum velocity (assessed over 30m), whereas figure 5 reveals MSS assessment only explained 35% of the variance in 400m SB performance in elite and sub-elite 800m runners. A commonly observed limitation in middle-distance runners during race surges may be their biomechanics (unpublished observation, Gareth Sandford). This element is often less accounted for in planning, and may explain part of the poor transfer of MSS to 400m SB (Gamboa et al., 1996; Thompson, 2016).

Further, the relatively high variation in 400m SB time, despite similar MSS profiles (figure 7.5), highlights the limitation of using 400m time alone as a representation of an athlete's 'speed capability' and could lead to inappropriate categorization of an athlete into their event group specialisation. The alternative approach, through accurately determining MSS, may allow a more detailed analysis of the factors that may be limiting the transfer of MSS across the athlete's ASR bandwidth, and highlight opportunities for performance improvement.

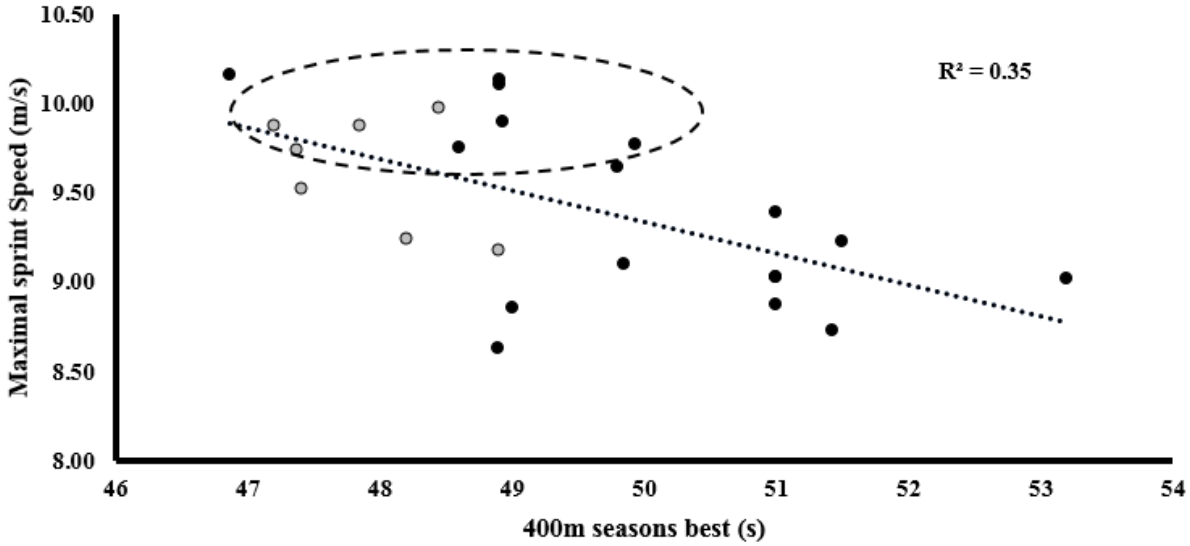

Figure 7.5. Relationship between 400m seasons best (SB) and the maximal sprinting speed (MSS) (r=0.60, large), as assessed by radar gun over a 50m maximal sprint from a standing start during the 2017 outdoor competition season (northern and southern hemisphere) in 7 elite (grey dots) and 17 sub elite (black dots) 800m runners (Sandford et al., 2018). 400m SB was taken from the competitive race season. The dashed oval sector highlights athletes with a similar MSS ≥9.75 m/s but with a large 400m SB range (47.20 – 49.94s).

7.4 What Factors Limit the MSS Transfer to 800m Race Pace?

Performance in maximal efforts <60s tend to be limited more by mechanical and neuromuscular aspects, than metabolic components (Bundle & Weyand, 2012; Sandford, Kilding, et al., 2018; Weyand et al., 2010), meaning these qualities represent important underlying characteristics for the surges that define race outcomes. Mechanical efficiency is defined as the ratio of work done (in this case running velocity) to energy used (Aura & Komi, 1986). Neuromuscular aspects refer to the nervous system and co-ordination of muscle contraction needed to perform the running task (Folland & Williams, 2007). Importantly, having co-ordination across a mechanical bandwidth of speeds in and around race pace, and the ability to smoothly self-adjust, will enable efficiency for race surges under fatigue (Kiely, 2016; Nummela, Keränen, et al., 2007). The following section (7.5, 7.6) discusses the neuromuscular, biomechanical and motor qualities that underpin race pace speed.

7.5 Running Economy or Motor Skill Driven?

Commentators often refer to middle-distance runners' technique as smooth and relaxed (Bushnell & Hunter, 2007; MacPherson et al., 2009).By Physiologists, however, this observation is incorrectly linked to running economy (RE). RE is defined as the energy demand for a given velocity of submaximal running, as is determined by measuring the steady-state consumption of oxygen (VO_2) and respiratory exchange ratio at submaximal speeds ≤ 85% $\dot{V}O_2$max (for reviews see Barnes & Kilding, (2015) and Saunders et al. (2004). Of course, an 800m event occurs above CS (e.g even 1:45 800 race pace =27.4 km/hr), beyond steady state submaximal running speeds (Figure 7.2), where the anaerobic contribution to exercise is substantial, thereby preventing accurate calculation of RE (Skinner & McLellan, 1980; Vanhatalo et al., 2011). Interestingly, Daniels & Daniels, (1992) demonstrated that elite 800m and 1500m runners were more economical at speeds greater than 19km/h, but less economical at slower speeds compared with marathon runners. However, in the absence of accurate measures of anaerobic metabolism (Davison, Someren, et al., 2009), it is difficult to conclude that middle-distance runners are more economical at faster velocities compared with their longer-distance counterparts (Saunders et al., 2004). Nevertheless, Trowell, Phillips, & Bonacci, (2017) showed no relationship between RE at 16 km/hr and 1500m race performance in national and international level female 1500m runners (performance time 4:23.31 ±9.65 min). For our speed type 400-800m subgroup, they may appear remarkably inefficient at submaximal running paces yet show remarkable race pace efficiency (unpublished observation, Gareth Sandford). While we are not implying that RE is not important, particularly for the 800-1500m subgroups, it equally does not indicate it should be a primary KPI for speed type and 800m runner specialists. Although Ingham et al. (2008) showed a moderate relationship (r=0.49) between RE and men's-800 speed, it is possible that the relationship was derived more from a subgroup of predominantly 800-1500m athletes.

7.6 Mechanical Efficiency

Figure 7.6 shows an overview of the requirements for smooth ‘surge’ transitions between 800m race pace and MSS. Smooth transitions refer to minimising the energetic cost of technical adjustments, primarily from changes in stride length (SL) and frequency (SF) that determine running speed (Moore, 2016). In distance runners these technical skills are less well developed and rarely prioritised as a skill in training (Lees, 2002; Thompson, 2016). Perhaps this may result from insufficient knowledge concerning SL, SF and contact time interaction at race pace (Seidl, Linke, & Lames, 2017). Alternatively, this may be due to the specificity of conditioning. For example, sprinters typically tend to work on force application through specific joints angles, at higher velocities than middle-distance runners to strengthen the weakest part of the kinetic chain (usually the ankle extensors) (Kulmala et al 2016). Interestingly in elite sprinters, Bezodis, Kerwin, Cooper, & Salo, (2017) demonstrated very large fluctuations in SF and SL (therefore MSS) in response to different training phases. The implications this may have for target 800m pace performance are unknown but may be important to consider in annual planning towards target races.

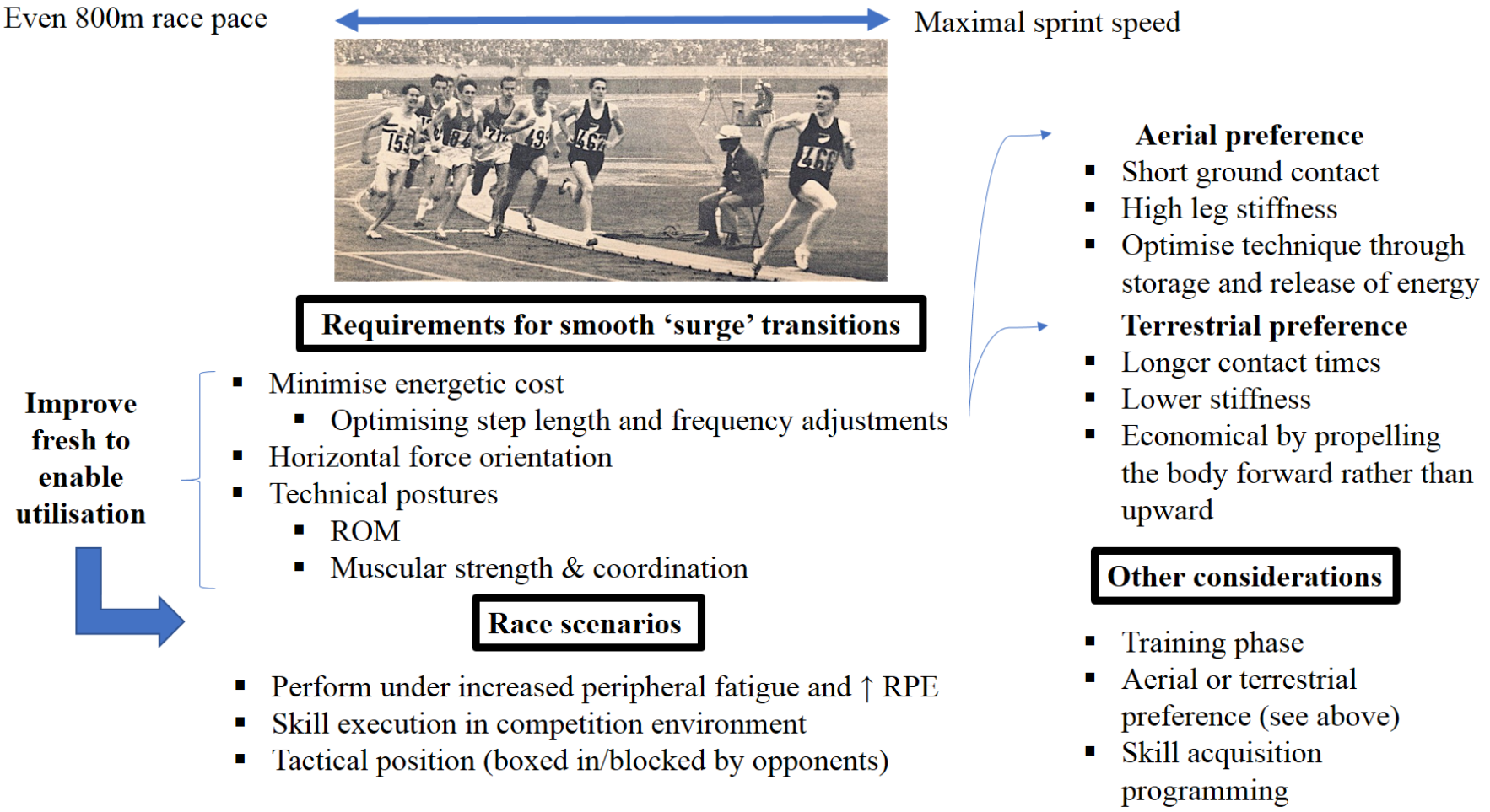

Figure 7.6. Overview of the factors affecting transitions of pace both fresh and within a race scenario, including mechanical preferences (aerial or terrestrial) and other factors that can affect the mechanical/co-ordination variables involved in pace transition. RPE – Rating of perceived exertion. ROM – Range of motion.

Whilst SL and SF ratios are usually self-selected (Högberg, 1952), co-ordination of both SL and SF across ASR bandwidth has some important biomechanical underpinnings that require further resolution. Trowell, Phillips, & Bonacci, (2017b) showed that hip flexion/extension angle range during swing, the thorax flexion/extension angle at toe-off and the plantar/dorsiflexion ankle angle explained 94% of 1500m race time in national and international male middle-distance runners (performance time: 3:49.66 $\pm$ 6.08 min). The authors acknowledged the individual variance in observed technique, meaning determination of individual biomechanical efficiency is paramount. Lussiana & Gindre, (2016) suggest this variance in part may be due to preferential aerial or terrestrial gait cycle preferences. The 100m world record holder, Usain Bolt, may be the perfect illustration of a terrestrial profile where the function of height and limb length create longer ground contact times, producing more impulse-per-step compared to his aerial counterparts, thereby allowing approximately 10% greater impulse-per-step (Beneke & Taylor, 2010). In 800m running context, even at race pace running velocities, terrestrial athletes with longer running contact times may produce the same impulse for a lower metabolic cost compared with their aerial, stiff and/or fast twitch counterpart. These presumptions offer many potential implications for optimising race pace/plan, strength and conditioning, as well as athlete mechanical cueing (internal or external preference (Winkelman, 2016)) that warrant further investigation. Importantly however, despite the different preferences identified, the race demands of a fast opening lap, or closing lap, by nature of the required speed, require a minimum MSS ability to be efficient at shorter ground contact times (Chapman et al., 2012) .

Without world class 800m data to this point, a biomechanical analysis of the men's 10,000m final from the 2007 World Championships may be a good starting point for understanding how a small ASR and inability to increase force orientation restrict performance potential. Here, Mathathi (3rd place athlete) elicits what appears to be 'good

technique to utilise mechanical energy effectively in the race's early laps, but was unable to speed up at the end of the race' (Enomoto et al., 2008). One can speculate, this was an athlete with a good RE, but with a small ASR and limited mechanical efficiency at faster race paces, unable to transition his SL and SF ratio at faster speed at the end of the race (assuming he would have the metabolic capability to sustain this intensity). By contrast, Bekele, the gold medallist in that same race, was described as 'maintaining a large SL during the race and changing his running velocity by increasing his SF, especially in the final sprint' (Enomoto et al., 2008). Ten years later, the International Association of Athletics Federations (IAAF) report (Hanel, 2017) on the 2017 London World Championships 2017 revealed Farah (1^{st}) and Cheptegei (2^{nd}) to displayed the same qualities as Bekele in maintaining a long SL and an increasing SF in the closing stages.

Under fatigue, on the second lap of an 800m, a decrease in running speed will align with decreases in SL and SF (Girard et al., 2017). Therefore, to increase running speed under fatigue, an athlete must increase either SL or SF. Bridgman, (2015), in a cohort of regional, national and international distance runners, recommended an emphasis on extending SL to achieve high velocities, with more favourable energetic cost than increased SF, though this is contingent on being able to produce more force during ground contact (Bridgman, 2015). Chapman et al. (2012), supporting earlier observations (Högberg, 1952), found that elite cohorts placed a greater reliance on increasing SF at higher speeds, suggesting SF capability is an important tool in the armoury of an elite distance runner, and a key quality underpinning the ASR.

Van der Zwaard et al. (2017), in Dutch international pursuit cyclists, showed a long muscle fascicle rather than a large muscle cross-sectional area (CSA) as being beneficial for achieving both high peak power and strong 15km time-trial performances, with an inverse relationship between CSA and $\dot{V}O_2max$. Perhaps to optimise 800m running pace, having both longer fascicles (with high contractile speed) and high percentages of slow-

twitch muscle (for high oxidative capacity) may be optimal for this event. In cycling, power-profiles are used to assess a range of power-outputs that may be experienced within a race , as well as optimising the pedalling frequency-to-gear ratio (Craig & Norton, 2001; Quod et al., 2010). A similar approach might be considered for middle-distance runners to optimise their mechanical efficiency in and around the race pace motor skills (figure 7.4), as small changes in gait lead to large differences in performance velocity (Bridgman, 2015; Chapman et al., 2012).

Acceleration – on the Fly vs From Standing

Pace transitions from a rolling start have been shown to have a much lower energetic cost than from initial standing acceleration in cycling (Martin, Davidson, & Pardyjak, 2007) and running (Di Prampero, 2005; Di Prampero et al., 1993; Di Prampero, Botter, & Osgnach, 2015). The challenge in the 800m is the tactical importance and fast speed of the modern day first 200m (Sandford et al., 2018). This suggests that there is not just a need to hone the efficiency of being relaxed at race pace, but also for being efficient at accelerating for positions at the tactical break after 100m, as well as ensuring tactical options on the first lap.

7.7 Perspective

The purpose of this Current Opinion article was to contextualise the role of the neuromuscular and mechanical elements of ASR in 800m running with recent evidence of speed demands increasing in world class 800m running, clarifying the role of MSS for this event group. No longer should it be considered that distance runners cannot improve their MSS (Bachero-Mena, Pareja-Blanco, & González-Badillo, 2017; Maćkała, Jozwiak, & Stodółka, 2015), which has important implications for potential splits over longer distances. Having a faster MSS can be a performance advantage for an athlete and ensuring that distance runners have the ASR framework required to handle surges in their

event demand is an important coaching pursuit alongside the concurrent development of aerobic physiology.

Advancing knowledge concerning speed transfer into 800m pace running, and its underlying components, is an important future research direction. Submaximal RE assessments are questionable for gaining insight into the capability of an athlete to perform the specific skill of 800m race pace running. Focus instead should be turned towards understanding the technical requirements from a motor control and biomechanical perspective, and how this may differ between aerial and terrestrial preference athletes. Utilisation of a 'speed profile' concept (figure 7.4) akin to the cycling model may assist to understand these individual differences between both mechanical and physiological subgroups discussed. Finally, better understanding of the strategies used to counteract fatigue and hold SL and SF during the closing stages of a middle-distance race are critical for limiting an athlete's deceleration at the end of a race (Mytton et al., 2015; Sandford et al., 2018; Chapter 3).

7.8 Conclusions

The aim of this review was to provoke interest in areas that are less frequently considered in developing a fast 800m runner. While MSS is well defined, the supporting paces within the ASR domain around 800m race pace require further definition, better quantification and investigation. New focus is required to advance beyond merely quantifying RE and $\dot{V}O_2max$. To do so requires an individualised, multidisciplinary sub-group focus to extend our knowledge of the middle-distance performance picture. Importantly, a new paradigm inclusive of the above areas alongside the classic aerobic physiological determinants of endurance running (Bassett & Howley, 2000; Joyner & Coyle, 2008) is critical for producing well-rounded 800m runners that can thrive in the modern-day cauldron of world class competition.

7.9 Chapter Link

Chapter 7 outlined the applications of MSS and ASR to 800m running. In Chapter 8, we aimed to more broadly describe the training characteristics of elite 800m runners, across the three athlete subgroups during the 2017 competition season, from the cohort in chapter 6. This enabled the MSS and $v\dot{V}O_2max$ component of training to be put in context of the other training stimuli a coach must consider.

Importantly, the training content in athletes with distinct subgroup characteristics will be suggested. The implications of these findings will be discussed using the ASR construct. Important attention will be given to addressing the application and potential trainability of the weaker ASR component in the respective sub-groups; developing aerobic capacity in the 400-800 athlete, and MSS for the 800-1500 athlete.

CHAPTER 8: TRAINING THE ELITE MALE 800M RUNNER: ADDRESSING THE COMPLEXITY OF DIVERSE ATHLETE PROFILES

Chapter 8

8.1 Abstract

Determining a training approach for a runner performing in the 800m event is arguably the most challenging of tasks for track running coaches. Diverse athlete profiles span a broad continuum of event phenotypes that can be categorized into three sub-groups: 400-800m, 800m specialist and 800-1500m. With substantial aerobic and anaerobic contributions required, the growing need for speed ultimately means programming for this event is nothing short of a juggling act. Training programmes across the 800m spectrum are scarce within the literature, resulting in a paucity of available scientific direction for coaches working in these event groups. The current manuscript provides a sample of elite 800m running training volumes, speed and gym work from competition training phase across the sub-group continuum. The implications of these findings will be discussed using the anaerobic speed reserve (ASR) construct (difference between an athlete's velocity at $\dot{V}O_2max$ ($v\dot{V}O_2max$) and their maximal sprint speed, MSS), which has been shown to be a useful tool for identifying distinct athlete sub-group specialists. Important attention will be given to addressing the application and potential trainability of the weaker ASR component in the respective sub-groups; developing aerobic capacity in the 400-800m athlete, and MSS for the 800-1500 athlete. As managing energetic cost across an 800m event is an important performance objective for the athlete, the role of acceleration and changes in inertia will also be addressed. To conclude, scientific principles to approach 800m sub-group training that consider both aerobic and neuromuscular components are suggested.

8.2 Training Approach Background

Scientific Literature

Scientific literature on middle-distance training (800-1500m) has largely focused on the 1500m/Mile (Bourne, 2008; Enoksen, Tjelta, & Tjelta, 2011; Tjelta, 2016), often alongside the 3000m-10,000m events (Tjelta, 2016). When examples of 800m training are shared, they are typically from 800-1500m athletes E.g Arthur Lydiard's 800m model included Peter Snell (Olympic Champion in 800m & 1500m) (Bourne, 2008). This may be due to several factors. First, the fact that the aerobic energy system dominates total energetic requirements of the 1500m event (84%) (Spencer & Gastin, 2001) may have tempted researchers to group this event alongside its longer distance counterparts (5km to marathon). The 800m, with its lower aerobic contribution (66%) (Spencer & Gastin, 2001) is more complex, with large anaerobic energetic contributions challenging to accurately measure (Davison, Someren, et al., 2009; Chapter 4). Second, aerobic variables (i.e. $\dot{V}O_2$) are more easily measured (Bundle & Weyand, 2012), leading again potentially to bias. Third, more recently realized 800m sub-groups (400-800m, 800m specialists and 800-1500m) bring a complexity to training that is not well understood by science and an ongoing challenge for coaches (Gamboa et al., 1996; Horwill, 1980; Sandford et al., 2018; Chapter 6). Consequently, principles of distinct training approaches across 800m sub-groups are lacking within the scientific literature, leaving a shortfall of support for coaches, practitioners and scientists.

Historical Approaches

Broadly, middle-distance training models recommend applying either interval- or volume-focused approaches, as influenced through the pioneering work of Stampfl, Igloi, Gerschler, Lydiard, Jordan & Bowerman, who famously coached many successful athletes to glory under such approaches (Bourne, 2008; Tjelta, 2016). However, as often

occurs with historical training method reporting, preferred pieces can be selected and branded as an approach by the author, when in fact athletes may have had encountered a more holistic development. For example, Arthur Lydiard's frequent prescription of hill bounding plyometrics and fartlek training is often overshadowed (or even omitted) in popular media by his concurrent mileage emphasis (up to 160km/week) (Lydiard & Gilmour, 2000). Importantly, many athletes that achieve international success are outliers, and often have natural talent in underlying speed or neuromuscular qualities, in addition to aptitude for aerobic development (Pickering & Kiely, 2017; Tucker & Collins, 2012).

The reality is few athletes have aptitude across both speed and endurance from day one (Pickering & Kiely, 2017). Therefore, a coaching paradigm that focuses solely on either volume or interval training year-round, may under-develop the opposing element, to the detriment of the athlete's performance. Scientific evidence supporting longstanding coaching observations of three male 800m subgroups (Gamboa et al., 1996; Horwill, 1980; Sandford et al., 2018; Chapter 6), provides a challenging programming puzzle, whereby athletes training for the same event, broadly supported by a 66.3±4% aerobic energy supply (800m performance time: 1:53±0:02) (Spencer & Gastin, 2001), require vastly different training approaches due to individual inherent abilities to adapt to certain stimuli (Pickering & Kiely, 2017).

The purpose of the current manuscript is to describe the training characteristics of elite 800m runners, across the three athlete subgroups during the 2017 competition season (Gamboa et al., 1996; Horwill, 1980; Sandford et al., 2018; Chapter 6) . Principles for approaching training with distinct athlete sub-groups will be suggested.

8.3 Modern Day Race Demands

The modern-day race demands of world-class 800m and 1500m running have been recently documented (Mytton et al., 2015; Sandford et al., 2018; Chapter 3). Briefly, male

800m World and Olympic medallists are now required to compete in an era that involves running faster first laps, including 100m sectors that are 0.5m/s quicker than past decades. Moreover, medallists in men's 1500m championships are most commonly differentiated by their 'last lap kick' (the decisive and final break from the pace as a sustained pursuit for the finish line) (Mytton et al., 2015). It is noteworthy to mention that diamond-league competitions that include planned pacemakers are often performed as 'gun-to-tape' in nature (Filipas et al., 2018), and the 2017 World Championship gold and silver medallists in the Men's 1500m won in 3:33 (min:ss) using this strategy (Stellingwerff, 2018b). Conversely, the women's 1500m final recorded a closing last 600m of 1:29 (min:ss) (Stellingwerff, 2018a). These diverse winning strategies highlight the challenge for the modern-day middle-distance coach and athlete. Therefore, a systematic training approach is needed to equip an athlete with the armoury needed for all tactical scenarios on race day.

8.4 Modern Day Elite 800m Training Characteristics

Insight into the training characteristics of elite 800m runners are presented in Table 8.1. Data were captured during the competition phase, and represent average training characteristics from a four-week block across the three male athlete subgroups (Sandford et al., 2018; Chapter 6). Whilst limited to only a single four-week training phase, results highlight the diverse training priorities of the different sub-groups, and offer a starting point for more detailed future research. For example, several papers have characterised the training distribution of elite distance runners (1500m-Marathon) (Esteve-Lanao, San Juan, Earnest, Foster, & Lucia, 2005; Kenneally, Casado, & Santos-Concejero, 2017; Tjelta, 2016; Tjelta & Enoksen, 2010), including notable 1500m case studies (Ingham et al., 2012; Tjelta, 2013). However, literature describing 800m training content is limited, and nearly no data describes these three distinct sub-groups (Table 8.1) (Sandford et al., 2018; Chapter 6).

Table 8.1. Training characteristics of elite male 800m (n=19) subgroups (Sandford et al., 2018; Chapter 6)

Elite Male Sub-group	800m Personal Best	Training Age (years)	Running Volume (km/week)	Gym Sessions per Week	Maximal Speed Sessions per Week
400-800m	1:46.21 ± 1.16	6.55±3.9	62.1 ±17.0	1.9 ± 0.7	1.2±0.7
800 specialists	1:46.37 ± 1.43	9.5 ± 3.9	76.7 ± 18.1	2.0 ± 1.4	0.8±0.7
800-1500m	1:49.53 ±1.28	8.50 ± 3.5	118.3 ± 27.5	2.7 ± 2.1	0.7±0.6

All data are presented as means and standard deviation. Training age – number of years in structured 4-5 days/week. Running volume – average weekly mileage from last 4 weeks. Gym – average number of strength and power sessions in the last 4 weeks. Maximal speed – average number of maximum speed (all out) sessions per week (reps up to and including 120m).

In attempt to provide a starting point, a k-means cluster analysis was performed to investigate differences in training variables between 800m subgroups (Sandford et al., 2018). One of the distinct differences in subgroup training content was the large differences in weekly mileage. Importantly, this data contrasts the presumption held by some that to reach international level standards, a high mileage of ≥110 km/week is necessary before the age of 19 (Tjelta, 2016). This data (Table 8.1) may highlight the importance of determining the likely inherent underlying physiological qualities of the runner prior to selection of the best training approach (Sandford et al., 2018; Chapter 6).

The following sections will focus on athletes at either end of the 800m continuum (400-800 or 800-1500), specifically offering suggestions of how to train the weaker part of their anaerobic speed reserve (ASR). E.g in a 400-800m athlete often this is the velocity at $\dot{V}O_2max$ ($v\dot{V}O_2max$), and 800-1500m – is the maximal sprint speed (MSS) component.

8.5 Aerobic Development in 400-800m Athletes

Training guidelines for the 1500m event and upwards is well described elsewhere (Kenneally et al., 2017; Tjelta, 2016), the principles of which largely suit an 800-1500m

athlete. For an existing 400m track running specialist transitioning to the 800m event, subject to prior training model, low initial levels of aerobic fitness characteristics may be expected (unpublished observations, Gareth Sandford). An initial approach to consider may be the use of short-interval work, where repeated short (10s-60s) efforts run at 100-120% v$\dot{V}O_2$max with active or passive recovery periods of a similar time range keep muscle metabolite accumulation low (Saltin & Essen, 1971; Wakefield, Benjamin & Glaister, 2009). Moreover, this may be most mechanically, physiologically and psychologically appropriate until a foundation in the aerobic stimulus, and motor patterns in gait are advanced (Buchheit & Laursen, 2013a; Pickering & Kiely, 2017).

Further, assuming a 400-800m subgroup possess a low percentage of slow twitch muscle fibre composition, even low intensity exercise (i.e., 50% $\dot{V}O_2$max) over short durations (i.e., 20 min) may require reliance on type ll fibre contribution (Krustrup, Söderlund, Mohr, González-Alonso, & Bangsbo, 2004), increasing the VO_2 slow component, where steady state exercise is unattainable (Poole et al., 2016a). Additionally, the Henneman size principle (Henneman, 1985) states that to recruit fast twitch motor units, a certain level of exercise intensity is required, again supporting the repeated short-interval approach (described above). Importantly, short-interval approaches contrast the potentially more well-known long-interval prescription that involves efforts around v$\dot{V}O_2$max of 2-4 minutes, with 2-3 min passive recovery (Buchheit & Laursen, 2013a). In 400-800m athletes, the increased dependence on anaerobic metabolism in low continuous (and additional neuromuscular loading with longer high intensity work), can create unwanted fatigue in the unfamiliar athlete, reducing quality of subsequent repetitions and potentially future training sessions.

Whilst potentially considered ‘anaerobic in nature’, substantial aerobic oxidative metabolic adaptations can occur with repeated high-intensity training. For example, Parolin et al. (1999) showed during repeated 30s maximal cycling bouts (4 minutes

recovery), that other than the first 15s of the first sprint, all subsequent repetitions beyond 6s were provided by 50% aerobic metabolism in healthy males. Kiely, (2017) recently highlights the importance of an ongoing novel stimulus in the athlete to increase allostatic load and promote adaptation. Without this ongoing adjustment, an athlete's performance may plateau, and aerobic properties may diminish.

During seasonal transitions as training emphasis changes, e.g larger volumes of 'faster' work in pre-competition phase, often replace already low volumes of low intensity continuous work, potentially resulting in aerobic detraining (Table 8.1). Whilst 400-800 athletes may compensate for their lower aerobic capability with a large MSS, the inherent ~66% aerobic contribution to the 800m event, requires continual aerobic development year-round (Spencer & Gastin, 2001). Thus, although the blend of continuous and interval-based approaches for the 400-800m subgroup athlete are not commonly applied, in the longer term this strategy may best optimise aerobic development and performance (unpublished observations, Gareth Sandford). Further, Coyle et al. (1988) showed in a homogenous group of competitive cyclists with similar levels of $\dot{V}O_2max$ that specific vascular qualities such as a high capillary density are likely due to the accumulation of consistent high volume training over 5+years, which differentiated cycling time to fatigue compared to a group of cyclists with less training experience (2-3 years specific cycling training). This finding suggests that a progressive overload of aerobic specific training may be required for success in events with large aerobic demands (e.g. 800m). Indeed, the performance limiting factor in the athlete shifts over time, requiring progressive adjustment of the overload stimulus for continued improvement (Kiely, 2017).

Casado & Ruiz-Pérez, (2017) and Kenneally et al. (2017) showed that a feature of Kenyan long distance running included extended time periods performing tempo running (extended runs at paces associated with Lactate Turnpoint ($_vLT_2$), which appears to be a much larger focus compared with elite Spanish runners (Casado & Ruiz-Pérez, 2017) .

Such training raises $_{v}LT_2$, largely through improving lactate shuttle capability (Brooks, 2007; Jones & Carter, 2000) , which is of importance to counter the high metabolic acidosis of race conditions (Bundle & Weyand, 2012). Applying this $_{v}LT_2$ stimulus at a low density and small volume in the initial training stages for a 400-800m athlete is closer to the athlete's mechanical bandwidth of comfort than low intensity continuous running. Additionally, $_{v}LT_2$ stimulus considers the 'size' principle, which recruits the fast twitch motor units for aerobic adaptation. (Figure 8.1). It

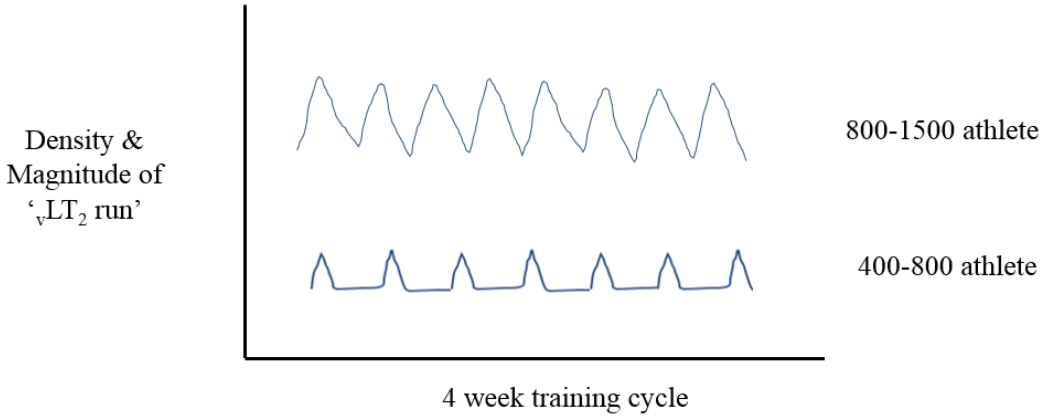

Figure 8.1. Hypothetical magnitude and density profile of $_{v}LT_2$ running stimulus for 400-800m and 800-1500m athlete.

Applying a $_{v}LT_2$ stimulus to a 400-800m athlete, in the volumes which it would apply to an 800-1500m athlete, is unlikely to be a 'bang for buck endeavour' and to achieve progression of this work, shorter interval blocks could be considered (e.g 5 min at $_{v}LT_2$, then 6 x400m off 20s at $_{v}LT_2$).

8.6 MSS - An Important Training Stimulus for the 800-1500m Athlete

Our elite sample (Sandford et al., 2018; Chapter 6) showed limited inclusion of maximal sprint speed work (MSS; the ceiling of the ASR) (Table 8.1). Notwithstanding the increased potential for injury with such training, this may be concerning considering its strong relationship with 800m performance (Bachero-Mena, Pareja-Blanco, Rodríguez-Rosell, et al., 2017; Sandford et al., 2018; Chapter 6), the potential for a larger ASR (as

function of faster MSS) to enable faster race pace efficiency (Sandford et al., 2018; Chapter 7), in addition to the neuromuscular qualities underpinning the last lap kick (Enomoto et al., 2008).

Periodisation paradigms that de-emphasize MSS work, often counter by prioritizing 'aerobic-base' training until the end of the northern-hemisphere cross-country season, and any form of speed work may not appear until January (in some cases as late as April). The delay of the MSS stimulus and the late introduction of this new and potent stimulus can result in injuries (unpublished observations, Gareth Sandford), reducing the likelihood of achieving performance goals (Raysmith & Drew, 2016). A common misconception with a 'no-sprinting' paradigm is the assumption the stimulus per se rather than the sudden spike in unfamiliar stimulus is casual with injury occurrence (Gabbett, 2016). Indeed, Malone, Roe, Doran, Gabbett, & Collins, (2017) proposed in team sports that too little, or too much MSS training stimulus increased injury risk (Figure 8.2) (Malone, Hughes, Doran, Collins, & Gabbett, 2018).

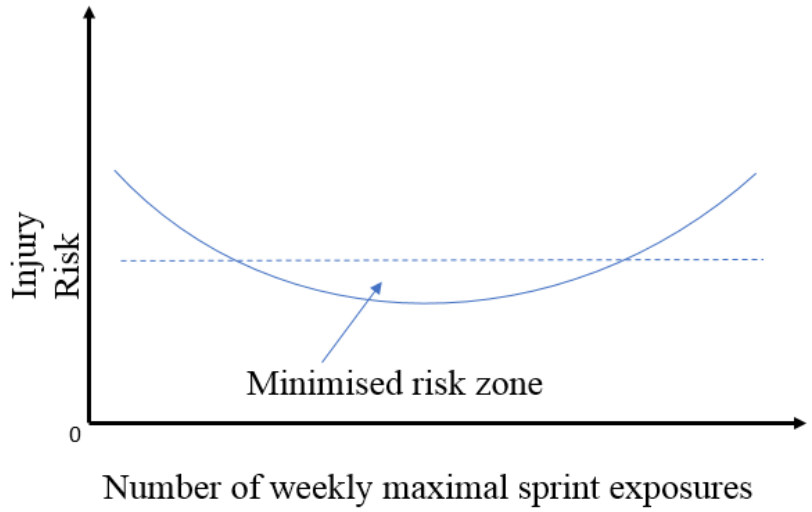

Figure 8.2. Hypothetical 'U' shape relationship between maximal sprint speed stimulus and injury risk. Adapted from Malone et al. (Malone et al., 2017) example in team sports.

A further common reluctance for MSS inclusion is the neural fatigue that negatively impacts subsequent training sessions, whereby force transmission at the neuromuscular junction is limited because of the amount of maximal sprint exercise performed in a prior session (Ross, Leveritt, & Riek, 2001). Unwanted neural fatigue transfer to subsequent training sessions may be managed through manipulation of density programming by athlete subgroup (e.g. Figure 8.1). For example, small but frequent densities of MSS (e.g. 2 x 40-80m 2-3 times a week at the end of the warm up) may maintain (and build in novices) this MSS quality, as volume of specific work is increased (unpublished observations, Gareth Sandford and Steve Magness). Importantly, if unaccustomed to this stimulus, a foundation in high frequency/plyometric movement and correct mechanics (e.g using hills) at lower densities (1-2/week) should be the first starting point. Robustness, durability and an ability to increase impulse/time are all key characteristics required in middle- and long-distance running performance (Rabita et al., 2015; Raysmith & Drew, 2016; Weyand et al., 2000). In support of this, our data reveals there is value placed on gym work across all sub-groups (Table 8.1).

Our data reveals strength and power gym content (also with neural considerations) is not-supplementary, but an integral part of the programme in the 400-800m subgroup, while the lower 0.7-0.8 day/week of MSS stimulus appears considered less important for 800m specialists and 800-1500 middle distance runners. Considering recent findings (Sandford et al., 2018; Chapter 3, 6, 7), with clear differentiation of speed on the last lap between medallists and non-medallists (Mytton et al., 2015), this training strategy might be reconsidered.

8.7 The Nuance of ‘Speed’ Stimulus

Speed-endurance work that typically consists of 7-15s duration efforts (Buchheit & Laursen, 2013a; Crick & Evely, 2011; Iaia & Bangsbo, 2010), should not be confused

with MSS work, which are primarily achieved using maximal 2-7s efforts (Crick & Evely, 2011; Iaia & Bangsbo, 2010). Specific repeated sprint work represents efforts ≥ 15s, with full recovery (e.g 3 x 300-400m, off 8 minutes; (Crick & Evely, 2011)). For repetitions longer than 10s, sustainable speed is decreased with longer durations, resulting in a lower specific stimulus for maximum velocity (Crick & Evely, 2011). Race pace efforts are likely to have a different emphasis (e.g 250's-300's at 800m race pace, off flexible rest), described as controlled smooth race pace with emphasis on maintaining mechanical rhythm, versus any specific workout that might be targeting anaerobic glycolytic adaptations.

The present data (Table 8.1) show that one or less MSS sessions per week occur during the competition phase of training in elite 800m and 800-1500m runners, perhaps due to inclusion of the more 'specific-endurance' type workouts in competition phase. It is also possible unclear distinction may exist between MSS, speed-endurance (150's,250s) and specific-endurance work (300's,400's), their respective adaptations and role in supporting 800m performance. Importantly, if MSS inclusion is a gap in a training programme, a potential opportunity is being missed. Chapter 7 (Figure 7.5) showed what a misleading representation 400m SB may be of an athlete's speed capability, and the value training MSS has on increasing the ASR, and therefore the potential framework to run faster race paces relaxed. MSS work from week one of the season, lays a foundation for speed-endurance and specific-endurance work later in the season, and the two qualities may have complimentary adaptations. The principle here is not that hard specific-endurance sessions should be included year-round, as these physiological adaptations can be achieved relatively quickly (Iaia & Bangsbo, 2010). Sustained use of large volumes of speed and specific- endurance work, should be used with care or risk maladaptation (Meeusen et al., 2013). An overview of training principles for applying different stimulus across 800m sub-groups is provided in table 8.2.

Table 8.2. Global training stimulus considerations across 800m sub-groups

Stimulus	Main rationale for inclusion	400-800m	800m	800-1500m
Maximal Sprint Speed	Mechanical, Skill acquisition	**	**	**
Acceleration	Mechanical, energetic cost of first 50m	**	**	**
Speed Endurance (efforts up to 15s achieving maximum sprint speed in repetition)	Physiological, mechanical	****	***	**
Specific Endurance (15-60s – maximum sprint speed isn't attained within repetition)	Physiological	***	**	*
All other Race Pace	Mechanical, Skill acquisition, Physiological	***	****	****
$\dot{V}O_2$max intensity	Physiological, Mechanical	*	**	***
Aerobic – lactate turnpoint ($_vLT_2$, VT_2, 'threshold')	Physiological	****	****	****
Aerobic volume (continuous work below ~80% $\dot{V}O_2$max)	Physiological	**	****	*****

1-5 rating provided for stimulus distribution across subgroups (5***** = Major Consideration, 1*=Minor Consideration). Application driven by context. Depending on sub-group, certain subgroups will have different emotional responses to stimulus and is a key consideration amongst training design.

8.8 Acceleration – The Forgotten Training Component

Whilst the 100-200m split is often the fastest 100m split in elite 800m running (Sandford et al., 2018; Chapter 3) this section does not represent the greatest metabolic cost (Di Prampero, 2005; Martin et al., 2007). Rather overcoming inertia in the first 50m represents by far the highest power (and thus E cost; figure 8.3) and this fact is rarely addressed in most 800m training paradigms.

Martin et al. (2007) in world-class kilo cyclists showed 73% of work done in the first 12s racing was from acceleration. Acceleration is a distinct motor skill and possession of a fast maximal velocity (from MSS) does not automatically equate to an efficient acceleration ability (Clark, Rieger, Bruno, & Stearne, 2017). Therefore, if 800m runners can develop the skill of acceleration, they may reduce the energetic cost of the first 50m of the race, reducing the amount of 'work-done' and preserve energetic resources for later in the race.

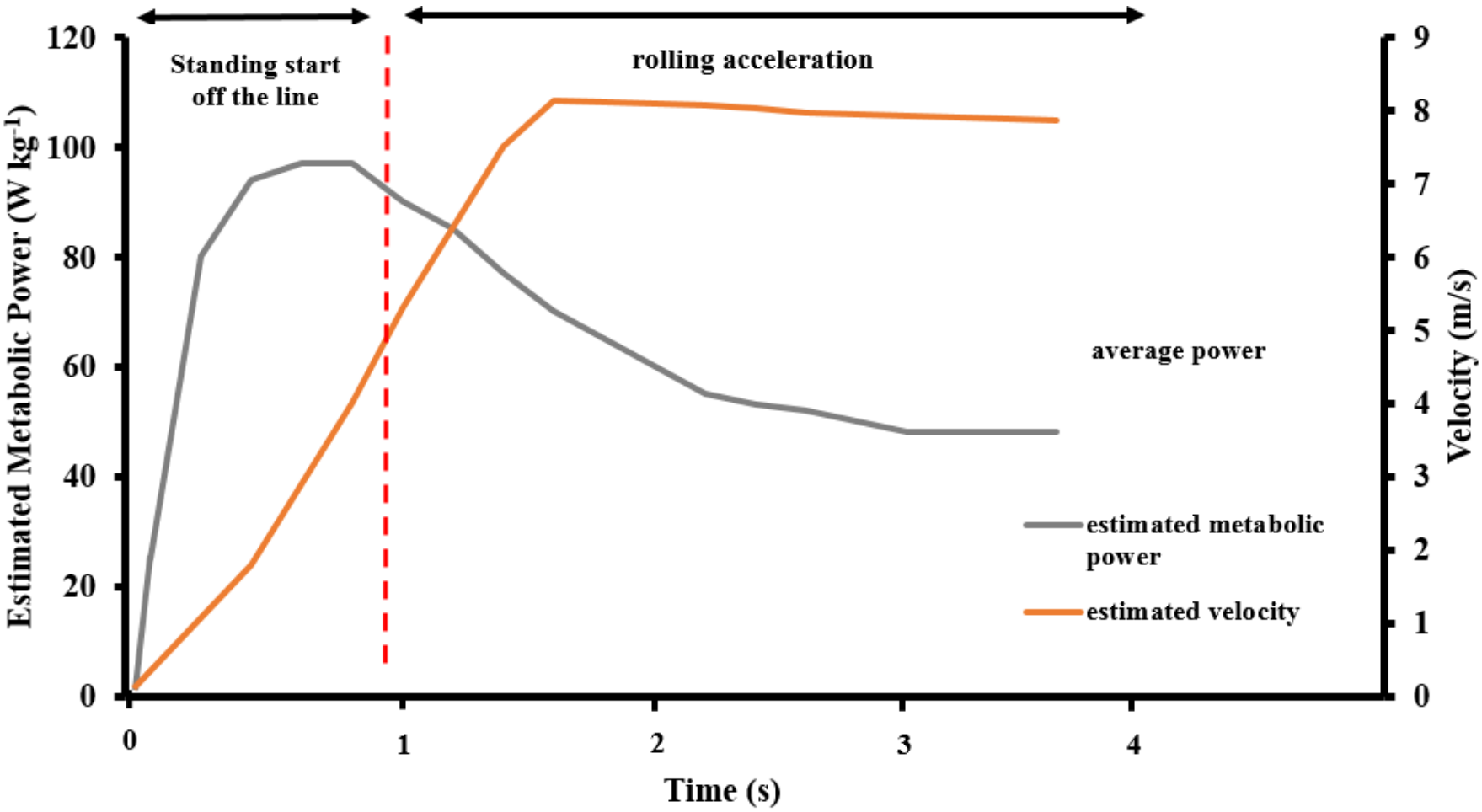

Figure 8.3. Hypothetical metabolic power trace from an 800m acceleration (standing start), showing highest metabolic power (energy cost) from the first few steps of the race – an element (acceleration) rarely found in 800m training paradigms. Adapted from Di Prampero, 2005; Martin et al., 2007.

8.9 Trainability

Haugen, Tonnessen, & Seiler, (2015) revealed the maximal trainability of MSS in the Norwegian sprint population as 8% from age 18 to peak performance at senior level, with an average improvement of 1.3 – 1.4%. However, in a middle-distance population, where coach education may often bias on aerobic physiology (Thompson, 2016), how often is MSS and its mechanical and neuromuscular qualities prioritised in distance running training methodology? A case study in a national level Polish 800-1500m runner (1:47.96/3:44.04), revealed a 4.7% improvement in maximum velocity over 50m after a 6-week strength and conditioning intervention (Maćkała et al., 2015). Perhaps presenting an 'untapped' level of trainability, higher than found in the sprint population who focus on mechanics, and speed/power year-round. By comparison, in a world-class 1500m case study, Ingham et al. (2012) presented a 13% increase in $v\dot{V}O_2max$ over a two-year period, from adjustments in sea-level training model with interventions such as altitude training available for further aerobic advancement (Chapman et al., 2014; Gore et al., 2013). The true trainability of the mechanical and neuromuscular determinants remains to be established in middle-distance population, with optimising mechanics at MSS likely having dual benefits for efficiency at $v\dot{V}O_2max$ and race pace (Sandford, Kilding, Ross, & Laursen, 2018b; Chapter 7).

Recently, Bezodis et al. (2017) , revealed the sensitivity of stride length and frequency (and therefore MSS) to phases of heavy lifting and high-intensity track work. Pertinent questions for the middle-distance community are how both mechanical and neuromuscular qualities can be developed as running drills alone may not be adequate (Azevedo et al., 2015). Race pace skills must be honed under typical high volumes reported in the weekly training, to culminate in having both aerobic and neuromuscular characteristics at their optimum for pinnacle events (Tjelta, 2016).

8.10 Conclusion

Whilst much can be learned from historical middle-distance running paradigms, singular training model approaches to the 800m need reconsideration in light of athlete sub-group diversity. The holistic modern-day 800m programme extends beyond solely physiological consideration, with concurrent development of mechanics, 800m race pace skill, and psychology all important components to the training approach. This is a sizeable task for coach-education within high performance organisations, where historically an aerobic physiology lense has dominated. Ultimately all athletes require the key performance determinants of the 800m event, although a nuance of application is required in line with athlete phenotype, with contextual information informing coach, athlete and sport scientist decisions.

8.11 Chapter Link

Chapter 8 outlined the modern-day elite 800m runner training principles through a balanced paradigm lens that considers both neuromuscular and mechanical components. The training data reported highlights the importance of determining the likely inherent underlying physiological qualities of the runner prior to selection of the best training approach.

Chapter 6 highlighted the potential for the speed reserve ratio (SRR) derived from the ASR, to differentiate elite 800m sub-groups. The lower component of the ASR: $v\dot{V}O_2max$, is typically measured in an exercise physiology laboratory, meaning that application of the ASR construct in the field may be limited to those with laboratory access and expertise. Therefore, chapter 9 sought to determine the relationship between average 'gun-to-tape' 1500m race speed (1500_v) and $v\dot{V}O_2max$ collected in the laboratory, to produce regression equations enabling the use of a 1500m race time to predict the $v\dot{V}O_2max$ component of the ASR in elite middle-distance runners.

CHAPTER 9: IMPLEMENTING ANAEROBIC SPEED RESERVE TESTING IN THE FIELD: VALIDATION OF $v\dot{V}O_2MAX$ PREDICTION FROM 1500M RACE PERFORMANCE IN ELITE MIDDLE-DISTANCE RUNNERS

Chapter 9

9.1 Abstract

Purpose: To determine the relationship between velocity associated with maximal oxygen uptake ($v\dot{V}O_2max$) and gun-to tape-1500m average speed (1500_v) in elite middle-distance runners.

Methods: Eight national and four international middle-distance runners completed a laboratory-measured $v\dot{V}O_2max$ assessment within six weeks of a non-championship 1500m gun-to-tape race. Anaerobic speed reserve, defined as the speed range from $v\dot{V}O_2max$ to maximal sprint speed (MSS), was calculated using both laboratory-derived $v\dot{V}O_2max$ (ASR-LAB) and 1500_v predicted $v\dot{V}O_2max$ (ASR-1500_v), with MSS measured via radar technology.

Results: 1500_v was on average +2.06 ±1.03km/hr faster than $v\dot{V}O_2max$ (moderate effect, *very likely*). ASR-LAB and ASR-1500_v mean differences were -2.1± 1.5 km/hr (large effect, *very likely*). 1500_v showed an extremely large relationship with $v\dot{V}O_2max$; r=0.90 ± 0.12 (*most likely*). ASR-LAB had a large negative relationship with 1500_v (r= -0.68±0.3; *very likely*), whereby a larger ASR-LAB was related to a slower 1500m performance time (i.e. faster 1500m athletes had a faster $v\dot{V}O_2max$). Using this relationship, a linear regression $v\dot{V}O_2max$ estimation equation was derived as: $v\dot{V}O_2max$ (km/hr) = (1500_v (km/hr)-14.921)/0.4266, SE_E +0.40 (+0.31 to 0.55) km/hr.

Conclusions: A moderate difference was evident between 1500_v and $v\dot{V}O_2max$ in elite middle-distance runners. The present regression equation should be applied for an accurate field prediction of $v\dot{V}O_2max$ from gun-to-tape 1500m races Between-athlete ASR comparisons should be considered alongside the $v\dot{V}O_2max$ and MSS landmarks as indications of athlete calibre. These findings have strong practical implications for coaches lacking access to a sports physiology laboratory that seek to monitor and profile middle-distance runners.

9.2 Introduction

Physiological testing of elite runners often follows a formal testing protocol in a laboratory consisting of a treadmill running assessment with metabolic gas collection, as well as various blood, perceptual and speed/time-based markers (Davison, van Someren, et al., 2009). Whilst there are merits of this approach, it leaves many non-funded coaches and athletes lacking specialist equipment or local expertise without the benefits testing can offer for athlete profiling and training evaluation. In addition, laboratory testing is less practical for coaches to implement within congested competition schedules, thereby posing a barrier to sport science integration. Importantly, practitioners must continually strive for opportunities to bring easy-to-implement solutions that hold high levels of ecological validity to the field (Lacome, Buchheit, Broad, & Simpson, 2018).

Recently, we showed a very large (r=0.74) relationship between elite 800m running performance and anaerobic speed reserve (ASR) (Sandford et al., 2018; Chapter 6), whereby athletes with larger ASR displayed faster 800m season's-best performances (as a function of their faster maximal sprint speed (MSS)). Specifically, the ASR measures the speed range from velocity at $\dot{V}O_2max$ ($v\dot{V}O_2max$, also known as maximal aerobic speed (MAS) in the field (Billat & Koralsztein, 1996; Buchheit, 2010)) to MSS. MSS can be accurately measured using radar technology (Haugen & Buchheit, 2016), timing gates or hand-timing in the field. $v\dot{V}O_2max$ is a marker of running efficiency (Jones & Carter, 2000), as opposed to a consistent physiological landmark and may be an important consideration for middle-distance runners, due to the proximity of $v\dot{V}O_2max$ to mean 1500m race pace (e.g. 57s first lap = 25.3km/hr) (Sandford, Kilding, et al., 2018b; Chapter 7). However, accurate measurement of $v\dot{V}O_2max$ is more challenging in the field, and typically requires laboratory-based procedures. As $v\dot{V}O_2max$ is a required component of the ASR construct, an easy-to-administer practical measurement method is needed specific to middle-distance performance.

Previously, in AFL players, the MAS estimated from the Université de Montréal Track Test showed 'moderate to strong' (r=0.69-0.84) agreement with the average speed in set distance time-trials between 1200-2200m (Bellenger et al., 2015). These findings highlight the potential for race distances in this bandwidth (e.g. 1500m) to be useful estimates of an elite runner's $v\dot{V}O_2max$. Therefore, the aim of this technical report was first to explore the relationship between average 'gun-to-tape' 1500m race speed (1500_v) and $v\dot{V}O_2max$ collected in the laboratory. A second aim was to produce regression equations enabling the use of a 1500m race time to predict the $v\dot{V}O_2max$ component of the ASR in elite middle-distance runners.

9.3 Methods

Eight national (n=4 senior, n=4 junior (U20)) and four international junior middle-distance runners participated in this study (sub-groups (Sandford et al., 2018; Chapter 6) detailed in table 9.1). On one occasion the athletes visited a laboratory in Auckland, New Zealand or Canberra, Australia (580m (Gore et al., 1996)) for $v\dot{V}O_2max$ assessment. Within six weeks of laboratory testing, a gun-to-tape 1500m (n=12) was selected for comparison alongside MSS assessment by a sports radar device (Stalker ATS II System, Radar Sales, Texas, USA Stalker). Each athlete provided written informed consent to participate in the study, which was approved by the Auckland University of Technology Ethics Committee and reciprocated by University of Canberra, Research Institute for Sport and Exercise.

Laboratory $v\dot{V}O_2max$ Assessment

Laboratory $v\dot{V}O_2max$ assessment started at 14km/hr or 16km/hr for junior males and 16 or 18km/hr for senior males. Starting speeds were chosen working back six stages from estimated end of test speed, guided by performance level, ASR, and recent training sessions, to provide the opportunity to maximise test time at faster speeds. As per Billat

et al. (1996), athletes performed 1km increments every 1 minute at a fixed 1% gradient to volitional exhaustion. $v\dot{V}O_2max$ was calculated by first identifying the 30s peak of VO_2 and then identifying the speed at which the first 15s of that peak occurred. If an athlete achieved VO_2peak during a stage that was not sustained for 1 min, $v\dot{V}O_2max$ was calculated in a pro rata manner (Halson et al., 2002).

$v\dot{V}O_2max$ Estimation from 1500m Race Time

1500_v was calculated simply as:

race distance (m) / time (s) = average velocity (m/s).

Analysis

All data are presented as mean ±90% confidence limits (CL), unless otherwise stated. Correlation magnitudes were rated; 0.1 (small), 0.3 (moderate), 0.5 (large), 0.7 (very large) and 0.9 (extremely large) (Hopkins et al., 2009). Linear regression equations and standard error of the estimate (SE_E) were obtained in Microsoft Excel and rearranged to enable $v\dot{V}O_2max$ prediction from $1500m_v$.

Between method comparisons of $v\dot{V}O_2max$ and 1500_v and the subsequent ASR (herein ASR-LAB, ASR-1500_v) were assessed using magnitude based inferences (Hopkins et al., $_2$009). The following threshold values for effect size (ES) statistics were used for $v\dot{V}O_2max$ and ASR-LAB ≥0.2 (small), >0.6 (moderate), >1,2 (large) and >2.0 (very large) and 0.3 (small), 0.9 (moderate), 1.6 (large) and 2.5 (very large) for 1500_v and ASR-1500_v, (Hopkins et al., 2009). The smallest worthwhile change (SWC) was determined as the standard deviation of the ASR method, multiplied by the ES.

Table 9.1. Description of study participants (n=12). All values are mean±SD.

Participation Level	Age (years)	Body Mass (kg)	Height (cm)	VO_2 Peak (ml/kg/min)	800m PB			1500m PB			3000m PB		
					N	Mean±SD (mm.ss.ms)	Range (mm.ss.ms)	N	Mean±SD (mm.ss.ms)	Range (mm.ss.ms)	N	Mean±SD (mm.ss.ms)	Range (mm.ss.ms)
National Junior	18.5±0.6	68.0±1.7	178.5±1.8	65.5±2.5	3	1:55.0±2.2	1:52.9-1:57.3	4	3:55.2±4.7	3:51.2-4:01.3	3	8:32.5±15.0	8:18.0-8:47.9
National Senior	22.0±1.8	68.6±7.2	182.6±4.5	71.4±2.1	4	1:49. 8±2.0	1:48.1 - 1:52.6	4	3:47.2±9.8	3:38.0-4:00.9	3	8:13.0±29.4	7:53.0 - 8:46.0
International Junior	17.3±0.5	60.4±3.5	173.1±4.0	72.0±3.3	4	1:53.7±1.2	1:52.3-1:55.0	4	3:46.4±1.4	3:44.3-3:47.5	4	8:19.7±3.0	8:16.8 - 8:22.4

9.4 Results

On average, 1500_v (23.39±0.88 km/hr) was +2.06±1.03km/hr faster than $v\dot{V}O_2max$ (21.33±1.85 km/hr) (moderate effect, *very likely*). The mean difference between ASR-LAB (11.5±2.5 km/hr) and ASR-1500_v (9.4±1.7 km/hr) was -2.1± 1.5 km/hr (large effect, *very likely*). 1500_v had an extremely large relationship with $v\dot{V}O_2max$ r=0.90 ± 0.12 *(most likely,* Figure 9.1).

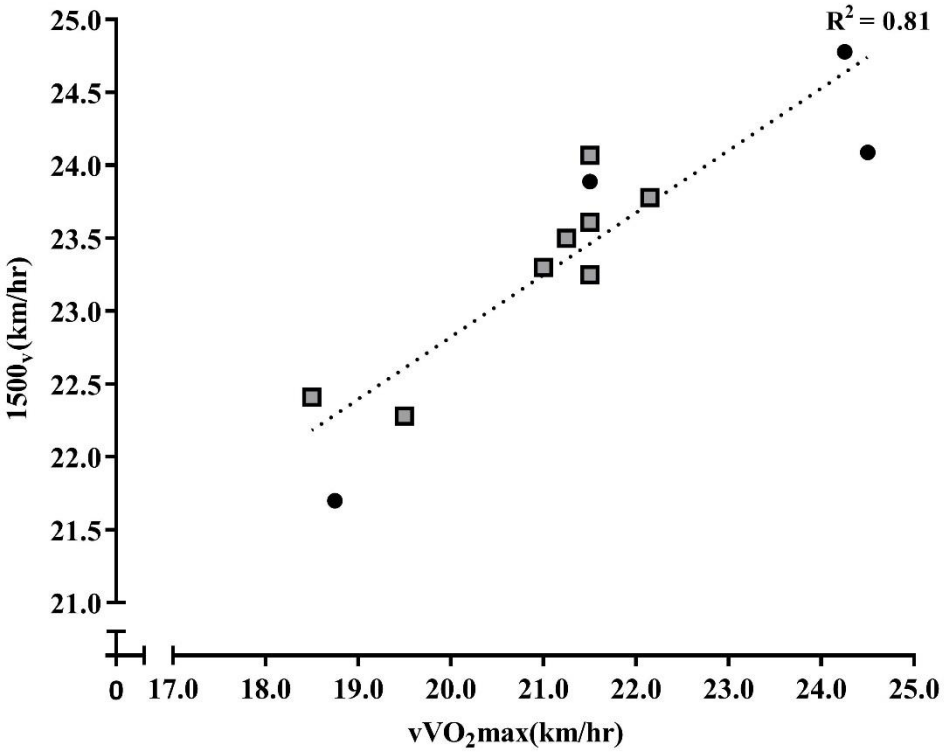

Figure 9.1. Relationship between 1500v (km/hr) and laboratory derived $v\dot{V}O_2max$ (km/hr). Grey squares and black dots represent junior and senior level athletes respectively.

ASR-LAB showed a large negative relationship with 1500_v (r= -0.68±0.3; *very likely*), whereby a larger ASR-LAB was related to a slower 1500m performance time (Figure 9.2a).

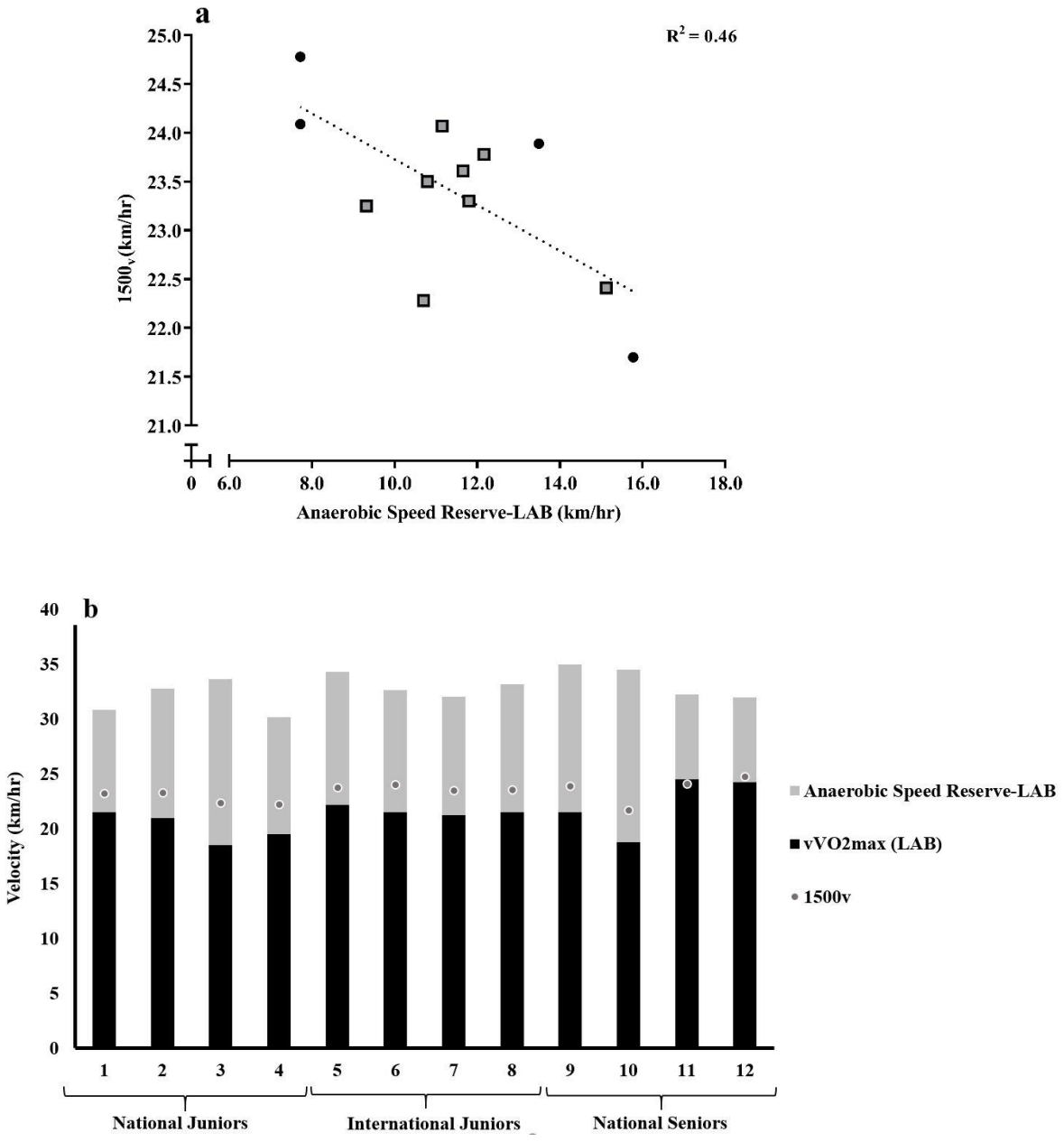

Figure 9.2 (a) Relationship between 1500_v and anaerobic speed reserve (ASR) (km/hr). Grey squares and black dots represent junior and senior level athletes respectively. (**b)** The ASR profiles of national juniors (N=4), international juniors (n=4) and national seniors (n=4). A comparison between Athlete 1 vs Athlete 12 illustrate how similar ASR must be assessed in context of velocity at $\dot{V}O_2max$ and maximal sprint speed to determine athlete calibre.

The regression equation for 1500_v and $v\dot{V}O_2max$ relationship was:

$y = 0.4266x+14.291$

where $y = 1500_v$ and $x = v\dot{V}O_2max$, revealing a SE_E of +0.40km/hr (+0.31 to 0.55).

9.5 Discussion

In the present study, we found an extremely large correlation between 1500_v and $v\dot{V}O_2max$ (Figure 9.1), though the moderately faster 1500_v suggests the present regression equation should be applied for a more accurate prediction of $v\dot{V}O_2max$ from gun-to-tape 1500m races.

The second important finding was the large negative relationship shown between ASR-LAB and 1500_v (figure 9.2a). Specifically, athletes with the larger ASR-LAB tended to have slower 1500m performance times. Interestingly, this contrasts our finding in the 800m (Sandford et al., 2018), which may reflect the larger aerobic component for 1500m (88%) vs. 800m (66%) events (Spencer & Gastin, 2001), highlighting an important principle in ASR application. That is, the ASR (e.g. an 11 km/hr bandwidth) should be provided within the context of an athlete's MSS (35 km/hr) and $v\dot{V}O_2max$ (24 km/hr), so that the complete profile of middle-distance running capability is appreciated (figure 9.2b). Indeed, ASR in isolation is not indicative of athlete calibre. In the present study, the larger ASR was related to slower 1500m times because $v\dot{V}O_2max$ may have been the limiting factor in the athlete's physiological profile (i.e. the faster athletes had a faster $v\dot{V}O_2max$). This suggests that, as reported in the 800m (Sandford et al., 2018; Chapter 6), until an athlete reaches a certain calibre (in the case of the 800m ~1:47) a minimum level of aerobic capability is required to be in the elite race. Once a runner reaches this threshold, MSS (and its underpinning characteristics) may be an important tool in race defining moments, such as surges.

The large difference in ASR between methods (-2.1, ±1.5 km/hr) highlight important principles for implementation. First, using 1500_v alone for the ASR landmark without the corrective equation presented above, would produce a prediction error of four times the SWC. Whilst practicality is important in elite populations, the accuracy of field estimates

in the present study highlights the need for concurrent awareness of relationships between field estimates and the controlled laboratory environment.

In the present study, time of data collection within the competition season was critical to allow for the 1500m race selection window for athletes participating in races described as ‘gun-to-tape’ time-trials. In such races, pace makers are used to help enable qualifying standard achievements for international racing or championship selection. Middle-distance running championship races are today typically ‘sit-and-kick’ races, whereby submaximal paces/efforts (≤Critical Speed) occur in the early laps, which precede an extreme surge on the last lap, distributing the utilisation of efforts in a very different manner (Jones & Whipp, 2002; Mytton et al., 2015), that would not be reflective of v$\dot{V}O_2$max.

9.6 Practical Application

In the current paper, 1500_v from a gun-to-tape race, overestimated laboratory v$\dot{V}O_2$max.Therefore, middle-distance coaches may be able to use 1500v prediction equations to estimate the lower component of the ASR, without requiring a laboratory. Our findings suggest 800m sub-groups (Sandford et al., 2018; Chapter 6) ,1500m specialists and junior athletes may benefit most from 1500_v assessment, with gun-to-tape race performance over longer distances taking years of consistent training to develop the required efficiency. Importantly, by nature of event specialisation, 400-800 and 800m specialists will rarely run a 1500m race, with contract, sponsors, anxiety over potential poor performance in unfamiliar race and competition schedule all barriers to racing ‘over-distance’. Despite this, coaches are familiar with performance times and may therefore be interested in the ‘1500m shape’ their athlete is in, without having to race them at 1500m. Our current method provides an alternative for a coach to estimate 1500m time

from $v\dot{V}O_2max$, giving access to information that may enable more informed training choices.

9.7 Conclusion

Moderate differences exist between 1500_v and $v\dot{V}O_2max$ in elite middle-distance runners. These differences show the regression equation derived from a gun-to-tape 1500m race is required to predict $v\dot{V}O_2max$ and ASR. These findings are of importance to coaches in the field looking to create an ASR profile and monitor ASR modifications across a season.

CHAPTER 10: OVERALL DISCUSSION AND CONCLUSION

Chapter 10

10.1 Summary of Findings

The modern-day middle-distance running coach has the ultimate programming puzzle challenge. Faster race sectors than ever before are apparent in the men's 800m (Chapter 3), while the 1500m last-lap kick and tactical surging scenarios appear to differentiate the medallists in championship competition (Mytton et al., 2015). Clearly, this 'need for speed' highlights the importance of developing and maintaining not only a highly efficient aerobic system, but additionally, in order to create 'medal differentiating moments', possess or develop an equally important anaerobic speed reserve (ASR).

To date, the profiling of middle-distance runners has been dominated by documentation of their aerobic characteristics (Berg, 2003; Thompson, 2016). However, the research presented throughout my thesis suggests that concurrent attention is required towards appreciation of the neuromuscular and mechanical aspects contributing to middle-distance race performance. The ASR is a construct that represents the speed range from $v\dot{V}O_2max$ to maximal sprint speed (MSS), both underpinned by diverse performance determinants. Therefore, ASR provides a first layer profile for determining an athlete's efficiency at maximal oxygen uptake and their limits of ground reaction force expression (at MSS). These two variables alone provide insight into the strengths and weaknesses of an athlete, and where opportunities for training progression may lie. While undoubtedly there may be deeper layers of physiological and biomechanical constructs that could be explored (thresholds, running economy (RE), ground reaction forces), the ASR, as outlined throughout my thesis, may offer the coach a potential assessment tool to help guide their training prescription.

Appreciation of the ASR required to compete in a middle-distance event, and specifically the surge split demands, is an important outcome from this thesis. For example, to run an 11s 100m sector relaxed in the first 200m of an 800m race, a 100m pb of approximately

10.6-10.7s may be required. For athletes in the 1500-10,000m events, a parallel approach can be applied to longer race sectors. For example, if the demand of the last lap of a 1500m is 50s, a 400m PB of 47-48s may be required to be able to perform this in a fatigued state.

Importantly, at some point, the ASR can be a limiting factor to an athlete's 'last-lap' closing speed. Therefore, coaches and athletes should ensure that: a) the ASR range is not limiting the athletes 400m potential, and b) with the MSS they do possess, the mechanical transition of that speed, through stride length and frequency adjustment, is optimised to enable efficient utilisation of the speed possessed at 800m race pace.

Considering the aforementioned, the overarching aim of this thesis was to further develop understanding of the physical qualities and tactical behaviours underpinning race surging in the men's 800m, with specific reference to the anaerobic speed reserve. A further aim was to provide frameworks that may assist to unravel the complexity of middle-distance running profiles in the hopes of developing more individual training and assessment approaches.

To address these aims, the following key questions were asked in each of the thesis chapters:

Chapter 3 – Study 1: What are the modern day tactical behaviours of the Men's 800m medallists at World Championship and Olympic Games events? How fast are the fastest 100m sectors, and has this changed over time?

Chapter 4 – Study 2: What are the tools available to measure the anaerobic qualities of the 800m runner?

Chapter 5 – Study 3: Do anaerobic speed reserve differences appear to exist between 800m and 1500m runners and within the 800m event group?

Chapter 6 – Study 4: How fast is the MSS in elite 800m runners? What is the relationship between ASR and 800m performance in an elite cohort? Can the ASR be used as a tool to better understand the variability that presents within a middle-distance athlete's profile?

Chapter 7 – Study 5: How does the ASR enhance surge capability? What is the relationship between MSS and 400m season's best? What are the requirements of smooth transitions between paces in an 800m race? What is the role of running economy vs. race pace efficiency for an 800m runner?

Chapter 8 – Study 6: What are typical training volumes of elite 800m runners? How does this differ across 800m sub-groups? What are the considerations for developing the aerobic system in a 400- 800m runner? What are the considerations for developing MSS in an 800-1500m runner?

Chapter 9 – Study 7: What is the validity of using a 1500m race performance to estimate laboratory v$\dot{V}O_2$max in elite runners? How should the ASR construct be implemented in the field?

The following section discusses the key findings from each of the chapters, along with the inter-relationship between the chapters.

Chapter 3 - Tactical Behaviours of Men's World and Olympic 800m Medallists

In my first study, I examined the longitudinal patterns of tactical behaviour performed by medallists in the men's 800m from 2000-2016. The study involved video analysis of each 100m sector to explore potential changes in pacing strategy, and surging speed. From 2009 onwards, it was found that men's 800m medallists ran faster first laps, and more 'gun-to-tape' pacing strategies than the 'sit-and-kick' 2000-2009 era, the latter format tending to parallel the typical 1500m race tactic (Mytton et al., 2015). Thus, the modern-

day men's 800m and 1500m events appear to have independently taken a divergence in their tactical behaviours, which may require different physiological characteristics related to performance (chapter 6).

From this analysis, the fastest 100m sectors within the 800m were on average 0.5±0.2 m/s (0.8±0.2s) faster from 2011-2016 than 2000- 2009, representing faster race demands. Most commonly the fastest sector was between 100-200m. These findings have substantial implications for the type of physiological and mechanical profile that may be required to perform a fast first 200m, and then be able to sustain 800m race pace for a further 600m.

Naturally, 800m championship racing and the required rounds performed will require an athlete with capacity to perform both gun-to-tape and sit and kick type strategies (Hanley & Hettinga, 2018; Jones & Whipp, 2002). Thus, training programmes should prepare athletes for both scenarios. The results of this chapter show a speed demand surpassing previous eras when the race is run in the 'gun-to tape' style, revealing important implications for training, tactical preparation and talent identification of 800m athletes.

Further, this study showed extremely large (r=0.94) correlations between athletes with higher world rankings prior to the championships and adoption of a positive pacing approach. Therefore, an athlete with high ranking, possessing both the speed to perform early surges and the aerobic capability to limit fatigue in the last 100m of the race, may maximise the chances of a podium finish through adoption of a positive pacing strategy. These findings raise the question of whether grouping 800m and 1500m athlete profiles (Ingham et al., 2008) is now appropriate given the faster speed demands highlighted in the men's 800m; a topic that was subsequently explored in Chapters 5 and 6. First however, this study highlighted the need for assessment of the tools currently available

to measure anaerobic energetics, as this may in part be a characteristic differentiating surge capability in the modern day 800m runner from their 1500m counterparts.

Chapter 4 – Anaerobic Energetics of Middle-Distance Running Performance

To better understand the qualities underpinning faster tactical behaviours, I revisited the tests currently utilised within the running literature to assess anaerobic energetics; a potentially important component of an athlete's ability to surge. Understanding the reliability of the current methods used for characterising workloads beyond $\dot{V}O_2max$ with average 800m race pace ~115-130% $\dot{V}O_2max$ was an important next step to inform the PhD direction.

Measurement of anaerobic energetics has long been problematic for the sport scientist (Davison, van Someren, et al., 2009). Indeed, current methods overall revealed a poor degree of validity and reliability. Further, where methods were more reliable, they were impractical to utilise with an elite population for anaerobic energetic assessment. Briefly, critical speed laboratory protocols showed a 7.96s (5.4%) error in 800m prediction. Maximally accumulated oxygen deficit (MAOD) methods showed a coefficient of variation (CV) of 4-10% (Medbø et al., 1988). The MART revealed inconsistent testing protocols across the literature and did not consider individual differences in mechanical efficiency which is likely a key determinant of performance on the test.

With a lack of appropriate tools to characterise anaerobic energetics, a step forward was needed to better understand the necessary speed range required to achieve the modern-day surge demands – the ASR became the designated tool. Indeed, the upper portion of the ASR, the MSS, had a CV of only 1.1% using radar technology, and was a feasible assessment tool for integration within the daily training routine of an elite 800m running population. Practically assessing $v\dot{V}O_2max$ however was more problematic, and this became the emphasis of chapter 9.

In summary, the ASR offers a practical and reliable step forward in defining an athlete's mechanical and neuromuscular ceiling for middle-distance running performance. These measures provide a 'box tick' for coaches around ensuring athletes have enough MSS to manage individual 100m sector demands in the 800m and the 1500m – 10,000m closing stages. Whilst the ASR does not depict the anaerobic energetics per se, it does provide the ceiling of non-sustainable force production and thus becomes a framework to optimise 800m race pace running, which is expanded on in Chapter 7. Determination of normative ASR values and the differences in profiles between world-class 800m and 1500m runners were both explored (Chapter 5) and tested (Chapter 6) in other studies as part of this thesis, to evaluate the relevance of the ASR construct to middle-distance running performance.

Chapter 5 – Estimating the ASR in World Class Male 800m and 1500m Runners

Understanding the characteristics underpinning running performance is a key objective of researchers, practitioners and coaches working with athletes. Having identified the potential opportunity of the ASR measurement in Chapter 4, that has important implications for race demands highlighted in chapter 3, here using estimation equations I tested the differences in ASR in world-class 800m and 1500m populations. The aim was to enhance understanding of ASR interrelationships in the middle-distance population, and specifically consider whether ASR could differentiate athletes within and between events.

The 30 fastest male 800m and 1500m runners from 2016 were selected from performance times across 400, 800m and 1500m. These times were substituted into previously validated equations (Bundle et al., 2003) to estimate each athletes $v\dot{V}O_2max$, MSS and ASR. Trivial and unclear differences in predicted $v\dot{V}O_2max$ were shown between 800m

and 1500m athletes. However, the MSS of 800m runners was most likely greater than that of 1500m runners. Whilst this may seem somewhat of an obvious conclusion as race demands are more divergent, the events are still today often assumed to be similar (Ingham et al., 2008). Indeed, in previous eras, athletes often "doubled up" to compete in the 800-1500m events. The estimations in this chapter suggest this is no longer the case.

Not only were the MSS and ASR differences substantial, but upon assessing the individual data, large individual variability within 800m athlete profiles was found that may have important implications for training approaches, race tactics and talent identification for sporting organisations. These estimations confirmed the need to further investigate the ASR construct using direct ASR measurement in an elite male middle-distance population, which lead to the focus of chapter 6.

Chapter 6 – Anaerobic Speed Reserve: A Key Component in Elite Middle-Distance Running

Following the estimations in chapter 5, it was clear the ASR could answer the question of 'how fast is fast enough?' in relation to the MSS demands required to manage the race surging illustrated in chapter 3. However, the estimation error within the predictions meant direct measurement was required of the ASR in an elite population. Further, the ASR showed promise in differentiating both between 800m and 1500m event specialists and within 800m sub-groups. Long standing coaching observation (Gamboa et al., 1996; Horwill, 1980) suggested there were three 'sub-groups' of 800m runner; speed types (400-800m), specialists (800m) and endurance types (800-1500m). However this was yet to be demonstrated or realised within the scientific literature (Bachero-Mena, Pareja-Blanco, Rodríguez-Rosell, et al., 2017; Bachero-Mena, Pareja-Blanco, & González-Badillo, 2017; Ingham et al., 2008). To directly address, I travelled to locations around

the world to test elite participants in their local training environment in the search for answers to the aforementioned questions.

ASR Profiling of 19 elite 800m and 1500m athletes revealed fruitful findings for the middle-distance community. First, a greater MSS (and therefore ASR) had a very large correlation with a faster 800m. Importantly, for the same MSS, having a greater MAS or ASR wasn't strongly related to changes in 800m time. This is a novel contribution that counters historical research assessing elite 800m runners, perhaps a sign of the strictly elite cohort in the present sample (Ingham et al., 2008). Put simply, in this elite population, a larger ASR was only important when it was as function of a faster MSS. MSS may therefore be a key component of differentiating the 1:47 800m runners from the 1:44-1:45 800m runners. However, attaining a time of 1:47 is contingent on already having a certain level of aerobic development ($v\dot{V}O_2max$, lactate threshold). Therefore, concurrent development of both elements of the ASR should always be forefront of mind for the coach in training programme design.

A key question from Chapter 3 was 'how fast is fast enough'; the answer to this question appears to be ~10 m/s from the present study data in elite level athletes. However, the gap between 1:44 and 1:40.91 (world record), remains unanswered – does the world record holder have larger capacities or is he more efficient with what he has? One can speculate that it may be an element of both.

For the first time, taking a scientific approach, three athlete sub-groups (400-800, 800m specialists and 800-1500) were revealed in this study, supporting longstanding coach observations (Gamboa et al., 1996; Horwill, 1980). Variation between the three clusters of 800m athletes could be best explained by ASR, SRR and 800m PB (r^2=0.87). Therefore, measurement of the ASR becomes an important marker for a coach, as the

800m sub-group may change over time depending on longitudinal adaptation to different training blocks.

The speed reserve ratio (SRR) taken from MSS/MSS is a practical tool (not requiring a cluster analysis) that can reveal individual variation in 800m athlete profile for coaches in the field (building on our modelling estimates in chapter 5). This framework enables training application for the coach, as will be described in chapter 8.

An important contribution of the present study was the global and truly elite representation of the study sample. Previous studies in 800m are limited to collection from one nation (Ingham et al., 2008). With reference to the study by Ingham et al. (2008) British 800-1500m running is notoriously known to take an aerobic training approach, as used successfully towards Steve Cram, Sebastian Coe and Steve Ovett's performances in the 1980's across both 800m and 1500m. Such cultural bias can skew interpretations and be misleading. Thus, the current cohort collected across 8 countries may lower bias, providing a more representative sample of the global 800m population.

Chapter 7: Maximal Sprint Speed and the Anaerobic Speed Reserve Domain; the Untapped Tools That Differentiate the World's Best 800m Runners

Whilst MSS and ASR demonstrated large and very large relationships with 800m performance in chapter 6, the term 'speed', within coaching vernacular, can result in a variety of different prescription outcomes. However, subtle but important differences may exist. The first aim of Chapter 7 therefore, was to specifically contextualise the role of MSS and the ASR domain for 800m running to enable more accurate application of training speed both in the field and for scientific research.

As I showed in Chapter 6, MSS explained 55% of the variance in 800m performance. This suggests that, generally speaking, a larger MSS may allow for an athlete to adjust

technique and apply more force as race surges demand (see Chapter 3). Additionally, a faster MSS, lowers the proportion of ASR at race pace, reducing the physiological strain of a given pace (Buchheit, Hader, et al., 2012). Further, middle-distance coach education has long focused on the important aerobic determinants of middle-distance running. Consequently, this has often been at the relative expense of neuromuscular and mechanical performance determinants (Berg, 2003). In light of the aforementioned, the present chapter aimed to address these factors under the ASR framework.

In middle-distance coaching, an athlete's 400m time is often used to represent an athletes' 'absolute speed' capability, which guides event specialisation, race splits and pacing strategies (Gamboa et al., 1996). As was shown very clearly in Chapter 7, this is an erroneous method with large variance in 400m sb (47.2-49.4s) across a group of 800m athletes with MSS ranging from 9.75 to 10.17 m/s. An MSS and 400m sb correlation of (r=0.59) was found, where MSS only explained 35% variance in 400m performance. By comparison, a very large (r=0.88) correlation, where MSS explained 77% of 400m performance, was found in national USA and Finnish 400m specialists (Nummela et al., 1996).

Differences in the transfer of MSS to 400m time may arise partly out of a training approach. Alternatively, 800m athletes have larger aerobic capabilities, and the limitation of performance less than 60s lies in the mechanical/neuromuscular component, and not aerobic energetic supply (Bundle & Weyand, 2012). Moreover, one area often overlooked in middle-distance is the ability for the athlete to smoothly self-adjust stride length and frequency between fast paces, which may enable an efficiency in race surges (Enomoto et al., 2008). Without extensive biomechanical analysis of elite men's 800m running to date, a biomechanical analysis of the men's 10,000m final from the 2007 world championship event was used to illustrate the importance of having an ASR to be able to

increase force orientation on the last lap. Without it, performance potential may be restricted, even with an excellent running economy (RE) (Enomoto et al., 2008).

Commentators often refer to middle-distance runners as having ‘efficient, smooth and relaxed technique’ (Bushnell & Hunter, 2007; MacPherson et al., 2009). Historically, RE has been incorrectly linked to such efficiency whereby assessment at 16-20km/hr (RE) is vastly different from the mechanical requirements at 800m race pace, e.g. even 1:45 800m pace is 27.4 km/hr (Bertuzzi et al., 2018). One of the likely factors explaining part of the remaining 55% variance in 800m performance (from chapter 6) is the mechanical efficiency at 800m race pace. A pertinent issue here is the current inability to accurately quantify the metabolism underpinning this pace, due to the large anaerobic component as highlighted in chapter 4. Yet, surges and transitions from this pace are key differentiators between medallists, so future investigations must continue to explore this phenomenon.

Chapter 8: Training the Elite Male 800m Runner; Addressing the Complexity of Diverse Athlete Profiles

The data in Chapter 6 supported longstanding coaching observations as to the existence of three distinct 800m runner sub-groups (Gamboa et al., 1996; Horwill, 1980). These can be broadly classified as 400-800m runners, 800m specialists and 800-1500m runners. Such diversity coming to the start line of an 800m event means that a uniform training approach across all 800m runners is inappropriate. Currently however, acknowledgement of this diversity within middle-distance science literature is absent. Chapter 8 presented four weeks of training data during the competition phase from the elite cohort studied in chapter 6. Training volumes were substantially different between subgroups, with large variance shown even within each sub group. E.g mileage for the 400-800 athlete was 62.1±18.1 km/week compared to 118.3 ± 27.5 km/week for the 800-1500m athletes.

These results reaffirm the need for identifying the athlete profile and subsequent sub-group prior to selection of the training approach. The SRR from Chapter 6 offers a framework to help inform this process. For example, on assessing a new athlete entering the training group, a coach would currently look at 400m, 800m and 1500m time to identify the 'sub-group'. With the error illustrated in chapter 7 of using 400m to identify speed, testing MSS and, $v\dot{V}O_2max$ to develop the SRR (chapter 6) adds a further tool to aid the coach in identifying the athlete's sub-group. As well, once sub-group is determined, this may help guide the training application of different stimuli for 800m runners, where differences in training density and magnitude of each stimulus across the sub-groups is required. Density and magnitude is defined as Frequency + Volume*Intensity; together meaning how much and how often training occurs within a week, month or cycle.

Subsequently, this paper addressed training solutions for developing the weaker 800m subgroup's attribute. Namely the aerobic component in 400-800 athletes and MSS in 800-1500m athletes. The aerobic oxidative stimulus for a 400-800m athlete may be best introduced using a combination of short interval training and continuous threshold running. Classic continuous long slow distance approaches that fall outside the athlete's mechanical bandwidth of comfort is unlikely to be a successful endeavour in the initial stages. Concerns of introducing the MSS stimulus in 800-1500 (and up to 10km athletes) usually consider injury risk and the neural fatigue as reasons for avoidance. This chapter argued that small but frequent doses of this work may build this quality if underpinned by good foundations in high frequency/plyometric movement and correct mechanics (Blagrove, Howatson, & Hayes, 2017; Maćkała et al., 2015; Rabita et al., 2015; Weyand & Davis, 2005). Once more, density of application is critical, where too much or too little increases overall injury risk (Malone et al., 2017). Introduction of MSS to the unaccustomed athlete may be an 18-month pursuit to develop the structural integrity and

load adaptation/comfort with the stimulus, as often MSS isn't widely employed across all 800m training paradigms. Additionally, the MSS stimulus (<7s) should be differentiated from speed endurance (up to 15s), or specific endurance (15-60s) (Crick & Evely, 2011), as the prolonged efforts with speed endurance or specific endurance substantially increase the neuromuscular/musculoskeletal system stress, as well as anaerobic glycolytic system engagement and resulting load (Buchheit & Laursen, 2013a).

The ability to accelerate at the beginning of an 800m race has important tactical significance, as shown in chapter 3 (Filipas et al., 2018; Sandford et al., 2018). This ability allows the athlete to be in a good position at the break out from lanes (100m into the race) and is potentially the fastest section of the race (see Chapter 3). The initial acceleration to overcome inertia provides the largest metabolic power (and thus energy cost) in an 800m race (Di Prampero, 2005; Martin et al., 2007). Importantly, this quality is rarely addressed in 800m training paradigms (chapter 7). The message here is that this needs consideration in the programme at low but frequent densities, as described by MSS. Improving efficiency in initial acceleration allows conservation of energetic resources for later in the race (Martin et al., 2007), perhaps reducing deceleration in the last 100m of the race.

Chapter 9: Implementing Anaerobic Speed Reserve Testing in the Field: Validation of v$\dot{V}O_2$max Prediction from 1500m Race Performance in Elite Middle-Distance Runners

Compared to MSS, which can be accurately measured using radar technology (Haugen & Buchheit, 2016), timing gates or hand timing in the field. The v$\dot{V}O_2$max is more challenging, typically requiring laboratory-based procedures (Billat & Koralsztein, 1996). Without an easy-to-administer practical measurement, application of the ASR construct would be limited to those with access to laboratory testing. Additionally, in

chapter 6 for the primary researcher to capture the ASR profiles of elite middle-distance runners in competition season a gun-to-tape 1500m race was utilised for MAS estimation, using field derived validated equations used previously in an AFL population (Bellenger et al., 2015). The importance of chapter 9 therefore was to determine the relationship between average gun-to-tape 1500m speed and $v\dot{V}O_2max$ collected in the laboratory in an elite middle-distance running population. A second aim was to produce a regression equation enabling the use of a 1500m race time to predict the $v\dot{V}O_2max$ component of the ASR, making this method easy to integrate in the field for coaches. In addition, ASR differences between the two methods were calculated (ASR-LAB and ASR-1500_v).

In early competition training phase, eight national and four international middle-distance runners completed a laboratory measured $v\dot{V}O_2max$ assessment within six weeks of a non-championship 1500m gun-to-tape race (1500_v). 1500_v was on average +2.06±1.03 km/hr faster than $v\dot{V}O_2max$. ASR-LAB and ASR-1500_v mean differences was -2.1± 1.5 km/hr. 1500_v revealed an extremely large relationship with $v\dot{V}O_2max$ in the lab. Overestimation of $v\dot{V}O_2max$ from 1500_v represents the clear need for an adjustment equation to be used for field application. Therefore, with one less calculation step than Bellenger et al., (2015), a predictive equation for estimation of $v\dot{V}O_2max$, from the average speed of a 1500m gun to tape race was produced; $y = 0.4266x+14.291$. Where $y = 1500_v$ and $x = v\dot{V}O_2max$.

Chapter 9 showed a larger ASR was related to a slower 1500m time. Interestingly this contrasts our finding in the 800m (Chapter 6), that may reflect the large difference in aerobic component for 1500m (88%) and 800m (66%) (Spencer & Gastin, 2001), highlighting an important principle in applying the ASR construct. That is, the ASR (e.g. an 11 km/hr bandwidth) needs to be provided within the context of an athlete's MSS (35 km/hr) and $v\dot{V}O_2max$ (24 km/hr), so that the complete picture of middle-distance running capability is appreciated. Indeed, ASR in isolation is not indicative of athlete calibre. In

this scenario, the faster athletes had a faster $v\dot{V}O_2max$ (and therefore smaller ASR). The MSS requirement in this case is to make sure the 1500m runner has enough to meet the event demands for closing speed of a slow race. Therefore, concurrent development and assessment of $v\dot{V}O_2max$ and MSS over time is paramount for the athlete and coach.

Moderate differences exist between 1500v and $v\dot{V}O_2max$, and large differences exist in ASR between methods. Thus, a regression $v\dot{V}O_2max$ equation derived from gun-to-tape 1500m racing is required for field utilisation with elite middle-distance runners. Using 1500_v alone without the corrective equation will provide error of prediction four times greater than the SWC, leading to an erroneous measurement for determining changes in an athlete's ASR over time.

From the present study, without requiring access to a sports physiology laboratory, coaches now have a practical way of assessing $v\dot{V}O_2max$ from a gun-to-tape 1500m race. Importantly for 800m specialists in their competitive season, by nature of specialisation, may not run a competitive 1500m race. Despite this, coaches may be interested in their athlete's current '1500m shape'. The method proposed in this thesis enables a 1500m performance estimation from $v\dot{V}O_2max$ in the lab, allowing application of ASR throughout the season.

10.2 Limitations

Although the thesis has advanced the understanding and application of elite 800m tactical behaviours, anaerobic speed reserve profiles, elite 800m sub-group complexity, and individual 800m assessment and training approaches, it is acknowledged that there are some limitations to the design and procedures adopted. Accordingly, the following limitations should be considered:

i. Whilst 13 championships were assessed in chapter 3, only seven of the championships had adequate footage of 100m splits of all medallists to warrant

inclusion in the analysis. Recent work in diamond league performance also illustrated the fastest race sector of the men's 800m as the first 200m of the race (albeit with pace makers) but with resolution to only 200m sectors (Filipas et al., 2018). Our results therefore show the importance of resolution for tactical analysis within 100m sectors. In addition, Filipas et al. (2018) support our notion that when the men's 800m race unfolds in a gun-to-tape strategy, the first 200m is the fastest sector and of critical tactical importance.

ii. A limitation of the sample collected in chapter 6 would be a more equal distribution of athletes across 800m sub-groups. First, all athletes tested were within the top 200 athletes in the world in 2017 and therefore an extremely high-level population. Access to testing elite athletes in groups I am not working with (in New Zealand) is a rare opportunity within the high-performance environment, therefore to achieve optimal numbers in each sub-group is of the upmost difficulty, not to mention the substantial geographical and financial challenge of such a pursuit (where with the present sample I visited 33 high performance centres across 8 countries over 6 1/2 months). Further with the change in event demands seen, and cohort analysed in chapter 5 it was clear there was a larger distribution of 800m specialists and 400-800 athletes than perhaps perceived in the middle-distance community (Ingham et al., 2008). Therefore, it may be a reality that less 800-1500m athletes are now being developed, as their probability of success (due to the extreme MSS qualities found in this event group) result in more 1500m specialists than 800-1500m participants making a 'normal' distribution of this population an unrealistic expectation.

iii. Some exceptional athletes were excluded from the sample in chapter 6 running ≥1:47.50 but spanning 800-1500 and 5km events with elite 1500m (3:36-3:41) and 5km (13:48-13:05) performance standards. This creates definition around the

800-1500m sub-group challenging. First such broad event specialisation seems most likely influenced by exceptional aerobic capability, alongside, athlete identity, cultural bias or coaching philosophy, without inspection of neuromuscular and mechanical qualities. Those who had success in both sit and kick scenarios versus those who were only strong in gun-to-tape races were differentiated by ASR, it seems a larger ASR may empower more tactical options.

iv. Utilising a race to estimate $v\dot{V}O_2max$ was appropriate for our logistical constraints of data collection, but the inherent variability of racing should not be ignored. To mitigate the inherent variability of tactical 1500m racing, utilisation of gun-to-tape 1500m race pacing is paramount. Field use of this method should ensure utilisation of the regression equations from chapter 9. Further it is noteworthy to reiterate the inherent variability in physiological laboratory measurement whereby $v\dot{V}O_2max$ CV is 4-5% (Billat et al., 1996) compared to the variability of elite middle-distance racing ~1% (Hopkins, 2005).

v. Due to the logistical and performance environment constraints of chapter 6, only a one-time snapshot of MSS was captured. Therefore, the assumption is that this was a valid and reliable representation of MSS capability. A confounder of this assessment is the variable training loads between squads and athlete sub-groups. However, by keeping collection in late pre-competition and early competition phase of training, athletes were tested at a time of season when they were under lower training volumes than in the cross-country season. Whereby athletes at that time of year are performing faster training sessions and therefore achieving speeds closer to their true maximum velocity.

vi. Chapter 8's training data was only across a 4-week sample prior to the testing day, during the competition season. The unique nature of the methodological collection in chapter 6 and 8 meant that testing had to be conducted minimizing disruption

to the performance training environment and coaching schedule to the squad I was visiting. Whilst our findings provide some insight, there is a need to characterise differences in key training metrics longitudinally.

vii. Further, it was not viable to capture v$\dot{V}O_2$max on the same day as MSS assessment in chapter 6. In an ideal world, these would be conducted in as close a proximity as possible. With participants scattered across eight different countries, within different professional, collegiate and national federation competitive schedules, it was decided a six-week window was an appropriate balance between our logistical reality and minimising the change in aerobic adaptation between MSS assessment.

viii. Throughout chapters 7 and 8 there are numerous hypothetical figures that need to be proven in studies. This is because as shown in chapter 1, only 11 papers had been written on ASR prior to the commencement of this PhD, and 0 in middle-distance running. It is our hope the work in the current thesis opens a new line of investigation for sport scientists in this area.

10.3 Practical Application and Significance

The following section will provide an overview of the key practical applications and significance of the studies undertaken in this thesis. How this thesis advances the field is displayed in figure 10.1.

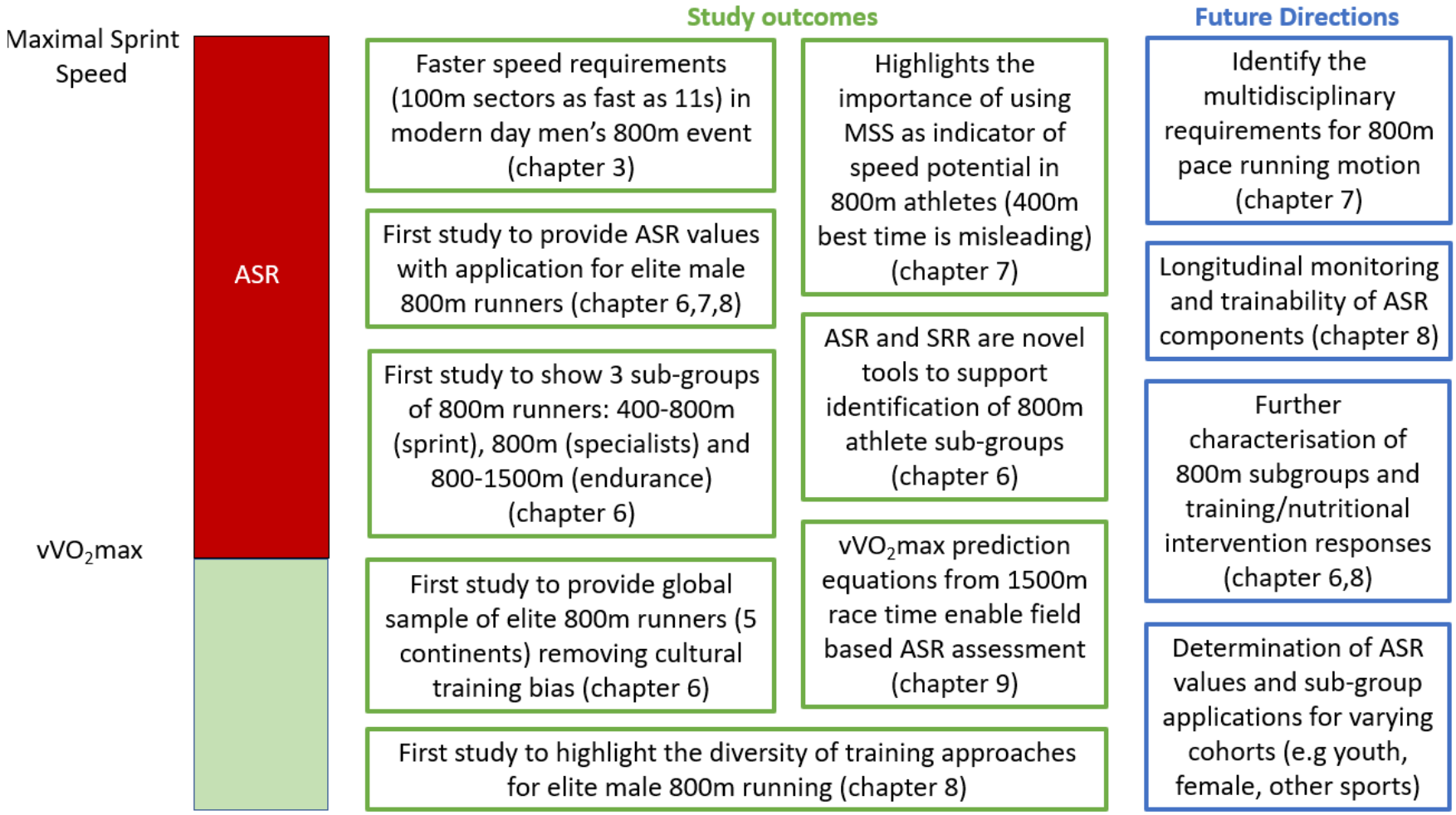

Figure 10.1. How this thesis advances the field

Chapter 10

Race Tactics of Middle Distance – What Differentiates the Medallists?

A key component underpinning the planning of an athletes training is a clear understanding of the event demands which form part of the formula for achieving performance goals. My findings highlight athletes possessing both large MSS and $v\dot{V}O_2max$, if highly ranked leading into the major championship may limit the medals to only those who also possess a large MSS and $v\dot{V}O_2max$ by running a gun-to-tape strategy in the final. Whereas a sit and kick tactic leaves the door open for everybody (Chapter 3). Indeed in 2007, the athlete ranked 37th ended up winning the world championship gold medal as the race first lap was 56s and won in 1:49 (min:ss) (a slow overall finishing time). Developing both ASR components is important for an athlete to be competitive in a multitude of possible surging scenarios (Jones & Whipp, 2002).

If an athlete's goal is to medal at a major championship (Olympic Games or World Championships), the following decision making tree provides important framework (Figure 10.2) for assessing performance goals. It is important to note, the factors discussed in that framework purely relate to the physical, whereby psychological, identity, cultural drivers and support structures are important for making the best decision for an athlete's event specialisation.

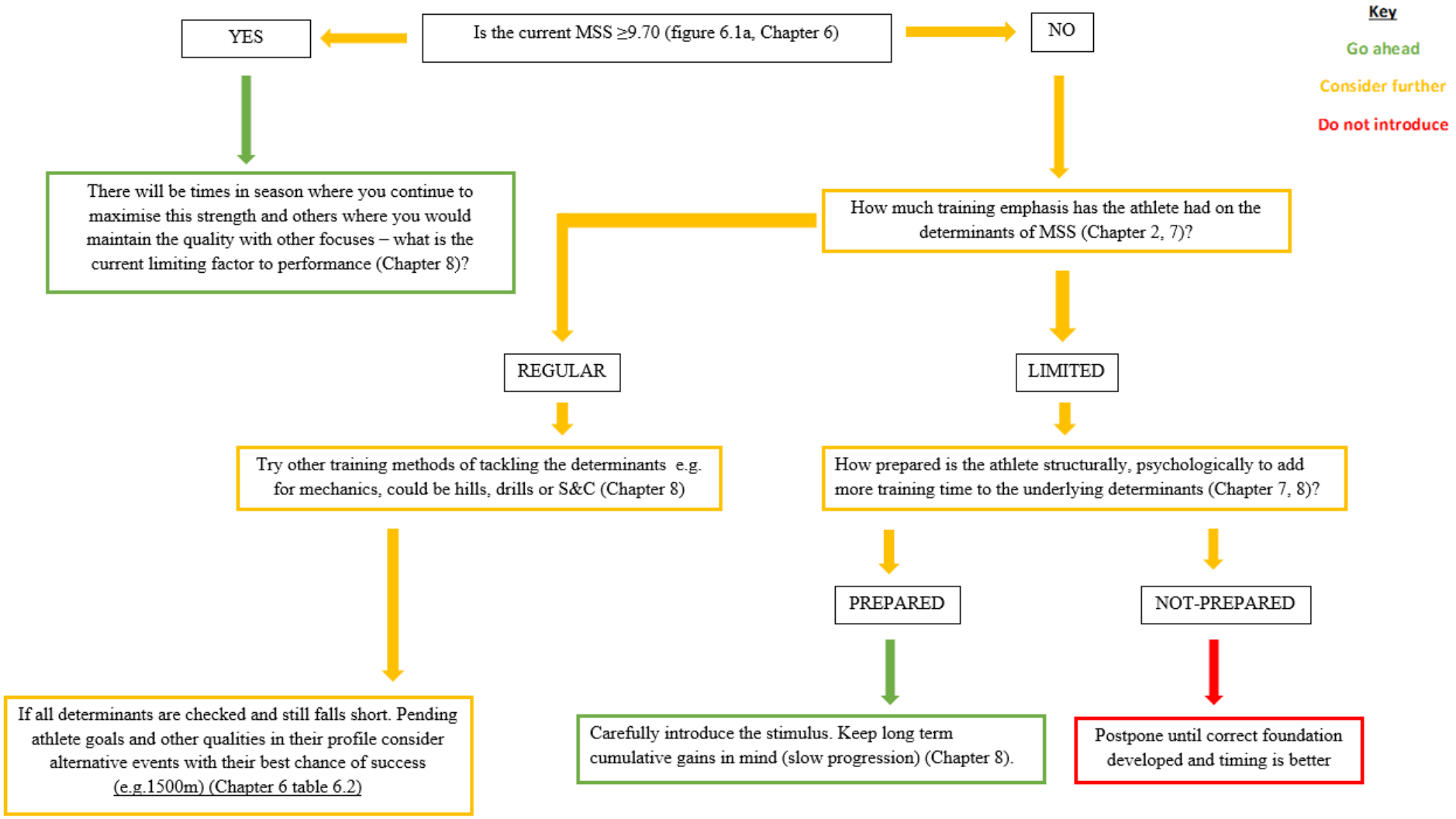

Figure 10.2. Application of maximal sprinting speed (MSS), from testing results to training implementation with distance runners

Anaerobic Speed Reserve – How Much is Enough – Contextualising Application for Middle-Distance

ASR provides a framework ensuring the athlete is equipped for the surge demands of a race. This could be applied to a 11s 100m sector in the men's 800m or in the last 400m of a 1500m or 10,000m race.

A common argument is 'I'm not currently in the lead pack in races and therefore am limited aerobically and not by my MSS'. Whilst that may be, the recommendation from this thesis is not that the training programmes shouldn't be concurrently developing the aerobic system, quite the contrary. What is strongly suggested is that waiting to develop MSS until you are in that lead pack, may be more challenging. In addition, a larger ASR (through function of a faster MSS) enables faster race paces at lower physiological strain, assuming concurrent metabolic conditioning to support non-sustainable force production (Buchheit, Hader, et al., 2012). MSS is a skill requiring co-coordinative and mechanical development as considered in chapter 7 (MacPherson et al., 2009). Concurrent development of these skills from the athlete development stages means that once the aerobic system has developed to a mature degree (Coyle et al., 1988), the athlete will have tactical flexibility in their armoury to be competitive in all race surging scenarios.

How Can We Better Understand the Complexity of Middle-Distance Running? A Road to Individualising Training Approach

The findings in the present thesis around training approach (Chapter 8) and the inherent diversity of 800m sub-groups (chapters 5 & 6) suggest complexity can be better understood by a training approach front-footed by the athlete's sub-group characteristics. The following checklist (figure 10.3) may aid a coach's decision-making to account for the sub-group diversity in training planning:

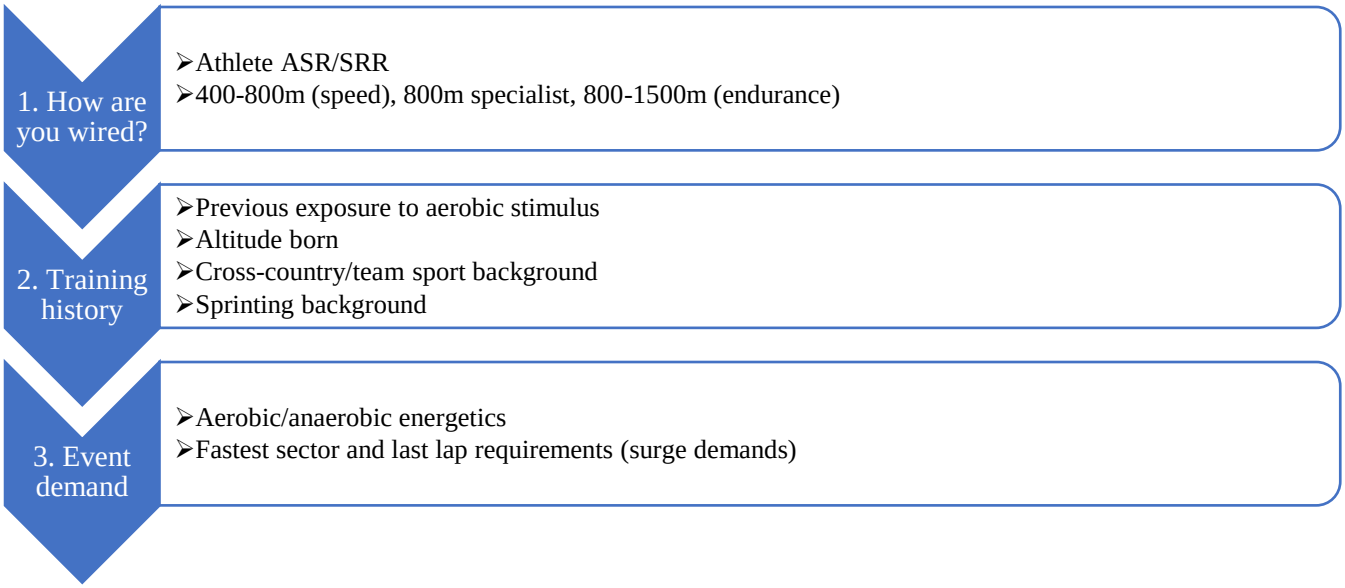

Figure 10.3. Decision making process to select 800m athlete training approach.

It is clear a 'one-size fits all' training philosophy would be inadequate for the complexity of the 800m. Neither volume only or intensity only paradigms are optimal for the 800m athlete, and a paradigm of both is required for optimal athlete development, with nuance in the application of stimulus to athlete sub-groups (Chapter 8). Perhaps it is not a puzzle, just acknowledgement of individual differences is key in developing an appropriate training approach (figure 10.3). Whilst recognising the logistical constraints for coaches working with larger squads, the ASR/SRR framework (Chapter 6) enables a coach to categorise their squad into sub-groups and therefore provides more nuance in application of different stimuli to a sub-group as described in Chapter 8.

The aim of this method is not to deter coaches from the inspection of detail and resolution in athlete profiles (through assessment of lactate threshold/running economy), but to provide something that is practical in the field to conduct, across large numbers. ASR may act as a bridge between coach and sport scientist that may lead to more questions, and a better collective understanding of training complexity moving forward.

Future Middle-Distance Research Methodology – Time to Delve Deeper?

Middle-distance running at the Olympic level has typically considered events ranging from 800m to 5000m (Lacour et al. 1990). The findings in this thesis suggest that such a broad grouping of middle-distance may no longer be appropriate with the inherent athlete diversity shown within the 800m. By focusing on 800m through to 5000m when assessing the impact of conditioning or nutritional interventions on 'middle-distance performance', one must consider a broad range of athlete profiles across the aerobic and anaerobic spectrum. Thus, a suggestion would be to address S&C and nutritional requirements for 800-1500m, and 3000-5000m as separate entities as seen in analysis by Daniels (Daniels & Daniels, 1992).

Furthermore, 800m sub-group categorisation, as highlighted throughout my thesis, should be assessed and reported within methods sections of scientific-related manuscripts, or at least a distribution of performance times across multiple distances. This would provide important insight into the effect of interventions on sub-group responses. Whilst this may be a paradigm shift for authors, this is an important step forward in deepening our understanding of the complexity of middle-distance running.

Middle-Distance Running Efficiency – More Than Just a Physiological Pursuit

Measurement of middle-distance running efficiency has long centred around RE at submaximal paces. Clearly this a paradigm that needs rethinking to truly provide resolution on the efficiency at target 800m race pace (Bertuzzi et al., 2018). Efficiency in the domain beyond CS, and into the ASR is an important discussion recently raised in the literature around quantification of intervention effects beyond critical speed (Denadai & Greco, 2017). Perhaps the best breakthroughs in addressing this question lie in collaborative efforts between the disciplines of biomechanics, physiology and skill acquisition (Bertuzzi et al., 2018; MacPherson et al., 2009).

Not only is efficiency at target race pace important, but having the co-ordination and mechanical awareness to be able to smoothly adjust mechanics across paces as races surge (MacPherson et al., 2009). Sometimes races have pre-surges within a race to achieve favourable tactical position (as shown in chapter 7, figure 7.3), and in the 1500m this may be a pre-cursor to the last lap kick. Those who can perform these transitions with lowest energetic cost may be in the freshest position to strike in the last lap kick of a 1500m or minimise deceleration in the last 100m of an 800m.

10.4 Future Research

As noted in chapter 1 and 2, the work on 'neuromuscular and mechanical determinants' of middle-distance running is relatively scarce in elite populations compared to our understanding of the aerobic component. This thesis raises many new avenues of research questions and opportunities to enhance middle-distance running performance.

First, from a race analysis methodological standpoint, our resolution of every 100m sector, and the important difference that presents in how a 200m split is run (12.5s+11.0s=23.5s) compared to (11.8s+11.7s = 23.5) should be employed in future middle-distance studies. Without capturing this resolution on races, critical information to race performance is lost, and incorrect assumptions are made regarding tactical behaviour and the true performance or energetic demands.

Chapter 4 illustrated anaerobic energetic measurement as the 'elephant in the room'. Much work lies ahead to quantify this important component in a valid, reliable and easy to apply format. It is likely one of the important performance determinants and differentiating characteristics between 800m sub-groups is the D' (so-called anaerobic work capacity). Until more appropriate measures are established, a large element of the middle-distance performance puzzle remains unresolved.

The results of chapter 6 clearly highlight that no-longer should scientific assessment of 800m athletes consider the event group as a homogenous cohort. Methodological sections should acknowledge the athlete sub-groups within the sample using ASR, SRR or as a minimum the presentation of performance times across multiple distances. This information truly matters in the interpretation and application of study findings by the readership.

SRR application to different populations warrants further investigation. For example, running populations that have lower training age, and therefore lower ASR, or MSS capability may skew SRR values outside of the benchmarks stated in chapter 6, thus highlighting important future investigation of how this concept applies to a talent identification context. The overarching concept here is that the variability within a population matters, including gender, training paradigm bias or other. Important outcomes from this research show that sample selection can clearly distort reality within a population, and points to the need for future collaborative efforts to truly answer the large questions.

Chapter 7 highlighted the clear need for better understanding stride length and frequency adjustments across paces in the ASR domain. Specifically, better quantifying the ability to co-ordinate between 800m pace and 'surge' paces in a mechanically efficient way so as to limit energetic cost is a poorly understood concept with important performance implications. How this capability changes across a year is an important question too, with evidence that stride length and frequency (and thus running speed) are sensitive to current training load (Bezodis et al., 2017). Chapter 8 provided insights of sub-group training differences, but further resolution is required. Longitudinal season distributions are sought after, and the fluctuations and trainability of the two ASR components between training phases and seasons is of interest to coaches and practitioners. Data to confirm the aerobic conditioning potential of a 400m athlete is also an important question, whether indeed the 400-800m is a 'transition' phase on

the path to becoming an 800m specialists (as the aerobic component layers and improves over time (Coyle et al., 1988) warrants investigation.

Chapters 7 and 8 highlight the potential that improving acceleration efficiency from the start line may spare energetic resource for the latter part of the race. This hypothetical scenario assumed from data on metabolic power in sprint cycling and 100m sprinting warrant investigation in an 800m population. With different athlete sub-groups, possessing different muscle power characteristics, the acceleration strategy may need to be balanced alongside the need to be in position at important tactical landmarks in the race. Better understanding of these interactions has important implications for race tactics and training planning of 800m athletes.

10.5 Concluding Remarks

In my thesis, the modern-day tactical behaviours in world and Olympic men's 800m runners were assessed, and showed faster first laps and faster individual 100m race sectors than previous eras (2000-2009) (chapter 3). Chapter 4 determined that current anaerobic energetic quantification was unreliable for 800m athlete assessment and that the ASR was the most promising tool as a step forward in this area. ASR estimation from previously established equations confirmed our assertions of the value of ASR as a tool to illustrate the potential neuromuscular, mechanical and physiological limits of world-class male 800m and 1500m runners (chapter 5). Our estimations illustrated large differences between MSS and ASR of 800m and 1500m runners countering claims these event profiles were similar. ASR showed promise as a tool to differentiate and identify sub-groups within and between middle-distance events but warranted direct data collection in an elite population to illustrate this concept.

Original insights from chapter 6 showed that a greater MSS (and therefore ASR) had a very large correlation with a faster 800m. Importantly, for the same MSS, having a greater MAS or ASR wasn't strongly related to changes in 800m time (chapter 6). For the first time with

scientific measurement, chapter 6 revealed three clusters of 800m athletes, defined broadly along a continuum as 400-800m (speed types), 800m (specialists) and 800-1500m (endurance types) supporting long-standing coach observations. ASR, SRR and 800m PB accounted for the greatest variation between the three clusters of 800m athletes (chapter 6). From these findings, chapter 7 offered clarification on 'speed' terminology, which has diverse interpretation and application within the middle-distance community, alongside highlighting multi-disciplinary opportunities for ASR application around defining 800m race pace as skill. Chapter 8 provided novel insights into the training approach of elite 800m running subgroups. Substantial diversity in the training approaches (e.g training volume) was revealed, from example training data collected in the elite population tested in chapter 6. To provide a practical field measure of $v\dot{V}O_2max$ for coaches without access to a laboratory, Chapter 9 established the relationship between gun-to-tape 1500m race performance and $v\dot{V}O_2max$. From this result, regression equations enabling the practical field use of 1500m race time to predict the $v\dot{V}O_2max$ component of the ASR in elite-middle-distance runners. Taken together, the chapters in this thesis have progressed our understanding of the modern-day demands of the elite male 800m runner, with particular appreciation for the utility of the ASR.

The aim of this thesis was to further develop understanding of the physical qualities and tactical behaviours underpinning race surging in the men's 800m, with specific reference to use of the ASR. Based on the present findings, I propose that ASR, and a particularly fast MSS, is a key component of elite men's 800m running. I aimed to provide an evidence-based assessment tool for coaches and athletes preparing for the 800m event, with specific application for Athletics NZ and the wider middle-distance community. ASR is a practical and effective tool for field utilisation, and should support current routine physiological testing to further unravel the understanding of complex middle-distance athlete profiles.

Looking forwards into the crystal ball of using ASR, it is my hope that these findings can be used as a vehicle to shift training approach paradigms towards more of a balance of neuromuscular/mechanical and aerobic training components combined. Finally, by making science more accessible to the field, I hope that more exploratory discussions between athletes, coaches and scientists emerge in the future, ideally contributing to further breakthroughs in athlete performance.

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CHAPTER 12: APPENDICES

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Appendix A1: Participant Information Sheet

Participant Information Sheet

New Zealand Elite Participants

Date Information Sheet Produced:

28/09/2016

Project Title

Defining the role of the anaerobic speed reserve in middle distance running

An invitation

Hi, my name is Gareth Sandford and I am a PhD Student at AUT, as well as Performance Physiologist for High Performance Sport New Zealand (HPSNZ) with Athletics New Zealand (ANZ). I invite you to participate in a project that will help define the role of the anaerobic speed reserve (ASR) in middle distance running (Figure 12.1). ASR can tell us about the inter-relationship between your maximal aerobic and anaerobic capabilities. This is an opportunity for you and your coach to gain fundamental knowledge for your training. The information will help inform individualised training approaches according to your strengths, which may provide competitive advantage for you in the upcoming season.

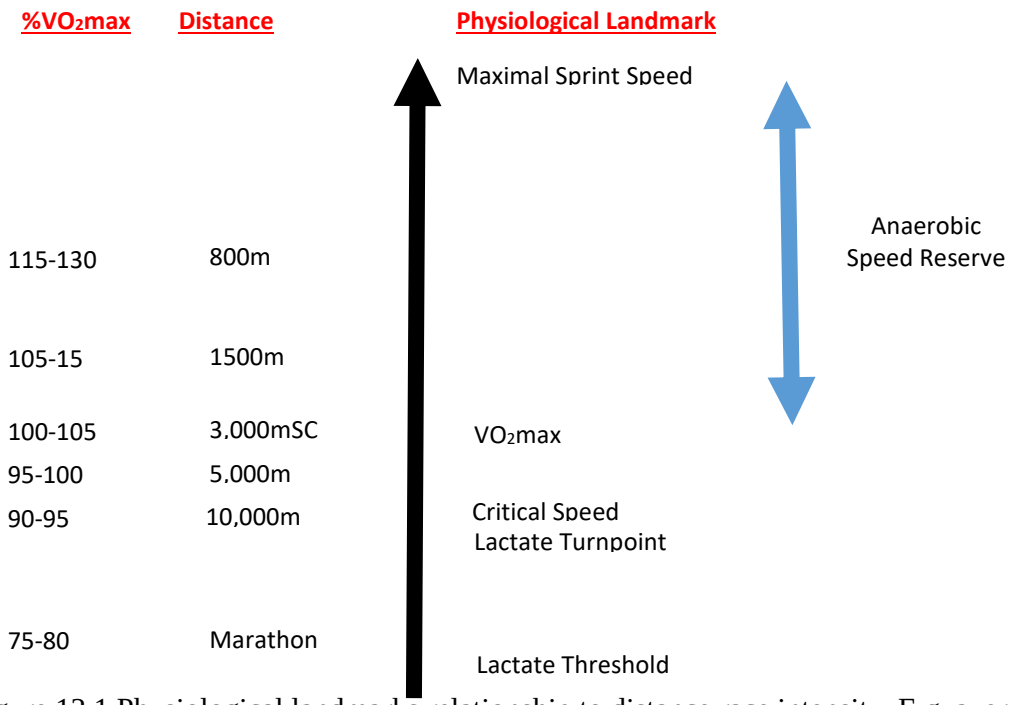

Figure 12.1 Physiological landmarks relationship to distance race intensity. E.g. average 800m race pace is approximately 115-130% of $\dot{V}O_2max$.

What are the benefits?

To yourself:

- You will benefit from this study as you will learn the strengths and areas of opportunity in your physiological profile. In the middle-distance events, both 'sprint' and 'endurance' type runners can end up in the same event, therefore it is important to provide resolution on your strengths in order to individualise your training and potential racing approach.
- The experience and information will be valuable for you and your coach in aiding the next direction for your training, and laying a benchmark for future follow up to see if training has affected the desired changes across key variables.
- Comparison will be provided against other elite benchmarks
- You are receiving complimentary testing that typically costs $250 or more.
- A feedback consultation with ANZ High Performance Coach and ANZ/HPSNZ Physiologist will be available, which also provides opportunity to utilise these expertise as a sounding/problem solving resource on your training programme if you wish.

To the sport:

- You can leave a legacy with the characteristics that underpin elite performance for the learning and development of ANZ distance running athletes and strategy towards the 2020 and 2024 Olympic Games and beyond.
- You'll be fostering knowledge share between nations for the advancement of middle distance running athletes, coaches and expertise.
- You'll be part of a project that is developing world leading knowledge in the middle-distance community that will nurture international collaboration for the development of group training opportunities with squads across the world.

Your participation in this research is voluntary (it is your choice) and whether or not you choose to participate will neither advantage nor disadvantage you in relation to my role with HPSNZ/ANZ.

What is the purpose of this research?

Specifically, we will determine typical values of anaerobic speed reserve across different 'sub-groups' of middle distance runners; such knowledge will act as a profiling tool for coaches, in order to guide individualised training and event specialisation within Middle Distance running.

In the last few years' new world records have been established in the Women's 1500m and Men's 800, with the depth across all middle distance running events increasing since the Sydney 2000 Olympics. Therefore, ANZ/HPSNZ are conducting research to look at new areas to advance our knowledge of developing speed, to be competitive in middle distance running on the international stage.

Consistently in the 1500m we see last lap speed as a key differentiator between medallists and non-medallists. In the 800m, particularly in the men's event we are seeing much more of a 'gun to tape' or 'long sprint' approach to the event. Ultimately there are a number of qualities that underpin an athlete's ability to perform 'gun to tape' or 'sit and kick' strategies. With a wealth of physiology research on aerobic qualities underpinning middle

and long distance running performance already available, one key area that is rather underexplored in middle distance running is an athlete's anaerobic capabilities.

Therefore, we propose to answer the following questions through this research project:

What are the anaerobic ceilings of middle distance runners?

What are typical athlete profiles for 'sprint' and 'endurance' type middle distance runners?

The outputs from this research will go towards my PhD project where the data collected will be de-identified for research purposes, journal publications and academic presentations. Data will remain de-identified when shared with other coaches and scientists in the project. In addition, these results will contribute to New Zealand's distance running strategy, and the development of the next generation of distance runners in New Zealand.

How was I identified and why am I being invited to participate in this research?

As a male or female middle distance runner, who in the last 2 years has performed a 400 time of 48s (Male) or 55s (Female); 800m time (min:sec) of 1:47.50 (Male) or 2:03.00 (Female), or 1500 time of 3:39.00 (Male) or 4:09.50 (Female), you are invited to be part of this research. As an athlete capable of this standard, you have an opportunity to leave a legacy of the characteristics that underpin a performance of your calibre, for the learning of future generations of runners and coaches alike.

However, you will not be able to take part in this research if you are injured.

How do I agree to participate in this research?

You will need to read through this information sheet and then sign an informed consent form before you can participate in this research. You are able to withdraw from the study at any time. If you choose to withdraw from the study, then you will be offered the choice

between having any data that is identifiable as belonging to you removed or allowing it to continue to be used. However, once the findings have been produced, removal of your data may not be possible.

What will happen in this research?

Your involvement in this research will require you to perform a one off visit to either HPSNZ centre in Auckland or Christchurch region (Auckland – AUT Millennium, Christchurch – Jelly Park) for countermovement, drop jump and sprint assessment (1 hour), followed by a 40-minute physiology assessment to determine your maximal aerobic capacity. In Christchurch the physiology assessment will take place at the University of Canterbury.

The HPSNZ Physiologists running these measurements are very experienced in running such tests and have the necessary qualifications. Your coach may also be present the testing session.

Further details of the procedures involved a testing session are below.

48 hours pre testing

Avoid strenuous training sessions (i.e. $\dot{V}O_2max$, top speed or speed endurance type track or heavy gym/conditioning sessions)

Avoid alcohol consumption.

On the day pre testing

Avoid consumption of ergogenic aids – e.g. Caffeine

Jump testing

Following a warm up you will perform 3 maximal countermovement jumps, followed by 3 drop jumps for measures of muscular power and vertical stiffness.

Sprint Testing

Upon completion of the jumps, and following a more extensive warm up, you will perform 3 maximal 50m sprints from a standing start for measurement of maximal sprint speed which provides the ceiling of an athletes anaerobic speed reserve.

Maximal aerobic capacity assessment

Following an hours break, you will attend the physiology lab for a 6-8-minute treadmill test to exhaustion assessing maximal aerobic capacity ($\dot{V}O_2max$), and the speed at which that is reached (speed at $\dot{V}O_2max$ ($s\dot{V}O_2max$). $s\dot{V}O_2max$ provides the base of an athletes anaerobic speed reserve and allows for assessment of the inter-relationship between your maximal aerobic and anaerobic qualities.

If you have any personal issues regarding the above procedures, please let the primary researcher know of these prior to the study so that these can be accommodated for.

What are the discomforts and risks?

During sprint and jump performance tests, minimal discomfort and perhaps mild soreness will be experienced, certainly less than a normal training session

During the laboratory testing of aerobic capacity, an effort of increasing intensity across 6-8 minutes will be required finishing when the you reach volitional exhaustion. Some fatigue will be experience as it is a test of maximal aerobic ability but no different to that experienced as a normal part of training sessions for middle distance running.

How will these discomforts and risks be alleviated?

Any risks will be alleviated by using thorough warm ups for the sprint and jump assessment and avoiding strenuous exercise in the 48 hours prior to testing.

What compensation is available for injury or negligence?

In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for injury by accident may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

How will my privacy be protected?

All the data gained during this study will only be available to the researchers involved, and ANZ/HPSNZ if consent is provided.

If the data is published in the public domain, your name as a participant will not be revealed and all participants will remain anonymous.

What are the costs of participating in this research?

The cost of time for this study is approximately 3 hours. Travel to venues if outside an official ANZ event will be at the athletes own cost.

What opportunity do I have to consider this invitation?

You will have up to 2 weeks to consider this invitation.

Will I receive feedback on the results of this research?

At the end of the study you will receive a written summary of the findings. Your individual results from the study will only be shared with your coach if you grant us permission.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor:

Name: Prof Paul Laursen

E-mail: paul.laursen@hpsnz.org.nz

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, Kate O'Connor, *ethics@aut.ac.nz* , 921 9999 ext. 6038.

Whom do I contact for further information about this research?

Please keep this Information Sheet and a copy of the Consent Form for your future reference. You are also able to contact the research team as follows:

Researcher Contact Details:

Name: Gareth Sandford E-mail: gareth.sandford@hpsnz.org.nz

Project Supervisor Contact Details:

Name: Prof Paul Laursen; E-mail: paul.laursen@hpsnz.org.nz

Approved by the Auckland University of Technology Ethics Committee on *21st March 2017*, AUTEC Reference number *16364*

Appendix B1: Consent Form

Consent Form

Project title: ***Defining the role of anaerobic speed reserve in middle distance running***

Project Supervisor: ***Adjunct Prof Paul Laursen, Assoc Prof Andy Kilding, Dr Angus Ross***

Researcher: ***Gareth Sandford***

- ○ I have read and understood the information provided about this research project in the Information Sheet dated 28/09/2016. **Yes/No**
- ○ I have had an opportunity to ask questions and to have them answered. **Yes/No**
- ○ I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without being disadvantaged in any way. **Yes/No**
- ○ I understand that if I withdraw from the study then I will be offered the choice between having any data that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible. **Yes/No**
- ○ I understand that all data collected will be de-identified when presented for research purposes, and allow for its use in journal publications, a PhD thesis and academic presentations. **Yes/No**
- ○ I am not suffering from heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness or injury that impairs my physical performance, or any infection **Yes/No**

- ○ I agree to take part in this research. **Yes/No**
- ○ I agree to allow the use of my collected data to be shared with my coach **Yes/No**
- ○ I agree to allow my de-identified data to be shared with other coaches and scientists involved in the project **Yes/No**
- ○ I agree to allow my collected data to be stored by High Performance Sport New Zealand/Athletics New Zealand, and understand it may inform future policy or coaching decisions for Athletics New Zealand **Yes/No**
- ○ I wish to receive a summary of the research findings (please tick one): **Yes/No**

Participants signature

:.....……

Participant's name:.....……

Participant's Contact Details (if appropriate):

Date:

Approved by the Auckland University of Technology Ethics Committee on 15th November 2016 AUTEC Reference number 16/364

Note: The Participant should retain a copy of this form.

Appendix C1: Training History Questionnaire

Training History Questionnaire

Name: _____ Age: ____ Club/Country: _____

400 PB & SB: _____ 800m PB & SB: _____ 1500m PB &SB: _____

How many years have you been in a structured training programme of 4-5 days training a week?

_____

What phase of training are you in (off-season, pre competition, competition)?

_____

Please provide your average weekly mileage/km from the last 4 weeks of training

_____

Please provide the average number of sessions per week you performed strength and/or power work in the gym in the last 4 weeks

_____

Please provide the total number of times per week you perform maximum speed work in the current phase (e.g. reps up to and including 120m only may be included here)

In YOUR personal opinion, would you consider yourself more of a ‘sprint’ or ‘endurance’ type middle distance runner?

In YOUR personal opinion, which distance/event would you consider to be your best?

Appendix D1: Ethics Approval

Appendices

20 October 2016A

Paul Laursen

Faculty of Health and Environmental Sciences

Dear Paul

Ethics Application: 16/364 Defining the role of the anaerobic speed reserve in middle distance running

Thank you for submitting your application for ethical review. I am pleased to advise that the Auckland University of Technology Ethics Committee (AUTEC) approved your ethics application at their meeting on 17 October 2016 subject to the following conditions:

1. Provision of full information about the international component of the research including:
    a. Who will be participating;
    b. Where it will be taking place;
    c. How participants will be recruited and by whom;
    d. How it is linked to the qualification involved;
2. Clarification of what will be involved in the verbal advertisement of the research and where and when this will occur;
3. Revision on the section on benefits in the Information Sheet, moderating the nature of the claims.

Please provide me with a response to the points raised in these conditions, indicating either how you have satisfied these points or proposing an alternative approach. AUTEC also requires copies of any altered documents, such as Information Sheets, surveys etc. You are not required to resubmit the application form again. Any changes to responses in the form required by the committee in their conditions may be included in a supporting memorandum.

Please note that the Committee is always willing to discuss with applicants the points that have been made. There may be information that has not been made available to the Committee, or aspects of the research may not have been fully understood.

Once your response is received and confirmed as satisfying the Committee's points, you will be notified of the full approval of your ethics application. Full approval is not effective until all the conditions have been met. Data collection may not commence until

full approval has been confirmed. If these conditions are not met within six months, your application may be closed and a new application will be required if you wish to continue with this research.

To enable us to provide you with efficient service, we ask that you use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

I look forward to hearing from you,

Yours sincerely

Kate O'Connor

Executive Secretary

Auckland University of Technology Ethics Committee

Appendix E1: Ethics Alteration

21 March 2017

Appendices

Paul Laursen

Faculty of Health and Environmental Sciences

Dear Paul

Ethics Application: 16/364 Defining the role of the anaerobic speed reserve in middle distance running

Thank you for submitting your application for an amendment to your ethics application. I am pleased to advise the amendment to the data collection protocols is approved, subject to the following condition:

1. Inclusion of advice concerning the finger-prick testing in the Information Sheet.

Please provide me with a response to the point raised in this condition, indicating either how you have satisfied the point or proposing an alternative approach. AUTEC also requires copies of any altered documents, such as Information Sheets, surveys etc. You are not required to resubmit the application form again. Any changes to responses in the form required by the committee in their conditions may be included in a supporting memorandum.

Once your response is received and confirmed as satisfying the point, you will be notified of the full approval of your ethics application. Full approval is not effective until the condition has been met. Data collection may not commence until full approval has been confirmed. If the condition is not met within six months, your application may be closed and a new application will be required if you wish to continue with this research.

To enable us to provide you with efficient service, we ask that you use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

I look forward to hearing from you,

Appendices

Yours sincerely

Kate O’Connor

Executive Secretary

Auckland University of Technology Ethics Committee

Appendix F1: Invited Comment Journal of Applied Physiology

MIDDLE DISTANCE RUNNING EFFICIENCY—QUANTIFYING INTERVENTIONS AT WORKLOADS ABOVE CRITICAL VELOCITY—MORE THAN JUST A PHYSIOLOGICAL PURSUIT?

TO THE EDITOR: The demands of world class 800 m running competition require exceptional tolerance of high-intensity running speeds far beyond critical velocity (CV) (11.0 s/100 m sectors; 5). In agreement with field observations, modifications in running economy measured during submaximal exercise may not translate to improved running performance over middle-distance race speeds (2). Therefore, quantification of running efficiency at speeds above CV may allow better assessment of adaptive responses to resistance training interventions.

The impact that a resistance training intervention imparts on 800 m "race pace" running may be difficult to define and quantify. Underlying improvements in high-intensity (>CV) running efficiency following a resistance training intervention may stem from biomechanical and anthropometric adaptations that include inter and intramuscular coordination and postural control as well as changes in passive stiffness of relevant tissue (and, as a result, leg spring stiffness) that ultimately reduce energy leakage during running (1, 4) to optimize the utilization of the available D′. In addition, resistance training can enhance ground reaction force application in both vertical and horizontal planes, both of which provide cocoordinative challenges that limit the ability to perform faster running speeds and may extend an athletes tolerance to high-intensity work. A multidisciplinary perspective that incorporates the sciences of biomechanics and motor control, alongside physiology, may allow us to view middle-distance running more as a skill, whereby an applied resistance training intervention can foster the development of the underlying components of importance for efficient high-intensity running and D′ of middle-distance runners (3).

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Gareth N. Sandford[1,2,3]
Simon Pearson[1,4]
Andrew E. Kilding[1]
Angus Ross[2,3]
Paul B. Laursen[1,2]
[1]*Sport Performance Research Institute New Zealand (SPRINZ) Auckland University of Technology Auckland, New Zealand;*
[2]*High Performance Sport New Zealand Auckland, New Zealand;*
[3]*Athletics New Zealand Auckland, New Zealand; and*
[4]*Queensland Academy of Sport Nathan, Australia*

CARDIOVASCULAR CHANGES RELATED TO RESISTANCE TRAINING ARE GREATER THAN TYPES III/IV AFFERENTS FOR EXERCISE TOLERANCE AND W′

TO THE EDITOR: The recent Viewpoint (1) postulates that resistance training can enhance exercise tolerance and W′ by reducing firing frequency of types III/IV afferents. However, both skeletal muscle vascularization and blood flow capacity can also play crucial roles in oxygen transport to muscle fibers, maximal oxidative metabolic rate, and clearance of fatigue-related metabolites, which have been shown critical to W′ (2, 3). Importantly, hemodynamic changes such as increase in blood flow, total capillary/arteriolar proliferation, and cross sectional area can occur in both trained and untrained skeletal muscle (2–4) and are greater in shorter concentric/eccentric (e.g., workout training) compared with longer (e.g., isometric/muscle stretching) muscle contractions (3–5). Overall, these components have been shown to exert more influence over critical power than firing frequency of types III/IV afferents or other components of fatigue, even in COPD and CHF patients (3, 4). Therefore, resistance training might be capable to improve muscle functions more likely by a broad spectrum of cardiovascular adaptations [e.g., neuronal nitric oxide synthase (nNOS), arteriogenesis, angiogenesis, microvascular O_2 transport and muscle blood flow] than the regulation over types III/IV afferents activity (2–4). Accordingly, cardiovascular adaptations need to be taken into account beyond firing frequency muscle types III/IV afferents on improvements of the exercise tolerance and W′, even in clinical populations.

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Anderson Luiz B. da Silveira[1]
Emerson Lopes Olivares[2]
Fernando de Azevedo Cruz Seara[3]
[1]*Laboratory of Physiology and Human Performance Department of Physical Education and Sports Federal Rural University of Rio de Janeiro, Brazil;*
[2]*Laboratory of Cardiovascular Physiology and Pharmacology Department of Physiological Sciences Federal Rural University of Rio de Janeiro, Brazil; and*
[3]*Laboratory of Cardiac Electrophysiology Carlos Chagas Filho Department of Biophysics Federal University of Rio de Janeiro*

Viewpoint: Resistance training and exercise tolerance during high-intensity exercise: moving beyond just running economy and muscle strength. *J Appl Physiol*, in press 2017. Denadai BS and Greco CC**.**

Comment on Viewpoint: Middle distance running efficiency – quantifying interventions at workloads above Critical Velocity – more than just a physiological pursuit?

Gareth N. Sandford [1,2,3], Simon Pearson[1,4], Andrew E. Kilding[1], Angus Ross [2,3] and Paul B. Laursen[1, 2]

Affiliations:

Sport Performance Research Institute New Zealand (SPRINZ), Auckland University of Technology, Auckland, New Zealand

High Performance Sport New Zealand, Auckland, New Zealand

Athletics New Zealand, Auckland, New Zealand

Queensland Academy of Sport, Nathan, QLD 4211, Australia

Appendix G1: **Invited Commentary Journal of Applied Physiology (Accepted)**

Comment: Use aerobic energy expenditure instead of oxygen uptake to quantify exercise intensity and predict endurance performance. Owen N. Beck, Shayla Kipp, William C Byrnes and Rodger Cram

Comment on Viewpoint: Relative exercise intensity should be quantified by physiological and mechanical thresholds

Authors: Gareth N. Sandford[1], Ed Maunder[1*]

Affiliations: [1]Sports Performance Research Institute New Zealand, Auckland University of Technology, Auckland, New Zealand

Defining relative exercise intensity is a pertinent issue raised by Beck *et al.* (Beck, Kipp, Byrnes, & Kram, 2018). However, the proposed method (Beck et al., 2018), whilst appropriate for *intra*-individual comparison, does not sufficiently address *inter*-individual differences. We propose relative exercise intensity is better quantified using individual physiological thresholds, namely lactate threshold (LT) and maximal lactate steady-state (MLSS), alongside the mechanical anaerobic speed reserve (ASR) (Bundle & Weyand, 2012), or the work rate range from maximum oxygen uptake ($\dot{V}O_{2max}$) to maximum sprint speed (MSS) or power. Indeed, these parameters can be used effectively in endurance sport to ensure training sessions evoke a given physiological stress and are conducted according to the desired training intensity distribution.

For instance, specific low-intensity training sessions are prescribed below LT such that they can be sustained for long periods and elicit low physiological stress. It is this point – that exercise is below the individual's LT - that defines the exercise as low-intensity. Where LT exists as a $\%\dot{V}O_{2max}$, or $\%\dot{E}_{aero}max$, varies between-individuals (Achten & Jeukendrup, 2004). Therefore, exercise at $60\%\dot{V}O_{2max}$ or $\dot{E}_{aero}max$ may be <LT in one athlete, but >LT in another, and thus of different physiological stress and relative

intensity. Similarly, defining high-intensity exercise (>MLSS) as a %$\dot{V}O_{2max}$ or %$\dot{E}_{aero}$max assumes uniform *inter*-individual mechanical ability at supramaximal workloads, but the individual's ASR may define this competence (M. Buchheit & Laursen, 2013). Indeed, ASR effectively explains inter-individual variation in time-to-exhaustion at >90%$\dot{V}O_{2max}$ (Blondel et al., 2001), and therefore the individualized relative exercise intensity.

Thus, to ensure the relative exercise intensity is consistent between- and within-individuals, use of individual physiological and mechanical thresholds seems most appropriate.